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ARTIFICIAL REEF DEVELOPMENT IN THE TURKS AND CAICOS: ENVIRONMENTAL ASSESSMENT AND PROPOSED PROJECTS

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ABSTRACT:

Nearshore sites in Grand Turk and Providenciales were evaluated for potential development of artificial reefs and shore protection barriers using mineral accretion technology. Environmental conditions were found to be exceptionally suitable. A pilot artificial reef project is proposed for the northern Providenciales, and a pilot breakwater project is proposed for western Grand Turk. Overall reef conditions were excellent, among the best in the Caribbean, but early signs of coral reef overgrowth by algae were found near tourist areas of Providenciales, suggesting that nutrient levels may already be becoming excessive. Algae overgrowth was also seen in reefs affected by natural deep water upwelling, indicating that the entire area may be fairly close to critical nutrient levels. A nutrient and algae survey is proposed to identify sites affected, the natural and human sources of nutrients, and policy options for reducing them. Some potentially low cost options for nutrient removal are outlined.

1. SITES AND METHODS

At the request of the Ministry of Natural Resources Department of Environment and Coastal Resources of the Government of the Turks and Caicos Islands and the Blue Planet Foundation, several sites along the west coast of Grand Turk and the north coast of Providenciales were examined as potential sites for use of mineral accretion to make artificial reefs and breakwaters by Dr. Thomas J. Goreau and Prof. Wolf Hilbertz during one week in early May 1995. Environmental factors assessed included the type of bottom, wave exposure, the oceanographic, hydrological, and geological settings, and potential energy supply via photovoltaic panels, windmills, or line current. As many SCUBA and snorkel dives were made as possible in the time available. Biological factors evaluated included the hard bottom cover occupied by live hard corals, soft corals and sponges, calcareous algae, fleshy algae, bare rock, dead coral, fish abundance and variety, and hard coral and algae species present. Sites which were examined included six dives on the edge reefs and walls of western Grand Turk including McDonald's, Amphitheatre, Finbar's, and the Anchor, the section of the Cockburn Town sea wall which is undergoing erosion, the northern point of the island, and the southern point of the island including nearby inshore reefs. Sites examined in Providenciales included three inshore sites along the North Coast, located in front of the Ramada Hotel, in front of Smokey's Beach Restaurant, and Smith Reef in front of a large new un-opened hotel (Holiday Inn?). Due to lack of time it was not possible to dive on the east coast of Grand Turk or on Providenciales. ← Bight Reef

2. SUITABILITY OF SITES FOR MINERAL ACCRETION

Site suitability depends on a) the nature of the bottom, b) wave energy, c) water quality, and d) energy supplies.

a) <u>Bottom type</u>.

Mineral accretion structures can be built on any type of bottom, but the best type is limestone rock because the structures will cement themselves solidly onto it, eventually becoming as massive and strong as a real reef. Unconsolidated limestone sand will also be cemented on to the base, but since structures on sand are not solidly attached to the bedrock they are prone to be toppled, rotatated, or moved by extremely large waves. Mineral accretion will continue on sporadically mobile structures as long as they receive current, but the structures are likely to be damaged when they move, and will absorb less wave energy in extreme events as some of the force is converted into motion of the structure instead of being absorbed. Unconsolidated non-limestone sediments will not harm the mineral accretion structure-forming process, but particles will be incorporated into the mineral accretion, giving it a "dirty" colour and possibly reducing its mechanical strength or inhibiting growth of reef organisms on it. Muddy waters can be used for mineral accretion breakwaters, but are unsuitable for living artificial reefs.

At most sites examined on western Grand Turk there was abundant hard limestone bottom in the form of several beach rock ridges parallel to the shore. Offshore parallel beach rock ridges provide ideal substrate for attaching artificial reefs, breakwaters, and wave baffles. Ridges along the shore were composed of virtually pure limestone-cemented sand, with conch shells. Ridges further offshore were increasingly colonized by corals and bored by clams and worms, indicating that their age increases with distance from the shore. This implies that these shorelines are retreating, as was confirmed by old residents and historical records. The rate of long-term shoreline retreat could be determined by Carbon-14 dating of beachrock cement crystals. The rarity of coral debris in the beach rock, compared to that found in beachrock in Jamaica and in South Pacific atolls, where it can predominate, suggests that hurricane events capable of creating coral rubble beaches have been much rarer in the Turks and Caicos in recent geological history. This is surprising given its proximity to the major hurricane alley across Hispaniola, Cuba, and the southern Bahamas.

Most sites in Providenciales also had large areas of hard limestone surface, but this was largely flat, and appeared to be composed of an older exposed rock surface rather than beach rock. The only exception was the site in front of the Ramada Inn, where the bottom near shore appeared to consist of unconsolidated limestone sand. The predominance of clean white sand and seagrass appears to be due to the calm and protected waters behind the barrier reef, which allows reef sand to accumulate near the shore. The beach profile on northern Providenciales was wide and gently sloping, indicative of a growing beach. No sites were found to have non-limestone sediments, and therefore all sites were suitable for living artificial reefs, although any structures made at the Ramada Inn site would have to be held down on top of the sand by their own weight and that of rocks packed inside.

b) Wave energy.

