CHAPTER 1.

INTRODUCTION

1.1 Project Background

St. John is the third largest island composing the United States Virgin Islands and it is located approximately 80 km east of Puerto Rico (Figure 1). This 50 km^2 island is well known because of its pristine beaches and the richness of its marine environment. Approximately 56% of the total land area and 23 km^2 of its offshore waters are located within the boundaries of the Virgin Islands National Park. An additional 47 km^2 of its offshore waters were designated as the V.I. Coral Reef National Monument in 2001. The National Park Service, local authorities and residents have been concerned with the potential environmental impact induced by the rapid development that has occurred on privately-owned lands over the past 30 years. Increases in erosion and sediment delivery rates to the marine environment are perceived to be one of the most important environmental issues on St. John (Rogers, 1998).

Several studies have used the sediments deposited in bays and salt ponds to assess the impacts of land use on long-term erosion rates on St. John (Hubbard et al., 1987; Nichols and Brush, 1988). Hubbard et al. (1987) concluded that extensive agriculture during the plantation era on the island had “exceedingly long-term repercussions” on the rate of sediment delivery to the marine environment, and that these effects still dominated the effects of more recent development. On the other hand, Nichols and Brush (1988) found that land use during the plantation era had no massive effect on sedimentation in the Reef Bay swamp.

More recent attempts have complemented sedimentation data with direct estimates of sediment production rates from different sources (Anderson, 1994; Sampson, 2000). These studies determined that the unpaved road network is probably the major source of sediment on the island (MacDonald et al., 1997, 2001). While these earlier studies provided a basic understanding of erosion processes on St. John, a more intense and longer-term study was needed to better understand runoff and erosion rates, and the delivery of sediment to the marine environment.

1.2 Study Objectives

The main tasks of this study were to:

- Measure sediment production rates from road travelways, identify the factors controlling erosion rates, and develop an empirical model for road sediment production;
- Measure runoff from a road segment and develop two event-based runoff models;
- Couple the road segment runoff model to a sediment-rating curve to compare suspended sediment yields to those measured by a sediment trap;
- Measure sediment production from streambanks, treethrow, undisturbed hillslopes, and road cutslopes.
- Develop a GIS-based sediment budget model (STJ_EROS) using empirical sediment production and delivery functions;
- Apply STJ-EROS to three basins on St. John and estimate the contribution of unpaved roads to watershed-scale sediment yields.

The results of this study are expected to become a useful addition to the literature on erosion in the Virgin Islands and the Caribbean. The results also can improve the assessment of erosion problems in several ways. First, sediment yield rates for small islands in the Caribbean are not well documented (UNEP, 1994). This study will provide one of the few estimates of undisturbed sediment yield rates for dry tropical islands in the Caribbean. Knowledge of these background rates is required in any attempt to quantify the effects of land development. Second, even though unpaved road networks have been recognized as an important sediment source in other regions, erosion from unpaved roads has been generally overlooked in the Caribbean. Third, the GIS-based STJ-EROS model will provide a means to quantify the relative contribution of different sediment sources, identify appropriate erosion control strategies, and aid in guiding future development.

1.3 Physiography of St. John

1.3.1 Topography

The topography of St. John is very rugged, as more than 80% of the island has slopes greater than 30%, and only about 9% of the island has slopes of 10% or less (CH2M Hill, 1979; Anderson, 1994). The island has a central ridge that runs east-west across the length of the island, and the highest point is Bordeaux Mountain at 387 m (Figure 1). Since the central ridge is closer to the northern coast of the island, watersheds draining to the south tend to be larger than their counterparts to the north. The shoreline is made up of sheltered coves or rocky promontories containing sand and cobble beach deposits.

This topography plays an important role in erosion and sediment transport processes. First, slope is a very important factor controlling surface erosion rates (Kirkby, 1980). Second, the steep topography affects the morphology of the stream network and its capacity to transport sediment.

1.3.2 Geology

The lithology of St. John is dominated by two distinct formations of volcanic origins (Meyerhoff, 1926; Donnelly, 1966; Rankin, 2002). The oldest rocks on the island are the basalt and volcanic wacke of the Water Island formation, and these were formed as volcanic flows on the ocean floor during the Early Cretaceous period. These volcanic rocks were eventually uplifted by regional tectonic stresses. The second period of rock development in St. John occurred as explosive shallow water and subaerial volcanism during the Late Cretaceous age.

