WORLD RESOURCES INSTITUTE

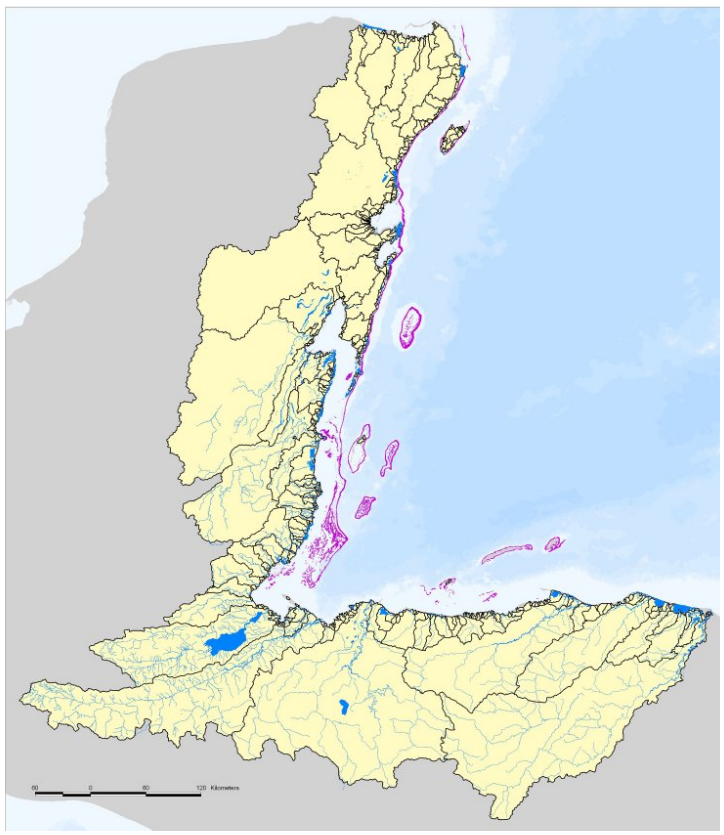
Hydrologic Modeling of Watersheds Discharging Adjacent to the Mesoamerican Reef

Analysis Summary - December 1, 2006

By: Lauretta Burke and Zachary Sugg

With analytical contributions from:
Will Heyman and Shin Kobara (Texas A& M University)
Laurent Cherubin, Christopher Kuchinke, Claire Paris, and Johnathan Kool (University of Miami)

Watersheds of the Mesoamerican Reef Region



Funded by:

Part of the ICRAN MAR Alliance:

In partnership with:

The ICRAN Mesoamerican Reef project was supported by the U.S. Agency for International Development (USAID) and the United Nations Foundation (UNF). The project is executed in conjunction with the United Nations Environment Program – Caribbean Environment Program (UNEP-CEP).

Collaborating on the watershed component of the ICRAN MAR partnership are WRI, UNEP – World Conservation Monitoring Center (WCMC) and the World Wildlife Fund (WWF).

Contents

List of Figures

List of Tables

List of Acronyms

CDM: Colored Detrital Matter
DEM: Digital Elevation Model
GEO: Global Environment Outlook
ICRAN: International Coral Reef Action Network
MAR: Mesoamerican Reef
N-SPECT: Nonpoint-Source Pollution and Erosion Comparison Tool
ROMS: Regional Ocean Modeling System
RUSLE: Revised Universal Soil Loss Equation
SeaWiFS: Sea-viewing Wide Field-of-view Sensor
SOA: Spectral Optimization Algorithm
SOTERLAC: Soil and Terrain Database for Latin America and the Caribbean
TSS: Total Suspended Solids
UNEP: United Nations Environment Programme
USAID: U.S. Agency for International Development
WCMC: World Conservation Monitoring Centre
WRI: World Resources Institute
WWF: World Wildlife Fund

Acknowledgments

This data CD was made possible through the generous contributions of the United Nations Foundation and the US Agency for International Development under the International Coral Reef Action Network (ICRAN) Mesoamerican Reef (MAR) project.

The World Resources Institute gratefully acknowledges the many partner organizations and colleagues who contributed to this project and the production of this data CD, including core ICRAN partners: UNEP-World Conservation Monitoring Centre (WCMC), and the World Wildlife Fund (WWF). Thanks to Emil Cherrington (Belize Coastal Zone Management Institute and Water Center for the Humid Tropics of Latin America and the Caribbean, CATHALAC) for data development and guidance on spatial data issues; Joep Luijten (consultant to UNEP-WCMC) and Lera Miles (UNEP-WCMC) for land-use scenario modeling; Eric van Praag (consultant to UNEP-WCMC) for facilitating the project's policy and training workshops; Liza Agudelo and Armeid Thompson (ICRAN MAR project); and Kristian Teleki and Nic Barnard (ICRAN) for encouragement and support throughout. Thanks to Will Heyman and Shin Kobara (Texas A&M University) for assisting with calibration of the hydrological model, and to Jamie Carter and Dave Eslinger (US National Oceanographic and Atmospheric Administration) for providing guidance on implementation of the N-SPECT model. Thanks to Claire Paris, Laurent Cherubin, Christopher Kuchinke, and Johnathan Kool (University of Miami) for adapting a circulation model to examine sediment dispersion along the Mesoamerican Reef; and to Nestor Windevoxhel and Alejandro Arrivillaga (The Nature Conservancy) for jointly supporting the circulation modeling. Thanks to Ramon Frutos (Belize Meteorological Department) for data on hurricane events and Jan Meerman (Belize Tropical Studies) for data on land cover and watersheds. Thanks to the World Bank / GEF Mesoamerican Barrier Reef System (MBRS) project for identifying N-SPECT as a useful tool. Thanks to Melanie McField (WWF and Smithsonian Institution) for constructive comments and guidance on impacts to the MAR; and Jose Vasquez, Sylvia Marin, Shalini Cawich and Gina DeFerrari (WWF) for their helpful collaboration under the ICRAN partnership. Thanks to Serge Andrefouet for provision of coral reef data for the MAR. Thanks to Suzie Greenhalgh, Daniel Prager, Janet Ranganathan, Isabel Munilla, and David Jhirad (WRI) for their valuable review and comments; and to Jenny Guiling (WRI) for provision of data for calibration of model results. Thanks to Ron Valenzuela (WRI) for editing the document and special thanks to Carolina de Rosas and Ruth Nogueron (WRI) for translating this paper into Spanish.

This data CD was made possible through support provided by the office of Guatemala-Central American Programs, U.S. Agency for International Development, under the terms of Grant no. 596-G-00-03-00163-00. The opinions expressed herein are those of the authors and do not necessarily reflect the views of the U.S. Agency for International Development or of UNEP.

Hydrologic Modeling of Watersheds Discharging Adjacent to the Mesoamerican Reef

Project Summary

This paper describes the methodology and results of a hydrologic analysis implemented by the World Resources Institute (WRI) as part of the International Coral Reef Action Network (ICRAN) Mesoamerican Reef (MAR) partnership. The objective of the analysis was to quantify the impact of human alteration of the landscape on land-based threats to the MAR to inform land-use planning, agricultural policy and practice, conservation priority setting, and risk mitigation efforts.

Over a two year period, WRI collaborated with many partners in the region to evaluate sediment and nutrients coming from land in over 400 watersheds that discharge adjacent to the MAR. The analysis evaluates the amount of sediment and nutrients (nitrogen and phosphorous) coming from each plot of land; the amount of eroded sediment and nutrients reaching the river mouth (coastal discharge point); and the amount of sediment reaching the reef. In addition, the analysis provides estimates of the increase in sediment and nutrient delivery resulting from human activities, and predictions of future sediment and nutrient delivery (in 2025) given varying land-use scenarios. This analysis is the first of this scope and level of detail for the MAR region.

The results provide a preliminary overview of regional patterns of sediment and nutrient runoff and delivery, and indicate how human alteration of the landscape can influence these patterns. To ensure that the project's results and analytical methods support action in the region, WRI makes the underlying data, analytical method, and modeling tools publicly available, and has conducted training sessions with users in the region. Based on this training, regional users can implement more detailed, focused analyses for smaller areas, calibrating them to local conditions.

All data used in the analysis and all model results, accompanied by metadata, are provided on the data CD, *Watershed Analysis for the Mesoamerican Reef*, WRI/ICRAN MAR project, 2006. This paper begins with background on the ICRAN MAR partnership and a summary of key findings, followed by a description of the analytical methodology and a summary of analysis results.

Project Background

Shared by Mexico, Belize, Honduras, and Guatemala, the Mesoamerican Reef (MAR), stretches over 1,000 km, and is the largest continuous reef in the Western Hemisphere. Alteration of the natural landscape for development, road construction, or agriculture can have adverse impacts on coral reefs through increased delivery of sediment, nutrients, and other pollutants to coastal waters. Threats from land clearing are higher in areas of steep slope, intense precipitation, and erosive soils.

Appropriate land-use practices in erosion-prone areas are essential for the management of watersheds to ensure that the transport of sediment, nutrients, and other pollutants to coral reefs is minimized. In the Mesoamerican region, over 300,000 hectares of land is allocated to the production of banana, oil palm, sugar cane, citrus, and pineapple crops. Eroded sediments as well as the residues of fertilizer and pesticides used in these industries drain through the rivers and streams and enter coastal waters along the Mesoamerican reef.

As part of the International Coral Reef Action Network (ICRAN) Mesoamerican Reef (MAR) project, the **World Resources Institute (WRI)** partnered with **UNEP-World Conservation Monitoring Centre (WCMC)** and the **World Wildlife Fund (WWF)** to provide comprehensive watershed analysis to complement the ICRAN MAR project's activities on Sustainable Fisheries and Sustainable Tourism.

The ICRAN MAR watershed analysis was developed to produce information and tools for examining the potential impact of different land use and development options in the region and the associated impacts on water quality on the MAR. The project aims to:

- Link patterns of land use within watersheds to the impacts at coral reefs, and identify reefs at greatest risk of degradation;
- Identify watersheds most vulnerable to erosion and those which contribute the most sediment and pollution to coastal waters;
- Adapt tools to forecast potential trends, evaluate different policy or development options, and facilitate improved land management within the region;
- Use the results of the models and diagnostic tools to help educate and encourage key stakeholders to adopt a suite of "better management practices" to reduce impacts on the coastal and marine resources.

The ICRAN MAR watershed project includes analytical components looking at land cover change and the associated impacts on runoff, erosion, and sediment and pollutant delivery to and transport within coastal waters. The project also includes on-the-ground activities with agricultural businesses to implement better management practices. Many local partners were consulted on modeling methods, for data input and evaluation, and on agricultural management practices. Three ICRAN partners collaborated on this effort:

- UNEP-WCMC – developed scenarios of land cover change and provided land cover data sets as input to the hydrologic modeling;

- WRI – implemented the watershed delineation and hydrologic analysis for the MAR region, performed analysis of vulnerability to erosion, and coordinated the circulation modeling along the MAR;
- WWF – led the work with agri-business to implement better management practices.

WWF's work with agricultural businesses focuses on reducing the presence of priority pesticides in the MAR marine environment and controlling soil erosion from major commercial agricultural sectors. WWF is working with business partners on banana, pineapple, citrus and sugar cultivation. The analysis performed under this project helps WWF and others to set priorities for targeting better land-management practices as well as to guide land-use planning.

Key Findings

This hydrologic analysis serves to integrate a wide range of data, and adapt modeling tools for an innovative, region-wide analysis for the MAR. The region-wide results presented in this paper should be considered preliminary and indicative of the overall pattern and magnitude of erosion and nutrient and sediment delivery across the region. An important aspect of the project is to provide these modeling tools to partners in the MAR region so that they might apply them at higher resolution to produce more detailed results for smaller areas within the MAR region. This approach will allow for refinement and better calibration of the model to local circumstances within the region.

The origin of sediments and nutrients reaching the MAR:

- Most of the sediment and nutrients delivered by watersheds along the MAR originate in Honduras. It is estimated that over 80% of sediment and over half of all nutrients (both nitrogen and phosphorous) originate in Honduras.