Wave forces are a critical parameter since mineral accretion structures are capable of absorbing wave energy up to a point at which forces become strong enough to break or topple the structure. As the structure ages, it becomes thicker, heavier, stronger, and more solidly attached to the bottom, so that the maximum energy it can absorb increases with time. Since hurricanes and northers are unpredicable events, there is always an unavoidable chance that a severe storm takes place which can damage the structure before it is sufficiently strong. However any damage can easily be repaired since mineral accretion will resume once current supply is restored, and damaged sections can be readily patched with steel wire mesh and filled in with new mineral accretion. Structures must be designed to stand up to the maximum wave energy which occurs in extreme events. For this reason it is best to mimic the structure of real coral reefs in many very high energy environments: low, flat, and solidly attached to the bottom.

Of the sites examined the highest wave energies appeared to be found in front of the eroding sea wall at Cockburn Town and the lowest at sites along the north coast of Providenciales, with intermediate values at other sites. This was indicated by the abundance of boulders and rocks at the first site as the result of sand being scoured away by storms, whereas other sites had abundant sand accumulating between beach rock ridges and on the beach. These differences in wave exposure appear to result from differing degrees of protection by offshore barrier reefs, which reach the surface along northern Providenciales, but which are absent off western Grand Turk, providing no protection from waves from the west. There appears to be an additional wave focusing effect at Cockburn Town due to the orientation of the bottom topography with regard to waves from the west or northwest. The predominant directions of long shore currents and sand transport appeared to be from north to south on western Grand Turk, and from east to west along northern Providenciales.

While all sites appeared to be suitable for mineral accretion, it was clear that the greatest technical problems would exist at the Cockburn Town seawall. Structures there would have to be lower and more strongly attached to the bottom to be effective and survive high energy events.

c) Water quality.

Several water quality parameters affect the success of mineral accretion structures and artificial reefs, including i) salinity, ii) temperature, iii) nutrients, iv) turbidity, and v) pollution. All parameters appear to be at least as good or better in the Turks and Caicos than they are in existing artificial reefs in Jamaica.

i) Salinity. The rate of growth of mineral accretion crystals increases as higher salinity increases the concentration of dissolved calcium and carbonate ions. Growth of mineral aggregate is very slow in fresh water, moderate in brackish water, high in normal salinity sea water, and highest in hyper-saline water because it is most super-saturated with limestone. Fresh water flow to the sea is very small because most of the groundwater is brackish. Low rainfall results in no rivers, a low groundwater table elevation, and minimal flows through the rock and sand into the sea. Coastal zone waters should have normal open ocean salinity, except under rare conditions of very heavy rainfall, or under extended calm, hot, and clear conditions when the salinity may be considerably elevated in shallow coastal waters and offshore banks due to evaporation. If it gets high enough, limestone may spontaneously crystallize and precipitate out of seawater, resulting in the formation of fine limestone crystals which turn the water milky. These sea water "whitings" were observed from the air over the Caicos Banks and in the shallow nearshore zone along the beach in Providenciales. Under these conditions sea water is highly super-saturated with dissolved limestone, and growth of mineral accretion will be exceptionally rapid. These conditions make the Turks and Caicos Islands better suited for rapid mineral accretion growth per unit energy input than Jamaica, where the coastal zone is frequently brackish in the rainy season due to the large number of rivers and extensive groundwater flow into the sea through caves and springs on that high, wet island.

ii) Temperature. The rate of mineral accretion growth increases at higher temperatures, which increase the degree of limestone supersaturation in sea water. Mineral accretion should grow more rapidly in summer than winter, and be maximal under hot, calm, clear, and salty conditions. Offshore ocean waters in the Turks and Caicos are somewhat cooler than in Jamaica, but shallow inshore waters could get warmer, especially under calm conditions, because shallow banks with restricted circulation are more common in the Turks and Caicos, and because inputs of cooler fresh water are not present as they are in Jamaica. Temperature conditions are therefore likely to be about as suitable as in Jamaica.

ii) Nutrients. High dissolved nutrients, especially phosphorus and nitrogen, stimulate the growth of fouling algae, which can block flow of sea water to the crystal surfaces, inhibiting mineral growth. Very high levels of nutrients cause excessive growth of weedy fleshy algae, which are capable of overgrowing corals on artificial reef structures. The mineral accretion process provides a strong competetive edge for organisms with limestone skeletons. Corals and sand-producing algae on artificial reefs in sewage-polluted coastal waters in Jamaica with grossly excessive nutrient levels were able to hold their own and grow very rapidly even though almost all corals and sand-producing algae on surrounding reefs were killed by weedy algae overgrowth. Because nutrient levels and algae abundance are much lower in nearshore waters in the Turks and Caicos than they are in Jamaica (see sections below) due to much lower population density and lack of sewage flow into the coastal zone, conditions will be more favourable for healthy growth of a coral reef community on mineral accretion structures.

iv) Turbidity. High turbidity inhibits the growth of organisms on the artificial reef by reducing light levels needed for photosynthesis of corals and algae, and by causing them to expend much of their energy in cleaning their surfaces of sediment, increasing respiration and decreasing growth rates. Due to the complete lack terrigenous sediments and coastal runoff, the only sources of turbidity are wave-suspended reef sand and whitings. These sedimentary materials are identical in compostion to mineral accretion, and will be readily incorporated into it without discolouring or weakening it. Due to lack of land based sources of sediments or of nutrients which can cause phytoplankton blooms to turn coastal waters dark and green, as in Jamaica, the waters around the Turks and Caicos are generally clear and blue, with much higher underwater visibility, so mineral accretion growth should be less inhibited by poor water clarity.