These rocks form the Louisenhoj formation. These formations have eventually undergone periods of deformation and magmatic intrusions that hydrothermally altered some of these rocks. A limestone formation was deposited after the second volcanic period, but these rocks only have limited exposure on the island.

1.3.3 Soils

Soils are dominated by the Cramer clay loam series, which is characterized by a fine clayey matrix with abundant coarse fragments (Soil Conservation Service, 1970). These soils tend to be shallow (< 30 cm), moderately permeable, well-drained, and underlain by nearly impervious bedrock. The moderate permeability and high infiltration rates of these soils largely preclude the development of Hortonian (precipitation-excess) overland flow. Shallow soils underlain by a nearly impermeable layer favor the development of saturation overland flow. When overland flow does occur, the dense vegetation and high proportion of coarse fragments in the soil result in a high surface roughness that reduces runoff velocities and the potential for erosion.

1.3.4 Climate

The climate of St. John is described as dry tropical. Rainfall on the island falls frequently in the form of brief showers caused by the orographic lifting of the predominant easterly winds (Calversbert, 1970). The island has been divided into five zones based on annual average precipitation. Values range from 89-102 cm on the East End to 127-140 cm close to Bordeaux Mountain (Bowden et al., 1970). There are no sharply defined wet and dry seasons, but there is a relatively dry season from about February to July and a relatively wet season from August until January.

Easterly waves moving through the Caribbean are important sources of rainfall from May through November, while cold fronts affect the rainfall regime the rest of the year (Calversbert, 1970). Easterly waves sometime develop into tropical storms and hurricanes, which may result in large amounts of rain, strong winds, and high seas.

1.3.5 Surface Hydrology

Potential evapotranspiration (PET) is very high throughout the entire year. Bowden et al. (1970) estimated PET for two climatic stations in St. John using the Thornwaite method, and determined that the average monthly PET is generally greater than average monthly precipitation. The deficit of rainfall relative to PET means that the island has no perennial streams (MacDonald et al., 1997). The combination of steep slopes, small drainage areas, shallow soils with low water holding capacities, and occasional intense storm events results in “flashy” runoff hydrographs with steep rising and recession limbs. According to MacDonald et al. (1997), there is little evidence for widespread Horton overland flow, so peak runoff is controlled primarily by saturation overland flow and subsurface stormflow.

Runoff processes have never been formally studied in St. John. The nature of runoff development has important implications in how sediment is produced, stored, and transported through the landscape. While short-lived storms during dry periods are not likely to trigger runoff in the streams (known as guts in the Virgin Islands), these events produce runoff and sediment from road surfaces. This sediment is deposited on the hillslopes or in the guts until a larger storm triggers sufficient runoff to transport it through the stream network.

1.3.6 Vegetation

The original forests of St. John were eliminated or degraded and are now in various stages of recovery. Dry evergreen forests and shrubs cover approximately 63% of the total land area, moist forest and secondary vegetation cover about 30%, while urban, wetland, and pasture each cover about 2% of the island (Woodbury and Weaver, 1987).

1.3.7 Land Use

The history of land use in St. John is very similar to that of most of the islands in the eastern Caribbean. Originally St. John was completely forested and experienced only minor changes during the settling of Amerindian groups. During the 1700's and 1800's, approximately 90% of the forests were removed to be replaced by sugarcane fields (Tyson, 1987). The decline of the sugarcane industry in the late 19th century forced the abandonment of agricultural fields and the beginning of the forest recovery period. The United States purchased the Virgin Islands from Denmark in 1917, and in 1956 Virgin Islands National Park was established. The park was designated an International Biosphere Reserve in 1976, and it is one of the few reserves that has both marine and terrestrial resources (Rogers, 1992). In 2001 an additional 47 km^2 of offshore waters were designated as the V.I. Coral Reef National Monument.

