# The Effects of Land Development on Sediment Loading Rates into the Coastal Waters of the Islands of Culebra and Vieques, Puerto Rico

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### **A. PROJECT BACKGROUND**

The coral reefs of Puerto Rico are among the most highly threatened marine ecosystems in the entire Caribbean Region, and pollution from inland sources ranks second only to overfishing as a high priority threat. Increased delivery of land-based sediments associated to coastal development is perceived to be one of the most important factors affecting the coral reefs of Puerto Rico. The proposed project will use a GIS-based tool to estimate sediment loading rates into the coastal waters of Culebra and Vieques, where indirect evidence suggests that observed declines in coral cover are associated with increases in sediment yields from land development.

A modified version of the St. John Erosion Model (STJ-EROS) (Ramos-Scharrón, 2004; Ramos-Scharrón and MacDonald, 2007a) was used to estimate sediment yields from 9.0 km<sup>2</sup> of land area draining to the Culebra coastline, and this is about 33% percent of the total land area of Culebra. The model was also be used to quantify sediment yield rates into the coastal waters of Vieques from the 3.2 km<sup>2</sup> Villa Borinquen watershed. Model results serve to assess the impact of current land development activities in sediment loading rates to the coastal waters of both Culebra and Vieques by comparing current estimates to background rates. The model results also allow us to identify individual sediment sources associated with high sediment yields.

The intended long-term objective of this project is to reduce the amount of sediment reaching the coastal waters of both islands. Results presented here provide a framework that will eventually facilitate the development of an erosion control management strategy. A pair of proposals has been submitted by this PI to the PR-DNER Costal Zone Program office (2009-10) and to NOAA (ARRA, Coastal and Marine Habitat Restoration Grant Program, 2009-11) to implement an erosion control strategy in Culebra. As part of these upcoming projects we will meet with stakeholders representing both the private and public sectors to identify additional sources of funds to further implement erosion control strategies.

Keywords: Coastal development, erosion, GIS model, water quality, coral reef ecosystem management.

### **B. RESEARCH PROBLEM**

Researchers suggest that a generalized decline in coral cover observed over the past three decades in the Caribbean Region may be associated with localized increases in the levels of anthropogenic stresses (Gardner et al., 2003). Recent estimates suggest that twothirds of the 26,000 km<sup>2</sup> of coral reefs in the Caribbean are at risk from at least one source of anthropogenic threat, and approximately one-third are perceived to be threatened by coastal development (Burke and Maidens, 2004).

The coral reefs of Puerto Rico are among the most highly threatened reefs of the entire Caribbean (Burke and Maidens, 2004), and inland sources of pollution rank second only to over-fishing as a high priority threat. Excess delivery of land-based sediments is an important control on the condition of coral reefs. A high concentration of sediment in the water column deteriorates water quality and reduces the amount of light needed for photosynthesis by symbiotic algae, while settling of sediment can smother existing coral or reduce the surface area suitable for new coral growth (Hubbard, 1986; Rogers, 1990). Even though land erosion is recognized to pose a major threat to nearshore ecosystems (Waddell, 2005) limited actions are generally taken to mitigate its effects (Lugo et al., 1981). A recent report by the U.S. Geological Survey indicates that current sediment delivery rates into the coastal waters of Puerto Rico are extremely high as they range between 570 and 1,900 Mg km<sup>-2</sup> yr<sup>-1</sup> (Warne et al., 2005), and this is particularly alarming when we consider that these rates reflect data that were collected mostly from stream gauging stations located upstream from rapidly developing coastal areas. No such type of data is yet available for the islands of Culebra and Vieques.

The islands of Culebra and Vieques display coral reef ecosystems characteristic of northeastern Caribbean marine biodiversity (Hernández-Delgado et al., 2000), and they represent highly valuable sources of fishing, tourism and recreational activities. Culebra also supports the first no-take marine reserve established in Puerto Rico, and houses several ongoing academic and community-based coral reef and reef fisheries management conservation projects. Culebra's and Vieques' nearshore coral reefs have been described as some of the most exceptional coral reefs in Puerto Rico (Simonsen, 2000), and this may be due in part to historic low doses of terrestrial sediment inputs originating from the relatively small watersheds that drain both islands and a sub-tropical dry climatic setting.

Long-term monitoring within the Luis Peña Channel Natural Reserve (LPCNR) in Culebra has shown an alarming 5-11% annual decline in percent coral cover since 1997 (Hernández-

Delgado and Sabat, in press). Indirect evidence suggests that the decline in coral cover may be associated with increased sedimentation resulting from recent coastal development. In 2004 the USCRTF identified Culebra as one of two priority sites in Puerto Rico needing a Local Action Strategy plan because of the perceived risk posed by the rapid rate of coastal development. The coral reefs in Viegues are considered to be in a poorer state than those in Culebra, and this has been attributed in part to higher sediment yields due to relatively larger watersheds in Viegues than in Culebra and historically more intense agricultural activities (MacGarrity and Deslarzes, undated; Deslarzes et al., undated). Current land development practices in Culebra-Viegues generally consists of vegetation removal, combined with ground leveling and compaction associated to construction (e.g., individual home sites and resorts) and opening of low-standard, steep roads that tend to remain unpaved for relatively long periods (Figure 1). Limited background information currently exists on this type of development on a sub-tropical dry climatic setting such as in Culebra-Vieques, but data from La Parguera (PR) and St. John (USVI) suggests that disturbed surfaces can erode at rates that are up to four-orders of magnitude higher than undisturbed surfaces (Ramos-Scharrón, 2004, 2006; Ramos-Scharrón and MacDonald, 2005, 2007b, 2007c), and that current watershed-scale sediment yields are up to 10 times higher than under undisturbed conditions (Ramos-Scharrón and MacDonald, 2007a).

The lack of a scientifically-based methodology that provides a broad cumulative effects perspective on erosion problems is partly to blame for the lack of any guided and effective erosion control action in Culebra and Vieques. The results of this project will allow the PR-DNER, as well as other public agencies and the general public to better evaluate the erosion problem in both islands. The results of this project could also aid in the development of similar projects elsewhere in Puerto Rico and the rest of the insular Caribbean by serving as an example for effective collaborative effort among state, federal and municipal government agencies, academia, and the local communities.

### C. GOALS AND OBJECTIVES

The main goal of this project was to assess the effects of unpaved roads in increasing sediment loading rates into the coastal waters of Culebra and Vieques. Assessments were based on the application of the Geographical Information System based STJ-EROS model (Ramos-Scharrón, 2004; Ramos-Scharrón and MacDonald, 2007a) to four areas in Culebra and one basin on Vieques. The full version of STJ-EROS estimates sediment yields from unpaved road travelways, road cutslopes, streambanks, treethrow, and undisturbed hillslopes based on empirical sediment production functions and sediment delivery ratios. The STJ-EROS program code was edited to take advantage of new software developments and to accommodate local conditions. First, the code was updated from its original AML (Arc Macro Language) format that used to run on ArcINFO 8.2 software to an ArcTool format built using the Model Builder feature available from the latest ArcGIS software version (version 9.3). Second, the modified version used for Culebra and Viegues lacks routines to calculate sediment contributions from streambanks and treethrow. Significant differences in the landscape and vegetation characteristics of these two islands were noted during my field visits and these observations suggested that these two routines were

unnecessary and that they would improperly describe local conditions (this is further discussed later in this report).

The modified version of STJ-EROS was used to estimate sediment yields from 9.0 km<sup>2</sup> land area in Culebra and a 4.3 km<sup>2</sup> basin in Vieques (Figures 2 and 3). Model results assess the impact that coastal development in the form of unpaved roads is having in sediment loading rates to the coastal waters of both islands. Model results will also allow us to identify points along the coastline with high sediment inputs, as well as to identify individual sediment sources associated with high sediment yields.

The results of this project will also be used to justify the need to conduct further research in Culebra and Vieques to address the adverse impacts of land-based sediment sources in nearshore coral reef systems. Sediment delivery estimates will also aid in the development of an adequate study design to quantify the relationships between watershed processes with ecosystem health and coral reef benthic structure. The results of the proposed project may also be used to encourage and guide public and private stakeholders in the development and implementation of erosion control strategies. STJ-EROS results are already being used by land managers and local communities in the Virgin Islands as the basis of coral reef restoration projects focusing on the reduction of land-based sediment loading rates. These projects include a partnership between the Island Resources Foundation and the Gulf of Mexico Foundation, the National Fish and Wildlife Foundation, and the Caribbean Regional office of the U.S. Fish & Wildlife to restore the coral reefs of Fish Bay in St. John.

