Technical Notes on the Reefs at Risk in Belize Threat Analysis

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This paper provides technical notes on the modeling methodology for the *Reefs at Risk in Belize* threat analysis.

Reefs at Risk Project Purpose

The *Reefs at Risk* project brings together knowledge on the location of coral reefs, and threats to coral reefs, as a basis for developing threat indicators. Wide-ranging information is consolidated within a geographic information system (GIS), including data on coral reef locations (maps); pressures on coral reefs (observed threats, pollution, physical impacts); changes in condition; observations of coral bleaching and disease; and information on the management of coral reefs. Once these data are collected and integrated, they are reviewed and improved, although many gaps in the information remain. The project then attempts to fill in some of those gaps through inferential modeling of threats to coral reefs from human activities, including coastal development, marine-based threats, and pollution and sediment from land-based sources. These threat estimates were calibrated using data compiled under the *Reefs at Risk in the Caribbean* project[1] and have been reviewed by local experts in Belize. Changing climate, coral bleaching, and coral disease are also significant threats to Caribbean coral reefs, but we were not able to model such threats using currently available data. The *Reefs at Risk in the Caribbean* report (included on this CD), however, presents current knowledge of the extent of and projections for these threats, within the context of the other pressures facing Caribbean coral reefs.

Threat Analysis Method

The project's modeling approach involves identifying sources of stress that can be mapped for each threat category. These "stressors" include simple population and infrastructure features, such as population density and location and size of cities, ports, and tourism centers, as well as more complex modeled estimates of riverine inputs. Model rules were developed to build proxy indicators of threat level for these stressors. This process involved the development of distance-based rules by which the threat declines as distance from the stressor increases. For ease of interpretation, these threats are simply divided into "low," "medium," and "high" categories. Substantial input from scientists in the region contributed to the selection of the stressors and threat rules (thresholds) developed, while the threat indicators were further calibrated against available information on observed impacts on coral reefs.

Table 1 summarizes the threat analysis method and limitations for each threat category. The following sections provide details of the threat analysis methodology for coastal development, watershed-based sources of sediment and pollution, and marine-based threats.

[1] Data from CARICOMP, AGRRA, Reef Check, and REEF were used. See a full description in a later section on model calibration and validation.

Table 1. Reefs at Risk Analysis Method

Threat	Analysis Approach	Limitations
Coastal Development	-Threats to reefs evaluated based on distance from settlements, ports, airports, resorts, and tourism centers, with size of these features taken into account. -Thresholds selected for each stressor based on guidance from project collaborators and observations of local damage from coastal development (including sewage discharge). Stressors aggregated into single map layer.	-Provides a good indictor of relative threat across Belize , but is likely to miss some site-specific threats. -Data sets used are the best available, but limitations regarding accuracy and completeness are inevitable. - Rapid growth of tourism sector makes it difficult to capture the most recent developments.
Watershed-Based Sources of Sediment and Pollution	-Watershed-based analysis links land-based sources of threat with point of discharge to the sea. -Analysis of sediment and pollution threat to coral reefs implemented for more than 3,000 watersheds discharging to the Caribbean. -Relative erosion rates estimated across the landscape, based on slope, land cover type, precipitation (during the month of maximum rainfall), and soil type.[a] Erosion rates summarized by watershed (adjusting for watershed size) to estimate resulting sediment delivery at river mouths. -Sediment plume dispersion estimated using a function in which sediment diminishes as distance from the river mouth increases. Estimated sediment plumes calibrated against observed sediment impacts on selected coral reefs.[b]	-Nutrient delivery to coastal waters probably underestimated due to lack of spatial data on crop cultivation and fertilizer application and resulting use of a proxy (sediment delivery) for indirect estimation.[c] -Sediment and nutrient delivery from flat agricultural lands probably underestimated, because slope is a very influential variable in estimating relative erosion rates.
Marine-Based Sources of Threat	-Threats to coral reefs from marine-based sources evaluated based on distance to ports, stratified by size; intensity of cruise ship visitation; location of dive sites and distance to shipping lanes.	-Estimates focus on ships in or near port, or along shipping lanes. Threats outside of shipping lanes are probably underestimated. -Mapping of dive sites is only a moderate indicator of likelihood of anchor or diver damage in an area, as many factors (presence of mooring buoys, intensity of diving, diver education) influence the likely impacts.

