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Global and Planetary Change 39 (2003) 191–199

GLOBAL AND PLANETARY CHANGE

www.elsevier.com/locate/gloplacha

Rivers, runoff, and reefs

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Received 7 September 2001; accepted 18 December 2002

Abstract

The role of terrigenous sediment in controlling the occurrence of coral reef ecosystems is qualitatively understood and has been studied at local scales, but has not been systematically evaluated on a global-to-regional scale. Current concerns about degradation of reef environments and alteration of the hydrologic and sediment cycles place the issue at a focal point of multiple environmental concerns. We use a geospatial clustering of a coastal zone database of river and local runoff identified with 0.5° grid cells to identify areas of high potential runoff effects, and combine this with a database of reported coral reef locations. Coastal cells with high runoff values are much less likely to contain reefs than low runoff cells and GIS buffer analysis demonstrates that this inhibition extends to offshore ocean cells as well. This analysis does not uniquely define the effects of sediment, since salinity, nutrients, and contaminants are potentially confounding variables also associated with runoff. However, sediment effects are likely to be a major factor and a basis is provided for extending the study to higher resolution with more specific variables.

Keywords: Reefs; Corals; Runoff; Coastal environment; Sediment transport

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1. Introduction

Coral reef communities are typically associated with clear, oligotrophic marine waters, and hard-bottom benthic substrates. Sediments (suspended or deposited) are almost universally recognized as having inhibitory or negative effects on reef communities. Veron (1995, pp. 122–123) states that "Sedimentary regimes, which include various associations between substrate type, turbidity and light availability, affect coral distributions on all scales from local depth restrictions to broad-scale biogeography." He goes on to say of coral diversity in the Indian Ocean (Veron, 1995, p. 157) "...the main pattern is created in the north by regional physical–environmental constraints (principally rivers and the sedimentary environment of the Asian continental coast)..."

This large-scale assessment is supported by Birkeland's (1997, p. 6) summary of contemporary ecolog-

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doi:10.1016/S0921-8181(03)00024-9

ical findings—he says that sediment and associated nutrients are usually considered the greatest threat to coral reefs and identifies the tropical western Pacific as an area of especially high sediment loading. This generalization is not in complete accord with the recent detailed assessment of Burke et al. (2002), who conclude that 88% of southeast Asian reefs are threatened by human activities, but identify sediment and nutrients as the primary threat for only 20%. This disagreement almost certainly stems from Hubbard's (1997, p. 57) observation that "Despite an impressive body of literature..., little quantitative information exists on the responses of reef organisms to sediment loading." This is particularly true at the meso- or regional scale, where one might hope to connect the big-picture trends and association with the more rigorous short-term, local case studies (Coral Siltation References, 2001).