### **D. METHODOLOGY**

#### **GENERAL INTRODUCTION**

STJ-EROS is a Geographical Information System model that uses empirical sediment production functions and sediment delivery ratios to quantify watershed-scale sediment yields (Ramos-Scharrón, 2004; Ramos-Scharrón and MacDonald, 2007a). The original program code consists of six input routines and five routines to calculate sediment production and delivery. The input routines have interfaces that allow the user to adjust the key variables that control sediment production and delivery. The other five routines use preset erosion rate constants, user-defined variables, and values from nine data layers to calculate watershed-scale sediment yields from unpaved road travelways, road cutslopes, streambanks, treethrow, and undisturbed hillslopes. STJ-EROS estimates sediment production rates from each of these five landscape units using empirical equations that were developed from data collected in St. John between 1998 and 2000 (Ramos-Scharrón, 2004). In STJ-EROS, the estimated rate at which terrestrial sediment is transferred to coastal waters is controlled by user-defined sediment delivery ratios (SDRs), where SDR is the ratio of sediment delivery to the gross erosion in the basin. In STJ-EROS the program allows users to choose SDR values ranging from 50% to 100% for areas with a high sediment delivery potential. These are areas that drain directly to the sea without an intervening coastal wetland or salt pond. SDRs for areas draining into coastal wetlands are assumed to range from 0% to 50%, and these catchments are defined as having a moderate potential for

sediment delivery. Catchments that drain to a wetland or pond without any surface pathway to the marine environment are assumed to have a SDR of zero.

The original version of STJ-EROS was written for the ArcInfo Workstation 8.2 software in Arc Macro Language code (AML). As described above, this code contained routines to estimate sediment yields from unpaved road travelways, road cutslopes, streambanks, treethrow, and undisturbed hillslopes (Ramos-Scharrón, 2004). As part of this project the code was updated so that it could run in the current version of the ArcGIS software (version 9.3). A major change in the model is that it has been prepared using the Model Builder feature available through the ArcGIS software. Model builder is a simpler way to develop model routines than scripting (i.e., writing a code), as it has a graphical flowchart interface that simplifies process organization. Model Builder also allows users to run the model through a simple interface made available as an ArcTool (i.e., windows-based and mouse activated).

The updated version of STJ-EROS only has three main routines: 1) a sediment delivery selection routine; 2) a road erosion and sediment yield estimation routine; and 3) a routine to calculate sediment production rates by surface erosion on undisturbed hillslopes. Field observations made in Culebra and Viegues led me to the conclusion that the streambank and treethrow routines were either unnecessary or likely to yield erroneous results. The streambank erosion routine is meant to estimate the contribution from erodible streambanks by the erosive action of water flowing along a channel feature. On St. John such types of erodible banks are common at the bottom portions of the larger watersheds (with drainage areas exceeding several  $km^{2}$ 's) where the fluvial network intersects relatively **Ramos Scharrón** 

extensive alluvial deposits. Such types of streambanks were not observed in Culebra or Vieques due to the small size of the watersheds and the lack extensive alluvial deposits. Therefore, streambank erosion was assumed to be negligible at the five study watersheds and no update was attempted on the streambank erosion routine. Similarly, forest cover in St. John is very different than that found in Vieques and Culebra due to slight but still important differences in climatic regimes. Therefore, the empirical treethrow functions developed from St. John data and used by STJ-EROS were deemed to be impractical for application on Culebra and Vieques and the treethrow routine was not updated.

#### **'SEDIMENT DELIVERY' ROUTINE**

The revised version of STJ-EROS begins with the 'Sediment Delivery' routine. This routine prompts the user to select the SDR parameter values for both high and moderate sediment delivery potential areas. Polygons defining each individual watershed are stored as feature datasets within a feature class called 'Watershed' (Appendix A). The routine prompts the user to select the name of the watershed or source area where the model is to be applied. In STJ-EROS the SDR values are meant to account for both hillslope and channel storage, including the potential storage by coastal wetlands, salt ponds, or mangrove swamps. Suggested SDRs for catchments with drainage areas of 0.1 – 5 km<sup>2</sup> such as the ones in Culebra and Vieques generally range between 50% and 100% (Walling, 1983). These values are recommended for estimating SDRs for drainages that have been identified as having a high sediment delivery potential. These areas are those that lack an intervening coastal

wetland or pond feature and therefore have direct access to coastal waters. In this project a 75% value was consistently used for all high sediment delivery areas.

The delivery of sediment from catchments with an intervening wetland or salt pond is complicated as their capacity to trap sediment before it enters the marine system is likely to depend on a large number of factors. No empirical study has been able to quantify the trapping efficiency of the types of coastal wetlands found in Vieques and Culebra. In the absence of reliable quantitative values, SDRs for areas draining into coastal wetlands are assumed to range from 0% to 50%, and these catchments are defined as having a moderate potential for sediment delivery. All moderate areas in this project were assigned a 25% SDR value.

The 'Sediment Delivery' routine is very simple. It begins by clipping the 'Sediment Delivery Potential' shapefile with the chosen 'Watershed' shapefile (Figure 5). The 'Sediment Delivery Potential' geo-database feature class contains polygons that define the spatial distribution of sediment delivery areas. These areas were defined by on-screen digitizing according to topography and the identification of wetland or salt pond features in aerial photographs (Appendix A). The routine then uses a series of "Select" and "Calculate Field" functions to assign the chosen SDR values to the appropriate polygons in a newly created 'SDR' value field. The "Merge" command is used to combine shapefiles containing individual sediment delivery potential polygons into a final single polygon shapefile that contains data for all areas within the watershed.

#### **'ROAD SEDIMENT DELIVERY' ROUTINE**

Of particular importance in Culebra and Vieques is to estimate sediment contributions from well-compacted, unpaved road surfaces as these tend to produce runoff and sediment even during brief rainfall events<sup>(17)</sup>. In addition, unpaved roads are found throughout most watersheds on both islands. It is important to note that the equations used to estimate sediment production rates from unpaved roads and undisturbed hillslopes in STJ-EROS are empirical and are based on data collected on St. John-USVI (Table 1). In the absence of locally-derived sediment production functions we must rely on those generated on St. John, which share a similar geologic background and only a slightly wetter climatic regime.

Statistical regression analysis on road erosion data collected from St. John showed that erosion rates from unpaved roads can be estimated from three main factors: 1) road segment scale average gradient (as a decimal) raised to the 1.5<sup>th</sup> power; 2) rainfall; and 3) time since construction or road grading related to maintenance activities (Ramos-Scharrón and MacDonald, 2005). These three factors are used by STJ-EROS to calculate the amount of sediment produced per unit area (kg m<sup>-2</sup>) for individual road segments. For a full description of the development of these erosion functions see Ramos-Scharrón and MacDonald (2005, 2007a & b).

A road segment encompasses the road surface between road drainage points (e.g., culverts). Annual rainfall rates in cm per year are used to calculate annual erosion rates in kg m<sup>-2</sup> yr<sup>-1</sup> and total sediment production is the product of erosion rate times the road surface area (total length times average road width). Time since construction and road grading

frequency control erosion rates by defining the amount of easily erodible fine sediment found on a road surface (Ramos-Scharrón and MacDonald, 2005). St. John data showed that roads that are graded at least once every two years had a mean sediment production rate that was 2.4-times higher than active roads that had not been graded for more than two years. Abandoned, very low traffic roads partly covered by near-ground vegetation eroded at a rate that was only 10% of ungraded roads (Ramos-Scharrón, 2004). These three categories (i.e., graded, ungraded, and abandoned) are used by STJ-EROS to calculate erosion rates, as each type has a different equation relating erosion to rainfall and slope.

Field surveys consisted in the collection of data needed to run the models. Precise mapping of both the road segments and the location of drainage points was done with a GPS unit combined with detailed field sketches and on-screen digitizing using a geo-referenced 2004 aerial photograph. Field sketches contained information related to surfacing (i.e., paved, unpaved, graveled), road segment geometry (i.e., length and widths of sub-segments) measured with a tape measure, slope measured with a hand clinometer, and road grading category. In the absence of precise time since construction or information on the frequency of grading, defining the grading category was based on a qualitative assessment of the road surface texture and vegetation cover. A road was identified as graded if its surface was dominated by a fine surface texture lacking vegetation and with only limited exposure of large rock fragments (Figure 4). Ungraded roads were identified as those that were still actively travelled, but had an abundance of coarse fragments on its surface (i.e., armored surface) and a very low vegetation cover density (Figure 4).

Abandoned roads were those that exhibited an armored surface and a high abundance of vegetation due to low traffic rates (Figure 4).

A total of 47.8 km of roads were surveyed in the field; 35.2 km in Culebra and 12.6 km in Vieques. Data for road segments for which no access was possible was estimated based on aerial photograph interpretation and GIS analyses. Roads that were not surveyed were assumed to have a standard 4.0 m width and were assumed to be ungraded. Drainage points were assumed to be located at topographical depressions. Slope in percent was calculated using the digital elevation model by taking the elevation difference between the top and lower ends of the road segment and dividing it by the length of the segment. Spatial and attribute data for both paved and unpaved roads was organized in a geo-database feature class named 'Roads' (Appendix A). Road drainage points were stored in a separate feature class named 'Drain'. Individual segments in 'Roads' are related to their road drainage points in 'Drain' by a common attribute named "Drain\_Id" (Appendix A).

The 'Road Sediment Delivery' routine calculates total sediment production (i.e., total erosion) from all individual road segments as well as their estimated sediment yield contribution to coastal waters (i.e., sediment delivery). This routine prompts the user to choose the watershed or source area where the model is to be applied, as well as the annual rainfall rate for the area. For the purposes of this project, a 100 cm per year estimate (39 inches yr<sup>-1</sup>) was used for all watersheds in Culebra and a 110 cm per year rate (43 inches yr<sup>-1</sup>) was used for the watershed in Vieques (OSU Spatial Climate Analysis Service, 2002).

