CHAPTER 6.

CONCLUSIONS, FUTURE RESEARCH, AND MANAGEMENT RECOMMENDATIONS

6.1 Runoff generation from hillslope plots and roads

Runoff volumes were measured from three 40 m^2 plots on undisturbed planar hillslopes and runoff rates were measured from a 230-m long, partially-paved road segment. The undisturbed hillslopes only generated runoff from precipitation events with at least 2.5-3.0 cm of rainfall (Figure 1; Chapter 4). In contrast, only 0.3 cm of rainfall generated runoff from the unpaved road segment (Chapter 3). The low runoff coefficients for the undisturbed hillslopes show that runoff represented less than 10% of the total rainfall, at least for the smaller storm events where all the runoff was captured. The runoff coefficients from the road segment often exceeded 10% and were as high as 70% for storms with at least 2 cm of rainfall (Figure 1).

Storm precipitation is a major control on the amount of runoff from undisturbed areas, but the amount of runoff varies among storm events with similar rainfall totals. The predictability of runoff volumes was improved when storm rainfall (P) was combined with an antecedent precipitation index (API). Runoff was generated from the hillslope plots only when storm precipitation exceeded 2.5-3.0 cm and the sum of P and API was at least 5 cm. Runoff from the road segment was strongly correlated with total precipitation regardless of the antecedent conditions.

These differences in the initiation and amount of runoff help explain the observed differences in sediment production. First, the amount of precipitation needed to initiate surface runoff from roads is at least an order of magnitude less than for planar hillslopes, and this greatly increases the frequency of surface runoff. Second, the higher flows on the road segment greatly increase the shear stress on the relatively erodible road surface.

Precipitation and runoff rate data from the partially-paved road were used to develop, calibrate, and validate two runoff models (Chapter 3). The first model (GA-UH) predicted runoff using the Green-Ampt infiltration equation and an empirically-derived unit hydrograph. The second model (GA-KW) used the Green-Ampt infiltration equation to calculate precipitation excess and a kinematic wave to route the resulting runoff. Model development and calibration were based on eight runoff events and yielded parameter sets with physically realistic values.

The two runoff models were validated by comparing predicted and measured hydrographs for 18 storms. Predicted hydrographs from the two models were very similar, but the GA-KW model performed slightly better than the GA-UH model. Both models predicted no runoff for most events with less than 0.7 cm of rainfall, and tended to underestimate peak flows. The absolute errors in predicted discharge did not increase with increasing storm size. Much of the error in estimating storm runoff was attributed to the difficulty of predicting the initial infiltration rate.

6.2 Measuring and predicting sediment production and delivery

A sediment budget provided the conceptual framework for measuring and modeling sediment production from both natural and anthropogenic sources on St. John. Estimated annual erosion rates at the plot, hillslope, and road-segment scale ranged over five orders of magnitude (Chapter 4). Mean sediment production rates from undisturbed areas were 27 g m^{-2} yr^{-1} at the plot scale, 0.5 g m^{-2} yr^{-1} at the zero-order catchment scale, and 8 g m^{-2} yr^{-1} for first-order catchments (Figure 2). The highest erosion rate for natural sediment sources was 10 kg m^{-2} yr^{-1} for streambank erosion. The uprooting of trees along stream margins was estimated to deliver 0.17 tons per kilometer of stream length per year, or 11 g m^{-2} yr^{-1} for a 15-m wide stream corridor.

Differences in the magnitude of sediment yields for undisturbed catchments are attributed in part to the scale at which the rates were measured or predicted. For example, the drop in sediment yields from the undisturbed plot (0.027-0.77 g m^{-2} yr^{-1}) to the zero-order scale (0.010-0.085 g m^{-2} yr^{-1}) stems in part from the higher potential for sediment storage on zero-order catchments relative to 40 m^2 plots. The addition of streambank and treethrow erosion appears to account for the higher sediment yields from first-order catchments relative to zero-order catchments.