v) Pollution. Pollutants such as heavy metals and hydrocarbons may be capable of inhibiting mineral accretion growth or poisoning organisms growing on it. Waters around the Turks and Caicos Islands have very little pollution because they are exposed to clean open Western Atlantic waters, and because there is little or no heavy industry. The major potential sources of pollution are not land-based but ship-based, from heavy freight and oil tanker traffic through the Turks Passage to the Windward Passage. Many ships going to and from the Panama Canal and Venezuelan and Mexican oil fields pass through the passage, so there is a risk of leaks, accidents, or groundings, especially in bad weather. This risk is greatest off Western Grand Turk, and greatly reduced in Providenciales as it is remote from major shipping lanes.

d) <u>Energy supply</u>.

Mineral accretion structures require a source of direct current, which can be supplied from alternating current using rectifiers or battery chargers, from batteries, from photovoltaic panels, or from windmills. All systems require an above water power source, connected to the structure via cables. The power sources are generally on land, but can be housed in above water structures mounted on poles in shallow water, if these are strong enough to weather storm waves. To date the only offshore power source artificial reef is one in Jamaica which is powered by 12 photovoltaic panels mounted on a 20 foot high pyramid constructed of bolted steel pipes in four feet of water. Such structures are hard to build and likely to be destroyed by hurricanes. Power losses in the cables generally limit the structures to within about 100 feet of the power source.

Experiments show that about one kilogram of mineral accretion is produced per kilowatt hour. This energy costs about US$0.10 in Jamaica, and around 2 to 3 times as much in Turks and Caicos when supplied from conventional power plants using imported oil or coal. Unit costs of photovoltaic and wind power are thought to be less than US$0.10 per kilowatt hour. These unit costs for producing the material are much less than seawalls constructed using conventional reinforced concrete, blocks, or precast tetrahedron construction techniques, which generally cost in the range of around $8,000 to $10,000 per linear metre of shoreline.

Most sites examined were relatively near sources of alternating current feeding buildings along the coast. If these are used, all that would be needed would be a small structure to house the rectifiers or chargers, and arrangements would have to be made to pay the electricity bills. It is anticipated that this could be assimilated by the Government of the Turks and Caicos Islands as an in-kind contribution to the project.

Use of renewable energy sources like photovoltaic cells and windmills is highly desirable because the sun provides free pollution-free energy and there is no need for foreign exchange to import expensive fossil fuels which generate carbon dioxide and other atmospheric pollutants. However initial capital equipment costs are higher, and suitable space is needed for solar cells and windmills. Both renewable energy sources appear to be highly favourable in the Turks and Caicos. The lower rainfall and clearer skies would result in higher solar energy fluxes than in Jamaica, and the low and flat topography does not block the trade winds, as in Jamaica. Higher rain, higher land elevation, and more vegetation are likely to make the availability of both wind and solar energy somewhat lower in Providenciales than Grand Turk.

For renewable energy sources to be used it would be desirable to have a fenced in enclosure on land just above the vegetation line, that is on private or crown land rather than on the public beach area. There is little vertical space available for windmills or horizontal space for solar panels at several of the sites. The area along the sea wall would not be suitable for either unless sufficiently raised above the sun and wind shadow of adjacent buildings, away from waves breaking over the wall. This would provide aesthetic problems, and possibly could interfere with Cable and Wireless tower operations. The sites in front of hotels are unsuitable for renewable energy supplies because the area is fully occupied with recreational uses, and line current is already available at shore buildings and piers.

Windmills come in a variety of sizes, with the axis mounted on a tower or pole as much as 10 metres high to get above the low wind surface boundary layer. Photovoltaic panels require about one fourth as much surface area as that of the mineral accretion structures they power. These can be mounted flat, or for maximum efficiency, framed in with two by fours to tilt at an angle of about 21 degrees to the south. Such an installation would not be as visually intrusive as a windmill, but would require a greater area of land. A site where such land might be available is crown land adjacent to Smokey's Beach Restaurant.

In general suitable energy sources are available at all sites, with the choice constrained by aesthetics, area, cost, and in-kind contributions of electricity or land.

3. PROPOSED PILOT ARTIFICIAL REEF PROJECT

The best sites for a pilot artificial reef would be along the north coast of Providenciales because these sites are the most protected, and because there is relatively little hard bottom to allow coral growth because of the large amount of sand. As a result there are relatively few reefs for snorkelling near the shore east of Smith Reef, and little coral, sea fans, or fish to be seen by visitors. An artificial reef in this area would therefore contribute to habitat improvement, to locally increasing fish stocks, and for snorkelling eco-tourism.

Of the three sites examined, artificial reefs are not needed off the Holiday Inn site because the hard ground offshore supports a patch reef suitable for snorkelling. The Ramada Inn site would have power available from the diving boat pier, but the offshore area within suitable distance is entirely sand or seagrass without hard ground. An artificial reef at this site would therefore have to sit on sand, held down by its own weight, and could move in a hurricane. Resuspended sand from the bottom will reduce coral growth rates. The large amount of recreational activity in the water could pose the risk of damage to the reef from tourists touching or standing on it or from boat traffic, so it should be surrounded by floats and a floating line with signs saying "Please look only, don't touch, take nothing but photographs, and leave nothing but bubbles".