The 'Road Sediment Delivery' routine begins by clipping road drainage points in 'Drain' with the watershed or source area polygon chosen by the user; so that the resulting data layer only contains drainage points within the area of interest (Figure 6). An "Intersect" command is used to pass the SDR values assigned by the user in the previous routine to all road drainage points according to their location. For the purposes of this project, road drainage points located within areas mapped as having a high sediment delivery potential were assigned a 75% SDR attribute value by this routine, while those in moderate delivery polygons were assigned an SDR value of 25%. A "Join Field" tool is then used to pass on the SDR value to the 'Roads' database based on each road's "Drain ID" attribute value and the SDR values previously assigned to each drainage point. After adding a series of attribute columns to later accommodate rainfall data, as well as sediment production, and sediment delivery estimates the routine sorts roads into different shapefiles according to their grading classification (i.e., graded, ungraded, and abandoned). Sediment production rates are then calculated according to its grading classification and road segment characteristics using the equations shown in Table 1 The total amount of sediment contribution from individual road segments into coastal waters is the product of total erosion times the SDR. The routine then 'Merges' roads of all the three different road grading types into one shapefile containing all road attribute data as well as sediment production and sediment delivery estimates. A 100 m buffered version of the watershed polygon is used to clip the roads shapefile to include all of these roads near the perimeter of the watershed in maps displaying the model results.

#### 'NATURAL HILLSLOPES' ROUTINE

The last routine is called 'Natural Hillslopes' and it calculates sediment production and yield rates by surface erosion from undisturbed hillslopes. These surface erosion and yield rates provide estimates on the amount of sediment reaching the coastal waters for undisturbed conditions and serve as a background estimate on which to assess the impact that the unpaved road network is currently having on sediment load rates. This routine prompts the user for the name of the watershed or source area where the model is to be applied, as well as the annual rainfall total.

The routine first creates a copy of the SDR shapefile resulting from the 'Sediment Delivery' routine and adds several fields to accommodate rainfall values and estimated sediment production and sediment delivery rates (Figure 7). Then the routine uses the watershed name chosen by the user to eliminate any dangling polygons that might have resulted during clipping of the original "Sediment delivery potential" geo-database. Then the routine calculates annual sediment production rates based on the equation shown in Table 1. As it was described for the road sediment production equations, the undisturbed hillslope equation was also developed based on empirical data collected at several sites in St. John. The validity of this equation to the surface erosion rates occurring in Culebra and Vieques is debatable but the resulting sediment production estimates should be within an order of magnitude of actual rates. For a complete description on the development of this equation see Ramos-Scharrón and MacDonald (2007a & b).

### **E. DESCRIPTION OF STUDY AREAS**

The modified version of the STJ-EROS model was applied to a 13.2 km<sup>2</sup> land area in the islands of Culebra and Vieques. The study areas were divided into four different sections on Culebra (8.9 km<sup>2</sup>) and one section in Vieques (4.3 km<sup>2</sup>). Road erosion analyses was also performed on PR-DNER managed areas in the immediacies of Bahía Mosquito in Vieques, but those were done with a spreadsheet version of the model and the results are shown separately in Appendix B. The five source areas cannot be labeled as watersheds in the strict sense of the word as they are each drained by several streams and smaller drainages (i.e., 'quebradas'). Therefore the sediment delivery estimates resulting from each area are not delivered at a specific location (i.e., stream outlet) or bay but are each spread over a 2 - 7 km long coastline. The four study areas in Culebra have been labeled Punta Soldado, Bahía Mosquito, Puerto Manglar, and Zoní; while the study area in Vieques is called Villa Borinquen.

The 1.6 km<sup>2</sup> Punta Soldado area is located on the southwestern tip of Culebra. Portions of this area drain towards Ensenada Honda, but other portions drain to coastlines outside of Culebra's main harbor- Ensenada Honda (Figure 2, 8a). Approximately 80% of the area was identified as having a high potential for sediment delivery into the marine system due to the lack of intervening wetlands that could serve as sediment retention zones (Figure 8b; Table 2). There are 11.2 km of roads within the area for an overall road density of 7.0 km per km<sup>2</sup>. A total of 62% or 6.9 km of the roads are unpaved, and this includes 2.4 km of actively used and frequently graded roads, 2.6 km of active but ungraded roads, and 1.9 km of abandoned roads. Unpaved roads have a mean slope of 11%.

The 3.3 km<sup>2</sup> Bahía Mosquito area also drains to portions of the coastline that are both inside and outside of Ensenada Honda (Figure 2, 9a). In contrast with the Punta Soldado area, only 20% of the Bahía Mosquito source area has a high sediment delivery potential (Figure 9b; Table 2). About 80% of the area drains towards wetland areas that are presumed to play an important role in trapping a portion of the sediment before it is delivered to coastal waters. The road network is 16.5 km in length and the road density is the lowest among all five study areas at 5.0 km km<sup>-2</sup>; 66% or 7.2 km of the roads still remain unpaved. About 2.8 km of roads (39% of unpaved) are frequently graded, almost half or 3.5 km are ungraded, and only 0.86 km (12%) have been abandoned or are only occasionally travelled.

The 2.2 km<sup>2</sup> Puerto Manglar area mostly drains to Puerto Manglar Bay and only contains zones with a moderate potential for delivering sediments to the coastal waters due to the abundance of wetland features (Figure 2, 10a, 10b). This area contains 11.7 km of roads for an overall road density of 5.3 km km<sup>-2</sup> (Table 2). About 8.9 km of roads or 76% are unpaved. Among unpaved roads only 21% and 22% are graded and abandoned (~1.9 km), respectively; the remaining 57% (5.1 km) were categorized as ungraded. The average slope of unpaved roads in this area is 7%.

The 1.8 km<sup>2</sup> Zoní area drains towards the east towards the Canal de Culebrita between the island of Culebrita and Cayo Norte (Figure 2, 11a). About 60% of the area was identified as having a high potential for sediment delivery while the remaining 40% drains towards Laguna Zoní which provides a buffer that prevents direct delivery of sediments into the marine environment (Figure 11b; Table 2). There are 9.54 km of roads in the Zoní source area for an overall road density of 5.3 km km<sup>-2</sup>; 69% or 6.6 km of these roads are unpaved (Table 2). Among unpaved roads 1.5 km or 23% are frequently graded, 2.8 km (42%) are ungraded, and 2.3 km (35%) are abandoned. The average slope of unpaved roads in the Zoní area is 8%.

The 4.3 km<sup>2</sup> Villa Borinquen basin is located just east of the town of Isabel Segunda and drains towards the northern coast of Vieques (Figure 3, 12a). There are no coastal wetland areas between this basin and the marine environment so the entire area is mapped as having a high potential for sediment delivery (Figure 12b). There are 29.4 km of roads in the Villa Borinquen area for a road density of 6.8 km km<sup>-2</sup>(Table 2). Villa Borinquen has the highest road density among all five study areas included in this report. About 18.2 km or 62% of the roads are unpaved, and among those one-quarter or 4.5 km are frequently graded, 12.7 km or 70% are ungraded, and only 0.9 km (5%) are abandoned. The average slope of unpaved roads within the Villa Borinquen basin is 8%.

### F. RESULTS

#### **GENERAL RESULTS**

STJ-EROS estimates that annual yield rates from the five study areas range between 0.2 - 0.7 Mg km<sup>-2</sup> yr<sup>-1</sup> (Figure 13). These rates are very low when compared to worldwide sediment delivery rates and they are an order of magnitude lower than those estimated for St. John (Ramos-Scharrón, 2004). The low range for values in Culebra and Vieques are due to the use of equations that produce very low estimates for natural hillslopes, the prevalence of coastal wetlands and thus lower sediment delivery ratios, and the absence of other types of sediment sources. Applications of the full version of STJ-EROS to three watersheds in St.

John show that streambank erosion tends to dominate sediment yields under undisturbed condition as they are responsible for 80 - 90% of the sediment delivered into the coastal waters from natural sources. As a result, sediment yield rates estimated for St. John are between 2 - 7 Mg km<sup>-2</sup> yr<sup>-1</sup>, and this is an entire order of magnitude higher than those in the Culebra and Vieques study areas.