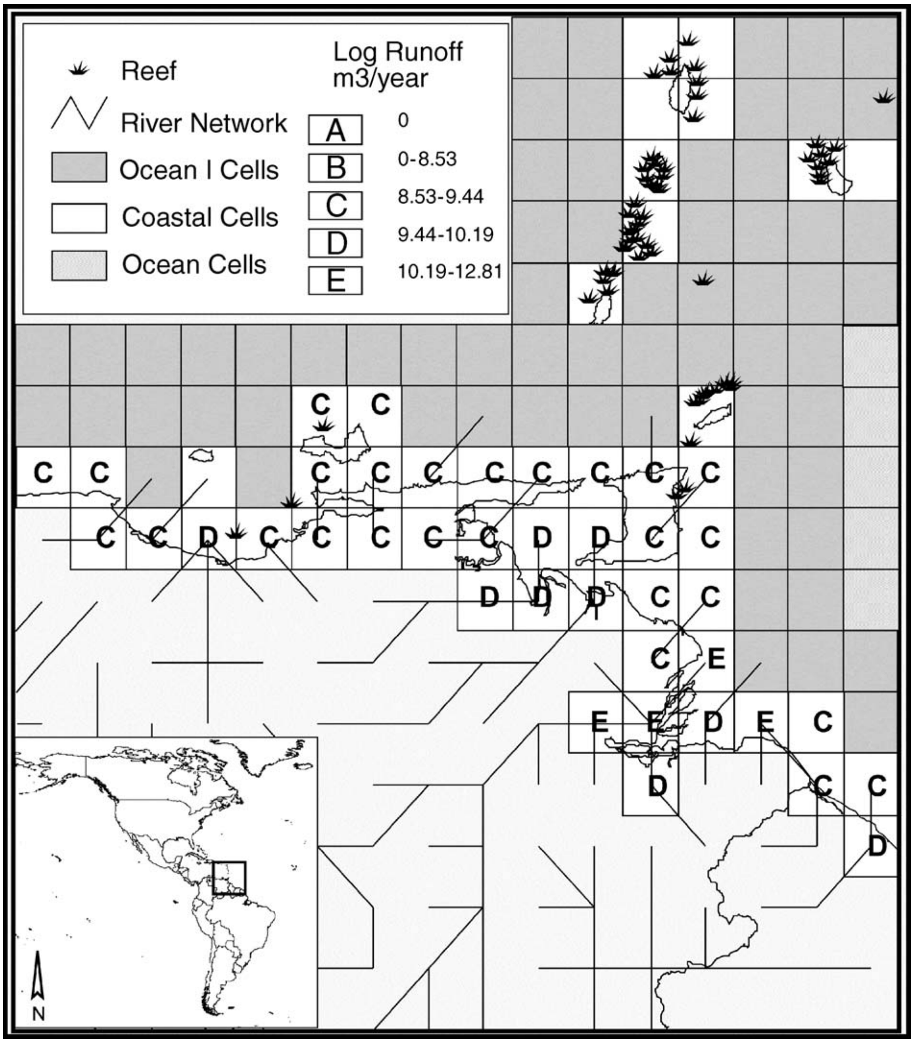


Fig. 1. Illustration of the grid cells and data sets used for clustering, using the Region of the Orinoco River (the major flow network) outflow as an example. Runoff categories were classified for the Coastal cells using log-transformed annual runoff values and the classes evaluated in terms of their deviation from a random distribution of reefs.

Coral reefs have recently achieved notoriety as one of the most endangered of marine ecosystems (Wilkinson et al., 1999), and the hydrologic cycle (and associated terrigenous sediment fluxes) are among the environmental factors that have been extensively altered by human intervention. The association of these two factors begs the question of what we might learn from large-scale studies that could elucidate local effects and start to develop a basis for prediction of responses. This paper reports the results of a global-scale statistical reconnaissance investigation of geographic relationships between reef occurrence and potential terrigenous sediment sources.

Topics of qualitative, if not quantitative, agreement among the sources cited above are the following points. Sediments create an unsuitable environment for coral communities in at least three ways:

- Unconsolidated sediment with no hard bottom is an unstable substrate for new coral settlement or reef formation. These conditions may persist over geologic time scales; soft sediments are inhospitable to corals whether or not there is any ongoing sediment deposition and sediment deposition stresses existing coral colonies.
- Acute sediment stress can result from the smothering effects of rapid sediment deposition—for example, by a storm-derived terrigenous runoff or sediment resuspension event.
- Chronic stress can result from an elevated suspended sediment load. This reduces water clarity and light levels, which is a potential stressor of photosynthesis-dependent coral reefs; in addition, continual low-level sedimentation can raise the coral's energetic cost of cleaning its living surfaces.

While this might suggest a simple inverse relationship between terrigenous sediment supply and reef occurrence or health, there are several confounding factors: (Smith and Buddemeier, 1992): (1) reduced salinity is both a chronic and an acute stress factor (as is reduced calcium carbonate saturation state) for reef organisms, so both the sediment and the freshwater that carries it may be 'independent' but covarying stressors; (2) nutrient loading may both increase turbidity (endogenous rather than exogenous sediment production) and enhance the ability of macroalgae to compete with corals for the benthic substrate; and (3) increased anthropogenic contamination of runoff and discharge means that toxic substances (e.g., biocides) that also correlate with sediment load may have some effects on community health. However, experimental evidence suggests that, in major river plumes directly entering an oceanic environment, sediment concentrations are detectable over a much greater area than are the effects on salinity or temperature (Cresswell and Tiledesley, 2000). We take this as justification for a first-order approximation of using runoff as an indicator of relatively large-scale sediment effects on reef distribution.