Sediment production from 21 unpaved road segments with varying contributing areas, slopes, and traffic loads was measured with sediment traps over the two-year study period. The mean sediment production rate from these road segments was 0.064 kg m^{-2} per centimeter of precipitation. Sediment production was related to total precipitation and to road segment slope. Sediment production rates for roads that had been graded within the last two years ranged from 0.57 to 58 kg m^{-2} yr^{-1} (Figure 2), depending on slope. Sediment production from ungraded roads ranged from 5.1 to 14 kg m^{-2} yr^{-1} for roads with slopes of 10 and 16%, respectively (Figure 2). The mean erosion rate for abandoned roads with a slope of 15% was 1.1 kg m^{-2} yr^{-1}. Although cutslopes eroded at rates ranging from 2 to 17 kg m^{-2} yr^{-1}, they were estimated to be responsible for only 9% of sediment measured at the road segment scale.

These annual erosion rates indicate that unpaved roads on St. John produce sediment at a rate that is up to four orders of magnitude higher than undisturbed plots and zero-order catchments. First-order catchments receiving sediment from unpaved roads had a mean sediment yield of 38 g m^{-2} yr^{-1}, or about five times the rate of comparable undisturbed first-order catchments (Figure 2).

STJ-EROS is an Arc/Info-based system that quantifies watershed-scale sediment yields based on empirically-derived sediment production functions and delivery ratios. Sediment delivery ratios are meant to reflect the retention of sediment by hillslopes, fluvial networks, and coastal wetlands. The STJ-EROS Arc Macro Language program code consists of six input routines and five routines that calculate sediment production and delivery (Chapter 5). Interfaces for the six input routines allow users to adjust the values of the variables controlling sediment production and delivery (e.g., rainfall rates and sediment delivery ratios). The remaining five routines use pre-set erosion rate constants, user-defined variables, and item values stored in nine input GIS data layers to calculate watershed-scale sediment yields from the combination of streambanks, treethrow, undisturbed hillslopes, unpaved road travelways, and road cutslopes.

Simulations with STJ-EROS indicate that sediment yields for undisturbed conditions would be 2.8 tons km^{-2} yr^{-1} for the Lameshur Bay basin, 7.3 tons km^{-2} yr^{-1} for the Fish Bay basin, and 0.6 tons km^{-2} yr^{-1} for the Cinnamon Bay basin (Figure 2). Estimated sediment yields under current conditions are 19 tons km^{-2} yr^{-1} for the Lameshur Bay basin, 65 tons km^{-2} yr^{-1} for the Fish Bay basin, and 25 tons km^{-2} yr^{-1} for the Cinnamon Bay basin (Figure 2). The latter values are 7-40 times higher than under undisturbed conditions, and in each case unpaved roads were the main source of sediment. The differences in the estimated sediment yields are mostly a response to differences in the amount of unpaved roads in each basin. The modeled sediment yields for undisturbed and current conditions are within the range of sediment yield and bay sedimentation rates measured by previous studies on St. John.

6.3 Recommendations for future research

STJ-EROS is a useful tool for estimating erosion rates and the delivery of sediment to the marine environment. The accuracy of these estimates is limited by the available hydrologic and geomorphic data. One of the most important limitations is the potential underestimate of sediment production rates by the sediment traps used in this study. The analysis in Chapter 3 showed that the sediment traps underestimate sediment production rates because they do not capture all of the silt-sized particles. An accurate estimate of the amount of these particles is important because these particles generally are suspended in the surface runoff and are readily delivered to the marine environment. A more detailed study is needed to quantify the trap efficiency of the sediment fences for different-sized particles.

The movement of sediment through the fluvial network and coastal wetlands is treated as a black-box in STJ-EROS due to the lack of data on sediment storage and transport rates. Predicted sediment yields are very sensitive to the user-defined sediment delivery ratios (Chapter 5). Additional measurements and theoretical analyses are needed to improve the predictions of land-use changes on watershed-scale sediment yields.