Current sediment yield estimates that account for both undisturbed hillslope and unpaved road contributions in the five study areas range between 20 – 125 Mg km<sup>-2</sup> yr<sup>-1</sup>, and these rates are 47 – 185 times higher than those under undisturbed conditions. Approximately 99% of the estimated total yields originate from unpaved road surfaces. The broad range of sediment yield estimates is caused by variable unpaved road densities and differences in the characteristics that control sediment production rates from the unpaved road network (i.e., grading types, slopes, etc.), as well as disparities in the relative abundance of sediment delivery potential areas. The range of sediment yield rates estimated for the study areas in Culebra and Viegues are on the high end or much higher than those estimated on three watersheds on St. John even though rainfall rates on St. John are slightly higher than those in the present study areas. The main difference between the study areas in St. John and those in Culebra and Viegues appears to be in the abundance of unpaved roads. While the unpaved road densities in St. John (between 0.8 and 2.1 km km<sup>-2</sup>) led to road-related sediment yields in the range of 9 – 17 Mg km<sup>-2</sup> yr<sup>-1</sup> (Ramos-Scharrón and MacDonald, 2007a), unpaved road densities for the present study ranged between 3.3 and 4.3 km km<sup>-2</sup> and they lead to road-related sediment yields in the order of 20 – 124 Mg km<sup>-2</sup> yr<sup>-1</sup> (Figure 14). Due to the lesser abundance of unpaved roads in St. John and the higher

background sediment production rates relative to the Culebra and Vieques study areas, the relative increase in sediment yields due to the unpaved road network in St. John is much lower and it ranges between 5 and 7 times above undisturbed conditions. The reduced abundance of unpaved roads on the three study areas in St. John is due in part to the existence of the VI National Park (VINP). Although unpaved roads are still found within VINP, road densities within Park limits are very small compared to private land and this maintains an overall lower road presence and hence lower sediment yield rates.

The spatially-distributed nature of STJ-EROS facilitates the quantification and display of sediment yields from different portions of the study areas and from each individual road segment. Maps exhibiting the model results show the areas that are more sensitive to development because of their relatively higher sediment delivery potential, and individual road segments delivering high quantities of sediment. These maps could also be somewhat deceiving as they might be interpreted to suggest that high sediment contributions stem from only a few road segments, instead of informing the viewer to the more realistic nonpoint source nature of sediment loading problems. A non-point source of pollution problem implies that sediment originates from a variety of sources and that these sources must be spread over large portions within an area of concern. Specific unpaved road segments producing large amounts of sediment might contribute a relatively higher proportion of sediment to coastal waters than other individual road segments producing less sediment, but over a large area the contributions from both moderate and high sediment producing roads might be very similar. The following sections discuss the results of STJ-EROS application to the five study areas.

#### **PUNTA SOLDADO**

STJ-EROS estimated that the total amount of sediment reaching coastal waters from the Punta Soldado source area is 203 Mg yr<sup>-1</sup>. Punta Soldado maps demonstrate that there are a number of road segments contributing sediment at a moderate to high rate (> 5 Mg yr<sup>-1</sup>) and that these segments are located throughout a large portion of the source area within high sediment delivery potential areas (Figure 8c). Although graded roads represent only 35% of the entire road network, they represent more than 70% of the sediment yield (Figure 15). Meanwhile, ungraded and abandoned roads compose 37% and 28% of the unpaved road network but are responsible for only 27% and 1% of the total sediment yield, respectively. A map displaying the location and magnitude of sediment contribution from individual road drainage points shows that most sediment produced within the study area is draining towards Ensenada Honda, while very little is draining towards other portions of the coastline (Figure 8d).

The results show that one single road segment measuring just over 100 m in length is responsible for delivering 17 Mg of sediment every year and this is about 8% of the total sediment yield for the entire area (Figures 8c and 16a). Meanwhile, unpaved road segments delivering between 5 and 15 Mg yr<sup>-1</sup> total 1.9 km in length or 28% of the unpaved road network but they contribute 121 Mg yr<sup>-1</sup> or 60% of the sediment being delivered to the coast. The Punta Soldado area presents a case in which a moderate to significant reduction in sediment yields could be achieved by attending erosion problems within a relatively small portion of the road network. The situation could still be described as a non-point source type of problem but with a few well-defined point sources. Still, an erosion control program

should address the contribution from all roads generating sediment at an excess of 5 Mg yr<sup>-1</sup> in order for it to be effective.

### Bahía Mosquito

The Bahía Mosquito maps displaying the results of the STJ-EROS application show that there are only a few road segments yielding high rates of sediment into the coastal waters and that most of these are located on the eastern portions of the source area where there is a high potential for sediment delivery (Figure 9c). These areas drain outside of Ensenada Honda and Bahía Mosquito. Graded roads represent 39% of the unpaved road network but contribute 69% of the sediment delivery. On the other hand, ungraded roads correspond to almost half of the unpaved road network length but only contribute 29% of the sediment. Contribution from abandoned roads in the Bahía Mosquito area is negligible (Figure 15). The total amount of sediment reaching the marine environment from the Bahía Mosquito area under current conditions is 150 Mg yr<sup>-1</sup> according to STJ-EROS.

A 210 m long graded road segment on the eastern side of the Bahía Mosquito area represents only 2% of the unpaved road network but is responsible for delivering about 25 Mg of sediment every year or 17% of the total sediment yield for the entire area (Figure 9c, 16b). About 1.4 km of unpaved road segments (13%) yield sediment at rates between 5 and 15 Mg yr<sup>-1</sup>, and they contribute 39% of total yields. Meanwhile, the 4.2 km of roads producing sediment at a slow rate ( $0.5 - 5 Mg yr^{-1}$ ) are so predominant, encompassing 39% of the entire unpaved road network, that they contribute 37% of the entire sediment yield. Controlling erosion from a road network such as the one found within the Mosquito Bay area is difficult

as the area presents a truly non-point source situation in which a significantly large percentage of the road network would need to be the focus of erosion control activities in order for them to effectively reduce sediment yields.

### PUERTO MANGLAR

According to STJ-EROS current sediment yields into coastal waters from Puerto Manglar are the lowest among the five study areas at 45 Mg yr<sup>-1</sup>. The road sediment delivery result map for Puerto Manglar shows that most unpaved roads are contributing sediment at a relatively low rate (Figure 10c). The maps show that sediment contributions are well-distributed throughout the entire area (Figure 10d). Graded and ungraded roads represent 21% and 57% of the unpaved road network within the Puerto Manglar source area and each road type contributes about half of the sediment reaching the coastal waters (Figure 15). Sediment contributions from the 1.9 km of unpaved roads are negligible.

A 145-m long graded road segment located in the central sections of the Puerto Manglar area is the only segment that contributes sediment at a rate exceeding 5 Mg yr<sup>-1</sup> and this equals 12% of the sediment yield for the entire area. The 3.1 km of unpaved road segments that deliver sediment at a rate between 0.5 and 5.0 Mg yr<sup>-1</sup> are responsible for 71% of the total sediment yield (Figure 16c). As described for the Bahía Mosquito area, this represents a truly difficult situation to control sediment contributions from unpaved roads. The Puerto Manglar area presents itself as a strong non-point source of pollution case in which many road segments are equally contributing to a high sediment yield rate problem.

Therefore, any significant reduction in sediment yields will require improving relatively long portions of roads and subsequently a significant amount of funds.

### Zoní

The spatial distribution of road sediment sources and drainage points in Zoní, as well as its natural drainage pattern, indicate that the delivery of sediment to coastal waters from this area is not concentrated at a particular location but are spread along a large portion of its coastline (Figures 11c, 11d). Graded and ungraded roads represent 23% and 42% of the unpaved road network and contribute about 49% and 45% of the total amount of sediment estimated to reach the coast. The 2.3 km of abandoned roads are responsible for only about 6% of the total sediment yield. The rate of sediment delivery into coastal waters from the Zoní source area is 52 Mg yr<sup>-1</sup> according to STJ-EROS.

Two road segments totaling about 300 m in length contribute sediment at a rate exceeding 5 Mg yr<sup>-1</sup> and they are responsible for a total of 14.9 Mg of sediment a year or 29% of the total sediment yield (Figure 16d). Roads yielding sediment at rates ranging between 0.5 and 5.0 Mg yr<sup>-1</sup> compose 2.4 km of roads or 54% of the unpaved road network and yield a total of 33 Mg yr<sup>-1</sup> or 64% of the total sediment yield. The Zoní area presents a zone in which moderate reductions in sediment yield rates could be achieved by attending a small fraction of road segments. Any attempt to mitigate sediment contributions from unpaved roads in this area should first target the two segments generating sediments at a very high pace before attending any other road segments.

#### **VILLA BORINQUEN**

There are a total of 18.2 km of unpaved roads within the Villa Borinquen area and according to STJ-EROS these are responsible for delivering a total of 435 Mg of sediment every year into the marine environment. These sediment yield rates are 2 to 10 times higher than the net sediment yields expected from any of the other four study areas included in this project. Maps showing the spatial distribution of sediment sources within this basin indicate that important sources are spread over large portions of the watershed (Figures 12c, 12d). The topographical arrangement of the basin also indicates that these sediments are being delivered to a rather narrow coastline and are thus capable of delivering huge amounts of sediment to a rather localized area.

Graded roads represent 4.6 km or 25% of the unpaved road network in the Villa Borinquen area but they are responsible for 61% of the total sediment delivery (265 Mg yr<sup>-1</sup>) (Figure 15). Ungraded roads compose 70% of the unpaved road network and contribute 40% of the total sediment yield (170 Mg yr<sup>-1</sup>). Contribution from the 0.9 km of abandoned roads is negligible.

There are six unpaved road segments that each yields more than 10 Mg of sediment every year (Figure 12c). These road segments total 1.1 km in length or 6% of the unpaved road network but are responsible for delivering 94 Mg of sediment per year or 22% of the annual yield (Figure 16e). Roads segments yielding between 0.5 and 10 Mg yr<sup>-1</sup> encompass 69% of the unpaved road network and 76% of the total yield. The conditions at Villa Borinquen described here show that sediment delivery from unpaved roads can be viewed both as a point and non-point source. While a few road segments contribute a significant proportion

of the sediment yield, erosion mitigation efforts must not only focus on the segments showing the highest sediment delivery rates, but also on other roads generating sediment at lower rates.