Sediment (and freshwater) inputs to the coastal zone have heterogeneous distributions dependent on climate, topography, and land use or cover. Marine impacts of all but the largest drainage basins are thought to be relatively localized; this small scale and heterogeneity has resulted in the impracticality of considering sediment and other runoff-related factors in global-scale correlations of environment and reef habitat (Kleypas et al., 1999). We present an initial reconnaissance study of reef distribution in relation to terrestrial runoff, both local and from the discharge of inland river basins. These results, which necessarily address the net combined effects of discharge-related stressors, are further examined to identify approaches to separating and defining sediment-specific controls.

2. Methods

2.1. Data

The LOICZ/Hexacoral Typology Database (http://www.kgs.ukans.edu/Hexacoral) is a collection of publicly available global data supplied in a 0.5° grid cell (illustrated in Fig. 1). Data sets used in this study are listed below:

Annual basin discharge and coastal runoff
30′ flow network representing riverine flow path combined with station and areal runoff data and a water balance model
University of New Hampshire and Kansas geological Survey Coastal Runoff Composite (2001)

(*continued on next page*)

Wave height
Discrete scaled measurement
Original LOICZ Database (1980 Times Atlas of the Oceans)
http://www.nioz.nl/loicz/data.htm

Tidal range
Discrete scaled measurement
Original LOICZ Database (1980 Times Atlas of the Oceans)
http://www.nioz.nl/loicz/data.htm

Chlorophyll a
Satellite imagery color units
SeaWifs (1997–2000)
http://daac.gsfc.nasa.gov/data/dataset/SEAWIFS/index.html

Average sea-surface temperature
COADS station data and NESDIS remotely sensed data
NCEP Climatology (1982–199)
http://tao.atmos.washington.edu/data_sets/sst_oi/

Minimum salinity
World Ocean Atlas
http://dss.ucar.edu/datasets/ds285.0/

ReefBase reef occurrences
Point locations of reefs; unverified
ReefBase (2001)
http://reefbase.org/database/default.asp

2.2. Analytical and visualization techniques

Geospatial analyses were done using a combination of k-means clustering, correlation statistics and geographic information system (GIS). K-means clustering and visualization were performed in LOICZVIEW, a package developed for geospatial applications (Maxwell and Buddemeier, 2002; LoiczView, 2001; Hexacoral, 2001). Correlations were analyzed using Microsoft Excel. ESRI's ArcView was used to generate spatial queries (buffers), data overlays, and final maps.

In order to develop a uniform classification basis for reef distribution, reefs/km^2 was developed as a variable by combining ReefBase inventories with the areas of the half-degree LOICZ-Hexacoral Coastal and Ocean I (nearshore) grid cells. The grid system, the terrestrial runoff flow network used, and the reef occurrences are all illustrated in Fig. 1. The geographic and depth range of analysis was selected for the optimum latitude and depth range for reef occurrence.

Based on Kleypas et al. (1999, Fig. 1), the limits for analysis were taken as 30°N and S latitude and a minimum depth per grid cell of 100 m. The depth range selected slightly oversamples the actual distribution, since there are no reefs reported below about 80 m. The latitude selection excludes some coral reefs and communities, which may extend to the vicinity of 40°. However, at high latitudes, the confounding effects of suboptimal temperature, light, and aragonite saturation state levels are much stronger, and we focus on 30°N–S range to maximize our chances of detecting a clear runoff signal (Kleypas et al., 1999).