The site examined in between, in front of Smokey's Beach Restaurant, is the most suitable, because there is low hard ground offshore to which a structure could be attached, there are few corals and fish, and there is less potentially disruptive activity on shore and in the water. One advantage of this site is that corals could be transplanted onto the structure only a relatively short distance from Smith Reef, and their growth rates on the structure compared with corals on the natural reef from which they were derived. The relative proximity to the patch reef will allow greater recruitment of reef fish, which would be much reduced in front of Ramada due to the long distance of sand and seagrass between it and the nearest reefs, which many reef fish are unlikely to cross. In addition crown land lies adjacent to the Restaurant on both sides, which could be used to house power sources from line current, windmill, or solar panels.

A pilot artificial reef could be constructed around 50 to 100 feet from shore, beyond turbidity caused by waves breaking on the shore, in around 5 to 10 feet depth. The size would depend on the amount of funding available for materials, and a suitable design and budget prepared. The final selection of location should be subject to a more detailed assessment of the entire shore, which was not possible given time limitations. The structure would be designed to allow corals to grow on the structure at a range of heights up to 3 to 4 feet above the bottom, and have a number of openings of various sizes to allow fish, lobster, and other marine animals to shelter within it. Typical designs for such a structures are shown in the accompanying diagrams by Wolf Hilbertz. Depending on the size of the artificial reef, and whether it is neccesary to construct a windmill or photovoltaic array, it should be possible to construct the artificial reef in several weeks to a month, once all equipment and materials are assembled. In addition a welder would need to be hired for a few weeks.

The artificial reef should be periodically monitored to ensure that it is working properly (this is easily seen from the bubbles rising from the structure), to monitor coral growth rate and fish populations through photographs or video recordings, transplant corals if needed, check on wires and power sources, and make repairs to cables and structure if needed after storms. Additional monitoring which would be useful if possible would include periodic measurement of water temperature, salinity, and turbidity. Such measurements could be done using portable instruments or underwater data loggers. Monitoring of the structure and biological community on it could initially be done by the construction team, and then become part of the responsibilities of the Fisheries Department. The pilot project should last at least three years, and become permanent if suitably successful. If the results indicate that it is worthwile, other artificial reefs could then be built along the shore to the east at distances suitable to provide "stepping stones" for reef fish recruitment.

4. PROPOSED PILOT SHORE PROTECTION PROJECT

Mineral accretion technology is the only artificial alternative to coral reefs capable of building a growing and self-repairing wave-breaking structure, and is ideally suited for breakwaters, wave baffles, and for sealing cracks and holes in sea walls. All other construction materials are quickly applied, rapidly reach maximum strength and then corrode and deteriorate continuously, while mineral accretion grows slowly but gets stronger all the time, and there is no corrosion of the underlying steel substrate as long as small electrical currents flow through it. A small pilot project to develop and test these applications is proposed for the area in front of the eroding sea wall in front of Government offices, legal and real estate offices, and the Cable and Wireless facility.

Several small scale pilot applications of mineral accretion could easily be tested at the site using line power and battery chargers. If these prove effective from both engineering and economic standpoints compared to conventional restoration and protection methods currently used by the Ministry of Public Works, they could then be applied on a larger scale.

In the first application, mineral accretion could be used to plug the cracks and openings which extend under the sea wall, allowing water to be forced into it and eroding the roadbed on the other side. There are two major sections which have been undermined. One of these could be protected using conventional methods such as poured concrete or gabion wire baskets. The other could be filled using the boulders which are lying around the area in abundance. These could be wrapped or sandwiched between layers of chicken wire or steel mesh, which would be charged so that mineral accretion cements the boulders to each other within a limestone matrix. The process would begin from the back to allow seawater to provide a source of dissolved minerals to crystallize on the mesh from the inside out. As mineral accretion fills the space additional mesh layers would be placed in front to seal it in. Channels can be included to allow seawater to provide dissolved ions to strengthen the interior. These could be spaces betweeen mesh layers, or provided by inserting PVC sewer pipe sections into the mesh and stone matrix. Once the infilling is sufficiently dense, these channels could also be filled in with mineral accretion.

If this method is successful, it can be used to repair and strengthen submerged portions of seawalls and breakwaters on a large scale. Such an approach will take longer than conventional methods because the aggregate will continue to grow for several years, but it is likely to be highly cost effective. Previous experience suggests that mineral accretion materials, if produced slowly, have the strength of reinforced concrete. If mineral accretion is produced very rapidly by using higher currents, the material is much softer. However it will eventually convert spontaneously to hard limestone with time. Therefore it is proposed to compare the efficacy of slow hard accretion growth versus very rapid growth and infilling with softer material which will subsequently harden in place. The latter would be faster, but there is more of a risk that the softer material could be washed out by storms before it hardens. This comparison can be done using two battery chargers in order to charge different parts of the same crack repair at different electrical current flow rates.

The second application of mineral accretion could be to strengthen and build up the submerged beach rock ridges which protect the shore. It is proposed to do so on a small pilot scale by using expanded steel mesh sheets (4 feet by 8), attaching them solidly to the beach rock surface by steel bolts embedded in concrete in holes drilled into the beach rock. Mineral accretion will then fill in the space between the the sheet and the beach rock, and will grow upwards. In effect artificial beach rock will be generated, and the submerged beach rock ridges changed from eroding structures into growing ones increasingly capable of absorbing more wave energy. Once again there is a trade off between the time it takes to become sufficiently strong and the possible interval before a major norther or hurricane, and it may be neccesary to repair damage and continue the process to achieve the full benefits. Areas of beach rock protected by mineral accretion and adjacent unprotected sections should be periodically photographed to record changes.