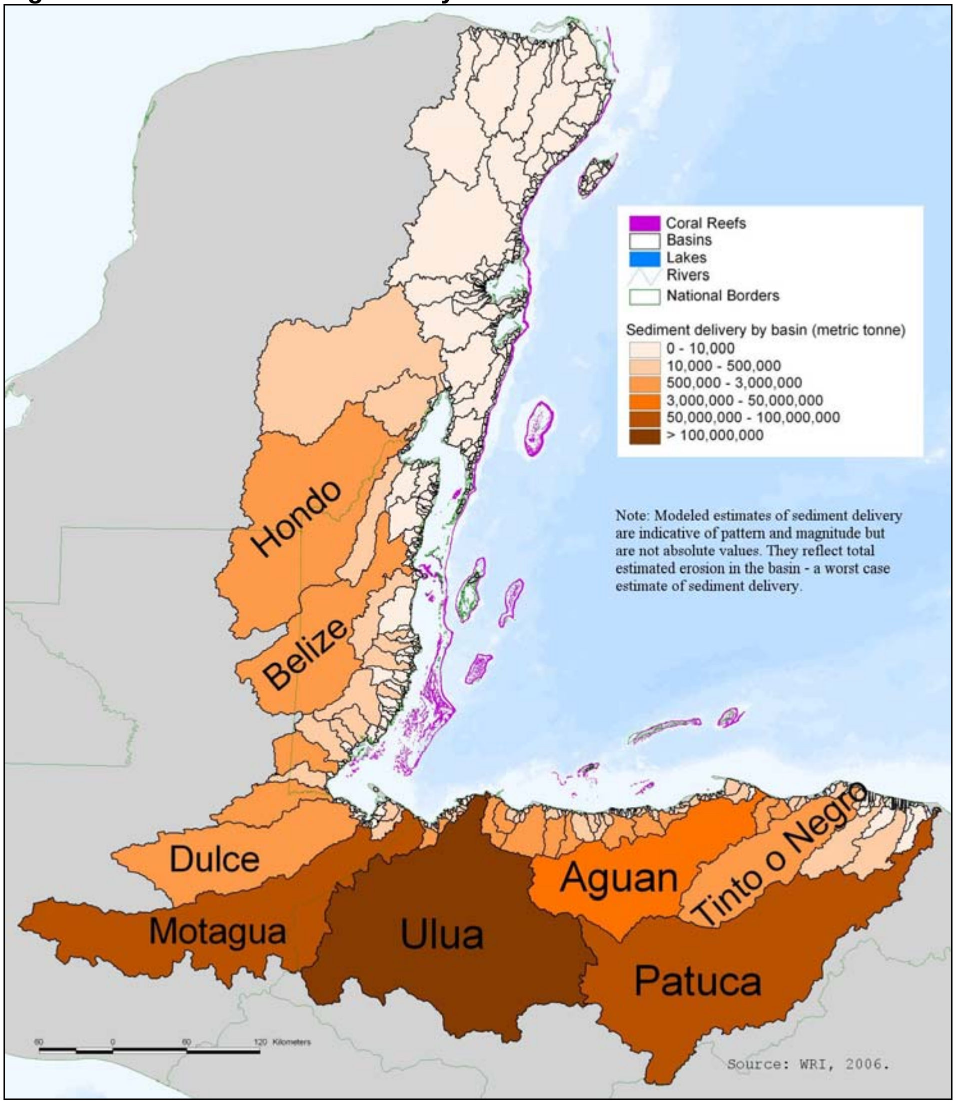
- Guatemala was identified as a source of about one-sixth of all sediments and about one-quarter of all nitrogen and phosphorous entering coastal waters along the MAR.

- The modeling suggests that compared to the other countries, relatively minor percentages of the regional sediment load come from Belize and Mexico. Belize contributes between 10-15% of nutrients and Mexico is estimated to contribute about 5%of the nutrients from all modeled watersheds. The estimate for Mexico is probably an underestimate, as the contribution of underground rivers is not included in this analysis.

- Of the 400 watersheds in the MAR region, the Ulua watershed in Honduras was found to be the largest contributor of sediment, nitrogen, and phosphorous. Other large rivers found to be significant contributors of sediment and nutrients are the

Patuca (in Honduras), Motagua (in Guatemala and Honduras), Aguan (in Honduras), Dulce (in Guatemala), Belize River (in Belize), and Tinto o Negro (in Honduras).

Figure A. Annual Sediment Delivery from MAR Watersheds



Runoff, erosion, and nutrient delivery to coastal waters are increasing:

- As a result of human alteration of the landscape, runoff and associated river discharge at river mouths has nearly doubled; sediment delivery at river mouths has increased by a factor of 20; nitrogen delivery has increased by a factor of 3, and phosphorous delivery by a factor of 7. (Ratios are based on model results for current (2003/04) land cover and on hypothetical natural (unaltered) land cover.)

The potential impacts of development and land-use paths are varied:

- Under land-use scenarios which favor free markets and little policy regarding the environment, nutrient delivery is likely to increase by about 10% by 2025, while sediment delivery might increase by 13% or more.

- If environmental policies that favor sustainable development are implemented, nutrient and sediment delivery are likely to be reduced by at least 5% from current levels, promoting recovery of degraded corals.

- Implementation of better agricultural management practices will yield additional reductions in sediment and nutrient delivery beyond those evaluated in this study, which has focused on the effect of changes in land cover.

Overview of Methodology

In collaboration with partners in the MAR region, WRI:

- implemented a watershed delineation for all land areas draining along the Mesoamerican reef;
- implemented a hydrologic analysis to examine sources of sediment and nutrients from this entire drainage area, as well as the delivery of sediment and nutrients to coastal waters;
- applied this hydrologic analysis tool to examine sediment and nutrient delivery for several land cover scenarios (current land cover, original or “natural” land cover, and three scenarios of land cover in 2025);
- provided outputs of the hydrologic analysis as inputs to a circulation model to examine sediment transport along the MAR; and
- collaborated with partners on calibration and validation of model results.

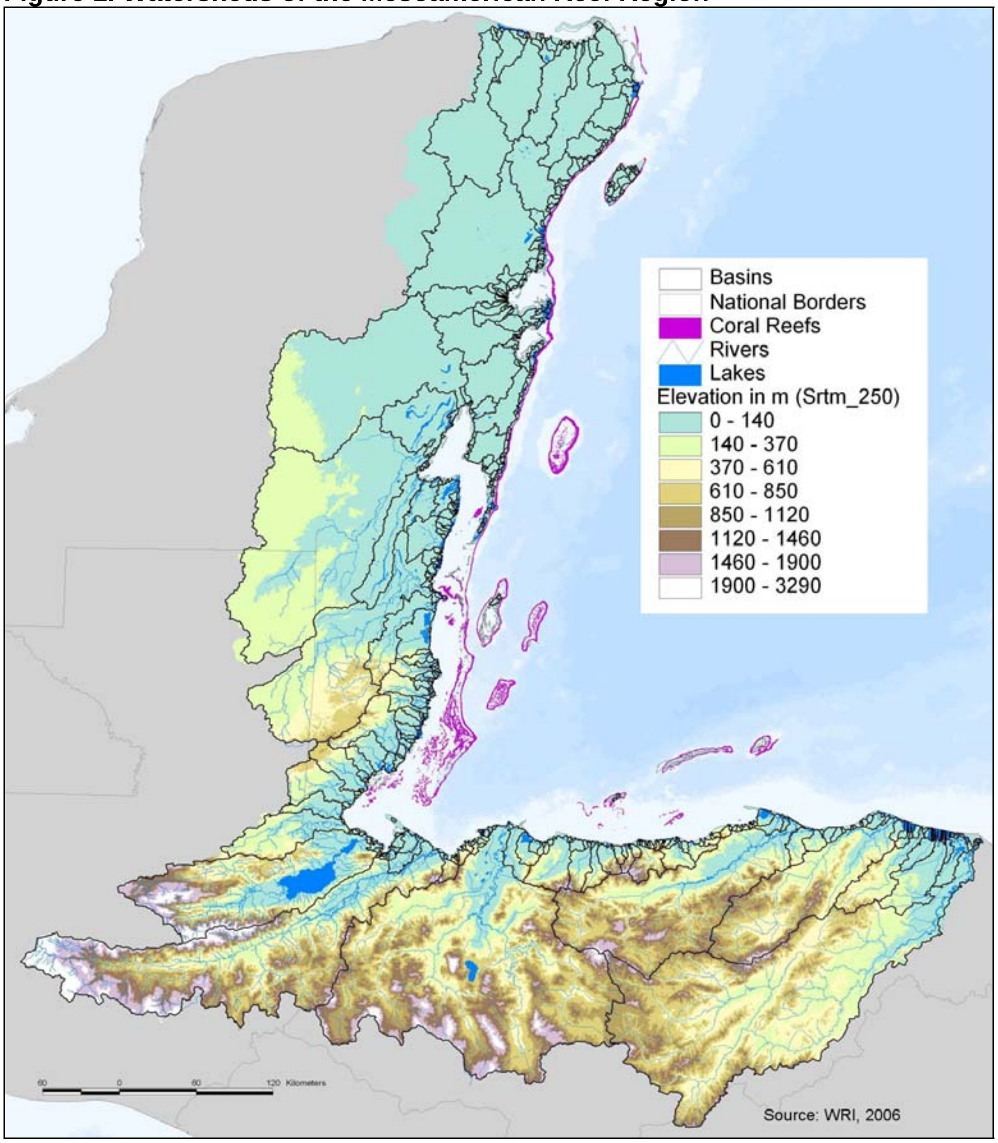
Watershed Delineation

Watersheds are an essential unit for this hydrologic analysis, as they serve to link a plot of land with its stream and river network, and its point of discharge to the sea. Watersheds were delineated from a hydrologically corrected 250m digital elevation model (DEM). This DEM is based on 90m resolution NASA Shuttle Radar Topography Mission (SRTM) data, which were projected and resampled to 250m resolution for use in this project’s land cover and hydrologic modeling. As elevation data from radar has inherent inaccuracies, such as capturing the tops of trees and buildings as part of the elevation, the elevation data needed some “correction” as part of the delineation process. Some mapped rivers and lakes were superimposed on the DEM through a process called “burning” the DEM. Rivers (as lines) from La Comision Centroamericana de Ambiente y Desarrollo (CCAD) and lake and lagoon data (polygons) from WWF were used to develop a data set for correction of the DEM.[1] This grid was superimposed (as -20m elevation) into the DEM to ensure that water was forced to flow in these depressions. This “burned” version of the data set was used for basin delineation in the Environmental Systems Research Institute’s (ESRI) ArcMap software. For each 250m grid cell in the DEM, the direction of water flow (FlowDirection) and the number of cells flowing into each cell (FlowAccumulation) was identified, as well as which cells comprise a basin (area draining to a single coastal point.) The 250m grid cell with the maximum flow accumulation in each basin was identified as the “pour point,” or point of discharge to the sea. Basins of less than 5 km^2 area were excluded. Over 430 basins of at least 5 km^2 area were identified. (Some additional technical notes on watershed delineation can be found at the end of this report.)

[1] See metadata on *Watershed Analysis for the Mesoamerican Reef* data CD for data sources, as well as the GIS data set used for correction.

This final set of watershed delineations for the MAR region benefited from several rounds of review and the provision of additional data by several project partners. Delineations were again reviewed at the ICRAN MAR watershed workshop held in Belize in August 2006. The watershed delineations are reliable for most of the MAR region, but are inaccurate for the Yucatan, due to widespread karst topography with underground rivers and lack of perennial surface waters.

Figure 1. Watersheds of the Mesoamerican Reef Region



Hydrologic Modeling

Threat from land-based sources of sediment and nutrients was evaluated using the Nonpoint Source Pollution and Erosion Comparison Tool (N-SPECT), developed by the U.S. National Oceanographic and Atmospheric Administration (NOAA). N-SPECT is a public-domain software which runs as an optional extension within ESRI's ArcMap software. N-SPECT combines information on the physical environment (elevation, slope, soils, precipitation, and land cover) to derive estimates of runoff, erosion, and pollutant sources (nitrogen, phosphorous and total suspended solids) from across the landscape, as well as estimates of sediment and pollutant accumulation and concentration in stream and river networks. N-SPECT was implemented at 250m resolution for the MAR region. Hence, N-SPECT evaluates each 250m resolution grid cell (6.25 ha area) for its contribution to runoff, sediment, and pollutant delivery within the watershed. The results of N-SPECT analyses are intended to be used as screening tools to help understand and predict the impacts of management decisions on water quality and, ultimately, on near shore coral reef health.