### **G.** CONCLUSIONS

Nearshore waters in the vicinity of the islands of Culebra and Vieques contain unique coral reef ecosystems that typify northeastern Caribbean marine biodiversity, and they represent highly valuable sources of fishing, tourism and recreational activities. These coral reef systems are currently being threatened by both natural processes and anthropogenic stressors. Among the anthropogenic stressors that are threatening the reefs of both Culebra and Vieques, sedimentation from terrigenous sources is perceived to be of utmost importance. Initial visits to both islands identified the unpaved road network as an important source of sediment due to its current spatial coverage and its potential for additional extension, its connectivity with the stream network and the marine environment, its long-term persistence as a sediment source, and its potential to produce sediment at very high rates.

As a result, the current project was devised to assess the impact that unpaved roads are currently having on the amount of terrestrial sediment reaching the coastline. For this purposes, the project relied on the STJ-EROS model which was developed by this author based on previous research done on the nearby island of St. John. STJ-EROS is a Geographical Information System sediment budget model that contains sediment production functions for both natural and anthropogenic sediment sources typical of small coastal watersheds such as the ones found in Culebra and Vieques. STJ-EROS was chosen because it suffices the intention to assess the sediment contribution from unpaved roads and because the geographic proximity between St. John and these study sites provides a certain climatic and geologic history control that allows us to trust the model's overall results. The STJ-EROS code was updated as part of this study so that I could run in the latest version of the ArcGIS software (version 9.3).

STJ-EROS was applied to five areas totaling 13.3 km<sup>2</sup> in the islands of Culebra and Vieques. The five areas were named Punta Soldado, Bahía Mosquito, Puerto Manglar, and Zoní all in Culebra, and Villa Borinquen in Vieques. A preliminary assessment on PR-DNER lands bordering Mosquito Bay in Vieques was also done as part of this study but that is presented as a separate report (Appendix B). Extensive field data collection was completed in both islands to collect the necessary information to develop the geo-databases required by the STJ-EROS model. A total of 48 km of roads were surveyed in the field for road surface type (i.e., paved or unpaved), road drainage location points (GPS referenced), width, slope, and road grading type (i.e., frequently graded, ungraded, or abandoned). Field data was entered into the proper geo-databases and any missing information for inaccessible areas was completed by aerial photo interpretation and GIS analyses.

STJ-EROS results show that sediment yield rates during undisturbed conditions range between 0.2 and 0.7 Mg km<sup>-2</sup> yr<sup>-1</sup>. These rates are very low even when compared to those estimated by STJ-EROS for the island of St. John because the study areas in Culebra and Vieques lacked contributions from other important sediment sources found in other islands. Of particular importance is the lack of well-defined streambanks at the bottom of the watersheds, as streambanks tend to dominate sediment delivery rates under natural conditions wherever they are found. Current sediment yield rates according to STJ-EROS ranged from 20 to 125 Mg km<sup>-2</sup> yr<sup>-1</sup> (45 - 440 Mg yr<sup>-1</sup>) and these rates are between 50 and 185 times higher than those estimated for undisturbed conditions. Sediment contributions from unpaved roads represent 99% of the estimated sediment yields.

The highest net and per unit area sediment yield rates estimated were for the Villa Borinquen (Vieques) and Punta Soldado (Culebra) areas with 440 and 200 Mg yr<sup>-1</sup> or 100 and 125 Mg km<sup>-2</sup> yr<sup>-1</sup>, respectively. The high rates for these areas are associated to their relatively high unpaved road density, their road characteristics (i.e., slope, grading categories), and their high potential for delivering sediment into coastal waters due to the absence of coastal wetlands. Per unit area sediment delivery rates for the Villa Borinquen and Punta Soldado areas are three to six times higher than those estimated for heavily impacted watersheds in St. John.

Maps displaying the spatial distribution of sediment sources show areas receiving large amounts of sediment from unpaved roads and coastal waters that might be potentially impacted by them. Careful interpretation of these maps is suggested as they could be easily mistaken to propose that the erosion problem in these source areas is point-based rather than its true non-point nature. Maps used in combination with a new set of graphs devised for this study show that sediment sources in each of the five study areas are not only spread throughout the source areas, but also that a relatively large number of road segments are contributing important amounts of sediment to the estimated sediment yields. In some cases, considerable amounts of reductions in sediment contributions can be achieved by only targeting the few fastest eroding road segments, but even in those extreme cases sediment delivery would not be reduced by much more than 20% if efforts are limited to those road segments. Therefore, any plan to effectively mitigate sediment contributions from unpaved roads into the marine environment of the islands of Culebra and Vieques should not only target fast eroding 'hot-spots' but also provide a comprehensive strategy to address erosion problems on other road segments that individually might not be contributing as much sediment but cumulatively play even a more important role than those 'hot-spots'.

### **H.ACKNOWLEDGEMENTS**

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# J. FIGURES



Figure 1. A newly constructed unpaved road in the Villa Borinquen area in Vieques (left) and an old but rilled unpaved road in the Punta Soldado area in Culebra (right).



Figure 2. Map of the island of Culebra showing the location of the four study areas.



Figure 3. Map of the island of Vieques displaying the location of the Villa Boriquen and Mosquito Bay source areas.



Figure 4. Close-up views of graded (top left), ungraded (top right), and abandoned (bottom) unpaved road surfaces. Graded road surfaces are characterized by the abundance of fine sediments and lack of vegetation. Ungraded roads surfaces are actively used by vehicles and therefore they usually have very little vegetation cover but are armored by coarse rock fragments. Abandoned roads are usually well armored by rock fragments and have a dense vegetation cover due to the lack of any frequent vehicle use.



Figure 5. Model builder flowchart for the 'Sediment delivery' routine in the modified version of the STJ-EROS model.



Figure 6. Model builder flowcharts for the 'Road sediment delivery' routine in the modified version of the STJ-EROS model.


Figure 7. Model builder flowcharts for the 'Natural hillslopes' routine in the modified version of the STJ-EROS model.



Figure 8a. A 2004 aerial image of the Punta Soldado study area in Culebra.



Figure 8b. Topographical contours, sediment delivery potential areas, and delineation of paved and unpaved roads in the Punta Soldado study area in Culebra.



Figure 8c. Annual sediment contributions to coastal waters from individual road segments in the Punta Soldado study area in Culebra.



Figure. 8d. Annual sediment contribution to the marine environment collected at each road drainage delivery point for the Punta Soldado study area.



Figure 9a. A 2004 aerial image of the Bahía Mosquito study area in Culebra.



Figure 9b. Topographical contours, sediment delivery potential areas, and delineation of paved and unpaved roads in the Bahía Mosquito study area in Culebra.



Figure 9c. Annual sediment contributions to coastal waters from individual road segments in the Bahía Mosquito study area in Culebra.



Figure. 9d. Annual sediment contribution to the marine environment collected at each road drainage delivery point for the Bahía Mosquito study area.



Figure 10a. A 2004 aerial image of the Puerto Manglar study area in Culebra.



Figure 10b. Topographical contours, sediment delivery potential areas, and delineation of paved and unpaved roads in the Puerto Manglar study area in Culebra.



Figure 10c. Annual sediment contributions to coastal waters from individual road segments in the Puerto Manglar study area in Culebra.



Figure. 10d. Annual sediment contribution to the marine environment collected at each road drainage delivery point for the Puerto Manglar study area.



Figure 11a. A 2004 aerial image of the Zoní study area in Culebra.



Figure 11b. Topographical contours, sediment delivery potential areas, and delineation of paved and unpaved roads in the Zoní study area in Culebra.



Figure 11c. Annual sediment contributions to coastal waters from individual road segments in the Zoní study area in Culebra.



Figure. 11d. Annual sediment contribution to the marine environment collected at each road drainage delivery point for the Zoní study area.



Figure 12a. A 2004 aerial image of the Villa Borinquen study area in Vieques.



Figure 12b. Topographical contours, sediment delivery potential areas, and delineation of paved and unpaved roads in the Villa Borinquen study area in Vieques.



Figure 12c. Annual sediment contributions to coastal waters from individual road segments in the northern portions of the Villa Borinquen study area in Vieques.



Figure 12c (cont.). Annual sediment contributions to coastal waters from individual road segments in the southern portions of the Villa Borinquen study area in Vieques.



Figure 12d. Annual sediment contribution to the marine environment collected at each road drainage delivery point for the southern portions of the Villa Borinquen study area in Vieques.



Figure 12d (cont.). Annual sediment contribution to the marine environment collected at each road drainage delivery point for the southern portions of the Villa Borinquen study area in Vieques.



Figure 13. Sediment yields from both undisturbed hillslopes and unpaved roads for the five study areas in Culebra and Vieques based on the application of the STJ-EROS model.



Figure 14. Relationship between unpaved road densities and estimated unpaved road sediment yields for the five study areas in Culebra and Vieques and three watersheds on the island of St. John (Ramos-Scharrón and MacDonald, 2007a). All estimates are based on the application of the STJ-EROS model.