Runoff data for St. John are very limited and this restricts the ability to develop, calibrate, and validate models. Government agencies and researchers should collaborate to develop a long-term program to collect data on runoff and sediment yields at spatial scales ranging from zero-order catchments to the larger watersheds such as Fish Bay. Quantifying runoff initiation, peak flows, and runoff coefficients at different spatial scales is a necessary first step towards modeling sediment entrainment and transport through the fluvial network. Similar efforts are needed to quantify the hydrology and sediment retention capacity of coastal wetlands.

Additional research is also needed to determine the ultimate fate of the sediment from terrestrial sources that is being delivered to the marine environment. Given the ephemeral nature of surface runoff on St. John, the delivery of sediment into the bays is very sporadic. Data on the residence time of sediment in different bays will help determine whether the effects of sediment on coral reef organisms are only present when a pulse of sediment is being delivered to the bays, or whether the effects of terrestrial sediment inputs are more chronic and persistent because the sediment remains in the bays over longer time periods.

6.4 Management recommendations

The findings from Chapter 2 can be translated into specific recommendations for reducing sediment production rates from unpaved roads. The steep, frequently-graded road segments should be the first target for implementing erosion control practices, as increasing slope and more frequent grading significantly increase sediment production rates. Roads and driveways with steep slopes should be paved immediately after construction. The frequency and amount of road grading should be kept to a minimum.

STJ-EROS can be a valuable tool for land managers. The model can compare sediment delivery rates from natural versus current conditions. As shown in Chapter 5, STJ-EROS can generate color-coded maps to identify the individual road segments that are contributing high quantities of sediment to the marine environment. STJ-EROS also may be used to assess the effect of different management scenarios, such as new road developments or proposed mitigation projects, on sediment production and delivery. The proposed changes can be readily evaluated by making the appropriate changes to the GIS data layers or user-defined input parameters. The ability to predict the effects of different management scenarios will allow managers to optimize sediment reduction efforts.

Potential users should recognize that the model results depend on the completeness and accuracy of the GIS data layers. On St. John, the data layers needed by STJ-EROS have been developed only for the Lameshur Bay, Fish Bay, and the Cinnamon Bay basins. Development of the data layers takes time, as some of the data must be collected in the field. Aerial photos or automated methods, such as combining a DEM with the road layer to calculate road segment slope, could be used to create or update the layers, but such approaches need to be validated before they can be more widely applied. The rapid expansion and alteration of the road networks on St. John also means that the road data layers must be updated at least every five years.

Both model users and land managers must understand the limitations of STJ-EROS. Many of the predictive equations were empirically derived from field data collected on St. John, so they are calibrated to the erosion rates and processes observed during the study period. Since the nearby islands of Culebra, St. Thomas, Tortola, and Virgin Gorda have similar geologic, topographic, and climatic conditions, STJ-EROS can probably be applied to these islands with minimal changes. The application of STJ-EROS to areas with physical characteristics different from St. John is only possible if the model is used in a relative sense—e.g., identifying road segments that have relatively high erosion rates. The use of STJ-EROS to estimate absolute erosion rates or sediment yields must be preceded by a field-based calibration. The field data can then be used to adjust or modify the sediment production and delivery functions currently in STJ-EROS.

Finally, it is important to recognize that STJ-EROS does not incorporate any anthropogenic sediment sources other than unpaved roads. Other changes in the type and intensity of land use can increase erosion rates and cause unpaved roads to play a relatively smaller role compared to other sediment sources. Any attempt to expand the sediment budgeting capabilities of STJ-EROS should consider incorporating other sediment sources, such as grazing, agriculture, and land clearing for residential or commercial development.

This study has shown that the expanding network of unpaved roads is significantly increasing the delivery of sediment to the marine environment around St. John. This increase should concern all who are interested in the conservation of the nearshore coral reef communities. Land development is inevitable in the Virgin Islands and most of the rest of the Caribbean, but stricter controls on land development must be enacted and enforced to reduce the amount of sediment being delivered to the marine environment. Land developers and local residents also must accept more of the moral and economic responsibility for limiting the adverse impacts of development. Collaborations, such as the Fish Bay Road Stabilization Program between the Virgin Islands Department of Planning and Natural Resources and the Fish Bay Homeowners Association, should be encouraged. Only through the widespread development of such collaborations will land development be able to coexist with a healthy, diverse, and visually appealing marine environment in the Virgin Islands and elsewhere.