N-SPECT can be run to evaluate annual or event-based runoff, erosion, sediment, and pollutant delivery. It can also be modified to evaluate these outputs on a monthly basis. N-SPECT runs can either calculate the accumulation of runoff, sediment, and pollutants across the landscape (this is the standard run) or "local effects," meaning how much sediment, pollutant, or runoff comes from each individual grid cell. All of these options were employed in the analysis of land-based threat along the MAR.

a. **Annual runs –** For the MAR region, N-SPECT was applied to evaluate annual runoff, sediment, and nutrient delivery associated with several different land cover scenarios - current land cover (circa 2003/04), hypothetical "natural" land cover, and three scenarios of potential land cover in 2025. In these "annual" runs, N-SPECT was run with a consistent elevation, slope, soils, and annual precipitation. Only the land cover data set was varied so that the influence of land cover change on sediment and nutrient delivery could be evaluated.
b. **Monthly runs –** N-SPECT was also run using monthly precipitation data in order to derive monthly estimates of runoff and sediment delivery at river mouths, which are essential inputs to the circulation modeling for the region, which is implemented on a monthly time frame.
c. **Local effects / sources of pollution –** N-SPECT was run in "local effects" mode on current land cover (circa 2003/04) in order to evaluate how much sediment and nutrients (nitrogen and phosphorous) originate from each individual 250m grid cell independent of contributions from adjacent / upstream grid cells.
d. **Storm Events –** N-SPECT was also applied to examine the sediment and nutrient runoff and delivery associated with hurricanes in the region. This application using the "storm event" feature of N-SPECT, used the same elevation, slope, and soils data as the previous runs, as well as current land cover (circa 2003/04), but used local precipitation data for the multi-day storm events.

GIS Data Sets

All GIS data sets used in the hydrologic analysis are in Universal Transverse Mercator (UTM) projection (NAD1927 for Central America datum). All data inputs and model results are available on the data CD, *Watershed Analysis for the Mesoamerican Reef,* WRI / ICRAN MAR project, 2006.

Input Data sets used in the hydrologic analysis using N-SPECT were:

1. **Elevation** – a 250m resolution digital elevation model was derived from 90m resolution NASA Shuttle Radar Topography Mission (SRTM) data.
2. **Soils –** Soils come from a vector (polygon) data set acquired from the Soil and Terrain Database for Latin America and the Caribbean (SOTERLAC).
3. **Precipitation –** monthly precipitation data come from a 1 km resolution global raster precipitation data set called WorldClim[2], which reflects long-term average precipitation. Monthly precipitation data were summed to produce annual rainfall estimates. All precipitation data were converted to inches for use in N-SPECT.
4. **Land Cover –** five representations of land cover were used to allow for evaluation of the effect changes in land cover have on sediment and nutrient delivery to river mouths along the MAR.
    - **"Current" Land Cover –** National "Ecosystem Maps" for Mexico, Guatemala, and Honduras (2003) and Belize (2004) were used as the basis of the current land cover map. Data were merged for the four countries and gridded at 250m resolution.[3]
    - "**Natural" Land Cover** - "Original" or natural land cover for Belize, Guatemala, and the Yucatan comes from a vector data set by Pronatura on "Original land cover." [4]

Land Cover in 2025. Three land cover change maps from 2005 to 2025 were developed for the MAR region, based on the Markets First, Policy First, and Sustainability First scenarios from the UNEP Global Environment Outlook (GEO)

[2] See 2005. Very High Resolution Interpolated Climate Surfaces for Global Land Areas. (14 pages) Description of the development of the WorldClim global climate data set. In *International Journal of Climatology*. *Robert J. Hijmans, et al*. on *Watershed Analysis for the Mesoamerican Reef* data CD, WRI / ICRAN MAR project, 2006.

[3] Some "nodata" cells for land cover along the coast were filled in based upon the land cover class of the nearest land cover cell. In addition, some locations were recoded as "water" based on data from Pronatura on waterbody locations in Belize, Guatemala, and the Yucatan.

[4] Land classes have been reclassified to match the classes used in the ICRAN MAR watershed analysis, and gridded at 250m resolution. For Honduras, the Ecosystem map of Honduras (2003) was modified as follows - "Cultivated" and "Developed" land cover was reclassified based on the adjacent land cover type, with the exception of water (not allowed to expand) and mangrove (only allowed to expand if below 20m elevation).

process.[5] The scenarios envisage differing social, political, and economic trajectories, emphasizing outcomes for the environment and human well-being.

- "**Markets First" scenario of land cover in 2025 –** In this market-oriented development scenario based on the GEO Market First Scenario for Latin America, most of the world adopts the values and expectations prevailing in today's industrialized countries. The wealth of nations and the optimal play of market forces dominate social and political agendas. Public policy is geared toward supporting commercial interests and promoting the open exchange of goods and services. Social and environmental policies receive little attention or financial support, for it is assumed that economic growth is in itself a sufficient route to progress. This scenario sees the greatest rate of agricultural expansion. The 250m resolution land cover data reflecting this scenario were developed at UNEP-WCMC.
- "**Policy First" scenario of land cover in 2025 –** In this scenario based on the GEO Policy First Scenario for Latin America, decisive initiatives are taken by governments in an attempt to reach specific social and environmental goals. A coordinated pro-environment and anti-poverty drive balances the momentum for economic development at any cost. Environmental and social costs and gains are factored into policy measures, regulatory frameworks, and planning processes. All these are reinforced by fiscal levers or incentives such as carbon taxes and tax breaks. Land use becomes better regulated, especially around riverine corridors. Associated 250m resolution land cover data were developed at UNEP-WCMC.
- **"Sustainability First" scenario of land cover in 2025 –** In this scenario based on the GEO Sustainability First Scenario for Latin America, a new environment and development paradigm emerges in response to the challenge of sustainability, supported by new, more equitable values and institutions. A more visionary state of affairs prevails, where radical shifts in the way people interact with one another and with the world around them stimulate and support sustainable policy measures and more accountable corporate behavior. Efficiency in the use of energy, land, and material resources is promoted. There are efforts to adopt an ecosystem approach to land use planning, with particular attention to watershed protection. Associated 250m resolution land cover data were developed at UNEP-WCMC.

---

[5] A quantification of land cover change was developed from preliminary inputs to GEO4 from the International Futures and IMAGE modeling teams, and a set of accompanying narratives were adapted from the Latin America and Caribbean group's input to GEO4. Protected area scenario maps were developed on the basis of international policy targets for the coverage of biomes and endangered species, and implemented differently in each scenario. The CLUE-S model was then used to allocate land cover change. Further information can be found in Luijten, J., Miles, L., Cherrington, E. (2006) *Land use change modelling for three scenarios for the MAR region*. Technical Report to ICRAN MAR project. UNEP-WCMC.

Modeling Erosion and Sediment Delivery

N-SPECT evaluates annual erosion for each grid cell based on the Revised Universal Soil Loss Equation (RUSLE) developed by the U.S. Dept. of Agriculture[6]. RUSLE combines aspects of slope, rainfall, soil, and land cover to estimate annual soil loss for that location.

Equation 1: RUSLE

Average Annual Soil Loss (tons/acre) = R * K * L * S * C * P

R – Rainfall-runoff erosivity factor
K – Soil erodibility factor
*L*S – Slope steepness and length factors*
C – Cover-management factor
P – Supporting practices factor

The input data sets listed above are elevation, soils, precipitation, and land cover. N-SPECT uses these data sets as the basis for deriving most of the factors that are used in the RUSLE calculation. Some of the derivations are complicated and are described below with additional detail in the technical notes at the back of this report. In summary:

- **LS-factor –** The LS factor adjusts erosion rates based on topography, assigning higher rates to longer or steeper slopes and lower rates to shorter or flatter ones[7]. Slope steepness (S) and slope length (L) are derived from the DEM by N-SPECT. These are combined into one "LS-factor" grid.
- **K-factor –** The SOTERLAC soils database includes the soil-erodibility factor (K-factor) attribute, which represents a soil's susceptibility to erosion by rainstorms. It is an integrated average parameter based on several different erosion and hydrologic processes. A low K-factor (about 0.05 to 0.2) indicates a high resistance to erosion and a high K-factor (about 0.4 or greater) indicates easily eroded soil. N-SPECT develops a GRID based on the K-factor for RUSLE calculations.
- **R-factor –** A grid of the rainfall and runoff erosivity factor (R) for the study area is an input to the N-SPECT model and must be acquired or developed by the user. R-factor represents the average annual erosive effect of storms and is based on an erosivity index (EI) calculated from the kinetic energy of storms and their maximum 30-minute rainfall intensities. These data were not available for the MAR region so an alternate method was used to approximate R-factor. Development of this factor is described in the next section.
- **C-factor –** Each land cover type, such as forest, grassland, or cultivated land has an associated cover-factor or C-factor. This is a relative erosion rate for the given land cover. (See Table 1.) Cultivated land, with a C-factor of .240 is rated as being 60 times as erosive as forest, which has a C-factor of .004. These C-factors

---

[6] USDA Agriculture Handbook No. 703, found on *Watershed Analysis for the Mesoamerican Reef* data CD, WRI / ICRAN MAR project, 2006.
[7] Ward, Andrew D. and Stanley W. Trimble. Environmental Hydrology, 2nd Ed. CRC Press, LLC. 2004.

for land cover in the MAR region were adapted from C-factors provided by NOAA in N-SPECT. Use of locally derived relative erosion rates would be a valuable refinement of the model.

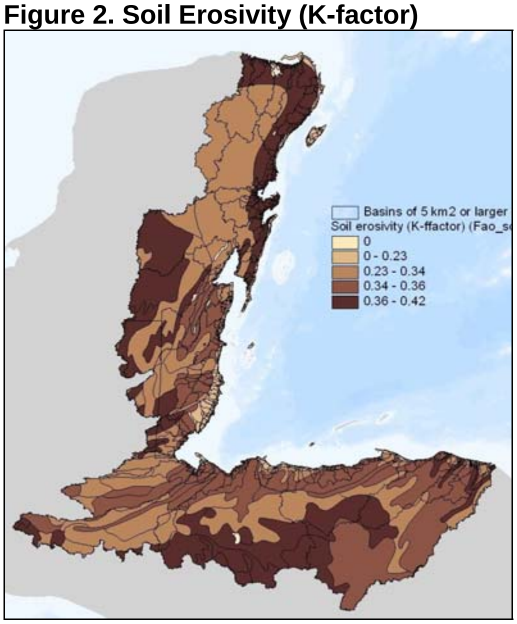
- **P-factor –** RUSLE includes a supporting practices factor or P-factor, which allows inclusion of the influence of conservation practices (such as strip-cropping and terracing) that control and mitigate erosion. The "Supporting Practices" factor module is not available in the current version of N-SPECT. For this reason, we have focused our analysis on the effect of change in land cover on sediment and pollutant delivery to river mouths adjacent to the MAR. In addition, information on specific management practices across the MAR region is fairly limited.

Table 1. N-SPECT C-factor Coefficients

Code	Land Cover Category	Cover-Factor
3	Low Intensity Developed	0.030
4	Cultivated Land	0.240
5	Grassland	0.050
7	Forest	0.004
9	Scrub/Shrub	0.014
10	Palustrine Forested Wetland	0.003
17	Bare Land	0.700
18	Water	0.000

Source: *USDA Agriculture Handbook No. 703*

Figure 2. Soil Erosivity (K-factor)

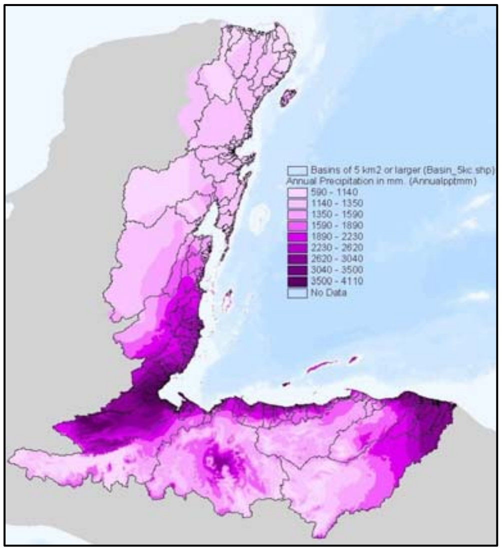


Source: Soil and Terrain Database for Latin America and the Caribbean

Precipitation and Rainfall Erosivity

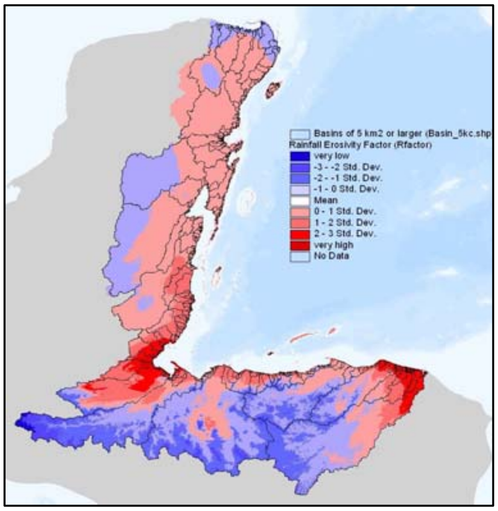
Precipitation Scenario: N-SPECT requires a raster (grid) precipitation data set, specification of the rainfall type in the region (from four synthetic 24-hr rainfall distributions), and the average number of "raining days," which is complicated by the large area and range of precipitation across the region. All annual model runs were conducted using a long-term average yearly rainfall grid (which needs to be specified in inches for N-SPECT), and number of rainy days per year set to 40.[8] This number of rainy days was selected based on calibration of the model to the MAR region by Will Heyman and Shin Kobara at Texas A&M University.[9]

Figure 3. Annual Precipitation Distribution



Source: WorldClim database

Figure 4. Rainfall Erosivity (R-factor)



Source: WRI, 2006

R-Factor: R-factor was empirically derived based on annual precipitation and elevation using an equation for rainfall erosivity in Costa Rica. Project partners at Texas A&M University performed statistical validation of the resulting R-factor for the MAR region and found this equation to be a statistically valid method for use in estimating erosion with the RUSLE for the MAR region.[10] The equation used for R-factor is included in the technical notes at the end of this report.