Figure 15. Annual sediment delivery rates for the four types of sediment sources accounted for by the STJ-EROS model.



Figure 16a. Figure shows the percent of unpaved road network length that contributes sediment at a given delivery rate, as well as the proportion that each road class (by sediment delivery rate) contributes to total sediment yields. The graph shows that 40% of the unpaved road network in the Punta Soldado area contributes sediment at a very low rate ( < 0.5 Mg yr<sup>-1</sup>) and that their sediment contribution is less than 5%. Most of the sediment yields originates from roads contributing between 0.5 and 10 Mg yr<sup>-1</sup> (~85%) and that the contribution from fast-eroding roads (> 10 Mg yr<sup>-1</sup>) represents less than 10% of the total yields.



Figure 16b. The graph shows that about 45% of the unpaved road network in the Bahía Mosquito area contributes sediment at a very low rate (< 0.5 Mg yr<sup>-1</sup>) and that their summed contribution is about 8% of the total estimated yield. Most of the sediment yields (~70%) originates from roads contributing between 0.5 and 12.5 Mg yr<sup>-1</sup>, and that the contribution from fast-eroding roads (> 15 Mg yr<sup>-1</sup>) is about 20% of the total yields.



Figure 16c. The graph shows that about 55% of the unpaved road network in the Puerto Manglar area contributes sediment at a very low rate (<  $0.5 \text{ Mg yr}^{-1}$ ) and that these roads are responsible for less than 20% of the total sediment yield. The graph also shows that the remaining 80% of the sediment being delivered originates from roads contributing between 0.5 and 7.5 Mg of sediment per year. There are no road segments contributing more than 7.5 Mg yr<sup>-1</sup> within the Puerto Manglar area.



Figure 16d. The graph shows that close to 40% of the unpaved road network in the Zoní area contributes sediment at a very low rate (<  $0.5 \text{ Mg yr}^{-1}$ ) and that these roads are responsible for less than 10% of the total sediment yield. The graph also shows that the remaining 80% of the sediment being delivered originates from roads contributing between 0.5 and 7.5 Mg of sediment per year. There are no road segments contributing more than 7.5 Mg yr<sup>-1</sup> within the Zoní area.



Figure 16e. The graph shows that about 25% of the unpaved road network in the Villa Borinquen area contributes sediment at a very low rate (< 0.5 Mg yr<sup>-1</sup>) and that these roads contribute only about 2% of the total sediment yield. The graph also shows that most of the sediment being delivered to the marine environment (~88%) originates from roads contributing between 0.5 and 10 Mg yr<sup>-1</sup>, and that the contribution from fast-eroding roads (> 15 Mg yr<sup>-1</sup>) equals about 10% of the total yields.

## K. TABLES

Table 1. Sediment production functions used by STJ-EROS to calculate contribution from undisturbed hillslopes and unpaved roads.

Annual sediment production rates (kg m <sup>-2</sup> yr <sup>-1</sup> )	Sediment production function (kg)
0.001	[6.4 x 10 <sup>-5</sup> ] x 14% rainfall x area x {1 + 3.4 x 0.004}
0.1 - 52 (slopes from 1-21%)	[-0.432 + 4.73 x slope <sup>1.5</sup> x rainfall] x road length x width x {1 + 3.4 x 0.06}
0.0 - 20 (slopes from 1-21%) 0.08 - 1.7 (slopes from 1-21%)	$[-0.432 + 1.88 \times slope^{1.5} \times rainfall] \times road length \times width \times \{1 + 3.4 \times 0.06\}$ [0.071] $\times slope \times rainfall \times road length \times width \times \{1 + 3.4 \times 0.001\}$
	Annual sediment production rates (kg m <sup>-2</sup> yr <sup>-1</sup> ) 0.001 0.1 - 52 (slopes from 1-21%) 0.0 - 20 (slopes from 1-21%) 0.08 - 1.7 (slopes from 1-21%)

Lengths and widths are in meters, slope is a decimal, area is in m<sup>2</sup>, and rainfall is in centimeters.

Empirical sediment production functions are in square brackets; corrections for the los of silt-sized particles from sediment traps are in {}

Items in italics are taken from GIS data layers.

Table taken from Ramos-Scharron and MacDonald (2007a)

Table 2. Total area	a, sediment del	ivery potential, a	and road network	descriptions of	the five stud	y areas.			
Basin	Area (km²)	High delivery potential (%)	Moderate delivery potential (%)	Total roads (km)	Total road density (km km <sup>-2</sup> )	Unpaved roads (%)		Road type (%	
							graded	ungraded	abandoned
Bahia Mosquito	3.3	20	80	16.5	5.0	99	39	49	12
Puerto Manglar	2.2	0	100	11.7	5.3	76	21	57	22
Punta Soldado	1.6	80	20	11.2	7.0	62	35	37	28
Zoni	1.8	09	40	9.54	5.3	69	23	42	35
Villa Borinquen	4.3	100	0	29.4	6.8	62	25	70	5

model.
STJ-EROS
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l sediment
Tabulatec
Table 3.

	Natural				
Basin	sediment delivery	Road sediment delivery	Natural sediment yield	Road sediment yield	Current/Natural
	Ŵ	g yr -1	Mg km <sup>-2</sup>	yr -1	
Bahia Mosquito	1.1	150	0.34	46	137
Puerto Manglar	0.5	45	0.22	20	91
Punta Soldado	1.1	202	0.67	124	185
Zoni	1.1	51	0.6	28	47
Villa Borinquen	3.2	435	0.74	101	137

# **APPENDIX A**

### SPATIAL DATABASE REQUIREMENTS FOR APPLICATION OF

ST. JOHN EROSION MODEL (STJ-EROS VERS. 2009)

#### ST. JOHN EROSION MODELING- SPATIAL DATABASE LAYER DEFINITION

#### Feature dataset: WATERSHED (PUNTA SOLDADO, BAHÍA MOSQUITO, PUERTO MANGLAR, ZONÍ, VILLA BORINQUEN)

Type: Polygon layer; NAD 1983 State Plane Puerto Rico Virgin Islands FIPS 5200; Units in meters

Description: Contains the boundaries of the five study areas as defined by 5 m contours.

Table Items:

Name	<u>Type</u>	Decimal Places
Shape_AREA	Ν	0
Shape_LENGTH	Ν	0

Item description:

<u>Name</u>	Description
Shape_AREA	Item defining the total areal of each polygon.
Shape_Length	Item defining the total perimeter of each polygon.
Name	Source area name given by the user.

#### ST. JOHN EROSION MODELING- SPATIAL DATABASE LAYER DEFINITION

#### Feautre class: **DRAIN**

Type: Point layer; NAD 1983 State Plane Puerto Rico Virgin Islands FIPS 5200; Units in meters

Description: Contains locations of all road drainage structures within the five study areas.

Table Items:

Name	<u>Type</u>	<b>Decimal Places</b>
DRAIN_ID	C	0

Item description:

NameDescriptionDRAIN\_IDA user-defined drainage structure identification code. These<br/>identification codes correspond to codes in 'ROADS' and serve to link<br/>an individual road segment with a specific road drainage structure. The<br/>relationship between a drainage structure and a road segment is not<br/>unique as a drainage point may drain more than one road segment.<br/>The code consists of a number.
# ST. JOHN EROSION MODELING- SPATIAL DATABASE LAYER DEFINITION

## Feature class: **ROADS**

Type: Line layer; UTM NAD 1983 State Plane Puerto Rico Virgin Islands FIPS 5200; Units in meters

Description: Contains locations of all roads within the five study areas

Table Items:

<u>Name</u>		<u>Type</u>		<b>Decimal Places</b>
SURVEYED		С		0
SURFACE		С		0
WIDTH	Ν		1	
SLOPE	Ν		2	
GRADING		С		0
LENGTH_M		Ν		0
SHAPE_LENGTH		Ν		4
DRAIN_ID		Ν		0

Item description:

<u>Name</u>	Description
SURVEYED	Describes whether the road segment was surveyed in the field or not.
	Values include 'yes', 'no', and 'null'.
SURFACE	Describes whether the road surface is paved or unpaved.
WIDTH_M	Defines the field measured average width of each individual road segments in meters.
SLOPE	Defines the field measured areally-averaged slope of each individual road segment in percent (m m <sup>-1</sup> ).
GRADING	Describes the frequency at which unpaved road segments are
	regraded according to the following three categories: 1) graded-roads that are graded for more than two years; 2) ungraded-roads that have not been graded in the last two years; 3) abandoned-roads that are
	infrequently used by light vehicles and have not been graded in over fifteen years.
LENGTH_M	Defines the field measured length of each individual road segment in meters.
SHAPE_LENGTH	Defines the field measured length of each individual road segment in meters.

## DRAIN\_ID A user-defined drainage structure identification code. These identification codes correspond to codes in 'DRAIN' and serve to link an individual road segment with a specific road drainage structure. The relationship between a drainage structure and a road segment is not unique as a drainage point may drain more than one road segment. The code consists in a user given number.