The third potential application is to build wave baffles in those sections which are inadequately protected because the beach rock ridges are absent in front of them, leaving them open to waves. Such structures would have to stand up into the waves, and would be subjected to enormous forces, causing severe engineering constraints. Wave baffles could be in the form of pyramids about 3 feet high, and would be equivalent to wire baskets which are able to cement themselves and their rocks to the substrate. They could be located in waters around 5 to 10 feet deep beyond the ends of the groins. A few could be constructed in various shapes and followed with time to see if they are effective in absorbing wave energy and trapping sediment, and to gain additional insight into the engineering and physical constraints on wave absorbers. This application could be the most technically difficult, but a pilot project is of great importance to determine if it is a practical approach to shore protection. A maritime civil engineer should assess the results. A first rate specialist in this area from Jamaica, David Harris (Construction, Management, and Engineering Services Ltd., 43 Lisa Avenue, Hillsboro, Maraval, Trinidad, tel: 809-622-3687, fax: 809-624-4388) is interested being involved in such projects.

All three applications could be tested on a fairly small scale, so that the cost of equipment and materials would be much less than for the artificial reef project. Perhaps a small fraction of the total project costs, say one fifth, could be used for pilot seawall projects, with the rest going to the artificial reef project.

It is useful to compare the relative costs of mineral accretion versus coral reefs and concrete breakwaters for shore protection. There is no doubt that a healthy natural reef is the best shore protection of all because it provides its environmental services at either no cost or at the cost of maintaining clean coastal zone water quality through sewage treatment and other conservation measures. Where a healthy natural reef exists, there is no need for an artificial reef, and building one would result in significant costs for relatively minor environmental benefit. However we propose to use mineral accretion where shorelines are inadequately protected because reefs are absent, or have been damaged by hurricanes or other factors and have not recovered.

In these cases the correct cost-benefit comparison is between building an artificial reef and the cost of either building a sea wall to protect the shore, or taking no action and paying the cost of destruction of physical infrastructure such as roads, buildings, etc. Building a sea wall provides a cost-benefit advantage over no action because the cost is less than the value of property wherever the shoreline is "developed". Regardless of construction materials or methods of construction, sea walls made of poured reinforced concrete, fitted stone blocks, loose stone blocks, or precast concrete tetrahedra cost in the range of around US$8,000 to 10,000 per metre of shoreline protected.

If we assume a standard seawall is 5 metres high and 1 metre thick, the amount of construction material required is 5 cubic metres per metre of shoreline. Using a density suitable for limestone or concrete of around 2.5 grams per cubic centimetre, this would weigh around 12.5 Tonnes per metre. If the same amount of material were produced using mineral accretion, the cost of the electricity needed to precipitate it would come to US$2,500 per metre, based on experimental data showing that one kilogram of mineral accretion is produced per kilowatt-hour of electricity, and using the Grand Turk residential electricity cost of around US$0.20 per kilowatt hour. If the cost of the steel mesh and the anode costs as much as the electricity (which is an overly generous estimate) the total energy and materials costs would be around one half the cost of conventional construction materials. If cheaper sources of electricity are available from solar panels or windmills, the cost of the mineral accretion structure would be correspondingly lower.

This analysis actually underestimates the total benefits of mineral accretion over conventional shore protection because:

1) conventional construction materials become constantly weaker with time as concrete and steel corrodes and rusts, while mineral accretion structures do not rust, become constantly stronger and heavier with time, and cement themselves to the seafloor,

2) mineral accretion structures are self repairing as long as the current is maintained and can be repaired in small sections using locally applied currents if needed, so repair costs are much less than conventional materials,

3) mineral accretion is the only artificial reef and shore protection method that attracts natural reef organisms and enhances their growth, providing additional benefits in terms of habitat restoration, fisheries, biodiversity protection, sand production for beach renourishment, and ecotourism.

We therefore conclude that use of mineral accretion structures for shore protection is highly favourable from a cost/benefit standpoint.

5. REEF ENVIRONMENTAL ASSESSMENT: GRAND TURK

During the one week available it was possible to dive only at a limited number of sites. Overall reef conditions were excellent, and probably are among the best in the Caribbean. Fish populations appeared to be pristine, with much greater species diversity, biomass, and fish size than seen in Jamaican reefs for over 35 years. This was especially noticeable in terms of the abundance of adult groupers, triggerfish, hogfish, snappers, jack, and barracuda, which have virtually vanished from Jamaican waters shortly after spearguns and diving became prevalent in the late 1950s. Abundance of other reef animals which have become rare where they are subject to harvesting in other parts of the Caribbean, such as turtles, lobsters, conch, and black coral, were also exceptionally high. Algae abundance was exceptionally low in the shelf edge reefs, with no sign of the weedy algae species that proliferate when nutrient levels are excessive and which are causing corals to be overgrown in most Caribbean reefs. There is therefore little doubt that diving here is among the best to be seen in the entire region.