---

[8] Note: Precipitation must be in inches for N-SPECT. A single number of rainy days must be selected for the entire study area, defined as the "average number of storms in a location in a year." The model was run with "Type II rainfall" selected, as this best represents areas with intense rainfall events.

[9] See document on "Hydrologic Model Calibration" on the *Watershed Analysis for the Mesoamerican Reef* data CD.

[10] Ibid.

Vulnerability of Land to Erosion

The N-SPECT model evaluates erosion and pollutants coming off the land for a given land cover. The project also evaluated the inherent vulnerability of the landscape to erosion based on slope, soil erodibility, and annual precipitation. This simplification of the RUSLE used in N-SPECT excludes land cover. It serves to identify vulnerable areas where conversion to an erosive land cover type should be avoided or, where converted, better management practices should be targeted.

Equation 2: Vulnerability of Land to Erosion -

$$\textbf{Vulnerability} = \mathbf{R * K * S^{0.6}}$$

R – Rainfall-runoff erosivity factor
K – Soil erodibility factor
S – Slope (in degrees)

Modeling Runoff and Pollutant Delivery

N-SPECT evaluates runoff based on soil characteristics, land cover, topography, and precipitation. Runoff calculations are based on curve numbers developed by the U.S. Department of Agriculture that reflect the general permeability of a given soil type.[11] Curve numbers are associated with a soil's hydrologic group classification (A, B, C, or D), which is a measure of the drainage potential or infiltration rate of the soil. Soils in Group A are well drained, while soils in Group D drain poorly and tend to be water-logged. Hydrologic group is an attribute contained in the SOTERLAC soils database. Curve numbers also depend on land cover types. N-SPECT selects curve numbers for use in runoff calculations based on the combination of hydrologic soil group and land cover type at each grid cell. These curve numbers are presented in Table 2.

Table 2. N-SPECT Runoff Curve Numbers (Coefficients) by Land Cover Type and Soil Hydrologic Group

Code	Land Cover Category	CN-A	CN-B	CN-C	CN-D
3	Low Intensity Developed	0.61	0.75	0.83	0.87
4	Cultivated Land	0.67	0.78	0.85	0.89
5	Grassland	0.39	0.61	0.74	0.80
7	Forest	0.30	0.55	0.70	0.77
9	Scrub/Shrub	0.30	0.48	0.65	0.73
10	Palustrine Forested Wetland	0.00	0.00	0.00	0.00
17	Bare Land	0.77	0.86	0.91	0.94
18	Water	0.00	0.00	0.00	0.00

Source: *Urban Hydrology for Small Watersheds TR-55, USDA-NRCS*

[11] Refer to *Urban Hydrology for Small Watersheds TR-55, USDA-Natural Resource Conservation Service (NRCS)* on *Watershed Analysis for the Mesoamerican Reef* data CD.

N-SPECT evaluates pollutant loads based on runoff, land cover, and topography. Coefficients representing the contribution of each land cover class to runoff of pollutants (nitrogen, phosphorous, and total suspended solids) are applied to land cover data sets to approximate pollutant loads. These coefficients reflect the expected pollutant mean concentration from each land cover type and were derived from published studies and research by NOAA and are provided with the N-SPECT model. Modeling can be made more accurate through the use of locally derived pollutant coefficients, but such data were not available for the MAR region. The coefficient derivation process is described in the *N-SPECT Technical Guide* on the *Watershed Analysis for the Mesoamerican Reef* data CD.

Table 3. Pollutant Coefficients for Phosphorous, Nitrogen, and Total Suspended Solids (TSS)

Class		Coefficients		
Value	**Name**	**Phosphorous**	**Nitrogen**	**TSS**
3	Low Intensity Developed	0.18	1.77	19.1
4	Cultivated Land	0.42	2.68	55.3
5	Grassland	0.48	2.48	55.3
7	Evergreen Forest	0.05	1.25	11.1
9	Scrub/Shrub	0.05	1.25	11.1
10	Palustrine Forested Wetland	0.20	1.10	19.0
17	Bare Land	0.12	0.97	70.0
18	Water	0.00	0.00	0.0

Source: *Urban Hydrology for Small Watersheds TR-55, USDA-NRCS*

Circulation Modeling

The University of Miami adapted a circulation model to examine the transport of buoyant matter along the MAR. (Buoyant matter includes suspended sediments, organic detritus, and dissolved nutrients.) The Regional Ocean Modeling System (ROMS) provides spatial and temporal modeling of ocean circulation and transport by currents of river discharge along the MAR. The model includes the barrier reef, reef lagoon, and adjacent oceanic waters, as well as bottom topography (bathymetry) at 1km resolution. The horizontal resolution of the simulation is 2km (grid cell size).[12] Both the state of the ocean (temperature, salinity, currents, and tides) and the surface fluxes (wind, rain, solar, and radiative heat fluxes) are accounted for in the model simulation of oceanic and coastal waters. They were taken from the Levitus ocean and atmospheric climatology,[13] which provides long-term monthly averages for a year. Monthly river discharge and sediment delivery (used as a proxy for buoyant matter load) were provided from the N-SPECT

[12] The vertical resolution of the ROMS model varies with distance from shore.
[13] For more information on Levitus climatology see http://ingrid.ldeo.columbia.edu/SOURCES/.LEVITUS94/ (ocean climatology) and http://icoads.noaa.gov/status.html (atmospheric climatology).

model.[14] Within the ROMS model, rivers are defined as point sources. The tracking of buoyant matter dispersal is computed in ROMS through hydrodynamic passive transport.[15]

From these methods, the model produces a climatology (reflecting long-term average conditions) of the circulation and buoyant matter transport in the MAR region. Four numerical simulations were done to understand the response of the ocean to the river runoff and sediment delivery associated with different land cover scenarios and storm events. The model was initiated with data reflecting "current" conditions (land cover for 2003/4 and mean monthly precipitation). The model was run for two model years to get to a valid equilibrium representation of accumulated river discharge and sediment delivery. The model reached its buoyant matter equilibrium in winter of the second year. All simulations for comparison were started at the end of that second year. Simulations were run to capture river discharge and sediment delivery associated with (a) the "current land cover" scenario, (b) the "sustainability first" scenario, (c) the Hurricane Keith storm event, and (d) the Hurricane Mitch storm event.

Model Calibration and Validation

Complex, multi-stage modeling should be validated at every possible stage of the analysis. This analysis serves to integrate a wide range of data, and adapt modeling tools for an innovative, region wide analysis. Where possible, data from published sources or proxy indicators derived from remote sensing were used to calibrate and validate model results, and these are described below. An important aspect of the project, however, is to provide these modeling tools to partners in the MAR region, so that they might apply them at higher resolution and then use local data to initially calibrate, and later validate model results. The region-wide results presented in this paper should be considered preliminary and indicative of overall patterns of erosion and nutrient and sediment delivery across the region.

1. **Evaluation of input data sets.** The best available region-wide data sets were used in this analysis. All input data sets (elevation, rivers, precipitation, soils, and land cover) were evaluated for spatial accuracy and attribute consistency. No

[14] Monthly estimates of sediment delivery (total erosion within the watershed) are provided as input to the ROMS model. These estimates overstate sediment delivery, but are indicative of relative distribution, seasonal patterns and the overall magnitude of sediment delivery. Within the ROMS model, the sediment was used as a proxy for buoyant matter, which includes suspended sediments, organic detritus, and dissolved nutrients.

[15] The "hydrodynamic passive tracer transport" of the ROMS model uses an "advection-diffusion" scheme which captures both transport by current (advection) and dispersion by turbulence (diffusion.) Using outputs of the ROMS model, the sources of the buoyant matter (river mouths) and destination (reef locations) are linked through a connectivity matrix.

input data was identified as having limitations that would significantly affect model results.[16]

2. **Calibration of runoff and rainfall parameters.** Runoff and erosion estimates are very dependent on two input parameters - the rainfall erosivity factor (R-factor) and number of rainy days per year. Project collaborators at Texas A&M University tested model input parameters (both R-factor and number of rain days) to calibrate the runoff and sediment delivery components of the model. The selected parameters achieved good correlations with discharge predictions from a water balance model, and erosivity estimates.[17] This calibration is described in detail in "Hydrologic Model Calibration" on the *Watershed Analysis for the Mesoamerican Reef* data CD.

3. **Validation of river discharge.** River discharge values from N-SPECT were compared with values calculated using a water balance model[18] which has compared well with actual runoff data in six watersheds in the Gulf of Honduras. Discharge estimates had comparable patterns and were generally within 25 percent of the published estimates.

4. **Local rates of erosion and pollutant runoff.** Within N-SPECT, erosion source estimates rely on application of the RUSLE, while pollutant runoff estimates rely on application of runoff curve numbers developed by USDA. Both of these estimation techniques are widely used. These equations could be made more accurate in the future through the use of locally derived erosion and pollutant coefficients, but such data were not available for the MAR region. Although only limited local data were available for validation of these estimates, the overall estimates of local erosion, N and P runoff (sources) were found to be within reasonable bounds compared to estimates from other areas.[19]

5. **Sediment and pollutant delivery to river mouths**. Few data from the MAR region are available for validation of model outputs. Sediment delivery results have been compared with survey data from the Watershed Reef Interconnectivity Scientific Study (WRIScS)[20] and modeled estimates from Thattai et al.[21] In

---

[16] SRTM data, radar-derived elevation data, have inherent inaccuracies due to detection of natural and manmade features such as trees and buildings. These errors will effect some slope calculations, but will not effect overall model results significantly.

[17] Water balance equation from Thattai, Deeptha, Björn Kjerfve, W.D. Heyman, 2003. Hydrometeorology and variability of water discharge and sediment load in the Inner Gulf of Honduras, Western Caribbean. *Journal of Hydrometeorology* 4: 985-995. Erosivity estimates from Mikhailova, E.A., R.B. Bryant, S.J. Schwager, and S.D. Smith. 1997. Predicting rainfall erosivity in Honduras. *Soil Science Society of America Journal*. 273-279.

[18] Thattai, Deeptha, Björn Kjerfve, W.D. Heyman, 2003. Hydrometeorology and variability of water discharge and sediment load in the Inner Gulf of Honduras, Western Caribbean. *Journal of Hydrometeorology* 4: 985-995.

[19] Ranges of reasonable values (low, typical, and high) were established for erosion (by applying the RUSLE), for nitrogen runoff (by applying a nitrogen balance equation) and for phosphorous runoff (by coupling RUSLE results with estimates of phosphorous concentration in the soil).

[20] Nunny, Rob, M. Santana, P. Stone, D. Tillet, and Prof. D. Walling, 2001. An Investigation of the Impact on Reef Environments of Changing Land Use in the Stann Creek District in Belize. Technical Report Module 3. The Watershed Reef Interconnectivity Study (WRIScS) 1997-2000.

addition, sediment delivery and sediment yield (per unit area) were compared with estimates for similar size and gradient watersheds from around the world.[22] Estimates of sediment delivery from N-SPECT were found to be higher than expected in the largest watersheds in the region. A key limitation of the N-SPECT model is that it does not adequately account for sediment and nutrient attenuation (loss or redeposition) within the watershed en route to the river mouth.[23] Overestimation is likely to be greater for sediments than nutrients, as large sediments are more affected by redeposition than nitrogen (in solution) or phosphorous (attached to smaller soil particles.) N-SPECT results, therefore, indicate a high end, or "worst case scenario" of nutrient and sediment delivery. Overall yields (per unit area) of N and P seem reasonable, given the expected ranges of N and P in runoff, described above. The estimates of sediment yield and sediment delivery by basin seem high, particularly for the largest watersheds. In the largest watersheds, sediment delivery might be overestimated by a factor of two to four. Estimates of sediment and nutrient delivery at river mouths, therefore, indicate the relative patterns and order of magnitude, but should not be regarded as accurate absolute values.