TABLE NOTES:
a. “Relative Erosion Potential” was estimated at WRI using a simplified version of the *Revised Universal Soil Loss Equation*, United States Department of Agriculture (USDA) Agricultural Research Service (Washington, DC: USDA, 1989).
b. Data from Reef Check surveys and expert opinion from the Reefs at Risk workshop were used to calibrate the estimate of threat from inland sources. Data on percent live coral cover and algal cover from Atlantic and Gulf Rapid Reef Assessment (AGRRA) surveys were used to evaluate results.
c. Although phosphorus is often attached to soil particles, nitrogen is highly soluble and moves more independently of soil particles.

The *Reefs at Risk in Belize* analysis of threat from coastal development and marine-based threats was implemented at 100 m resolution. The analysis of sediment and pollution threat from land-based sources (LBS) comes from *Reefs at Risk Caribbean* (WRI, 2004) which was implemented at 1 km resolution for the Wider Caribbean region (using 1 km resolution elevation and land cover data). A higher resolution (90m) analysis is underway under the ICRAN Mesoamerican Reef (MAR) project. This analysis, which should be completed in early 2006 will replace the LBS results on this CD. The methodology described in this document is scale-independent and can be implemented at finer scales, where more detailed data are available.

THREAT: Coastal Development

Poorly managed coastal development can threaten coral reefs through dredging, land reclamation, mining of sand and limestone, dumping of spoils, and runoff from construction. Sewage discharge from human settlements increases nutrient and bacteria levels in coastal waters and can have an adverse impact on reef health. In addition, poorly managed tourism can harm coral reefs both through poorly planned and implemented construction and through careless recreation on reefs.

Analysis Method

Threats to reefs from coastal development were evaluated on the basis of distance to settlements, ports, airports, resorts and tourism centers (see Table 2).

Table 2. Model Rules Implemented for Coastal Development Threat Analysis

Subject / Stressor	Qualifier	High	Medium	Low
Settlements	Over 40,000	0 – 5 km	5 – 10 km	
Settlements	Over 10,000	0 – 2 km	0 – 4 km	
Settlements	Over 5,000		0 – 2 km	
Ports	Medium	0 - 5 km	5 - 10 km	
Ports	Small	0 - 2 km	2 - 5 km	
Airports	International Airport		0 – 8 km	
Airports	Airstrips – Existing and Proposed		0 – 6 km	
Tourism Centers	Areas with high visitation		0 – 2 km	
Hotels / Resorts	Over 100 rooms		0 – 4 km	
Hotels / Resorts	61 to 100 rooms		0 – 3 km	
Hotels / Resorts	41 to 60 rooms		0 – 2 km	
Hotels / Resorts	21 to 40 rooms		0 – 1.5 km	
Hotels / Resorts	11 to 20 rooms		0 – 1 km	
Hotels / Resorts	5 to 10 rooms		0 – 500 m	

The components described in Table 2 were combined into an aggregate coastal development threat estimate (THR_CD). Coral reef locations are overlaid and classified by this adjusted threat estimate.

Data Sets Used in Coastal Development Threat Analysis:

- Settlements in Belize – Settlement_Points from Jan Meerman / Belize Tropical Forest Studies, 2004.
- Ports— BZ_ports from CZMAI, 2005.
- Airports and Airstrips — BZ_Airstrip from CZMAI / Civil Aviation Dept, 2005.
- Tourism centers— extracted from CZMAI “Coastal Uses” data, CZMAI, 2005.

- Hotels in Belize– bz_hotels_updated from WWF, TNC and Belize Tourist Board, 2005.

THREAT: Sedimentation and Pollution from Inland Sources

Agriculture and other land use activities far inland can have an adverse impact on coral reefs through the increased delivery of sediment and pollution to coastal waters. A watershed-based analysis of land-based sources of pollution (LBS) was implemented to develop a preliminary estimate of this threat.