Live coral cover on hardground was high, around 70% in most places. Almost all Caribbean coral species were seen. Corals largely showed healthy colouration, and appeared to be growing well. Unusual red coloured varieties of *Monastrea cavernosa*, *Montastrea annularis*, and *Mycetophyllia* species were common, perhaps reflecting a common local symbiotic algae variety. Partial bleaching was seen in *Montastrea cavernosa* and other species, but was rare. Only one case of black band coral disease was seen. Small patches of gelatinous reddish or greyish coloured blue-greeen algae (possibly *Lyngbya* and *Schizothrix* sp.) were seen, but were far less common and damaging to corals than in Jamaica. There was an abundance of clean white limestone bedrock suitable for coral larval settlement, nevertheless rates of juvenile coral recruitment appeared fairly low in comparison with equivalent sites in Jamaica. Perhaps this is because few coral larvae are supplied by Western Atlantic waters since few healthy coral reefs lie up-current of Grand Turk.

Surprisingly, there was clear evidence of recovery from significant coral mortality events in the past. First there was a surprising amount of dead coral surfaces (about 20% of live coral) which had not been overgrown with fleshy algae (except coatings of encrusting red limestone algae). Based on the amount of bioerosion taking place on them by sponges, worms, and clams that have colonized them and the sizes of young corals of different species which had settled and grown upon dead corals, this could have happened around 5 or 10 years previously. This mortality could have been due to damage from the 1985 hurricane. We were not able to find divers who were familiar with the area before the hurricane who could confirm whether an important mortality event had taken place. The exact date of the event could be determined by studying the annual banding patterns in surviving corals.

A second line of evidence comes from the abundance of large round head corals (*Montastrea annularis*, *Montastrea cavernosa*, *Siderastrea siderea*, *Colpophyllia natans*, *Meandrina meandrites*, *Diploria strigosa*, and *Diploria* *labyrinthiformis*) which had clearly died over much of their surfaces, but which had proceeded to recolonize the dead skeleton from surviving sections. The thickness of new growth of coral overgrowing the dead portions of the same colonies implied once again that high mortality had occurred in the past decade. It appeared that significant fractions of coral tissue had died at that time, perhaps due to hurricane damage. The dead coral heads, and the underlying portions of those which had recovered, appeared to be highly rounded and symetrical, implying that such partial mortality events, which would have resulted in corals with more irregular shapes, had been rare in the past. A further interesting feature was the absence of elkhorn coral, and the extreme scarcity of staghorn corals, which might have been expected to be abundant in this habitat.

Low algae abundance could be due to several factors: low nutrient levels, high sea urchin grazing, or high fish grazing. Abundances of the black grazing sea urchin, *Diadema antillarum*, whose death has been blamed for algae overgrowth in other Caribbean reefs, was extremely scarce or completely absent at all sites. Since it's population in Grand Turk has not recovered from the 1983 epidemic die off, sea urchin grazing cannot be a factor in the low algae abundances. In Jamaica, where sea urchins have fully recovered in many places, they are now unable to control fleshy algae except directly in their nesting burrows, suggesting that their algae grazing effects have been overestimated or confused with eutrophication. Fish grazing is certainly a factor. The major source of reef limestone sand is usually the calcareous green *Halimeda* algae, a favourite food of parrotfish. Virtually all *Halimeda* seen were cryptic, hidden in cracks or nested between the branches of fine branching corals, with all protruding growth bitten off flat. It is therefore likely that the green and red branching calcareous algae are controlled by parrotfish grazing. The lack of sufficient calcareous algae causes parrotfish to switch to a less favoured food, corals. Parrotfish were observed to graze on certain coral heads marked by many bite marks, which now almost never happens in Jamaica, where suitable algae are abundant, growing much faster than they can be grazed, and where large parrotfish are now rare.

Fringing reefs at the southwest corner of the island also showed clear signs of past physical destruction in the form of large piles of broken staghorn and elkhorn coral debris, cemented together by encrusting calcareous red algae. Here there was clear evidence of extensive recruitment of young corals on clean dead coral surfaces, especially staghorn (*Acropora cervicornis*), elkhorn (*Acropora palmata*), finger corals (*Porites porites*, *Porites furcata*, and *Madracis mirabilis*), head corals (esp. *Diploria strigosa* and *Diploria labyrinthiformis*), encrusting corals (especially *Porites astreoides*, *Porites branneri*, and *Diploria clivosa*), and platy corals (*Agaricia agaricites* and *Agaricia tenuifolia*). Reef fish were abundant, and all *Halimeda* were chewed down as far as possible between coral branches and rock crevices. Weedy algae species were rare or absent. Non-weedy fleshy algae species such as *Dictyota* and *Laurencia* species were found on top of the reef platform where waves prevent fish from grazing. These reefs show excellent recovery and provide good snorkelling close to shore.

The virtual absence of the weedy high nutrient indicating algae species and the scarcity of algae turf could be due to either high fish grazing or low nutrients. Various lines of evidence suggest that the latter may be the most critical factor. Nutrients are very low in tropical open ocean waters. Few measurements have been made in the area, but nitrate concentrations in Grand Turk of around 0.1 micromole per litre of nitrate in surface water have been reported, one of the lowest values measured in coastal coral reef habitat (p. 215 in W. Adey & K. Loveland, 1991, Dynamic Aquaria, Academic Press). On Grand Turk there is no surface or groundwater drainage of nutrients into the sea. Weedy inshore algae species indicative of excessive nutrients were absent in this zone. most nearshore rock surfaces were clean and white, but small dense clumps of non-nuisance algae species like *Cymoplia barbata, Padina sanctae-crucis, Cystoseira myrica, Chnoospora minima*, and *Dasya harveyi* are found on shallow beach rock in the surf zone where fish grazing is minimal.