The runoff data are highly skewed because of a relatively small number of large river basins with runoff values very large compared to individual coastal cells and to most coastal drainage basins. Log$_{10}$ transforming the runoff data normalizes the data and permits more effective use of the clustering tools. Table 1 gives the distributions of cell types and ReefBase reef numbers in the 30°N to 30°S latitude band studied.

2.3. Clustering

We utilized LoiczView k-means clustering to compare reef distribution and stream discharge. The initial experiment clustered the log$_{10}$ of the total annual runoff and overlaid reef distribution. The second experiment clustered stream discharge, wave height, tidal range, chlorophyll a, average sea-surface temperature, and minimum salinity. The third experiment supervised the multivariable clustering process using the cluster means of the original clustering (runoff only) to define archetype points for the new

Table 1
Cell, reef, and runoff statistics

Cell type	Coastal
Cells, total number	4116
Cells with runoff values	3051
Cells with reefs	1093
Reef cells/total cells	0.2655
Cells with reefs and runoff	588
(Reef+runoff) cells/runoff cells	0.1927
Number of reefs	6055
Number of reefs in runoff cells	2481
Reef numbers/total cells (Rt)	1.4711
Reef numbers/runoff cells	0.8132

Table 2
Supervised cell clustering of $\log_{10}$ runoff (m^3/year), wave height, tidal range, chlorophyll a, average sea-surface temperature, and minimum salinity with reef occurrence statistics

Cluster	No. reef cells	Reef cells	Total cells	Reefs	Average log discharge	Deviation	Location quotient
3	752	305	1057	1745	0	0.1798103	1.122229
2	333	31	364	431	6.91	− 0.2870225	0.804891
10 (unclassified)	37	0	37	0	8.88	− 1.4710884	0
6	127	31	158	137	9.32	− 0.6039998	0.58942
7	278	55	333	605	9.37	0.3457284	1.235015
4	507	313	820	1572	9.43	0.4459847	1.303167
1	341	179	520	1114	9.5	0.6712193	1.456274
0	169	6	175	23	9.63	− 1.3396599	0.089341
9	208	69	276	275	9.71	− 0.4747116	0.677306
5	150	18	168	122	9.74	− 0.744898	0.493642
8	191	16	207	31	9.78	− 1.32133	0.101801

Clusters are listed in order of increasing log average discharge (annual) corresponding with Fig. 2.

clusters and setting a criterion of one standard deviation from the cluster mean for inclusion in one of the supervised clusters; points outside of this distance were grouped into a single additional ‘unclassified’ cluster (Table 2).

We compared the number of cells and reefs in each cluster to the ratio of the total reef cells to total cells. The study area consisted of 4116 0.5° coastal grid cells, with 1093 of those cells containing 6055 reef point locations. If reefs were randomly distributed through all cells, the most probable number would be 1.47 reefs/cell. The deviation from normal and the location quotient (Walford, 1995) provide the basis for comparing selected subsets of cells to demonstrate lower or higher reef occurrence probability than the norm.

$$\text{Deviation from normal} = (\text{reefs in cluster}/\text{cells in cluster}) - (\text{total reefs}/\text{total cells})$$

$$\text{Location quotient} = (\text{reefs in cluster}/\text{cells in cluster}) / (\text{total reefs}/\text{total cells}).$$

2.4. Buffering

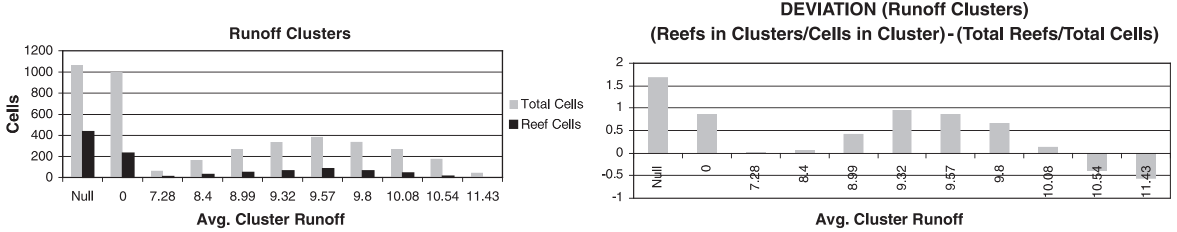
Reef occurrences in the Ocean I cell class (immediately offshore from the coastal cells) may also be influenced by coastal runoff, but cannot be straightforwardly clustered with the runoff as can the coastal cells that contain both reef and runoff variables. In order to examine possible long-range connections, we created a 1.5° buffer around the center point of the high runoff coastal cells (ESRI ArcView). This effectively extended the area of comparison into both the offshore Ocean I cells and adjacent coastal cells that may have had lower local runoff inputs.

