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Water and Wastewater needs for the Caribbean - 21st Century

CWWA

Coral Reefs, Sewage, and Quality Standards

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◆ IMPORTANCE OF CORAL REEFS AND THREATS TO THEM

Coral reefs are the most important marine natural resource of Jamaica and most Caribbean islands, providing the bulk of fisheries catches and marine bio-diversity, the source of sand for the beaches on which the tourism economy is based, and protecting the shore from erosion by storm waves. Maintaining the health of the coral reefs is therefore critical in protecting coastal infrastructure (seawalls, docks, roads, houses, hotels, etc.) and employment (in fisheries, tourism, and services).

In most parts of Jamaica reefs have significantly deteriorated in recent years (Goreau, 1959; Goreau and Goreau, 1973; Goreau, 1992), compromising the valuable ecological services which the reefs provide. Degraded reefs have most corals replaced by fleshy algae. They are not attractive to divers and snorkelers except for first time novices, support very limited fish populations, and they virtually lack both growing coral which break waves in shallow water and sand-producing algae which renourish beaches. Consequently, waves break with greater force on the shore, increasing erosion, and little new sand is generated to replace that which is lost. Degraded reefs show a great reduction in water clarity, affecting their quality for recreation. When degraded reefs are damaged by natural disasters such as hurricanes, there is little recovery afterwards because young corals are unable to find bare limestone on which to settle and grow due to dense coverage by fleshy algae. Good recovery of shallow coral reefs in Jamaica from hurricane damage is now restricted to a few remote areas (Goreau, in press). As a result, visible erosion is taking place at most white reef-derived sand beaches, and coastline accretion is largely restricted to brown sand beaches derived from erosion inland, which have little tourism potential due to their muddy water.

The causes, and even the existence of reef deterioration have been controversial, because a complex mixture of factors, including hurricanes, erosion, human physical impact, epidemic diseases of marine organisms, overfishing, and climate change, have all played roles (Figure 1). Because all these factors act together to stress reef communities, protecting coral reefs requires a very broad range of simultaneous policy steps to reduce stresses to reefs whose origin lies in (a) in-water activities (fishing methods, anchor damage, dredging, etc.), (b) in regional activities taking place in the adjacent and up-current watersheds (pollution, erosion, etc.), and (c) activities in distant parts of the planet (climate change, sea level rise, global warming).

❖ MARINE POLLUTION IN THE CARIBBEAN

Public awareness of water quality problems usually focuses on surface contaminants which can be seen and smelled such as garbage and petroleum slicks, or toxic wastes, and insufficient attention has been paid towards the much more pervasive problems of excessive nutrient levels and declining water clarity in the coastal zone. Large oil spills have occurred in recent years around the Caribbean in Mexico, Panama, Puerto Rico, and Cuba prompting clean up efforts which have often been too little and too late to prevent serious local damage to reefs and beaches. Tar balls and oil slicks have become increasingly common in the last two decades (Jones, in press), and submerged trash, primarily plastic bags, styrofoam, tin cans, and bottles are now seen on almost every dive where they were once too uncommon as to elicit comment. Surveys have shown that trash on beaches derived from both from land-based and ship-based sources (Jones, in press).

As the Caribbean is an enclosed sea, floating oil or trash will ultimately wash up on shore, so a Caribbean-wide ban on dumping at sea and provision of shore reception and treatment facilities is required. Steps towards this goal are now underway under the sponsorship of the International Maritime Organization and the United Nations Environment Programme. These would be far more effective if the Cartagena Convention, (an agreement signed by all Caribbean states obligating them to pollution monitoring and clean up,) were to be implemented. Dumping of locally-derived toxic waste has been relatively rare due to the modest level of industrial development in the region, but there is extensive offshore dumping of chemical wastes from the pharmaceutical industry in Puerto Rico which has been blamed for causing massive fish kills in Puerto Rico and the Dominican Republic, and there have been numerous attempts to use sites in the Caribbean as repositories for toxic wastes from North America and Europe.

Dramatic as the impacts of acute toxic pollution are, serious impacts on marine life have been relatively limited in space and time, whereas the impacts of excessive nutrient levels have become pervasive, threatening the health of reefs in most of the Caribbean (Lapointe, in press). Coral reefs are the marine ecosystem which is most adapted to extremely clear, clean water, and which has the least tolerance for any deterioration in water quality. While this has been known for a very long time, it is only recently that it has become clear just how low nutrient levels must be to maintain healthy reefs. While nutrients are essential for all biological growth, a healthy reef maintains an exceptionally high level of biomass and productivity by recycling very small amounts of nutrients supplied in the water. Most surface waters in the tropical open ocean contain virtually undetectable levels of nutrients, since all is taken up by the growth of microscopic planktonic algae. The rate at which new nutrients are provided by upwelling of deep nutrient-rich water is extremely limited in the Caribbean because the most nutrient-rich bottom waters in the Western Atlantic are unable to enter the Caribbean due to restricted passageways between the Lesser Antilles, and deep cold waters are effectively isolated from the surface by the extremely thick layer of warm surface water which prevents nutrients mixing upwards into surface waters. Land-based sources of nutrients therefore have a tremendous impact on the near-shore zone.