6. **Sediment Transport to Reef.** Modeling of the extent of buoyant matter reaching the MAR estimated in the ROMS model is being compared to Colored Detrital Matter[24] (CDM) maps derived from Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite imagery. The Spectral Optimization Algorithm (SOA)[25] was used to process SeaWiFS data in the optically complex[26] waters of the Caribbean Sea along the MAR. The output product, $a_{\mathrm{CDM}}(443)$ (called CDM) is an absorption coefficient which is a good proxy for the buoyant matter transport. Figure 5 reflects the lag between mean monthly river discharge and mean CDM in processed SeaWiFS images.

---

[21] Thattai, Deeptha, Björn Kjerfve, W.D. Heyman, 2003. Hydrometeorology and variability of water discharge and sediment load in the Inner Gulf of Honduras, Western Caribbean. *Journal of Hydrometeorology* 4: 985-995.

[22] John D. Milliman and James P. M. Stvitski, 1992. Geomorphic / Tectonic Control of Sediment Discharge to the Ocean: The Importance of Small Mountainous Rivers. In *The Journal of Geology*, 1992, volume 100, p. 525-544.

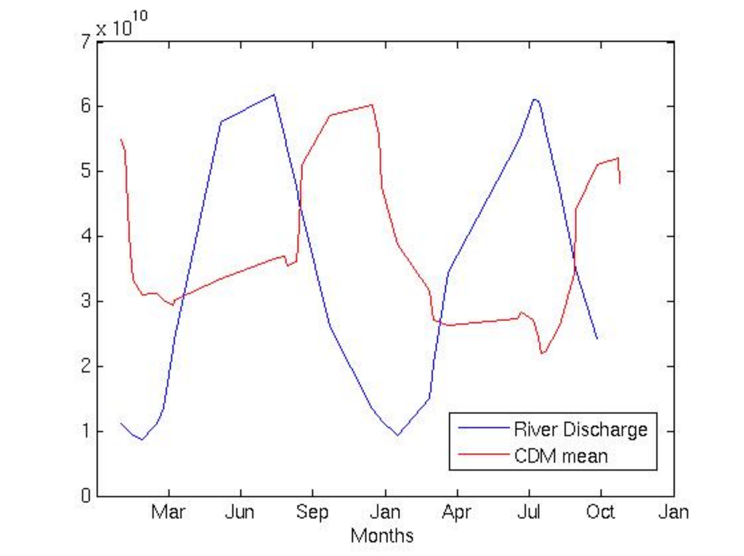
[23] N-SPECT applies a sediment delivery ratio (SDR) within each individual grid cell to adjust sediment load, but not across the basin to account for redeposition en route to the river mouth.

[24] CDM includes dissolved organic carbon from soil and plants, often referred to as Colored Dissolved Organic Matter (CDOM), plus detrital particles (dead organic matter).

[25] Kuchinke, C.P., H.R. Gordon, L.W. Harding, Jr., and K.J Voss, A coupled oceanic and atmospheric spectral optimization algorithm for ocean color imagery in Case 2 waters: a validation for Chesapeake Bay, SUBMITTED FOR PUBLICATION, *Remote sensing of Environment* (2006).

[26] Optically complex waters include multiple constituents such as colored dissolved organic matter as well as phytoplankton.

Figure 5. Temporal Relationship Between N-SPECT River Discharge Estimates and the Mean Colored Detrital Matter (CDM) Absorption Coefficient from Imagery for the North of Honduras



Source: University of Miami, 2006.

CDM classifications from SeaWiFS images are used to evaluate two aspects of the ROMS circulation model results – (1) the seasonal variation of the buoyant matter plume dispersion patterns, and (2) the seasonal variation of the total buoyant matter concentration. Buoyant matter plumes from the ROMS circulation simulation were compared to the CDM classifications along transects perpendicular to the coast.

Seasonal patterns are similar between the estimated buoyant matter plumes from the ROMS simulations and the seasonal trends observed in the SeaWiFS data, though there is considerable year-to-year variation in the latter. Overall, the model agrees very well with the observations both in time and location. Some discrepancies exist, however, in the structure of the gradient of the plume. If we compare the position of the edge of the average CDM plume from SeaWiFS and the modeled buoyant matter plumes, the CDM plumes varies seasonally between 10 and 40km while in the ROMS model the plume is almost always 40km wide. Such a difference could be due to a diffusion coefficient used in the ROMS model, which is too small. Validation of the circulation model is described in greater detail in “Dynamics of Buoyant Matter in the MAR Region” on the *Watershed Analysis for the Mesoamerican Reef* data CD.

Limitations of the Analysis

Any multi-stage modeling process will have inevitable inaccuracies, so it is vital to be aware of model limitations and only use results appropriately.

Limitations of Hydrologic Modeling

A key limitation of the N-SPECT model is that the model does not adequately account for sediment and nutrient attenuation (loss or redeposition) within the watershed en route to the river mouth. As a result, estimates of sediment and nutrient delivery at river mouths are exaggerated. The absolute numbers are not accurate, but are indicative of the overall magnitude and patterns of sediment and nutrient delivery across the region. These estimates are still useful for examining relative patterns and the implications of different policy scenarios, because the estimates of percentage change are valid.

A second limitation of the modeling is the focus on the role of land cover change without considering the effect of specific land management practices. This emphasis arises from two issues. For the MAR region, information was only available on land cover type and not on the location of specific management interventions. In addition, detailed information on reductions in erosion and nutrient runoff associated with each of the agricultural management practices is not currently available. Once this information is developed, however, it should be possible to evaluate benefits in N-SPECT by treating each management intervention on each land cover type as a new, unique land cover category with a specific land cover factor (C-factor) and pollutant coefficients for the given category (i.e. citrus crops with erosion control). This would be a valuable extension to the current analysis.

Another limitation of the model is that dams, which serve to trap sediment, have not been included in the model. It should be technically possible to develop a function to include dams, provided that information on sediment retention rates by dams is available. This feature could be considered in local applications of the N-SPECT model.

Limitations of Circulation Modeling

Regarding the circulation modeling of the MAR, the first limitation is that the result is a climatology. Namely, the circulation is representative of the most common conditions that one would encounter each year if every extreme or unusual weather or ocean state event were removed. It reflects long-term average conditions. Therefore, day-to-day comparison between the model circulation and current observations is irrelevant. But if compared with observations during the same month over several years, then common patterns can be found and compared to the model results.

The second limitation is the sparseness of the CDM interpretations because of cloud cover in the SeaWiFS images they were derived from. For example, there are few clear SeaWiFS images of the MAR region during the summer months. However, there are enough observations to recover the global trend of the CDM concentration over a year as shown in Figure 5.

The third limitation is that there is no direct relationship between the CDM absorption coefficient and the CDM concentration. Direct measurements from water samples, which are not available yet, are necessary to get such information. Therefore, only the circulation model can be used to estimate the buoyant matter load to the reefs.

Finally, in the numerical model, buoyant matter will not accumulate or deposit, but will be constantly transported until flushed out of the domain. However, it is possible to estimate how much buoyant matter would accumulate by counting how much passes by any location. The model and the observations reflect the maximum extent of the plume and its behavior over time.

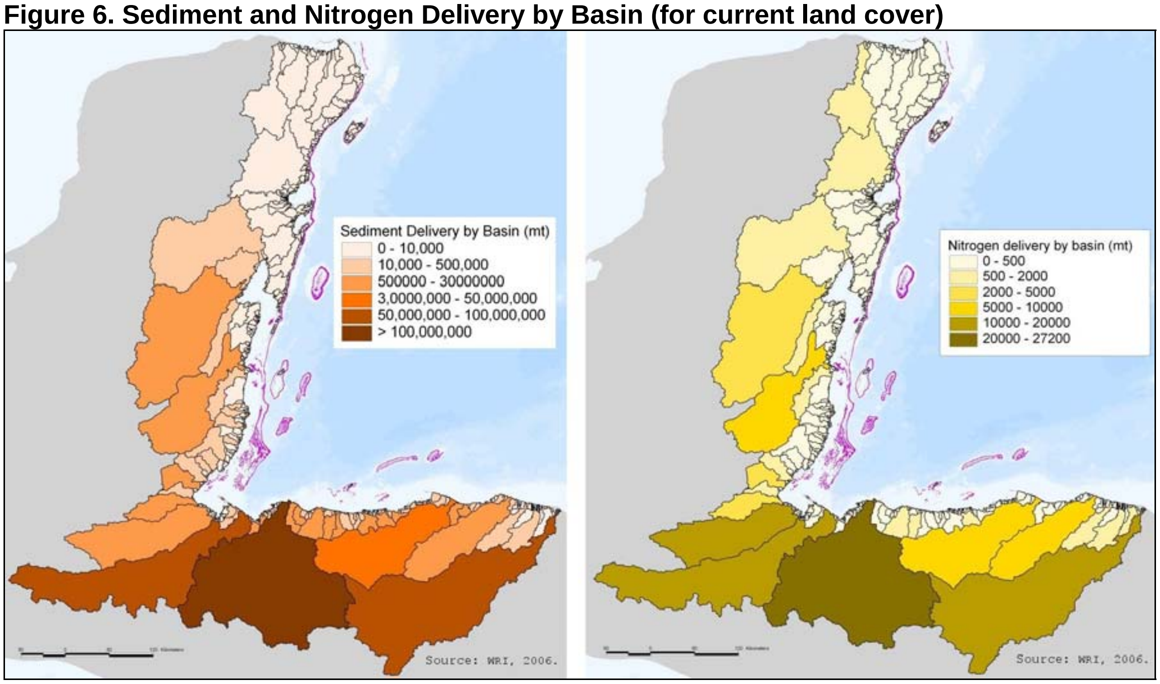
Analysis Results

The presentation of results first focuses on basin-level delivery of sediment and pollution to more than 400 river mouths along the MAR. We initially examine sediment and pollutant delivery given current land cover (2003/04) and subsequently compare these to results which use other land cover scenarios ("natural" land cover and three scenarios of land cover in 2025). Next, we examine sediment transport in coastal waters along the reef. Finally, we present an analysis of the vulnerability of the land to erosion and an evaluation of the local origin of sediment and pollution.

1. Sediment and Pollutant Delivery given Current Land Cover (2003/04)

N-SPECT was used to evaluate accumulation of sediment, nitrogen (N), phosphorous (P), and total suspended solids (TSS) in more than 400 watersheds across the MAR region. The maps in Figure 6 reflect the relative accumulation of sediment and N at river mouths across the region. The Ulua watershed in Honduras was found to be the largest contributor of sediment, N, P and TSS. Other rivers identified as large contributors of sediment and nutrients are the Patuca (in Honduras), Motagua (in Guatemala and Honduras), Aguan (in Honduras), Dulce (in Guatemala), Belize River (in Belize), and Tinto o Negro (in Honduras). (Watershed names are provided on the map in Figure A in the Key Findings.)

Figure 6. Sediment and Nitrogen Delivery by Basin (for current land cover)



2. Comparison of Results for Current Land Cover (2003/04) to Hypothetical Natural Land Cover

To evaluate the impact of human alteration of the landscape on sediment and pollutant delivery to river mouths along the MAR, the N-SPECT model was run on both current (2003/04) land cover and on hypothetical natural (unaltered) land cover. Table 4 provides a comparison of the land cover distribution for these two time periods. River discharge, sediment delivery, and pollutant delivery (nitrogen, phosphorous, and total suspended solids) to over 400 river mouths is summarized in Table 5. Human alteration of the landscape has nearly doubled runoff and associated discharge at the river mouths. The N-SPECT model suggests that sediment delivery has increased by a factor of 20, while nitrogen has increased by a factor of 3, phosphorous by a factor of 7, and TSS by a factor of 5.