3. Results

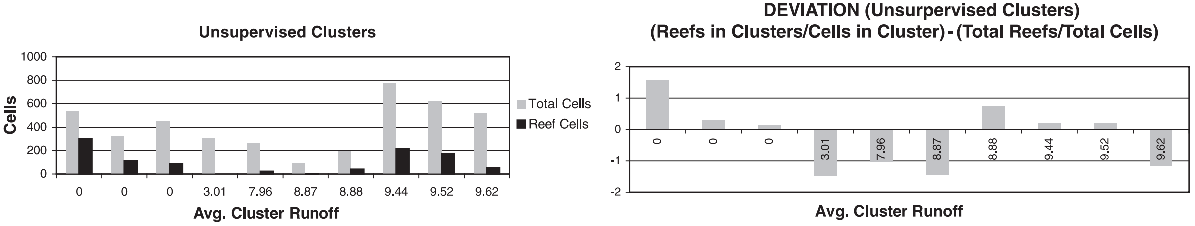
Fig. 2 summarizes experimental outcomes in terms of each cluster’s deviation from a normal distribution. Fig. 2A shows an apparently normal distribution of reefs and total cells vs. log runoff for those cells that have actual runoff values; the large number of null data and zero runoff data cells apparently skews the left portion of the distribution, but this reflects the observation above—that large runoff occurrences are relatively few and localized in the world coastal zone. The deviation plot in Fig. 2A, however, shows runoff has a strong anti-correlation with reef distribution for runoff values in excess of 10^{10} m^3/year.

When runoff is clustered along with the other five variables that are known to control or limit reef distribution and the results ordered in relation to cluster runoff means, the distribution is not well-behaved, and there is no convincing evidence of dominant control by runoff (Fig. 2B).

A. Single variable (runoff) clustering



B. Environmental variables clustered (unsupervised)



C. Environmental variables supervised by original runoff clusters

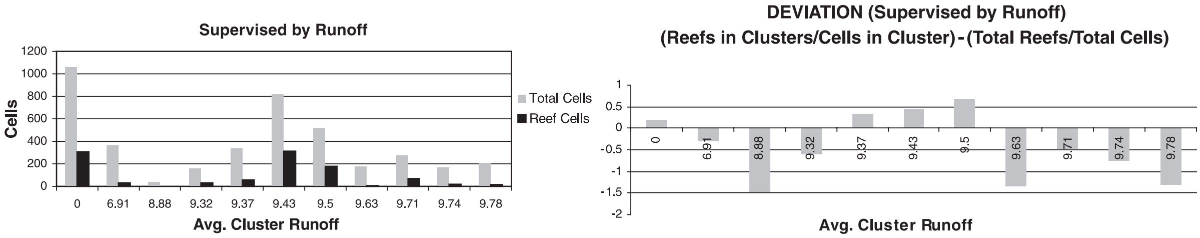


Fig. 2. K-means clustering results from three 10-cluster analyses of log runoff. (A) Unsupervised runoff; (B) unsupervised runoff, chlorophyll a, wave height, tidal range, average sea-surface temperature, and minimum salinity; (C) environmental variables supervised by runoff.