◆ ALGAE OVERGROWTH OF REEFS AND DISSOLVED NUTRIENTS

While it might be thought that reefs would benefit from more nutrients, very small additions quickly become excessive. Any aquatic ecosystem can undergo eutrophication, the uncontrolled growth of "weedy" nuisance algae which smother normal plant and animal life when nutrient levels are elevated, just as dumping large amounts of fertilizer on land results in prolific growth of weeds unless these are removed. Eutrophic ecosystems are dominated by a handful of useless species which replace the normal highly diverse ecosystem, and their extremely high rates of algae growth and of decomposition stimulates growth of bacteria and fungi. These can completely remove oxygen from the water wherever circulation is restricted, causing death of higher organisms and creation of zones which are virtually barren of fish and bottom-dwelling organisms such as shellfish and which stink with the rotten egg smell of hydrogen sulphide. This happened in Kingston Harbour, where a study of bottom-dwelling organisms ended when oxygen levels catastrophically fell to levels too low to support them (Wade, 1976). Coral reefs and seagrass beds in the Harbour died, and fish are now confined to a shallow surface layer in which oxygen dissolves from the atmosphere by winds and waves. Under calm conditions the supply of oxygen is greatly reduced, causing massive fish kills. Both a complete halt to nutrient inputs and many years, perhaps decades to centuries, would be required before the accumulated organic matter decomposes and oxygen levels can build up to allow fish and bottom-dwellers to live in deeper waters.

Eutrophication of rivers, lakes, and coastal waters receiving organic wastes has long been known for causing desirable fish and shellfish species to be replaced with algae blooms, which may be toxic to organisms consuming them. Because water clarity and recreational value deteriorate, this has prompted development of water quality standards designed to identify the maximum nutrient levels which allow the original ecosystem to remain intact. Most marine water quality standards have been developed for cold climates, especially for estuaries. Estuaries are intrinsically low-diversity ecosystems compared to coral reefs. They are adapted to much higher levels of nutrients than reefs because they receive large amounts of nutrients, freshwater, and mud from river discharges, which are typically largest in the early spring following snow melt and runoff. Acceptable levels of nutrients that are low enough to prevent eutrophication of temperate estuaries are many times higher than those which trigger eutrophication of coral reefs, so these criteria cannot be applied to coral reef habitats. In the absence of tropical data, nutrient standards designed for cold estuaries have been mistakenly applied to the tropical coastal zone. An even more serious error is to use drinking water quality standards, defined by nutrient concentrations capable of causing medical damage to humans (especially methemoglobinemia of infants due to excessive nitrate and nitrite concentrations in drinking water), which are even higher. Because reefs are the most sensitive of all ecosystems to changes in water quality, the critical levels of nutrients which need to be maintained are far lower for than any other ecosystem, indeed levels which would be regarded as normal in any other marine ecosystem. Protection of reefs from eutrophication requires the use of water quality criteria specific to coral reefs.

Recent research in the Caribbean and in the Great Barrier Reef of Australia has established the critical levels of nitrogen and phosphorous which must not be exceeded if reefs are to remain healthy without being overgrown by weedy algae (Lapointe et al., 1992, 1993, in press; Bell, 1992). These concentrations are:

1.0 micromoles per litre of nitrogen as nitrate and ammonia

1.0 micromoles per litre of phosphorous as ortho-phosphate and organophosphate

These values are in the molecular concentration units used by chemists and oceanographers. In the weight units more often used in the wastewater literature these translate into:

Nitrogen:	0.014 ppm N	or	0.040 ppm NO_3
Phosphorous:	0.003 ppm P	or	0.007 ppm PO_4

◆ NUTRIENT LEVELS IN JAMAICAN COASTAL WATERS

Nutrients enter the Jamaican coastal zone from streams and submarine springs supplied by groundwater seepage. Measurements around 1980 found nitrate levels in Discovery Bay in the range of 5 to 10 micromoles per litre (Goreau, unpublished). By the late 1980s these had risen to around 10 to 15 micromoles per litre, and ecological replacement of corals by weedy algae was nearly complete (Goreau, 1992). Samples analysed for nitrogen and phosphorous showed that the source of nitrogen was from freshwater (figures 2-4), and the concentrations were sufficiently high that they exceeded critical levels down to a depth of 100 feet on the outer reef slope. Similar nutrient values were found all along western St. Ann, from Rio Bueno to Dunns River (Goreau, Lapointe, and Macfarlane, unpublished). Because of the much larger sewage discharges from highly developed areas near Ocho Rios, Montego Bay, and the South Coast, those areas certainly have considerably higher values. While the main source of nitrogen was from subsurface drainage of the interior of the watershed, it appears that growth of population and tourism along the shore in the 1980s provided local phosphorous inputs which had been previously lacking, causing rapid eutrophication.