Table 4. Comparison of Natural and Current Land Cover (percent in each cover type)

Land Category	Natural	Current
Developed / Urban	0.0%	0.3%
Cultivated	0.0%	32.4%
Savanna / Grassland	1.8%	1.6%
Forest	82.4%	50.6%
Scrub / Shrub	8.3%	10.4%
Wetland / Mangrove	6.0%	3.2%
Bare / beach / unknown	0.4%	0.3%
Water	1.1%	1.2%

Source: ICRAN MAR, 2006

Table 5. Comparison of Regional Results for Annual Model Runs for Current and Natural Land Cover

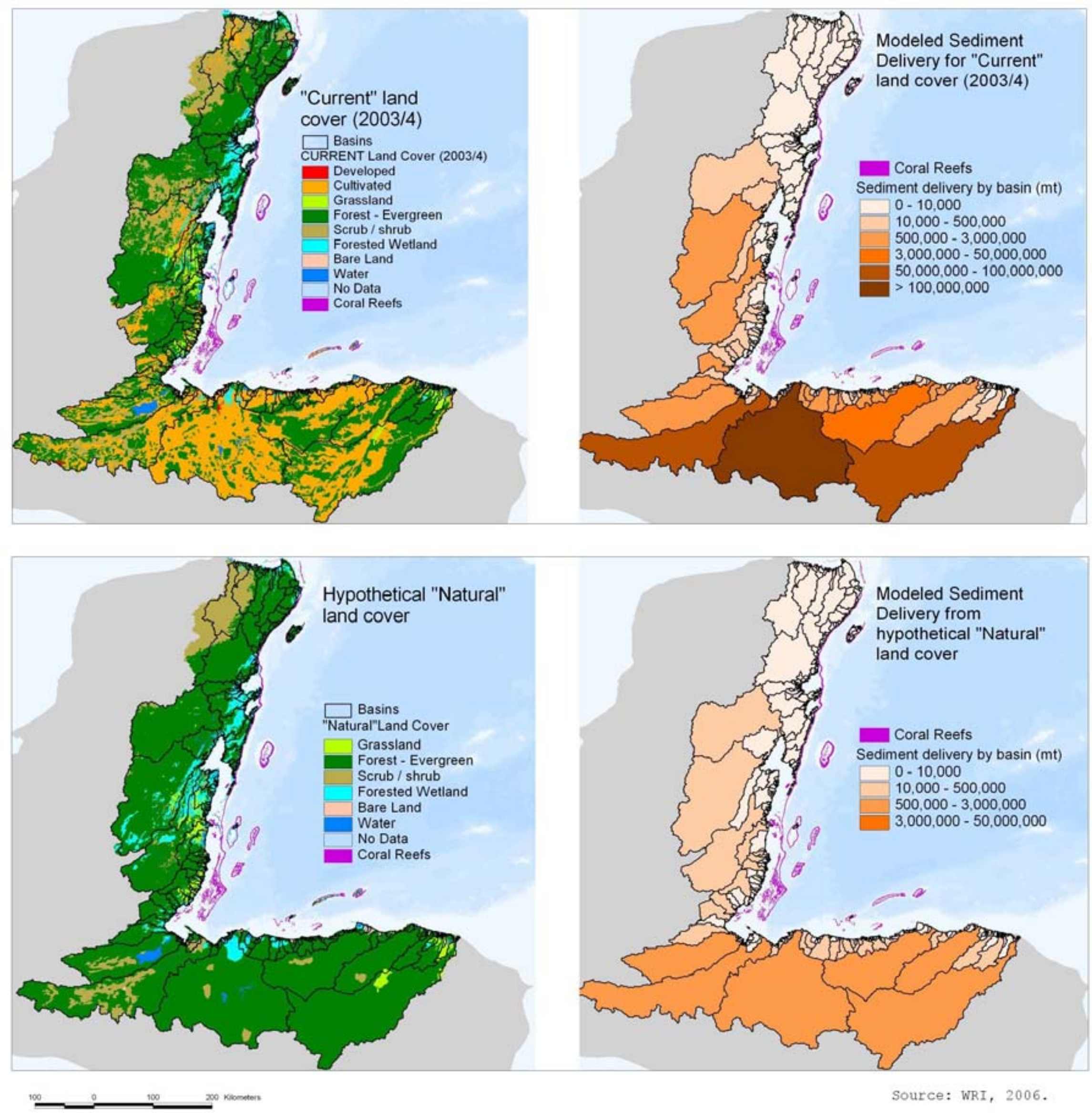
Scenario	Discharge (x 10^9 m^3)	Sediment (x 10^9 mt)	Nitrogen (x 10^3 mt)	Phosphorous (x 10^3 mt)	TSS (x 10^3 mt)
Current (2003/2004)	60	370	130	17	2,400
Natural (no development)	34	17	45	2	470
Ratio of Current / Natural	2 X	22 X	3 X	7 X	5 X

Note: Sediment, N, P and TSS delivery represent upper bound estimates for the region, as loss of sediment or nutrients due to redeposition or other processes is not accounted for. The values reflect overall erosion and pollutant runoff within the region, and are indicative of the overall magnitude of sediment and nutrient delivery, but should not be regarded as absolute values. The relative relationship between the scenarios is valid.

Source: WRI, 2006

Figure 7 presents both land cover and sediment delivery results for current land cover and hypothetical natural land cover.

Figure 7. Modeled Sediment Delivery from "Current" and Hypothetical "Natural" Land Cover



3. Comparison of Current Land Cover to Three Development Scenarios in 2025

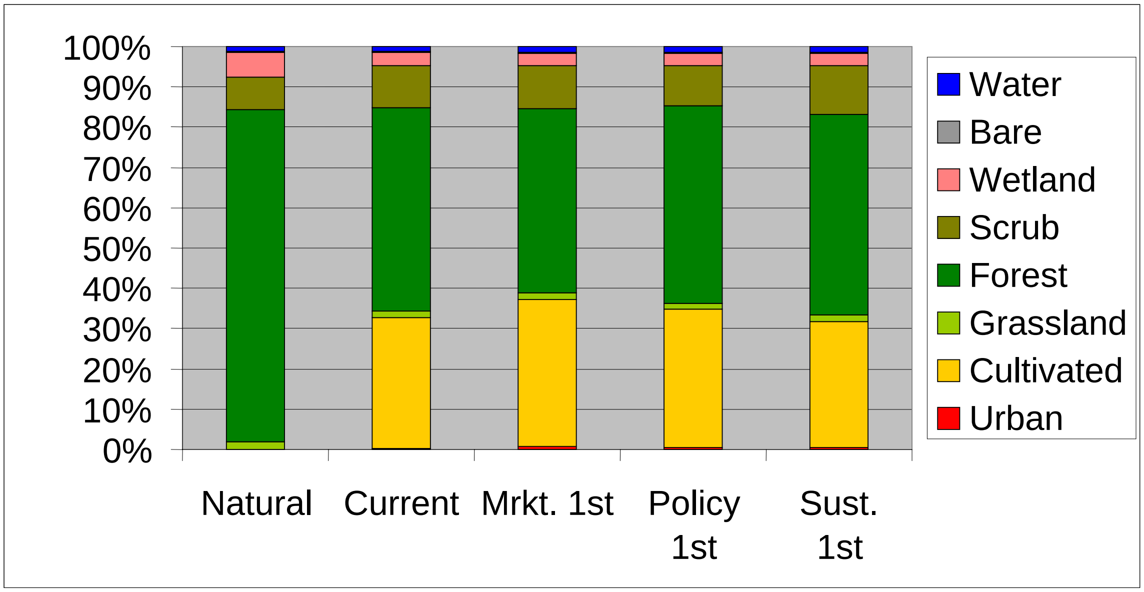
Scenarios of land cover change in the MAR region though 2025 are used to evaluate the impact of land cover change on river discharge, sediment, and pollutant delivery. Table 6 and Figure 8 reflect the distribution of land cover in these scenarios. The N-SPECT model was run on these three land cover scenarios and results are summarized in Table 7. The N-SPECT model suggests that the Markets First scenario would result in a 13% increase in sediment delivery relative to that of current land cover, while sediment would only increase by 5% under the Policy First Scenario and would decrease by 5% under the Sustainability First Scenario. Nutrient and TSS delivery would also increase significantly from current land use under the Market First Scenario (8 – 11% increases in nitrogen, phosphorous, and TSS delivery are projected). At the other extreme is the Sustainability First Scenario which could result in a 4 - 5% percent decline in nutrients and TSS, based solely on changes in land cover. Additional reductions in sediment and nutrient delivery can be achieved through the implementation of better agricultural management practices, which were not considered in these scenarios.

Table 6. Comparison of Land Cover Scenarios (percent in each cover type)

Land Category	Current	Markets First	Policy First	Sustainability First
Developed / Urban	0.3%	0.6%	0.6%	0.5%
Cultivated (Ag)	32.4%	36.7%	34.2%	31.3%
Savanna / Grassland	1.6%	1.5%	1.5%	1.7%
Forest	50.6%	45.8%	48.9%	49.8%
Scrub / Shrub	10.4%	10.6%	9.9%	11.9%
Wetland / Mangrove	3.2%	3.1%	3.2%	3.1%
Bare / beach / unknown	0.3%	0.3%	0.3%	0.3%
Water	1.2%	1.4%	1.4%	1.4%

Source: ICRAN MAR, 2006

Figure 8. Land Cover Distribution Within Each Scenario



Source: ICRAN MAR, 2006

Table 7. Comparison of Regional Results for Annual Model Runs for Current Land Cover and Three Scenarios in 2025

Scenario	Discharge ($x 10^9 m^3$)	Sediment ($x 10^9$ mt)	Nitrogen ($x 10^3$ mt)	Phosphorous ($x 10^3$ mt)	TSS ($x 10^3$ mt)
Current (2003/2004)	60	370	130	17	2,400
Markets First	63	420	140	19	2,630
Change from Current	5%	13%	8%	11%	10%
Policy First	61	390	135	18	2,480
Change from Current	2%	5%	3%	5%	4%
Sustainability First	59	355	125	16	2,300
Change from Current	-2%	-5%	-4%	-5%	-4%

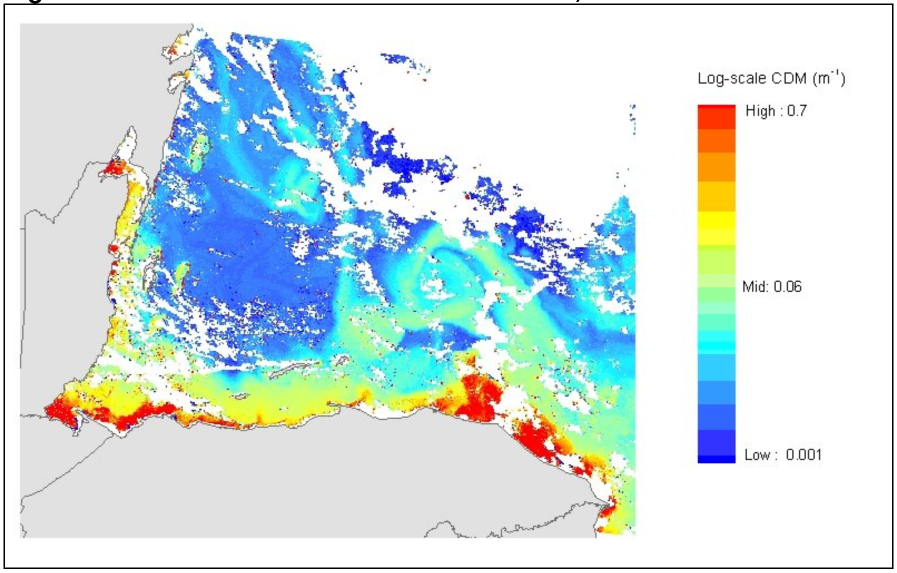
Note: Sediment, N, P, and TSS delivery represent upper bound estimates for the region, as loss of sediment or nutrients due to redeposition or other processes is not accounted for. The values reflect overall erosion and pollutant runoff within the region, and are indicative of the overall magnitude of sediment and nutrient delivery, but should not be regarded as absolute values. The relative relationship between the scenarios is valid.
Source: WRI, 2006

4. Extreme Events

Using the N-SPECT model, WRI has modeled runoff, erosion, and sediment delivery in the MAR region during extreme rainfall events, such as hurricanes. An analysis of the Hurricane Keith storm event in Belize was implemented for an area that covered 90 watersheds in Belize.[27] During the five-day storm event (Sept. 29 – Oct. 3, 2000), discharge from these 90 watersheds was estimated at approximately 30% of the normal (modeled) annual total discharge, while sediment delivery was approximately 50% of the normal annual. Impact of rainfall during Hurricane Mitch (Oct. 27-30, 1998) was evaluated for over 100 watersheds in Honduras.[28] Discharge was estimated at approximately one-third of the normal (modeled) annual total and estimated sediment delivery was over two-thirds of that predicted for an average year. This analysis highlights the significant impact large storm events have on sediment delivery in the coastal zone. Figure 9 shows the extent of the CDM plume on November 10th, 1998, approximately two weeks after Hurricane Mitch.

[27] Precipitation data for Hurricane Keith was provided by the Belize Meteorological Department.
[28] Precipitation data for Hurricane Mitch comes from the US Geological Survey (USGS).