## ST. JOHN EROSION MODELING- SPATIAL DATABASE LAYER DEFINITION

## Feature class: **SEDIMENT DELIVERY**

Type: Polygon layer; NAD 1983 State Plane Puerto Rico Virgin Islands FIPS 5200; Units in meters

Description: Displays the spatial distribution of the potential for terrestrial sediments to be delivered to the marine environments. The criteria used to develop the delivery potential zones is based on the interaction between guts draining a specific sub-catchment within a basin and detention ponds, salt ponds, or wetland areas (see description below). Sediment delivery potential zones have been defined for all five study areas.

Table Items:

Name	<u>Type</u>	<b>Decimal Places</b>	
DEL_POT	С	0	
AREA_M2	Ν	0	

Item description:

<u>Name</u>	Description
POTENTIAL	A qualitative description of the potential for terrestrial sediment
	delivery into the marine environment based on the interaction
	between a gut draining an area and any detention ponds, salt ponds,
	or wetland areas. Areas are divided into one of the following four
	categories: 1) 'no'- Areas with no potential for sediment delivery
	include those drained by a gut that is interrupted by a pond or
	unchannelled area and lacks any surface pathway connecting it to the
	marine environment; 2) 'moderate'- areas that drain into a pond or
	wetland area that has a channel-like feature connecting it with the
	marine environment; 3) 'wetlands'- All wetland areas are identified
	separately, but they are considered to have the same delivery potential
	as moderate areas; and 4) 'high'- areas drained by a gut that is not
	interrupted by any pond or wetland area, so that it is able to directly
	deposit sediment into the marine environment.
AREA_M2	Item defining the total area of each delivery potential polygon in m <sup>2</sup> .

# **APPENDIX B**

### **INTERIM REPORT**

### LAND EROSION AND SEDIMENTATION OF MOSQUITO BAY, VIEQUES-PUERTO RICO

#### NOTES, CALCULATIONS, AND INITIAL RECOMMENDATIONS BASED ON A BRIEF FIELD ASSESSMENT

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#### I. INTRODUCTION

The onsite and offsite effects associated to increased levels of land erosion and sedimentation are considered to be some of the most serious environmental problems worldwide<sup>(1)</sup>. Human land uses for agriculture, urban development, resource management, and recreation are responsible for increasing erosion rates on hillslopes and thus for enhancing the rate of sediment delivery to both freshwater and marine habitats. Land erosion related issues within the Caribbean Region are as varied as its physiographic characteristics and land use practices. Land disturbance has been widely recognized as the main cause of accelerated erosion rates, but there is very little information on past or current sediment delivery rates to the marine environment<sup>(2)</sup>. Historically there have been few efforts to remedy this problem<sup>(3)</sup>, and this lack of attention can be partly attributed to the lack of data and spatially explicit models to quantify sediment sources and help establish priorities for remediation.

The island of Vieques has had a complex land use history that includes agriculture, pasture, recreational, and military practices. Current land development practices on the island generally consist of vegetation removal, combined with ground leveling and compaction associated to construction (e.g., individual home sites and commercial buildings) and opening of low-standard, sometimes steep roads that tend to remain unpaved for relatively long periods. Limited background information currently exists on this type of development on a sub-tropical dry climatic setting such as in Vieques, but data from La Parguera (PR) and St. John (USVI) suggests that disturbed surfaces can erode at rates that are ten to four-orders of magnitude (10 to 10,000) higher than undisturbed surfaces<sup>(4,5,6)</sup>, and that current watershed-scale sediment yields are up to 10 times higher than under undisturbed conditions<sup>(7)</sup>. In addition to increasing the total sediment load into coastal waters, impacted areas such as unpaved road surfaces may also increase the frequency at which sediment is delivered to the marine environment. Research conducted on the island of St. John has shown that

only 5 mm of rainfall are needed to generate runoff on unpaved roads, while approximately 10 times more rainfall (~6 cm) are required to initiate overland flow on undisturbed surfaces<sup>(8)</sup>.

As part of a PR-Department of Natural Resources Project titled 'The Effects of Land Development on Sediment Loading Rates into the Coastal Waters of the Islands of Culebra and Vieques, Puerto Rico' I visited Vieques and the Reserva Natural de Bahía Mosquito with Mr. Raúl Santini (Coastal Zone Program, PR-DNER) on 20-24 June 2008. The objective of this project is to estimate the rates of sediment delivery to coastal waters of Culebra and Vieques by use of the STJ-EROS model. The goal of our field visit was to conduct field surveys of unpaved roads to develop the geodatabases necessary for applying STJ-EROS to the Villa Borinquen and Bahía Mosquito areas of Vieques. STJ-EROS is a Geographical Information System model that was developed by me based on previous work conducted on St. John (USVI)<sup>(7,9)</sup>. Its application allows users to estimate the rate of sediment yields into the bay at a watershed or sub-watershed scale, while also allowing for the identification of contributions from individual unpaved road segments.

During our trip to Vieques we met with local PR-DNER personnel (Mr. Edgardo Belardo, Mrs. Aliziris Rivera, and Mr. Erick Bermúdez) who expressed concerns related to the sediment contribution from land-based sources to Bahía Mosquito. Of particular concern was the unpaved road network that provides vehicular access to Bahía Mosquito and Playa Panteón (Figure 2). Sediments suspended in the water column of the bay may affect its bioluminescence by decreasing the availability of sunlight needed by dinoflagellates for photosynthesis. Whether actual sedimentation (i.e., settling) of sediments may have detrimental effects on the bioluminescence of the bay is unknown to me at this time.

#### II. SEDIMENT CONTRIBUTION TO BAHÍA MOSQUITO

Unpaved roads contained within the boundaries of DNER-managed land in the vicinity of Bahía Mosquito were surveyed during our field visit (Figure 2). Field surveys included measuring local slope with a clinometer, measuring width with a tape measure, identification of road maintenance type (i.e., frequently bladed by heavy machinery [fine textured, with no vegetation], active roads not frequently maintained [moderate to coarse texture and very little vegetation], or abandoned roads [coarse texture, with a dense vegetation cover]), and mapping of road length and location of drainage points with the aid of a GPS unit. Four main road segments were identified to be draining to Bahía Mosquito: 1) Northwest Mosquito top- upper portions of road that provides access from Sun Bay to BM; 2) South Mosquito top- upper portions of the road from Sun Bay to BM; 3) South Mosquito bottom- lowermost portions of the road from Sun Bay to BM; and 4) Playa Panteón- section of road that connects BM with Playa Panteón. The geographical layout and general description of the roads are shown in Figures 1 and 2 and Table 1. These four road segments comprise the main sources of sediment draining into Mosquito Bay within the boundaries of the DNER-managed areas.

Data collected in the field was used to estimate the individual sediment contribution of each of the four surveyed road segments. Calculations were done by hand as the geodatabases needed to run STJ-EROS have not been developed at this time. The calculations are based on the same sediment production equations used by STJ-EROS:

$$\mathrm{Er}_{a} = -0.432 + 4.73 \cdot (\mathrm{S}^{1.5} \cdot \mathrm{P}) \tag{eq. 1a}$$

$$\mathrm{Er}_{\mathrm{u}} = -0.432 + 1.88 \cdot (\mathrm{S}^{1.5} \cdot \mathrm{P}) \tag{eq. 1b}$$

where  $Er_g$  and  $Er_u$  are the respective sediment production rates for graded and ungraded roads in kg m<sup>-2</sup>, S is segment slope in m m<sup>-1</sup>, and P is total precipitation in cm<sup>(4,5,9)</sup>. This formulation of the model

in explicitly indicates that graded roads with a given slope produce 2.5 times as much sediment as a comparable ungraded road.

An annual rainfall rate of 115 cm (~45 inches) was used for estimating sediment production rates for the four road segments. A summary of the results are shown in Table 1. Even though the Northwest Road is expected to produce more sediment than any of the other three road segments, this is likely to be an overestimation of its actual contribution to Bahía Mosquito. Equations 1a and 1b are intended to estimate the amount of sediment that reaches the bottom of the road segment (sediment production). The actual sediment contribution of a particular road segment is not only a function of how much sediment it generates but also where it drains in relation to a particular water body and its connectivity with the bay. Several of the drainage points along Northwest Road drain into the wetland area surrounding Bahía Mosquito. These areas are typified by moderately to densely vegetative cover as well as a very gentle slope, characteristics that make it very prone for sediment entrapment. Even though experts agree on the ability of such environments to trap sediment, no data is available to quantify their efficiency. In the lack of any available data in this calculation I have assumed that only 25% of the sediment delivered to those vegetated areas reaches the marine environment, and this is in agreement with STJ-EROS applications in St. John <sup>(7)</sup>. Therefore the actual contribution of Northwest Road is expected to be closer to 0.9 Mg than the 3.6 Mg calculated from equation 1a (1 Mg = 1 metric ton). By assuming a dry bulk density of 1.3 Mg  $m^{-3}$ this translates into approximately 0.7 m<sup>3</sup> of sediment entering Bahía Mosquito from this road segment every year.

On the other hand, all other three road segments (i.e., South Bahía Mosquito top and bottom, and Playa Panteón) deliver sediment directly into Bahía Mosquito. Figures 3a and 3b are pictures of the delivery point from all of these three road segments and show the lack of any vegetative buffer. The estimated efficiency of these three road segments in delivering the sediment they produce on their surfaces is 100%. Therefore these three road segments are expected to deliver 6 Mg or about 4.6 m<sup>3</sup> of sediment every year into Mosquito Bay. The total contribution from all four road segments is therefore 6.9 Mg or 5.3 m<sup>3</sup> of sediment per year.