Negril, located at the western tip of the island, has seen explosive tourism development and population growth in the last two decades. Concentrations of nutrients were evaluated in the Nigril area in 1991 by Greenway (1991), who reported that nutrient levels were low and typical of unpolluted waters, even though every single sample analysed exceeded the acceptable criteria for reefs for both nitrogen and phosphorous. Analyses made in 1992 by Wade (in press) showed even higher values in the range of 10 to 20 times the acceptable levels. Over the last 4 years, the reefs of Negril have been subjected to unprecedented algae overgrowth, with the result that the coverage of algae on the bottom now equals or exceeds that of corals. These values suggest that nutrient concentrations need to be reduced by 90 to 95% or more to allow ecosystem recovery. Ongoing efforts to establish a conservation area to protect the reef, on which the area's tourism is built, will not succeed unless this happens soon. The major river and groundwater nutrient sources in Negril are shown in figure 5.

The Port Antonio region in eastern Jamaica is also the site of a proposed conservation area. This part of the island has some of the lowest population densities due to mountainous topography and high rainfall. A survey was conducted of nitrate levels in all major freshwater sources, including rivers, springs, and drainage ditches along the entire proposed Port Antonio Marine Park shoreline in early 1994 (Goreau, Wirth, and Bourke, unpublished). Figure 6 shows the nitrate concentrations measured. The values of nitrate in micromoles per litre are equal to the number of times which these freshwater inputs must be diluted by pure seawater containing absolutely no nitrate in order to bring concentrations below acceptable levels. The measured inputs to the to the coastal zone must be diluted out by factor of between 2 and 45 times before their nitrate contents are sufficiently low.

These estimates of needed dilution are too low for at least three reasons, so that the actual dilution of freshwater inputs needed over the reef may be considerably greater. First, only nitrate nitrogen was measured, but ammonium nitrate was low, because these came from water draining sewage, mangroves, or wetlands. Under such conditions organic matter contents are high, oxygen levels are low, and nitrate is rapidly consumed by bacteria and converted into ammonium, organic nitrogen, or gaseous forms of nitrogen. Therefore the disolved nitrogen content has been underestimated for those samples. Secondly, it was not possible to analyse phosphorous contents for those samples, yet analyses in other parts of Jamaica suggest that phosphorous contents are typically more limiting than nitrogen (Lapointe, in press), and even greater dilution may be needed to bring phosphorous below acceptable levels than nitrogen. Thirdly, the dilution figure is based on assumed zero nutrients for offshore waters. A value of only 0.5 micromoles per litre of nitrate in offshore waters would require a dilution twice as great. Surface waters entering the Caribbean are influenced by seasonal discharges from the Orinoco and Amazon rivers, and often have values in this range. Bell (personal communication) has expressed the concern that nutrients from these remote South American sources could become high enough for Eastern Caribbean surface ocean water to cause eutrophication even in the absence of local land-based nutrient sources. He has obtained data suggesting that nutrient for both nitrogen and phosphorous. Analyses made in 1992 by Wade (in press) showed even higher values in the range of 10 to 20 times the acceptable levels. Over the last 4 years, the reefs of Negril have been subjected to unprecedented algae overgrowth, with the result that the coverage of algae on the bottom now equals or exceeds that of corals. These values suggest that nutrient concentrations need to be reduced by 90 to 95% or more to allow ecosystem recovery. Ongoing efforts to establish a conservation area to protect the reef, on which the area's tourism is built, will not succeed unless this happens soon. The major river and groundwater nutrient sources in Negril are shown in figure 5.

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◆ PHYSICAL FACTORS, NUTRIENT SOURCES, AND EUTROPHICATION

To determine the extent of nutrient reduction that is required it is necessary to consider the balance of nutrient inputs into each segment of the coastal zone (figure 8), and the extent to which nutrients are removed through biological uptake and diluted by exchange of water between the coastal zone and offshore areas. Biological uptake and exchange are highly variable, poorly quantified, and in any case not subject to direct human control. In general, the more eutrophic an area becomes the less representative dissolved nutrient concentrations in the water column will be of the actual inputs, since most nutrients are quickly taken up by algae. The greater the degree of physical water mixing with offshore waters by waves and winds the lower the nutrient concentrations will be. Consequently bays and shores with restricted circulation will have higher nutrient levels and be much more easily eutrophied than headlands, open waters, or areas with strong offshore currents.