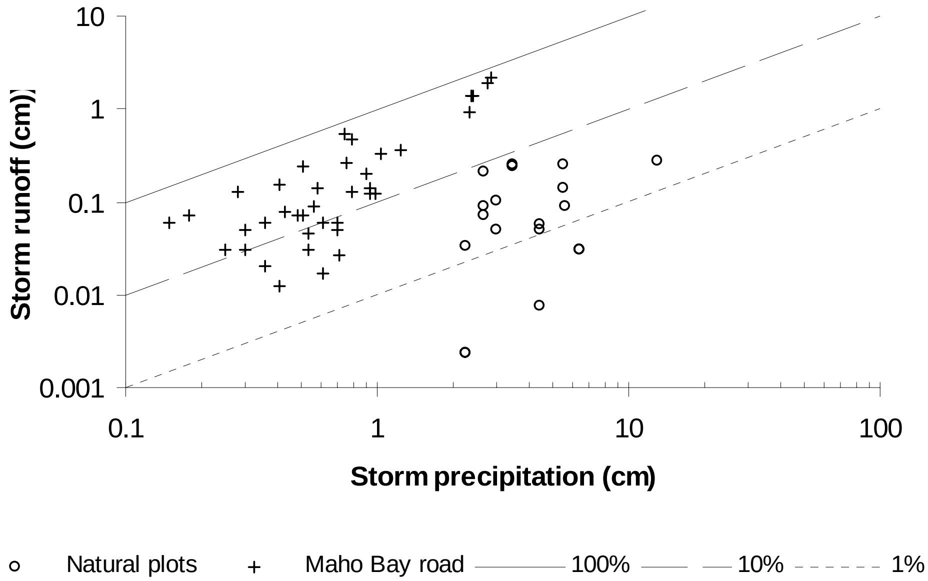

Figure 1. Relationship between storm precipitation and runoff for hillslope plots and road surfaces in St. John. Lines represent 100%, 10%, and 1% runoff coefficients.

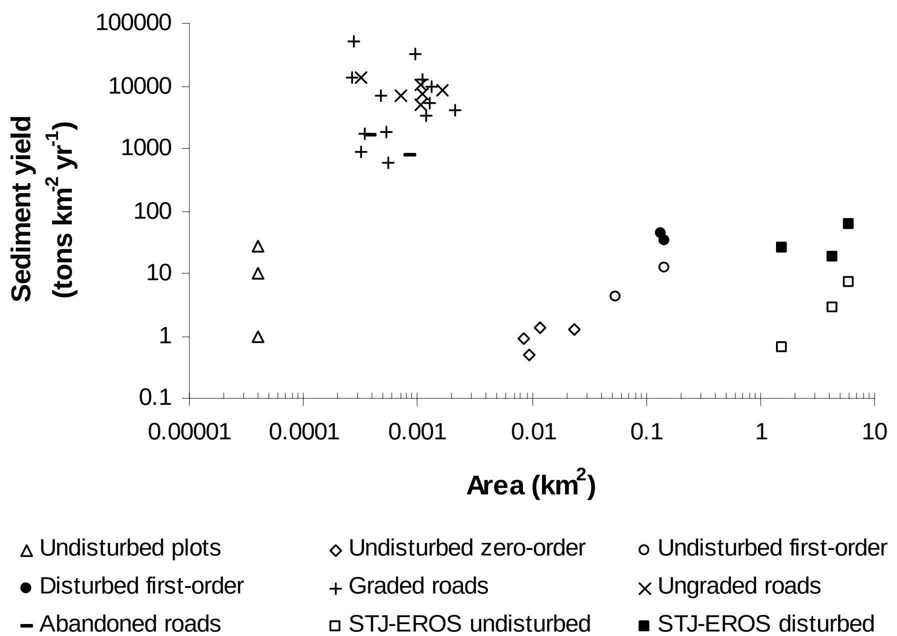

Figure 2. Relationship between sediment yields and contributing area for different landscape units on St. John.