The total watershed area draining into Bahía Mosquito is approximately 5 km<sup>2</sup>. If we assume that erosion rates from natural processes in this area are within the range of values of those measured in similar sub-tropical dry settings in nearby St. John (USVI)<sup>(5)</sup> and La Parguera (PR)<sup>(6)</sup> it is then possible to estimate the annual sediment delivery rates into Mosquito Bay under natural conditions. Measured surface erosion rates from undisturbed lands in St. John and La Parguera range between 1 and 10 Mg km<sup>2</sup> yr<sup>1</sup>, therefore annual delivery of sediment from natural erosion into Mosquito Bay could be expected to range between 5 and 50 Mg yr<sup>1</sup>. Assuming a dry bulk density of 1.3 Mg m<sup>-3</sup>, this translates into 3.8 and 38 m<sup>3</sup> annually. If the 0.64 km<sup>2</sup> Mosquito Bay had a 100% sediment retention capacity and all of the sediment would settle at the bottom of the bay this would translate into a sedimentation rate in the order of 0.0006 to 0.006 cm per year, or only 0.6 to 6 mm in 100 years. These rates are within the range of values estimated from sediment core studies in the highly impacted Coral Bay watershed in St. John (USVI) which range between 0.01 to 0.2 cm per year<sup>(10)</sup>.

Land use practices such as those found within the watershed draining into Mosquito Bay may increase watershed-scale sediment delivery rates by as much as ten times over undisturbed conditions. Assuming that this is the case in Mosquito Bay then this would mean that over 100 years of such land use, total sedimentation would account for 6 to 60 mm (1.5 to 15 inches).

Any estimate that implies a sedimentation rate of 8 feet (2.43 m) over the last 50 years would require a sediment loading rate into Mosquito Bay of 31,100 m<sup>3</sup> of sediment per year (40,400 Mg per year). Normalized by watershed area this implies a sediment yield rate of 8,100 Mg km<sup>2</sup> per year. This is very unlikely as this would require this watershed to yield sediment at rates that are higher than those measured from any other watershed in the world. The implied yield exceeds those from the

most highly erodible lands in the world, including those drained by the Yellow River of China which have a sediment yield range between a few 100's and ~5,000 Mg km<sup>2</sup> per year <sup>(11)</sup>.

#### III. PRELIMINARY EROSION CONTROL RECOMMENDATIONS

The 6 Mg of sediment estimated to be delivered to Mosquito Bay from the four road segments within DNER-managed lands represent a 1.1 to a 2.2 increase above sediment yields under natural conditions (5 to 50 Mg yr<sup>-1</sup>). Therefore, my recommendation is to implement an erosion control plan to mitigate the adverse effects that this increased rate of sedimentation might be having on the quality of the marine habitat in Mosquito Bay. My recommendations will focus on the three road segments that drain into the same common delivery point along the south shores of Bahía Mosquito and only address issues related to sediment production and delivery into the bay from these road segments. Erosion control measures should also be implemented along the Northwest Mosquito Road, but priority should be given to controlling erosion along the other three road segments.

Erosion control methods may be selected from proven "hard" and "soft" practices described in regional <sup>(12)</sup> and general handbooks <sup>(13)</sup>. The different methods available can be grouped into four categories depending on how they address the processes controlling surface erosion or sediment delivery. The first type of methods includes those meant to reduce the shear stress of runoff flowing over eroding surfaces. A reduction in the shear stresses (i.e., forces) applied by overland flow on a road surface could be achieved by the construction of physical barriers that prevent runoff from flowing over the road travelway for extensive lengths. These types of structures include, but are not limited to, water bars, dips, deflectors, and culverts <sup>(14)</sup>. The effectiveness of such measures depends on the slope of the road segment and the spacing between structures (i.e., the more tightly spaced the runoff structures the lower the erosion rate and therefore the higher the effectiveness in

reducing erosion rates). Use of runoff control structures has been proven to be an effective erosion control method on the island of St. John <sup>(15)</sup>.

Water bars, swales, and culverts are some of the types of BMP's that may be considered (Figure 4). While in the field, DNER personnel and myself were able to identify about 6-7 points where these types of structures could be implemented along both Mosquito Bay road segments (i.e., top and bottom segments), while only one spot was located along Playa Panteón road. I would recommend building solid and permanent structures with reinforced concrete (e.g., cemented swales), as according to local DNER personnel previous attempts to rely on native soil waterbars have provided only a temporary solution as they quickly become ineffective once destroyed by vehicular traffic and erosion.

Drainage structures may also be considered to belong to the second group of methods, that is, those that reduce connectivity between the sediment source and the water resource. When road drainage structures are used to divert water off the road prism instead of allowing runoff to be directly delivered to the coast, the method is in effect also reducing the length of road delivering sediment to the marine environment and this induces an additional reduction in the amount of sediment derived from roads. Empirical observations taken from forested areas throughout the U.S. suggest that most of the sediment tends to remain in close proximity to the road prism. Sediment traps such as the ones shown in Figure 5 may be combined with drainage structures to improve the effectiveness of the vegetation in retaining sediment.

The third class of erosion control methods includes those meant to improve the erosive resistance of the road surface. Measures to improve the erosive resistance include paving with concrete or asphalt, and applying different types of geotextile materials or coarse gravel. Paving and

geotextile treatments improve resistance by adding a highly cohesive medium that protects the underlying material from the effects of shearing stresses, while gravel increases the critical shear strength of the road surface. Paving with concrete could be applied to both Mosquito Bay road segments to reduce sediment delivery rates. Paving should be accompanied by proper road runoff management in the form of cemented swales and/or ditches and culverts. Due to chemical decomposition, asphalt should be avoided. Any intention to pave the road should evaluate the potential increase in vehicular traffic that typically follows paving and its consequential effects on the marine resources of Bahía Mosquito.

Gravel should be avoided on the roads leading toward Bahía Mosquito because traffic tends to quickly rework the arrangement of the gravel layer, therefore requiring frequent maintenance on actively used roads to retain its effectiveness. Another problem with gravel is that the shear stresses of overland flow during intense storms can be strong enough to erode and transport up to coarse gravel-sized material (~16-32 mm) <sup>(4,8)</sup>. Application of non-degradable, porous material and/or implementation of re-vegetation measures should be considered for the wide barren area currently used as an improvised parking zone at the boat ramp area to reduce its sediment contribution.

Controlling vehicular traffic is another type of action that could be considered, particularly for the south Mosquito Bay bottom road segment (Figure 2). Traffic intensity is considered to be one of the main factors controlling sediment production rates from unpaved road surfaces <sup>(15)</sup> and reducing the number and weight of vehicles allowed on the road could decrease erosion of the road segment. This action should be combined with others such as the installation of runoff control structures to improve its efficiency. Access control could also be coordinated with actions to promote revegetation to reduce the barren and exposed surface areas.

As in most issues related to non-point sources of pollution, mitigating a problem at a specific site will not provide a thorough solution to an environmental problem that originates on many different areas of a watershed. Additional erosion control efforts should also be implemented in the upland areas of the watershed draining into Mosquito Bay. Efforts conducted by DNER within their managed areas could be used as examples to promote the application of similar Best Management Practices in other areas of the Mosquito Bay watershed and throughout Vieques.

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Figure 1. Aerial photograph (2004) and map of Mosquito Bay watershed.



Figure 2. Aerial photograph (2004) and map of Mosquito Bay and the four surveyed road segments.



**Figures 3a and 3b.** Bottom section of South Mosquito Road where it drains into Mosquito Bay. Notice the lack of any vegetative buffer zone to prevent sediment produced on the road surface from entering directly into the Bay.





**Figure 4.** Different types of runoff control structures that can be applied to unpaved roads draining to Bahía Mosquito.



Figure 5. Two examples of silt-fence type sediment traps.



Examples of silt-fence sediment trap BMP's used in Parguera-PR (left) and St. John-USVI (right). When properly installed and maintained, and when combined with other types of BMPS's these types of sediment traps can be very effective in reducing the amount of sediment reaching downslope water bodies.

**Table 1.** General description and estimated sediment contribution from DNER managed unpaved roads draining into Mosquito Bay.

Road segment	Length	Average	Slope	Surface	<b>Erosion rate</b>	Sediment
	(m)	width (m)	(%)	type	(kg m <sup>-2</sup> yr <sup>-1</sup> )	contribution
						(Mg)
Northwest Mosquito	810	4.0	2	graded	1.11	0.9*
South Mosquito top	270	4.3	3	graded	2.39	2.8
South Mosquito	170	3.8	4	graded	3.92	2.5
bottom						
Playa Panteón	220	2.5	4	ungraded	1.30	0.7
Total	1470	3.8	2.7			6.9

\* Even though 3.6 Mg of sediment are estimated to be produced from this road segment, only 25% of the sediment generated from Northwest Mosquito Road is expected to be delivered to Bahía Mosquito due to the layout of its drainage points and the effectiveness of well-vegetated, flat areas in retaining sediment.