Because ocean currents and tides are highly variable on seasonal scales and vary strongly as a function of weather patterns, many areas may become eutrophic on a seasonal basis or for intervals following periods of extended calm weather. In addition nutrient inputs are highly variable because they depend on seasonal variations of the resident population, river runoff, and groundwater discharge. Nutrient inputs therefore need to be reduced to an extent that is both site-specific and seasonally dependent as well as subject to weather fluctuations. Therefore nutrient inputs need to be lowered sufficiently that excursions of nutrients above critical concentrations are avoided under the worst case scenario. Assuming nutrient levels measured are representative of average conditions, a general mass nutrient mass balance model indicates that the proportional input reduction needed will be (O-S)/O where O is the observed average concentration and S is the standard maximum acceptable concentration. Focusing only on surface discharges or sewage is insufficient, since the total nutrient inputs from all sources must be taken into account. Where non-sewage nutrient sources are also present, such as agricultural runoff, the proportional reduction in sewage inputs needed is even higher.

It is traditional to divide nutrient sources into point and non-point sources, which are generally equated with sewage and agricultural sources respectively. But two other non-exclusive divisions are also helpful, surface and groundwater sources, and sewage and non-sewage sources. Sewage can be a non-point groundwater source in areas typical of most of Jamaica where "soak-away" septic tanks are used. Agricultural sources can be point sources where animal manure is drained or flushed out of stables and pens. The relative role of sewage, agriculture, and natural nutrient sources needs to be determined by direct measurements of each source type in each watershed. Without such a breakdown it will not be possible to determine either the amount of sewage nutrient reduction required, to determine either the amount of sewage nutrient reduction required, to determine the efficiency of fertilizer use, or to design integrated agricultural strategies which maximise agricultural production, minimise fertiliser wastage, minimise groundwater contamination, and contribute to sound coastal zone protection.

In order to minimise damage to coral reef ecoystems and promote their eventual recovery the fullest possible biological tertiary sewage treatment should be applied to all terrestrial nutrient sources. This should also include agricultural point sources from animal pens wherever this is feasible, since livestock such as cattle may excrete as much nutrients as 15 people. The rational use of fertilisers also plays a role, since fertiliser applications often exceed the uptake capacity of the crops, leaving the rest to leach into and contaminate groundwater. Fertiliser elemental ratios need to be carefully optimized to match plant uptake ratios. Plants utilise elements which they most lack, but the other elements are present in excess and will not be utilised. Fertiliser trails in Jamaica often fail to yield satisfactory growth increases, meaning most of the fertiliser is wasted. This is probably due to the geochemical peculiarities of limestone soils, which impose strong trace element limitations, so that standard imported NPK fertiliser formulations which lack the needed trace metals do not allow plants to utilise much of the nitrogen and phosphorus.

Since most sewage in Jamaica is discharged directly into the ground, it may play at least as important a role in groundwater contamination as agricultural runoff, and some nutrients discharged via submarine springs along the North Coast could have their origin in the densely populated rural areas in the centre of the island. In the limestone mountains which cover most of Jamaica the water table is sufficiently deep down that tree roots cannot reach it, and in these areas groundwater nutrients are unlikely to be intercepted and taken up. This is why many Jamaican limestone areas have such high nitrogen levels. On the other hand, phosphorous is prevented from leaching by being adsorbed by limestone and soils.

In contrast, nutrients discharged into surface waters exposed to light are readily taken up by growth of algae and plants. While this causes eutrophication of the receiving bodies of water, this can readily be managed so that most nutrients are stripped out of the water in a relatively confined area. This process, biological tertiary treatment, traps and recycles the nutrients (Devi Prasad, in press; Wilson, in press), rather than allowing them to cause uncontrollable proliferation of algae over a large area of coastline. Secondary sewage treatment alone is inadequate because even if secondary treated effluents are sufficiently free of particulates, dissolved organics, and odours to be "fit to drink" (which is too often not the case), they contain invisible, odourless dissolved nutrients which are far too concentrated for coral reefs. Coastal zone nutrient control strategies should therefore be based on keeping sewage effluents in the air and light so that the nutrients can be used for intensive production of plants on land, rather than hiding them deep and dark underground where they will flow to the sea, robbing the land of potential production and stimulating growth of weedy algae which destroy the valuable productivity of corals, sand producing algae, and fish.