In contrast to Western Atlantic surface waters, those below the thermocline have nitrate concentrations around 20 micromoles per litre, or 200 times higher. Recent work by Brian Lapointe and Peter Bell have shown that the critical concentrations of nitrate above which weedy algae overgrow reef corals is around 1.0 micromoles per litre. If surface ocean water had no nitrate at all, a mixture of only one part in 20 of deep water would put the nitrate levels above the critical value, so deep water upwelling could provide the major natural source of external nutrients to the reef. In the central Caribbean there is an extremely thick layer of warm surface water, seasonally varying from 400 to 600 feet deep, which prevents colder water and nutrients from rising. Deep Caribbean waters have much lower nutrient levels than the Atlantic Ocean because deep Atlantic waters are unable to penetrate into the Caribbean past the shallow sills. In contrast the warm surface layer near the Turks and Caicos is much thinner than the Caribbean, and so the contribution of deep mixing, upwelling, and internal wave breaking is likely to result in much larger nutrient flows into surface water than in the Caribbean Basin. Periodic upwelling is reported along the Western Wall of Grand Turk, and during the period of observation an upwelling event caused a phytoplankton bloom to generate distinctly green water over the shelves for a few days, followed by huge numbers of thimble jellyfish washed in from offshore. Upwelling takes place on this shore because the trade winds push surface water offshore, causing deep water to rise to replace it.

Evidence for deep nutrients upwelling was visible from ecological observation on the upper part of the vertical wall. The vertical wall, despite the abundance of gorgonians, antipatharians, black coral, sponges, and fish, had the appearance of a reef subject to moderate eutrophication, in sharp contrast to the shallower reefs. The weedy algae *Lobophora variegata* was absent or very rare on the shelf and shelf edge reefs, but began to appear at about 30 to 40 feet depth on the uppermost section of the vertical wall. It increased in abundance with depth down to 100 feet and as far as could be seen below, covering about half of the wall surface and overgrowing the bases of platy corals (*Montastrea annularis* and *Agaricia lamarckii*) on it. This was seen at every site dived on. This algae, formerly rare in Jamaica, became a major cause of coral death in many Caribbean reefs exposed to moderately high nutrients after the 1983 die-off of *Diadema antillarum*. However lack of *Diadema* grazing is not the cause of its abundance here, because they are shallow back reef dwellers which were certainly never abundant on the vertical deep fore reef wall. If they were the cause one would expect to see even larger amounts of *Lobophora* in the shallow well-lit reefs where *Diadema* formerly lived, yet this area is free of it. The increase of *Lobophora* with depth, despite declining light levels, suggests that its growth is being driven by nutrients being upwelled from below along the wall.

Although there was no opportunity to dive on the northern and eastern side of the island due to lack of time, boat, and suitable weather, local dive operators (Dave and Mitch) reported that algae abundances are higher on the shallow barrier reef and wall on that side of the island. As that area is up-current of all human inputs, the source of nutrients for these algae is likely to be the entrainment of deep water in the flow of water over the shelf, upwelling, and internal wave breaking. These ecological observations suggest that many of the deeper and more remote reefs around Grand Turk are undergoing some degree of eutrophication, in sharp contrast to the shallow shelf reefs, and therefore that the whole area may be close to the eutrophication limits of coral reefs due to natural nutrient inputs.

6. REEF ENVIRONMENTAL ASSESSMENT: PROVIDENCIALES

Due to very limited time, it was only possible to examine three nearshore sand, seagrass, and patch reef areas between Grace Bay and The Bight, and there was no chance to examine the barrier reef, fore reef buttress zone, or the wall. However Renata Wallner, who dived in Providenciales and who accompanied me on all dives in Grand Turk, indicated that the Providenciales sites appeared to have larger reefs and bigger corals than seen at any of the dive sites in Grand Turk.

In sharp contrast with Grand Turk, clear evidence of eutrophication was seen in the nearshore reefs of Providenciales. At Smith Reef every coral head and gorgonian was being overgrown from the base up by thick masses of the algae *Lobophora variegata* and *Microdictyon marinum*. These had overgrown the bases of the coral tissue up to 5 or 10 centimetres. The underlying coral tissue was still alive when these were pulled off, indicating that the overgrowth by algae was a recent phenomenon which had not yet had a chance to kill the coral tissue. Fish populations were normal as all fishing is banned on the north coast since it is a national park, but *Diadema* was rare. In front of Smokey's there was little coral, but dead conch shells and *Halimeda* in the sea grass beds were overgrown with weedy turf algae. This was not seen in Grand Turk, and indicates that these sea grass beds are subjected to higher nutrient levels and are undergoing early stages of eutrophication.