The island currently is believed to be experiencing the highest sediment production and yield rates in historical times (MacDonald et al., 1997). Development on privately-owned lands outside the park boundaries has increased drastically over the past 30 years. Homesite development may affect erosion processes by: (1) clearing of forest vegetation; (2) displacing soil and rock into unstable areas; and (3) increasing the density of unpaved roads. For example, a 1971 aerial photograph indicated 8.3 km of roads in the 6.0 km^2 Fish Bay basin. By 2000 the road network had increased to 23.2 km with 13.1 km or 56% still unpaved. The unpaved road density of 2.2 km km^{-2} in the Fish Bay basin contrasts to the unpaved road density of 0.8 km km^{-2} in the 4.3 km^2 Greater Lameshur Bay basin (Nemeth et al., 2001). The Greater Lameshur Bay basin has remained mostly undeveloped, as most of it is within VINP.

1.4 Literature Review

1.4.1 Erosion Studies in St. John

One of the first publications dealing with erosion issues in the Virgin Islands was by Hubbard (1987). This report did not include any data, but it provided a good summary of the status of sediment-related management strategies, and drew attention to the potential effects of sedimentation on coral reefs. It identified siltation and light attenuation as the most important adverse effects of increased sedimentation rates. Upland development and marine dredging were highlighted as the two main causes of these increased rates.

A contemporaneous study assessing the long-term impacts of historical development in St. John concluded that "[land] development impacts appear to still be exerting a secondary control behind the factors of watershed size and [bay] geometry" (Hubbard et al., 1987). The observed long-term decline in coral growth rates was attributed to the long-term delivery of sediments eroded during the plantation era.

Long-term sedimentation rates were estimated from core samples taken from the Reef Bay swamp and Mandal Pond on the southern part of St John (Nichols and Brush, 1988) (Figure 1). These deposits consisted of 8% sand, 23% silt, and 69% clay, and the estimated sediment yield rates were on the order of 40 tons per year over the past 3,000 years. The authors concluded that the effects of humans on sedimentation rates over several thousand years were minor compared to the natural variations.

The ANSWERS model was applied to the Great Cruz Bay basin and the estimated suspended sediment loads for individual storms with recurrence intervals of less than two years ranged from 15 to 4,100 tons km^{-2} (Ramsarran, 1992). These sediment yield rates are up to two orders of magnitude higher than the annual sediment yields estimated by other studies.

Watershed-scale sediment yield rates for St. John were estimated to range from 7 to 40 tons km^{-2} yr^{-1} as part of a sediment budget study (Anderson, 1994). These long-term estimates are at the low end of rates for tropical forests, but are justified by the occurrence of low erodibility of the soils, the relatively dry climatic regime, and the rare occurrence of mass wasting processes (De Graff et al., 1989; MacDonald et al., 1997). Anderson (1994) concluded that current sediment yield rates are higher than during any other historical period. Application of a simple GIS-based road erosion model (ROADMOD) identified the unpaved road network as an important source of sediment. The unpaved road network was estimated to be quadrupling natural sediment yields in the Fish Bay basin, while in Lameshur Bay roads were estimated to be increasing sediment yields by only 40% above background levels (Anderson and MacDonald, 1998).

Anderson and MacDonald (1998) made the following recommendations for future research: (1) estimate erosion from road cuts, fill slopes, and drainage ditches; (2) develop a time-dependent variable for estimating road erosion rates; (3) calibrate the road erosion model to individual runoff events so that varying weather conditions can be simulated; and (4) integrate the road sediment production model with hillslope and stream channel sediment production and delivery models. This study addresses most of these recommendations.

In another study, runoff and sediment production rates were measured from undisturbed hillslopes and road surfaces (Sampson, 2000; MacDonald et al., 1997). Plots on undisturbed hillslopes produced runoff only during large rainfall events related to hurricanes and no measurable sediment. Plots on unpaved roads produced measurable amounts of runoff for all storms exceeding 6 mm of rainfall. Sediment production rates from unpaved roads were strongly correlated with storm energy. Road-segment scale sediment production measured by sediment fences ranged from 0.1 to 7 kg m^{-2} yr^{-1}. Erosion rates at the road-segment scale were only 20-30% of the values measured at the plot-scale (0.9 to 15 kg m^{-2} yr^{-1}).