Analysis Method

Watersheds are an essential unit for analysis, since they link land areas with their point of discharge to the sea. We have implemented a watershed-based analysis of sediment and pollution threat to coral reefs. This analysis incorporates land cover type, slope, soil characteristics, and precipitation for all land areas, using a simplified version of the Revised Universal Soil Loss Equation (RUSLE) (USDA, 1989) in order to estimate relative erosion rates for each 1-km resolution grid cell. These relative erosion estimates are summarized by watershed. Since not all erosion makes its way to the river mouth, sediment delivery ratios (based on watershed size) were applied in order to estimate relative sediment delivery at the river mouth. Sediment plumes were estimated on the basis of relative sediment delivery and distance from each river mouth. Any given location can have contributions from multiple rivers. Model results were calibrated on the basis of available data on river discharge, sediment delivery, and observed impacts on coral reefs. It should be noted that relative erosion rates and sediment delivery are being used as a proxy for both sediment and pollution delivery.

Model Implementation

Step 1) The first step of the analysis involves estimating likely relative erosion rates for each 1-km resolution grid cell using a modified, simplified form of the Revised Universal Soil Loss Equation (RUSLE) (USDA, 1989).[1] Information on slope, land cover type, precipitation, and soil porosity were integrated to develop an indicator of relative erosion potential (REP) for all land areas within the wider Caribbean.

Data Sets Use in the 1 km resolution analysis
REP relies upon four input data sets:

a) **Percent slope** (derived from USGS HYDRO1K digital elevation model, 2000), (1000-m resolution)
b) **Relative erosion rate** by land cover type. The Global Land Cover Characteristics (GLCC) Database (USGS / Loveland, 2000) using International Geosphere-Biosphere Program land cover categories was reclassified to relative erosion rates, ranging from 15 (for forest) to 220 for barren land. (See Table 4 below) These relative erosion rates are based on published work involving conversion factors.[2] (1000-m resolution)

[1] See http://msa.ars.usda.gov/ms/oxford/nsl/rusle/.
[2] Estimates of erosion from different land cover types (table 4) are based on Berner, E. and Berner R. 1987. The Global Water Cycle: Geochemistry and Environment, pp. 183-189. Yale University, Prentice-Hall International and Nyborg, Petter A. 1995. Assessment of Soil Erosion in Sierra Leone. The World Bank, Washington.

c) **Precipitation** for the peak rainfall month (mm), based on monthly precipitation surfaces from Global Arc CD (U.S. Army CERL and Center for Remote Sensing and Spatial Analysis (CRSSA), Cook College, Rutgers University, "Global ARC" CD, 1996.) This variable was chosen instead of mean annual precipitation because it is more indicative of the extreme rainfall events and because it captures more of the rainfall variability in the area. (0.08 DD or 9342-m resolution)

d) **Soil porosity**. A polygon database on soil type (UN Food and Agriculture Organization (FAO), "World Soil Database," 1995) provided soil texture and porosity attributes. Soil porosity is the soil characteristic used in calculations because of its relationship with infiltration capacity of the soil. (5000-m resolution)

Table 4. Land Cover and Associated Relative Erosion Rates

GLCC_ CODE	LAND COVER CATEGORY	RELATIVE EROSION RATE
19	Water bodies	5
1-5	Forest (All types of closed forest)	15
6	Closed shrub land	45
7	Open shrub land	50
8	Woody savanna	60
11	Permanent wetlands	80
9	Savannas	100
14	Cropland/natural	120
10	Grasslands	125
12	Croplands	200
13	Urban and built-up	210
16	Barren or sparse vegetation	220

Equation 1:

REP (by 1-km grid cell) = pct_slope * Land_cov_eros_rate * Precip_mm * porosity / 1,000

Within this analysis, slope is the most influential input variable, followed by land cover, precipitation, and soil porosity. The most influential areas in the landscape in terms of high relative erosion rates are steep slopes with land converted to agriculture.

Step 2) Watershed boundaries were developed for the region using a modified DEM (USGS HYDRO1K, 2000). At WRI the DEM was "filled" and rivers and lakes were "burned" as to improve the accuracy of the watersheds. Rivers are based on HYDRO1k rivers. This resulted in a data set of more than 2,100 watersheds with a minimum size of 35 sq km draining into the Caribbean.

Step 3) Two indicators indicative of erosion within the watershed were calculated for each watershed:

mean REP for the basin (an indicator of average erosion rates for the basin) (**REP_MEAN),** and
total relative erosion within the basin **(REP_SUM).**

Step 4) An indicator of relative sediment delivery at the river mouth was estimated by multiplying total relative erosion in the basin (**REP_SUM)** by the sediment delivery ratio **(SDR)** for the basin, which is a function of watershed size. **SDR = 0.41 * basin area (in sq km)**$^{-0.3}$. This factor comes from published research on watersheds in the Western Caribbean.[1]

Step 5) Model results were calibrated against the limited number of observations of river discharge and sediment delivery for which estimates were available.[2]

Step 6) We estimated relative sediment plumes across the wider Caribbean by dispersing sediment from the river mouth using a distance-based degrading function. Relative sediment dispersion is based on the sediment delivery estimates at the river mouth and the distance from the river mouth. We used a 10 percent reduction in sediment per km from the river mouth.