Using the means of the runoff-based clusters to supervise the clustering of all six environmental variables yields a pattern (Fig. 2C) rather similar to that of Fig. 2A, but with one or two negative deviations in the low runoff range. The major contributor to this anomaly, however, is the 'unclassified' cluster of leftovers from the supervision process, which is also by far the smallest cluster. If this is disregarded, the high runoff clusters again show evidence for reduced reef occurrence, but this time in the presence of clustering that includes five other independent environmental variables.

The buffer analysis provides a visual confirmation of the statistical plots as well as spatially limiting the effect to Ocean I cells (ocean cells adjacent to coastal cells). Fig. 3 shows Southeast Asia, a particularly reef-rich area. The 1.5° buffers around the center points of high runoff (>log 9.8 m^3/year) demonstrate the conspicuous absence of reefs relative to the non-buffered areas.

The world (30°N–S) contains 7478 Ocean I cells containing 2909 reefs producing a density of 0.389 reefs to cells. 1672 Ocean I cells are within 1.5° buffers of high runoff—a density of 0.283. Potentially, this change in densities could indicate observed runoff inhibition of reef distribution may extend to reef communities beyond the coastal zone.

4. Discussion

4.1. Runoff and reef distributions

The datasets employed are estimates and approximations, both with regard to the detailed runoff

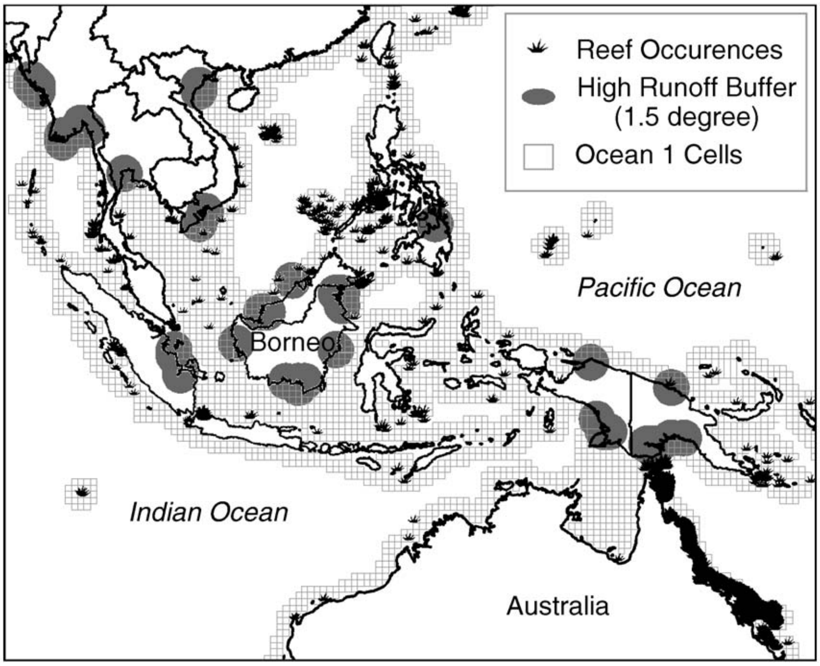


Fig. 3. Southeast Asia and northern Australia, illustrating the distribution of the coral reefs in Ocean I cells (Fig. 1) relative to 1.5° buffers around the center points of coastal cells (or about 1° around the cell boundaries) containing basin runoff values in excess of $10^{10.5}$ m^3/year.

values and the number and exact locations of coral reefs. Nonetheless, at the global scale, the results of this study show a strong anticorrelation between high runoff values and the occurrence of coral reefs in the coastal zone. The results shown in Fig. 2 suggest significant hydrologic inhibition of reef formation in no more than 12–20% (the two or three clusters with the most negative deviation value) of the coastal cells studied—an observation consistent with the heterogeneous nature and localized influences in the coastal zone. The progressive decline in reef occurrence above a runoff value in the range of 10^{10} m^3/year is qualitatively consistent with expectations.