❖ POPULATION DENSITY AND TERTIARY SEWAGE TREATMENT

Coastal zone eutrophication in Jamaica is being repeated throughout most of the Caribbean as a result of the very high population densities of all but a few islands. Tabulations of population density of tropical islands around the world (Tables 1 and 2) show that the same is true of many Pacific and Indian Ocean islands. The relationship between population density and eutrophication is especially clear in the San Blas Islands of Panama. In this archipelago there are 50 inhabited islands, each around 100 meters or less across, with an average of around 1,000 people each, and around 300 uninhabited islands. Although the Cuna Indian population are subsistence fishermen, there is little evidence of overfishing. During a brief survey of the region in early 1994 all the larger populated islands were observed to have eutrophication-indicating algae all around the shoreline, but these were absent from all uninhabited islands or those which only had a few resident families (Goreau, unpublished). It appears that a coastal population density of no more that roughly 500 persons per 100 metres of shore generates too much nutrients for a viable coral reef to survive in the absence of sewage nutrient removal. This can be defined as the human carrying capacity of the reef. Similar eutrophication has been observed at the Club Med in Moorea, French Polynesia, where the secondary-treated sewage from 500 people at an isolated hotel provides a point source causing eutrophication over 100 metres of coastline (Goreau, unpublished) even though this is an area with very strong tidal currents. The maximum sustainable population near a reef is therefore probably less than around 5,000 persons per kilometre. As the interior of Moorea is uninhabited, the coastal population density reefs can tolerate will be even lower when there are additional nutrient sources derived from island via groundwater flow, shore currents are less, and sewage is treated to less than secondary levels.

Virtually every populated coastline near reefs around the world is now well above this limit, making adjacent reefs unsustainable in the face of human population density. Many reefs in Jamaica and elsewhere have now reached the point where so little live coral remains that decades will be required for new corals to settle and grow even after all excess nutrient inputs are removed. Nutrient reduction strategies need to focus first on those areas where coral cover is still sufficiently high that the reefs can quickly recover once nutrients are reduced, allowing them to help seed recovery in more damaged areas. If these reefs are lost, restoration of the marine habitat will be impossibly slow. In many places there is little time left to act. With the exception of islands with very low population density (mostly flat islands without surface water), protection of the coral reefs requires that virtually all sewage generated be treated to tertiary level to increase the fraction of nutrients intercepted and removed prior to discharge to the coastal zone. Even though coral reef habitats require the very highest technology of sewage treatment, sewage treatment plants proposed in tropical areas rarely include tertiary treatment, usually on grounds that this is too complicated and expensive. The point of this paper is that tertiary sewage treatment and use of appropriate nutrient water quality standards are nowhere more necessary on environmental grounds.

Tertiary treatment has been widely regarded as costly and complex by governments and international funding agencies because in cold countries expensive chemical treatment is needed to remove nutrients since plants can't grow year-round. In the tropics biological treatment is always effective, cheap, and require only modest areas (Devi Prasad, in press; Wilson, in press). Often this can be done in wetlands, ecosystems which are excellent for removing nutrients and have few other economic uses unless they are drained, causing the destruction of their nutrient and sediment removal capability and deterioration of water quality in the adjacent coastal zone. In most cases biological tertiary treatment is technically practical, economically feasible, and environmentally necessary when contrasted to loss of fisheries, tourism, shore protection, and other ecosystem services which only healthy reefs can provide. Where coastal nutrients are sufficiently excessive, tertiary treatment of the entire population in coastal areas alone will be inadequate, and attention also needs to be paid to sewage entering groundwater from soak away pits in the interior of the island. The sewage collection and treatment plans for Montego Bay, Ocho Rios, and Negril, which focus on the coastal strip hotels and upscale areas along the main roads and do not include squatter settlements or hillside communities, will therefore be inadequate to reduce coastal nutrients to sufficient levels to protect reefs unless they are made far more ambitious. The remote, isolated, and mountainous character of many interior areas makes sewage collection systems and treatment plants prohibitively expensive. Soak-away pits should be replaced with sealed composting or dry toilets in such areas to prevent leaching of nutrients into the groundwater which will eventually flow into the sea.

If we are to protect reefs we must convert the source of marine environmental damage into a fertilizer for useful productivity based on nutrient recycling (Macfarlane, in press). Biological tertiary treatment systems must be actively managed to maintain maximum productivity and nutrient removal in minimal areas by harvesting and composting the biomass produced and using it to produce useful sources of fuel and fibre where pathogens or trace chemical contaminants make them unsuitable fertilisers for food production. Harvesting is necessary because where biological tertiary treatment is unmanaged, plants will take up only the nutrients they can use, and the excess will flow on into receiving waters. Prevention of coal reef eutrophication is therefore closely linked to replacing our wasteful "throw away" lifestyle with a "reduce, reuse, recycle" ethos toward sewage nutrients, rather than hiding sewage underground or in the ocean. While numerous other policy steps are also needed to protect reefs (Table 3), including limitations on climate change, full biological tertiary sewage treatment in all populated areas in one of the most important in sustaining coral reef health.