1.4.2 Road Erosion

Erosion of road surfaces has been identified as an important erosion problem in a wide variety of forested areas. Roads have proven to be an important source of sediment in forested areas of the Pacific Northwest of the United States (e.g., Reid et al., 1981), New Zealand (Fahey and Coker, 1989), Australia (Grayson et al., 1993), Kenya (Dunne, 1979), Ecuador (Harden, 1992), and on St. John in the U.S. Virgin Islands (MacDonald et al., 1997). The seriousness of the problem in the United States may be appreciated by the following statement: "… sediment production from forest roads is the greatest problem in the mountains of the Pacific coast from Alaska to California, the northern and central Rocky Mountains, and the mountainous East" (Burroughs et al., 1991). Surface erosion from roads can be an important source of fine sediment, even in areas with a high frequency of mass wasting (e.g., Reid et al., 1981).

In sloping terrain the road prism typically consists of three main surfaces: the travelway, cutslope, and fillslope. Since erosion processes act at different rates on each of these surfaces, sediment production rates were measured from both road travelways and cutslopes.

Travelways have been the subject of numerous studies, and they can be the main source of fine sediment being delivered to streams (e.g., Reid, 1981). The road tread poses a challenge to researchers because these surfaces are affected by unique processes, such as traffic and regrading, that can affect erosion rates. Ramos (1997) suggested that the factors affecting sediment production from roads can be grouped into two categories: (1) those that significantly change over time; and (2) those that are more stable with time. Variable factors include road age, road use, road maintenance, the particle-size distribution of the road surface material, road drainage patterns, and climate. Constant factors are primarily road surfacing, and road gradient.

Sediment production from cutslopes may be induced by mass wasting, rockfall, dry ravel, rainsplash, and rilling (Ramos, 1997). Studies have shown that sediment production rates from cutslopes may be controlled by cutslope age, climatic regime, aspect, cutslope gradient, strength of parent material, vegetation density, and hillslope drainage area. Sediment produced from cutslopes is never delivered directly to the fluvial system, as it is first routed to an inside ditch, where it is either transported by runoff or removed during maintenance operations. This study estimates the rate at which cutslopes contribute to road-segment scale sediment production.

A large number of methods have been used to quantify road sediment production and the contribution of roads to sediment yields (Ramos, 1997). One general approach has been to measure watershed-scale sediment yields from areas before and after road construction (e.g., Beschta, 1978; Rice et al., 1979; Anderson and Potts, 1987; Grayson et al., 1993). Other studies have quantified small-scale sediment production rates from centimeter-scale rainfall simulators (Harden, 1992), bounded field plots with rainfall simulators (e.g., Johnston et al., 1980; Burroughs and King, 1989; Burroughs et al, 1991), small bounded plots under natural precipitation events (e.g., Vincent, 1979; Sampson, 2000), and flume experiments (Zhang and Cundy, 1987). Other studies have measured sediment production rates at the road segment scale by measuring runoff rates and collecting suspended sediment samples manually (e.g., Reid, 1981) or with automatic samplers (Kahklen, 1993), flow splitters (e.g., Swift, 1984), or sediment-runoff collection troughs (e.g., Luce and Black, 2001). Others have estimated road erosion rates from volumetric analysis of rilled surfaces (Froehlich, 1991; Anderson and MacDonald, 1998). The sediment fence method (Robichaud and Brown, 2002) was used to measure sediment production rates from unpaved roads as part of this study. This method was also used to measure road erosion rates in a smaller, shorter-term study on St. John (MacDonald et al., 2001).

1.4.3 Sediment Budgets

According to Reid and Dunne (1996) a sediment budget is "… an accounting of the sources and disposition of sediment as it travels from its point of origin to its eventual exit from a drainage basin." The method for developing a sediment budget was first outlined by Gilbert (1917) and first implemented in a field-based measuring strategy by Leopold et al. (1966). The methodology gained popularity in the early 1980's when it was recognized as an useful tool to assess the effects of forestry and other land disturbances on sediment production and sediment yields. Swanson et al. (1982) define a sediment budget as "a quantitative description of the movement of sediment through a single landscape unit". This definition implies the estimation of sediment production rates from areas with relatively homogeneous physical characteristics. In this study landscape units were defined and used to stratify measurements of sediment production measurements from natural and anthropogenic sources. These data were used to develop empirical sediment production models within a GIS-based sediment budget model (STJ_EROS).