Statistical support for a global-scale pattern based of reef occurrence related to runoff does not actually determine the mechanisms or forcing functions involved. As noted earlier, several factors associated with river discharge and runoff could have a negative impact on coral habitat. This is consistent with the idea that sediment load and deposition is a significant reef-inhibiting factor, but it does not rule out the possibility of other confounding or synergistic influences. We consider the results shown in Fig. 2 an important testimonial to the power of runoff-related factors—considered alone, runoff shows a strong anticorrelation with reef occurrence Although its effects are less clear when it is considered as one of six concurrent factors, simply organizing the environments into runoff-based classes caused the signal to reappear quite strongly even in the presence of the other five variables (Fig. 2C).

An alternative view can be obtained by grouping the clusters into 'superclusters' according to their deviation values—strongly negative, moderately negative, or positive. These results, with weighted average runoff values for the classes, are given in Table 3. Here again, the overall relationship is strongly evident (seen in Fig. 2C).

4.2. Environmental interpretations

Water and sediment discharge to the coastal zone are among the parameters most altered by human intervention (Vörösmarty et al., 1997). In large river

Table 3
Composite clusters combined by reef incidence deviation value

Deviation range	No. of cells	No. of reefs	Rn	Deviation	Weighted mean log discharge
< − 1	419	54	0.129	− 1.34	9.64
− 1 to 0	966	965	0.00	− 0.47	8.60
>0	2730	5036	1.84	0.37	5.78

systems, the tendency has generally been toward more regulation and lower total and peak flows, suggesting that the coastal zone effects of sedimentation might be diminishing. From a coral reef standpoint, however, these effects will be significant only within deltaic and estuarine areas that are poor habitat to start with because of the large deposits of soft sediment. The greater impact is likely to occur at the scale of small coastal basins, where land conversion and deforestation increase runoff and erosion, to the detriment of near-shore reef environments. Changes at this scale are poorly resolved with the global-level variables and half-degree grid used in this reconnaissance study, which are more appropriate to assessing large spatial and temporal scales than local effects. The study of Burke et al. (2002) was carried out at a more local scale; interestingly, their conclusions that a minority of the reefs are threatened by sediment and nutrient loading is qualitatively consistent with our observation that only a minority of basin outflows (the largest) are clearly associated with inhibited reef occurrence.

4.3. Future research

Measures can easily be taken to further explore the relationships suggested by this preliminary study. Monthly runoff values are now available, and the next generation of river databases will contain sediment load and nutrient flux values (C. Vörösmarty, personal communication). These can be used to more directly explore the question of the relative importance of sediment and other parameters. The increasing availability of ocean color and other remotely sensed datasets also provides tools for linking water quality to sources of sediment and nutrients and to the ecosystems of interest. Similarly, as more complete and verified reef databases become available (see, for example, Burke et al., 2002), studies at higher spatial resolution will be justified. Further experimentation with tuning the proxy variable selection used to project runoff effects offshore seems promising, as do more detailed and perhaps higher resolution regional case studies.

5. Conclusions

- At a global scale, there is persuasive evidence that annual runoff values $>10^{10}$ m^3/year (referred to a 0.5° grid cell) are associated with strongly reduced occurrence of coral reef communities.
- Use of clustering and GIS shows potential for extending the assessment of coastal effects into offshore waters, and suggests the occurrence of some longer-range connection between coastal runoff and reef habitat suitability. Proxy variables may also prove useful in extending the application to multivariate clustering.
- In view of the rapidly evolving tools and databases becoming available, it is feasible to conduct more detailed and sophisticated studies of basin sediment yield, climatic and anthropogenic influences, and possible ways to separate or determine the effects of the correlated variables.

Acknowledgements

We thank Charles Vorosmarty, Pamela Green, and their colleagues for assisting us by making available the river discharge database. James Syvitski and members of the IGBP Water group provided encouragement and useful discussion. Jeffrey Fowler assisted with some of the calculations and Mark Schoneweis with figure preparation. This work has been supported in part by US National Science Foundation grant OCE 00-03970, the IGBP-LOICZ program, the GEF Office of the United Nations Environment Programme, and NEDO-Rite SEECS Project (M. Isobe, P.I.).

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