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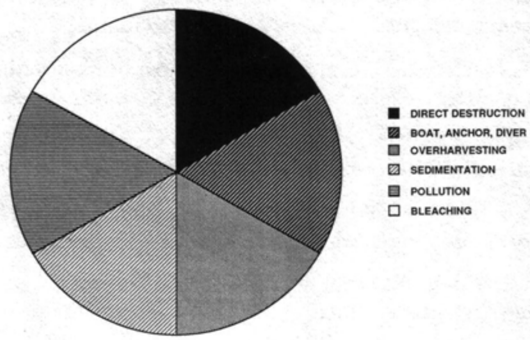
FIGURE 1

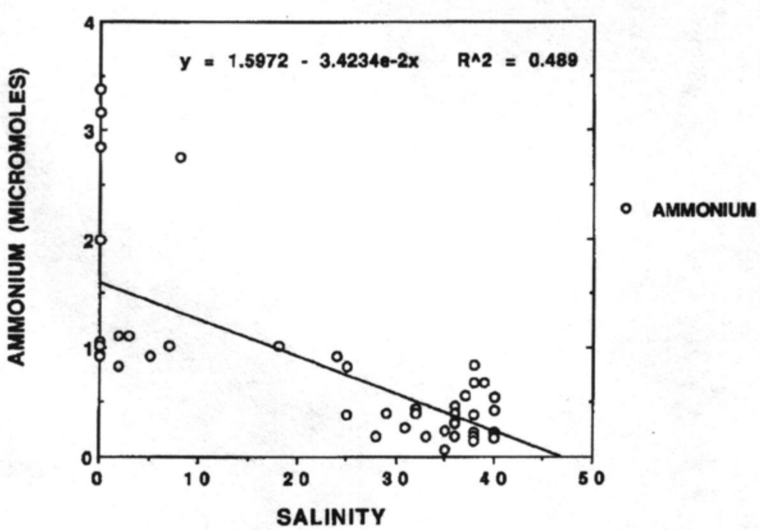
MAJOR FACTORS CAUSING REEF DEGRADATION



3. RELATIVE IMPORTANCE OF DIFFERENT FACTORS VARIES FROM REEF TO REEF

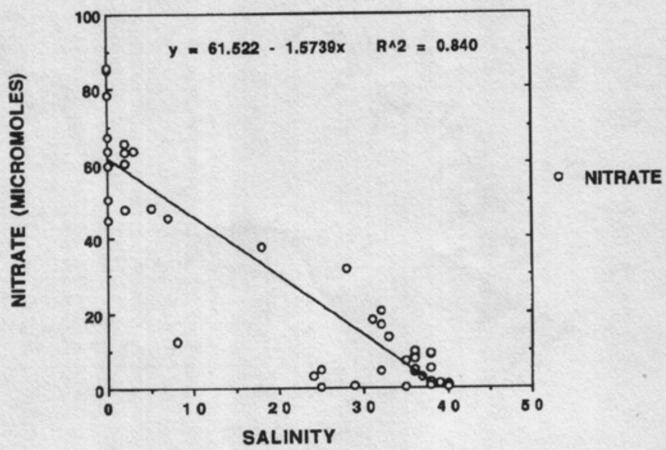
The major human factors causing reef degradation include in-water activities, activities in the adjacent watersheds, and global climate change. The diagram is schematic because the relative importance of each factor varies from reef to reef depending on their physical setting, local practices, and population density.

FIGURE 2



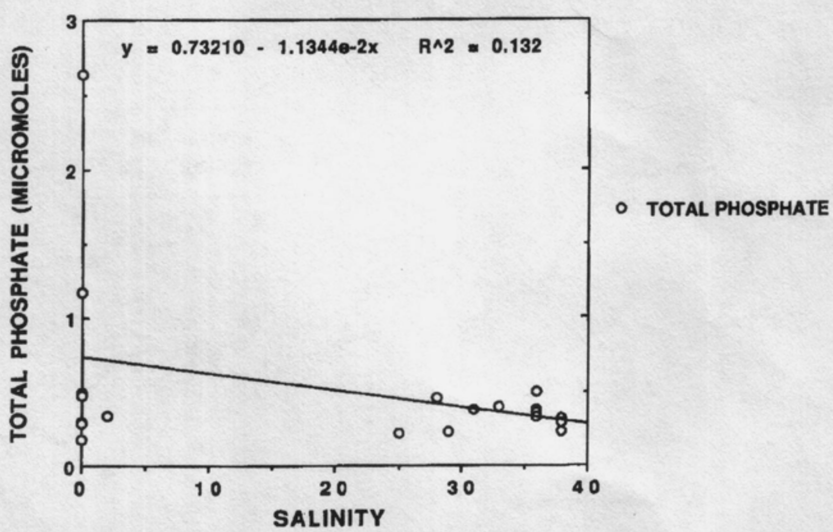
Ammonium concentrations along the north coast of Jamaica as a function of salinity. Ammonium is enriched in fresh water sources by a factor of around four times above seawater values.