Figure 9. CDM Plume Extent on November 10, 1998



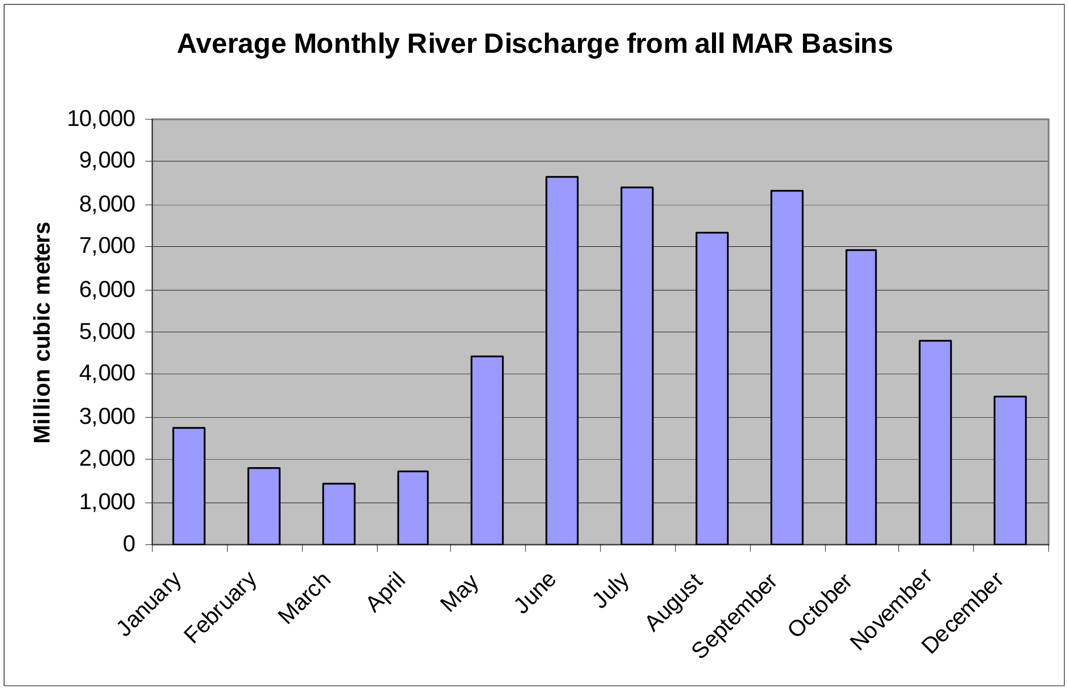
Source: Colored detrital matter (CDM) plume extent interpreted from SeaWiFS imagery by Christopher Kuchinke, University of Miami. Note: the Spectral Optimization Algorithm (SOA) replaces the entire 'standard' SeaWiFS atmospheric correction and bio-optical algorithm.

5. Buoyant Matter Transport along the MAR

WRI applied the N-SPECT model on a monthly basis to develop estimates of average monthly river discharge and sediment delivery for both the "current" land cover and "sustainability first" land cover scenarios. These were used as input to the ROMS ocean circulation model run at the University of Miami to predict buoyant matter transport along the MAR. The ROMS model results reflect seasonal variation of buoyant matter plume extent and concentration. Full year animations of buoyant matter circulation for both scenarios are available on the *Watershed Analysis for the Mesoamerican Reef* data CD. A more detailed description of the ROMS circulation model application and results, as well as observations of circulation patterns from SeaWiFS is included in "Dynamics of Buoyant Matter in the MAR Region" on the same data CD[29]. Figure 10 reflects the seasonality of river discharge estimated by the N-SPECT model.

[29] Cherubin, L.M., C. Kuchinke, C.B. Paris, and J.Kool, 2006. Dynamics of Buoyant Matter in the Meso-American Region reefs from SeaWiFS data and from a high resolution numerical simulation. University of Miami. Final report to World Resources Institute.

Figure 10. Estimated Monthly River Discharge from N-SPECT



Source: WRI, 2006

Results from the two scenarios can be compared to explore the potential impact of changes in land use on the modeled buoyant matter delivery to the MAR. The plume extents and concentration from the two scenarios can be compared on a month-by-month basis, or annual summary statistics can be developed to reflect the mean annual buoyant matter concentration at each reef location, the maximum annual concentration, or the number of months where the concentration exceeds some threshold.

Figure 11 reflects the simulated buoyant matter plume for December for both current land cover and the Sustainability First scenario. The ROMS model predicts a less extensive and less concentrated buoyant matter plume off of the coast of Honduras during December, but predicts increased concentrations in two semi-enclosed bays of the Yucatan – Baha de la Ascension and Bahia del Espiritu Santo. Much of this change is due to decreased sediment delivery in the Sustainability First scenario. The increase in buoyant matter along the Yucatan, however, results from a change in the circulation predicted by ROMS along the MAR. Much like variability in weather, there is variability in ocean circulation. During winter in the Sustainability First scenario, the usual anticlockwise rotating gyre north of Honduras is replaced by the Caribbean current. The current flows straight from the eastern tip of Honduras to the coast of the Yucatan carrying sediments from Honduras.

Figure 11. Simulated Buoyant Matter Concentration Along the MAR for December (Current Land Cover and Sustainability First Scenarios)

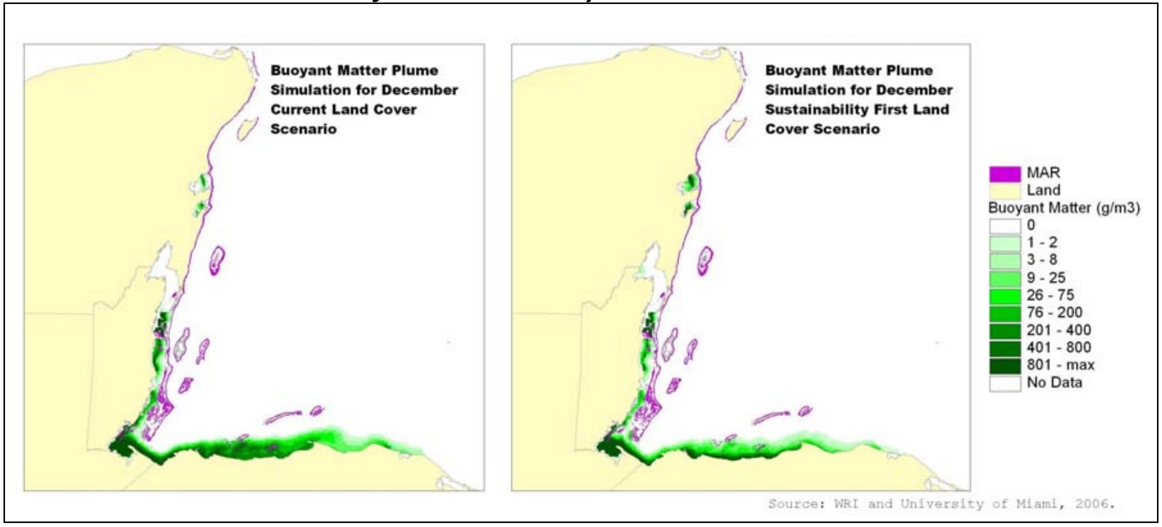


Figure 12 reflects the maximum buoyant matter plume extent and concentration for the year for the same two land cover scenarios. ROMS simulations suggest that under the Sustainability First scenario the buoyant matter plume extent and concentration will be reduced along the coast of Honduras, and less buoyant matter will reach the barrier reef in southern Belize. The simulations again predict increased concentrations in the semi-enclosed bays of the Yucatan. These reductions in buoyant matter plume extent could result from changes in sediment delivery resulting from land cover change (reductions in cultivated land) as well as due to variability in the ROMS simulations.

Figure 12. Maximum Annual Simulated Buoyant Matter Concentration Along the MAR (Current Land Cover and Sustainability First Scenarios)

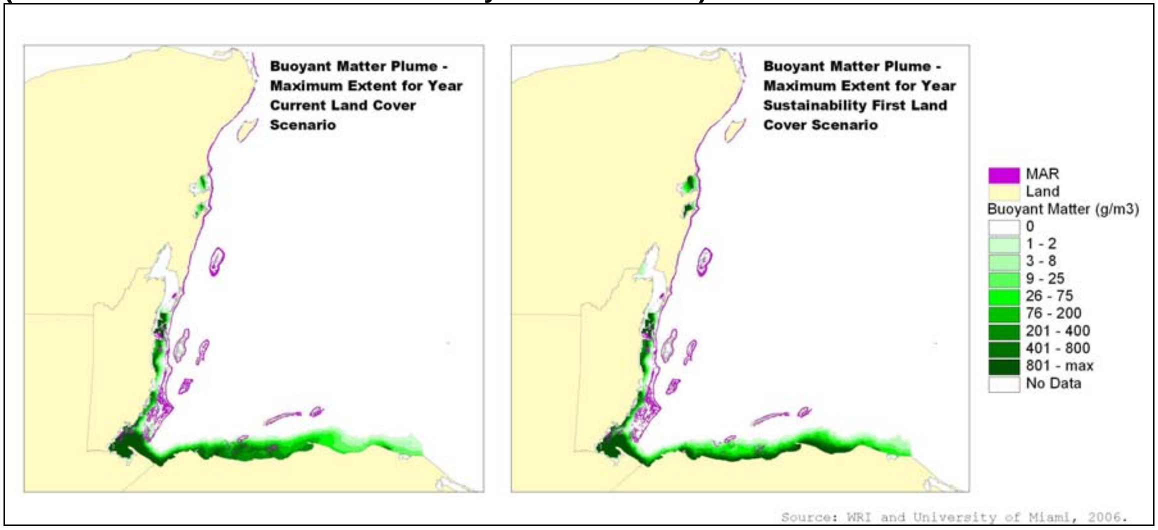
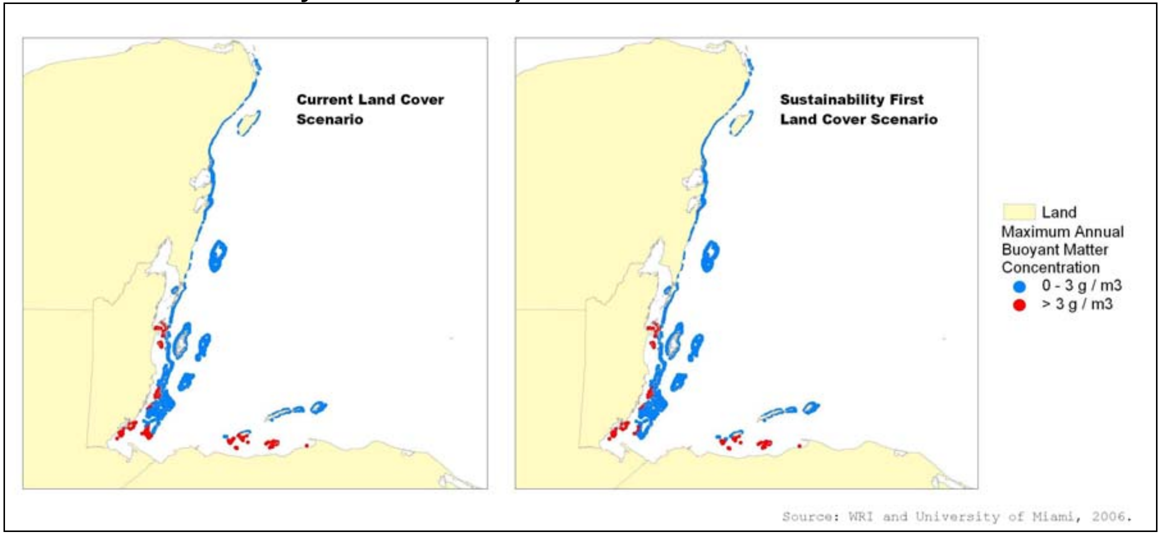


Figure 13 depicts coral reefs of the MAR, mapped whether or not the buoyant matter concentration exceeds 3 grams per cubic meter (g / m^3) during any month of the year. Under the ROMS simulation for current land cover, 12% of the coral reefs of the MAR exceed this threshold, while under the Sustainability First scenario, this proportion drops to 10%. This improvement points to the significant effect that improved land management can have on sediment and pollutant delivery to the MAR.