Model results for the Mesoamerican reef region were clipped and projected in UTM (Zone 16, NAD1927) for this data CD. These estimates of relative sediment delivery will be replaced by a higher resolution analysis currently underway under the ICRAN MAR project.

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THREAT: *Marine-based Threats*

Marine-based activities threaten coral reefs through pollution from ports, oil discharge and spills, ballast and bilge discharge, dumping of garbage, and direct physical impacts from groundings and anchor damage.

Analysis Method

Threats to coral reefs from marine-based sources of pollution were evaluated on the basis of distance to ports stratified by size, volume of cruise ship visitation, and distance to dive sites and shipping lanes.

Table 6. Model Rules Implemented

Subject / Stressor	Qualifier	High	Medium	Low
Ports	Medium	0 - 10 km	10 – 25 km	
Ports	Small	0 – 4 km	4 – 10 km	

[1] Thattai, D., B. Kjerfve, and W.D. Heyman, 2002. “Hydrometeorology and variability of water discharge and sediment load in the inner Gulf of Honduras, Western Caribbean,” in *Journal of Hydrometeorology.*

[2] River discharge and sediment delivery estimates are required for validation of this model. At the time of publication, we had river discharge estimates for 13 rivers (correlation is .94 with our modeled results) and have sediment deliver estimates for only 5 rivers (correlation is .88 with our results). Further evaluation of the model results was done by expert reviewers.

Ports	Very Small	0	0 – 4 km	
Cruise Ship Ports of Call	Based on number of calls	Up to 5km	Up to 10 km	
Shipping Lanes	Multiple Uses	0 – 1.5	1.5 to 4 km	
Dive Sites	Mapped / known		0 – 1 km	

The above components were combined into an aggregate threat estimate, with coral reef locations overlaid and classified.

DATA SET USED IN THE ANALYSIS OF MARINE-BASED THREATS

Ports— BZ_ports from CZMAI, 2005.

Cruise ships (volume of visitation)—Information for this data set was derived from the "Choosing Cruising" website http://www.choosingcruising.co.uk, and georeferenced at WRI, 2003.

Shipping Lanes – BZ_shipping_lanes from CZMAI, 1993.

Dive Sites – extracted from CZMAI "Coastal Uses" data, CZMAI, 2005.

Model Limitations

The *Reefs at Risk* analysis approach is a simplification of human activities and complex natural processes. The model relies on available data and predicted relationships but cannot capture all aspects of the dynamic interactions between people and coral reefs. The *Reefs at Risk* analysis provides a series of regionally / nationally consistent indicators of human pressure on coral reefs. A strength of the analysis lies in applying a modeling approach to regionally consistent data sets. However neither the data sets nor the modeling approach are perfect. There are inevitably omissions and other errors in the "input data sets," such as land cover, shipping lanes, and tourism centers. In addition, the models are limited by the available data sources. For example,

- In the analysis of land-based sources of sediment and pollution, since we lack spatial data on agricultural crops and fertilizer application, we use sediment as a proxy for both sediment and pollution delivery.
- In the analysis of coastal development, we have information on current hotels and tourism centers, but lack information on proposed developments.
- We were not able to model the threat related to coral bleaching, coral disease, or changes in storm frequency because of the lack of spatial detail in region-wide physical and oceanographic data sets, and some uncertainties, such as the cause of many of the diseases.

Table 1 Summarizes model limitations by threat category.

The *Reefs at Risk in Belize* model results should be regarded as our best attempt to evaluate relative human pressure on coral reefs in Belize, using currently available sources. It should be noted that these are indicators of pressure, rather than condition. In areas identified as threatened, however, degradation of coral, including reduced live coral cover, increased algal cover, or reduced species diversity, is likely within the next five to ten years. For Comparison with threats to coral reefs across the Caribbean, see *Reefs at Risk in the Caribbean* (on this data CD.)