FIGURE 3



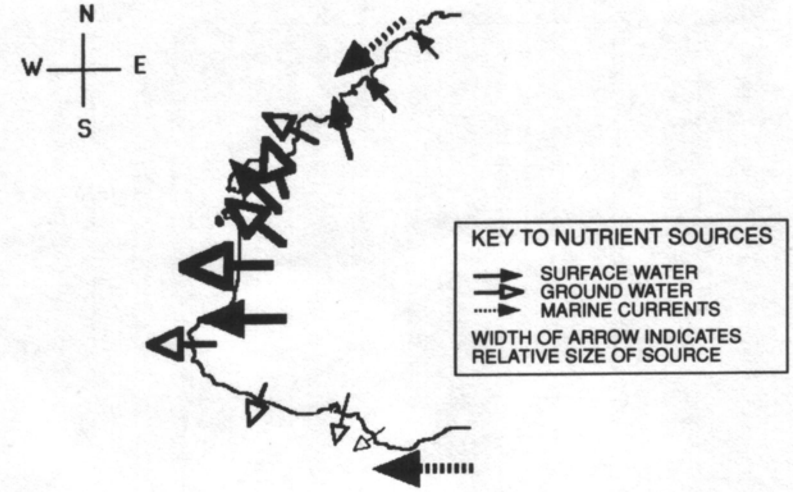
Nitrate concentrations along the north coast of Jamaica as a function of salinity. Nitrate is enriched in fresh water sources by around a hundred times over sea water values. Almost every measurement exceeds the critical level.

FIGURE 4



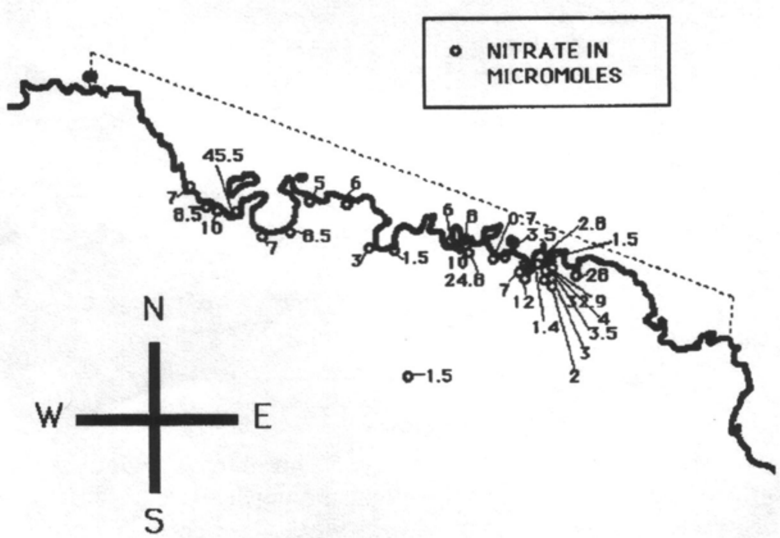
Total soluble reactive phosphate concentrations, including both orthophosphate and organophosphate, along the north coast of Jamaica as a function of salinity. Phosphate is only very weakly enriched in fresh water sources over marine values due to strong adsorption by limestone and soils. As a result direct sewage releases of phosphate to the coastal zone probably dominate over groundwater sources.

FIGURE 5



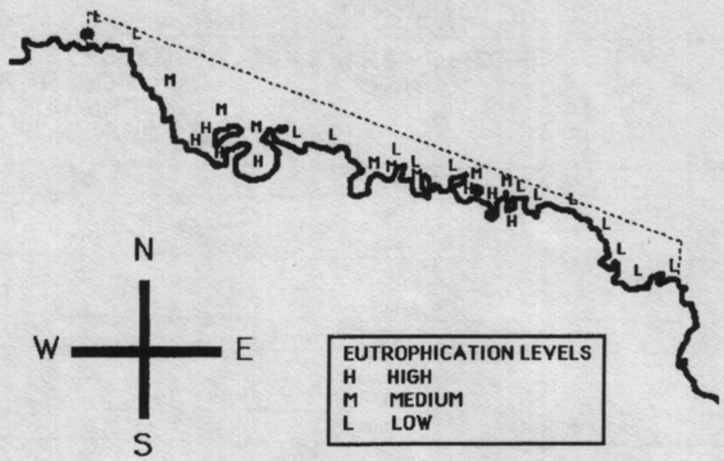
Nutrient sources to the coastal zone in the Negril area a indicated by nutrient measurements in the sea and in freshwater, and by the distribution of overgrowth of coral reefs by high nutrient-adapted algae. The size of the arrows indicates the relative size of the sources.

FIGURE 6



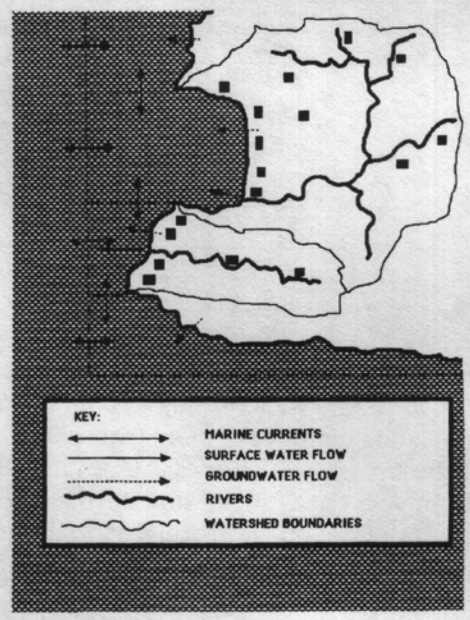
Nitrate concentrations in rivers, streams, springs, and drains along the shore near Port Antonio. Almost all supply nitrate in excess of desirable levels.