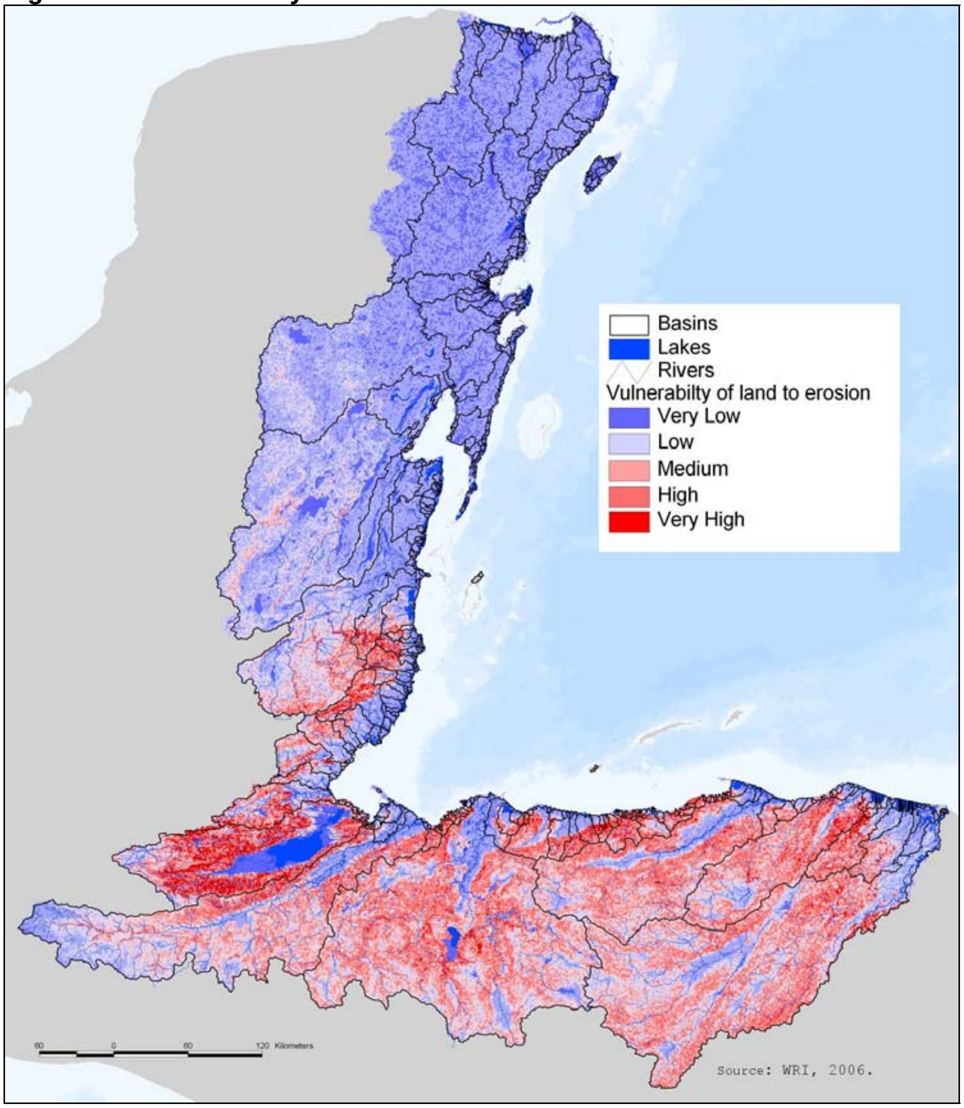
Figure 13. Mesoamerican Reef Mapped by Buoyant Matter Concentration (Current Land Cover and Sustainability First Scenarios)



6. Vulnerability of the Land to Erosion

Development of land management priorities requires detailed local-level information on sources of sediment, and the vulnerability of areas to erosion. WRI has developed a landscape-wide indicator of the vulnerability of land to soil erosion. It incorporates the slope of the land, soil erodibility, and annual precipitation into a 1 km resolution indicator of the relative vulnerability of the land to erosion. This indicator does not consider the current land cover or land use. Rather, it provides an overall indicator of erosion-prone areas, and therefore, a guide to areas where restrictions on development, or the implementation of best agricultural management practices should be encouraged. Vulnerability is high in many areas in Guatemala and Honduras as well as some mountainous areas in Belize. (See Figure 14.)

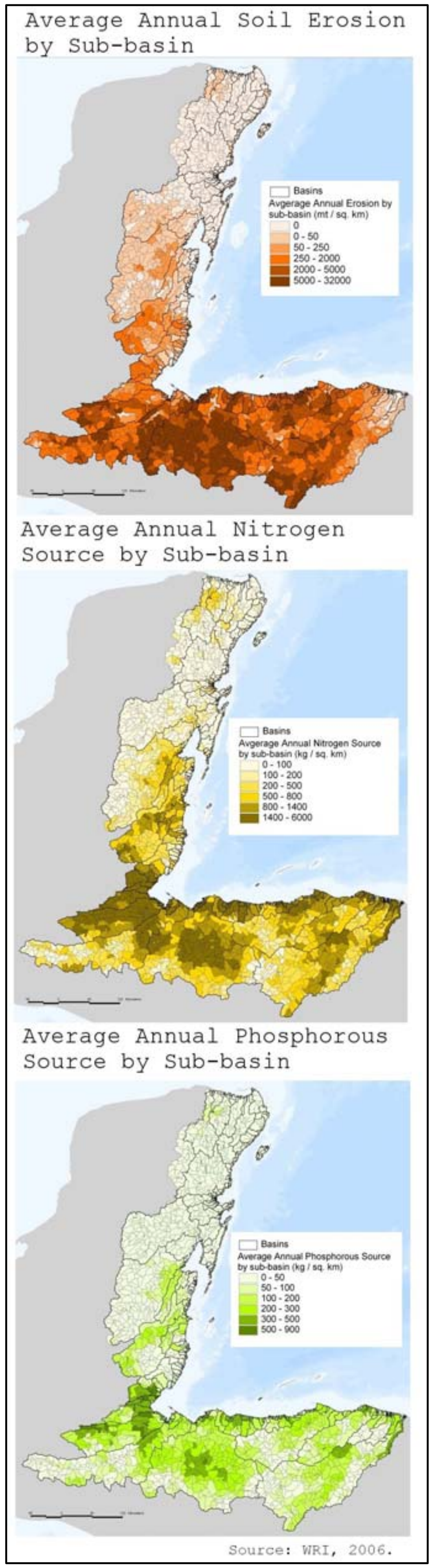
Figure 14. Vulnerability of Land to Erosion



7. Local Sources of Sediment and Nutrients

N-SPECT was run in “local effects” mode to evaluate the amount of eroded sediment and nutrients originating from within each 250m resolution grid cell, independent of contributions from adjacent or upstream grid cells. The evaluation was done using current land cover (2003/04). These results were summarized by sub-basin, as an aid to priority-setting and the targeting of better management practices. The following maps reflect the average erosion, Nitrogen runoff, and Phosphorous runoff per grid cell within each sub-basin. Overall watershed boundaries are also shown both for reference and to allow a linking of sources within the sub-basins with the previous maps of sediment and nutrient delivery by basin.

Figure 15. Average Contribution of Sediment, Nitrogen, and Phosphorous by Sub-basin



Local sources of sediment, N, and P were also summarized by country. Most of the sediment and nutrients delivered by watersheds along the MAR originate in Honduras. The model suggests that over 80% of sediment originates in Honduras, while 17% of sediment originates in Guatemala. Relatively minor percentages come from Belize and Mexico. Honduras is also the largest source of nutrients (55% of N and 60% of P), while Guatemala contributes about one-quarter of all N and P in these watersheds. Belize contributes about 12-13% of both N and P, while Mexico is estimated to contribute about 5% of the total of these nutrients from all modeled watersheds.

Table 8. Percentage of Erosion, Nitrogen, and Phosphorous Sources by Country within MAR Drainage

Country	Erosion (Percent of total)	Nitrogen (Percent of total)	Phosphorous (Percent of Total)
Honduras	83%	55%	60%
Guatemala	17%	26%	25%
Belize	1%	13%	12%
Mexico	0%	6%	4%

Source: WRI, 2006

Conclusion

The analysis presented in this paper provides a regional overview of the magnitude and pattern of sediment and nutrient delivery to coastal waters of the MAR. Based on this analysis, we conclude that:

Policy action is needed to address the contributions from agricultural lands.
Most of the sediment and nutrients delivered to the MAR from watersheds in the region come from agricultural lands in Honduras and Guatemala. The contributions of Belize and Mexico are substantially less, but still pose a threat along their coasts. Many promising initiatives to decrease pollution within the region are underway. These include sustainable forestry management and integrated watershed management in Guatemala; improved land use planning, reforestation and soil conservation programs in Honduras; and similar initiatives in Belize and Mexico. These important efforts need public support, recognition, and continued investment.

Results can help identify areas in need of better agricultural management.
This analysis identified vulnerable areas where conversion to an erosive land use should be avoided, or where converted conservation practices should be implemented. It also identified areas with high erosion and nutrient runoff, where better agricultural management practices should be targeted.

Policies that support sustainable development can reduce sediment and nutrient delivery.
As evidenced by our findings, land-use planning, integrated watershed management, and other policies that support sustainable development can help to lessen erosion and pollution runoff, thereby decreasing sediment and nutrients reaching the MAR.

More detailed modeling is needed to create more accurate information at higher resolutions.
Regional-scale analyses are useful for providing an overview and for prioritizing areas in which action is needed. However, local analyses provide more detailed and accurate information that policymakers need in order to target their interventions. The tools provided on the data CD, *Watershed Analysis for the Mesoamerican Reef* (WRI/ICRAN MAR project, 2006), allow users to perform more detailed analyses of sediment and nutrient delivery within smaller areas in the MAR region, such as at the watershed level.

More specifically, the N-SPECT model can be applied to individual watersheds or groups of watersheds using the 90m elevation data provided or with the user's own data. More detailed local modeling will improve the accuracy of the results, by using higher resolution data on slopes and land cover, and by calibrating the model to local soils and precipitation regimes.

It would be valuable to extend the current analysis to include the effect of improved agricultural management practices on erosion and pollutant runoff. Such an extension would require detailed information on how each practice influences erosion rates and pollutant runoff coefficients. Once such information is available, it should be possible to use N-SPECT to evaluate reductions by treating each management intervention on each land cover type as a unique category with specific erosion and pollutant runoff characteristics. For example, citrus groves with cover crops planted to reduce erosion might be treated as a separate category.

Enhancements to the model are needed to improve the accuracy of sediment and nutrient delivery estimates.
We recommend that the N-SPECT model developers make investments to enhance the model to account for sediment redeposition and nutrient loss during transport within watersheds. This would result in a modeling tool that is more capable of estimating actual sediment and nutrient delivery at river mouths. The accuracy of these estimates could then be evaluated with field measurements.

Analyses such as these can help to evaluate progress in reducing land-based sources of threat.
A number of national initiatives, as well as donor-funded regional initiatives, seek to reduce or mitigate threats to the MAR. This analysis can help these initiatives to estimate their progress by giving them the information they need to ensure they are moving in the right direction.

Transnational natural resource management can be strongly supported by analyses such as these.
To mitigate and reduce the land-based threats to the MAR, constructive regional cooperation among a variety of stakeholders is necessary. Examples include the multilateral cooperation agreements among the four countries involved in this analysis, and agreements between the agriculture and tourism sectors and civil society groups. This tool works across borders and sectors, creating information that allows productive discussion on threat origins and potential mitigation measures.

The International Coral Reef Action Network (ICRAN) collaboration will continue to support the application of analysis results and modeling tools in the region. For more information on ICRAN, please visit: **www.icran.org.**

For questions or comments about this analysis please contact:

Lauretta Burke (lauretta@wri.org) and Zachary Sugg (zsugg@wri.org)
World Resources Institute
10 G St. NE,
Washington, DC 20002
+1 (202) 729-7600
On the web at: reefsatrisk.wri.org

Additional Technical Notes

1) **Watershed Delineation -** We delineated watersheds at 250m resolution at WRI using both N-SPECT and ArcMap. We needed to run the delineation in N-SPECT so that it would accept the DEM, and be able to detect river locations (where flow accumulates) and watershed boundaries. N-SPECT, however, lumps coastal watersheds, which is not useful for examining specific river discharge or sediment delivery. To get around this, we extracted the flow direction output from N-SPECT and used this as the basis for deriving more detailed basins in ArcMap (using the BASINS command in ArcTools\Spatial Analyst). We also ran Flow Accumulation in ArcMap to identify rivers and streams. We combined flow accumulation and basins to identify the point of high flow in each basin, and assigned this point as the "pour point" or river mouth.

2) **Slope Length in N-SPECT.** We did two watershed delineations in N-SPECT. One was based on the "burned," or hydrologically corrected DEM and resulted in a good watershed delineation. The other was based on a "raw" or unburned DEM and resulted in a poor watershed delineation, but more accurate slope and "slope length" calculations. (A burned DEM has an artificially steep slope along the burned rivers.) As such, we ran both watershed delineations, and copied the slope-length grid (called LSgrid in N-SPECT) from the "raw" delineation to the "burned" delineation. We then ran all future processes on the "burned" accurate delineation, which now includes a more accurate slope-length grid.

3) **R-**factor – the equation used for R-factor :

R = 3786.6 + 1.5679 * (Precip in mm) – 1.9809 * (Elevation in m)

R is in metric units (MJ * mm * ha-1 * h-1 * y-1) or (megajoule * mm per hectare per hour per year.) However, N-SPECT requires US units: (hundreds of feet * tonf * inch * acre-1 * hour-1 * year-1). One can convert from metric to US units by dividing by 17.02.

Reference: USDA-ARS Agriculture Handbook No. 703