The development of a sediment budget also requires a routing component. STJ_EROS uses sediment delivery ratios to estimate watershed-scale sediment delivery rates. The sediment delivery ratio (SDR) has been defined as the ratio of sediment delivered to the catchment outlet to the gross erosion occurring within the basin (Walling, 1983). SDR's have been used in previous GIS models, as they provide simple sediment routing procedures when the data required for more physically-based models are not available. The sediment delivery ratios used in STJ_EROS calculate the long-term ratio of sediment delivered to the marine environment (i.e., not retained within the fluvial network, salt ponds, or coastal wetlands).

1.5 Organization of Dissertation

This dissertation is organized into six chapters. Chapter 2 discusses the measurement and modeling of sediment production from 21 unpaved road segments with varying slopes, drainage areas, and frequency of grading. Chapter 3 presents detailed runoff and suspended sediment measurements from an unpaved road segment in the Maho Bay area, and the use of these data to develop and test two runoff models. Sediment production rates from streambank erosion, treethrow, undisturbed areas, and road cutslopes are presented in Chapter 4. Chapter 5 describes the development of the STJ-EROS sediment budget model and its application to three different basins on St. John. Chapter 6 presents the overall conclusions of the study, identifies additional research needs, and presents recommendations for resource managers and regulatory agencies.

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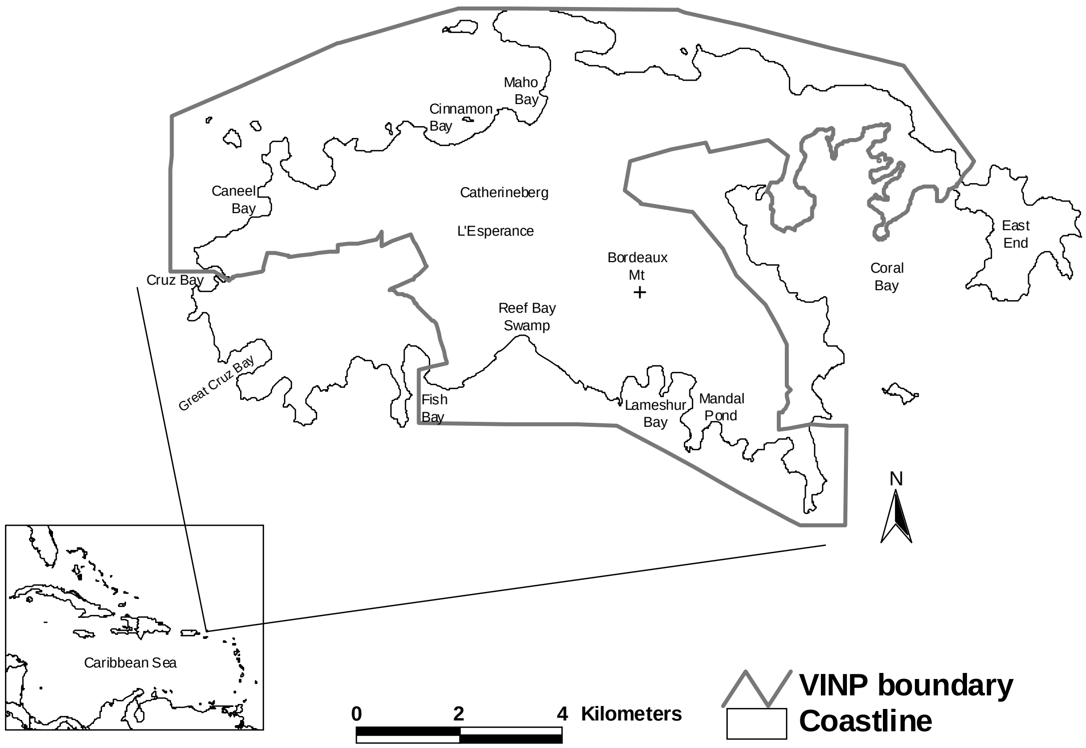

Figure 1. Map of St. John showing the boundaries of Virgin Islands National Park.