FIGURE 7



Reef eutrophication in the Port Antonio area is closely related to nutrient inputs, and is present in all populated bays but absent along shores with very small coastal populations.

FIGURE 8



Schematic diagram showing the coastal zone divided into watershed basins and adjacent coastal zones. The arrows indicate sources of nutrients into the coastal zone which must be evaluated in a mass-balance model.

TABLE 1

ISLAND	POPULATION DENSITY (PEOPLE PER SQ. KM) >200	BLEACHING XX=SEVERE X =MODERATE + =PROBABLE ? =UNKNOWN
SINGAPORE	4527.5	?
BERMUDA	1094	X
OKINAWA	944	XX
MALDIVES	785.2	XX
BARBADOS	604.7	X
TAIWAN	562	?
MAURITIUS	543.6	+
TUVALU	500	+
NAURU	476.2	X
ZANZIBAR	381	+
PUERTO RICO	366.7	X
ARUBA	321.2	+
US VIRGIN ISLANDS	312.9	X
MARTINIQUE	302	+
SAINT VINCENT	283.5	+
MARSHALL ISLANDS	281.8	+
COMORO ISLANDS	271.6	XX
GRENADA	267.4	X
SRI LANKA	257	?
GUAM	255	?
TRINADAD AND TOBAGO	249.3	+
HAITI	248.4	+
NETHÉRLANDS ANTILLES	238.8	X
JAMAICA	227	XX
SAINT LUCIA	233	X
PHILLIPINES	216	+
AMERICAN SAMOA	206	XX
REUNION	204	X

Tropical islands of the world ranked according to population density. Table 1 shows islands with population densities of more than 200 persons per square kilometre, and Table 2 those with less than 200. Assuming that population distribution is relatively uniform, it is likely that all the former are close to general regional coastal eutrophication and require virtually complete tertiary sewage treatment to protect reefs. Those below are likely to have eutrophication largely around the major population centers. Eutrophication occurs even in Australia, the lowest density island of all shown. Coral bleaching is unrelated to population density, and therefore not related to local pollution.

TABLE 2

ISLAND	POPULATION DENSITY (PEOPLE PER SQ. KM) <200	BLEACHING XX=SEVERE X =MODERATE + =PROBABLE ? =UNKNOWN
GUADELOPE	197.8	+
FED.STATES OA MICRONESIA	162.4	+
SAINT KITTS AND NEVIS	160.9	+
SEYCHELLES	158.2	+
DOMINICAN REPUBLIC	156.4	+
ANTIGUA AND BARBUDA	152.3	+
SAO TOME E PRINCIPE	131.7	?
TONGA	131.2	X
SAINT MARTIN	114	+
ANGUILLA	105	?
KIRIBATI	103.3	X
CUBA	98.4	X
INDONESIA	98	XX
CABO VERDE	97.9	?
DOMINICA	95.9	+
MONTSERRAT	94	+
CAYMAN ISLANDS	92	XX
MARIANA ISLANDS	85.4	?
BRITISH VERGIN ISLANDS	80	X
COOK ISLANDS	72	+
WESTERN SAMOA	55.8	XX
FRENCH POLYNESIA	50	XX
FIJI	40.9	X
BELAU	34.9	+
BAHAMAS	19.3	X
MADAGASCAR	19	?
VANUATU	13.2	+
SOLOMON ISLANDS	12.3	+
PAPUA NEW GUINEA	9	+
NEW CALEDONIA	8	?
NIUE	7.7	+
TURKS AND CAICOS	6	+
AUSTRALIA	2	X

WHY ARE OUR CORAL REEFS DYING?		
SYMPTOMS	**CAUSES**	**SOLUTIONS**
Corals overgrown by seaweed	Fertiization of the coastal zone by nutrients from sewage and agriculture	Tertiary treatment of all sewage to remove nutrients, more efficent use of fertilizers
Corals smothered by sediments	Erosion of soils	Reforestation of coastal watersheds, no-till agriculture, contour ploughing
Corals turning white (Bleaching)	Excessively high temperature	Global agreements to halt global warming and greenhouse gas buildup
Corals damaged by anchors	Sport divers and boats	Install moorings
Overfishing	poverty inappropriate fishing techniques	Establish fish reserves, halt spearfishing, dynamite, poisons, develop mariculture

Symptoms, causes, and solutions of the major factors causing coral reef degradation.