Smith Reef lies immediately in front of a very large (200-300 room?) hotel which is under construction and is unoccupied. Therefore the source of nutrients must be coming from up-current sources to the east. All sewage on the island is discharged into the groundwater, and as Providenciales has a fresh groundwater aquifer, and is higher and rainier than Grand Turk, it is likely that sewage nutrients are flowing through the beach into the nearshore zone. Large hotels use so much water that they are likely to actually raise the groundwater table beneath them, increasing nutrient flows into the sea. It is therefore possible that the source of nutrients are land-based, derived from development along the beach. If this is the source of nutrients, then the entire nearshore area may be above or near the eutrophication threshold, and will deteriorate significantly, like other Caribbean islands, once the hotel is occupied and other hotels and villas are developed. Nutrient levels in the coastal zone of Providenciales may therefore already lie near or just above the tolerance limit of its inshore reefs, whose continued survival may require reduction of nutrient inputs through density limits or through use of improved sewage treatment to intercept and remove the nutrients. The low current development densities in Providenciales indicate just how sensitive reefs are to nutrient additions, and the need for prompt further steps to ensure that the Turks and Caicos do not suffer the same reef deterioration as virtually all over-developed and over-populated Caribbean islands.

7. PROPOSED ALGAE AND NUTRIENT SURVEY

Ecological observations of algae and corals suggest strongly that while many Turks and Caicos reefs are in prime condition, there are several sites where algae overgrowth appears to be due to either natural or human-caused nutrient inputs, and is unlikely to be caused by inadequate grazing due to overfishing or sea urchin die off, as has been proposed by some researchers in other parts of the Caribbean. These circumstances make the Turks and Caicos an ideal natural laboratory to determine the nutrient limits for healthy coral reefs, and the role of nutrients versus grazing in controlling algae abundance, factors which are seriously confused in many other locations.

It is proposed that a detailed survey of dissolved nutrient levels and of algae species and abundance should be done in the Turks and Caicos. Such a survey would serve critical coastal zone management needs as well as being of fundamental scientific importance. By making transects from the shore out to deep water, and along the shore, the sources of nutrients can be identified, and policy options to control them can then be rationally devised. The survey should identify all species of algae, and measure dissolved nitrate, ammonium, orthophosphate, organic phosphorus, chlorophyll, temperature, and salinity. It should also include measurements on groundwaters, and offshore open ocean surface waters, while using sampling bottles on lines to analyze the temperature and nutrients in deep water.

It is recommended that funding be sought for the Fisheries Division to conduct a baseline survey throughout the Turks and Caicos Islands, followed by periodic monitoring at selected sites. The proposed work would be done by fisheries officers trained in sampling, sample preservation, and analysis by scientific advisors knowledgable in nutrient chemistry, nutrient dynamics, and algae taxonomy and physiology. The recommended scientific advisors for such a proposal are Dr. T. Goreau and Dr. Brian Lapointe, who have worked for a decade on the relationship of nutrients to algae species abundance and growth rates in Jamaica. Dr. Lapointe has done similar work in Florida, the Bahamas, Bermuda, Belize, and the eastern Caribbean. Dr. Lapointe, who is based in the Florida Keys, has all needed sampling and analytical equipment available in his laboratory, including groundwater sampling devices. If a boat is available for the project, the survey field work could probably be carried out in a month.

Such a survey should be regarded a very critical priority for efforts to understand and preserve the coral reefs, by identifying and forestalling potential problems before they can build up to the disastrous levels they have now reached in so many other places. Marine National Park and Fisheries management in the Turks and Caicos provide remarkable models for the rest of the Caribbean, but preserving coastal zone water quality is critical to their long term success. By identifying the water quality standards needed to protect the reefs, Turks and Caicos can also take the lead in keeping its waters the cleanest and most beautiful in the Caribbean region.

8. SEWAGE, GROUNDWATER, NUTRIENT REMOVAL, AND BIOLOGICAL TERTIARY TREATMENT

If the nutrient survey work identifies significant sewage-derived nutrient inputs to the coastal zone in Providenciales, it will be neccessary to intercept and remove these nutrients before they can enter the coastal zone. The current practice of allowing raw sewage to contaminate groundwater will no longer be feasible if the island is to have both tourism and healthy reefs in the future. The conventional options, a sewage collection system feeding a sewage treatment plant, deep injection well, or deep ocean outfall, may be impractical because of the great cost. Another expensive option would be construction of sealed sewage storage tanks which are pumped out, but this would require transport for treatment by a sewage plant which would need to be constructed. Two far cheaper options should be explored to prevent nutrient contamination.

The first involves use of dry sealed toilets to replace soak away flush toilets and pit latrines. These systems cost no more to make than ordinary toilet systems, but are designed so that no water at all is used. This alone could cause tremendous economic savings since rainwater is so scarce and since desalinazation water is so expensive. The toilets are vented and screened so they are odourless and free of insects. Since the holding tank is completely sealed, the human wastes cannot contaminate groundwater and coastal water by leaching nutrients. Dry toilets are often built with two chambers. After about a year or two of normal operation the first chamber is filled, sealed, and the toilet moved over the second chamber. After a suitable interval, the first chamber is shoveled out. The material is a disease-free compost, smelling like earth rather than sewage, which makes an excellent fertilizer and soil additive. Given the extremely poor organic content of the local soils, use of this material would serve to increase soil productivity by recycling the nutrients into growth of plants on land, rather than merely fouling the waters. There is an active program of constructing such toilets underway in Jamaica by several of the organizations with which I work, and plans and technical advice are readily available. Such non-polluting toilets could be required in all new construction, and loan programs or grants of materials to those willing to do their own construction according to specified plans could be pursued to allow gradual replacement of existing residential soak away toilets and pit latrines with dry toilets.

Retrofitting existing large hotels or villas to dry toilets may not be feasible except at considerable cost, so other approaches may be needed to reduce nutrient contamination from existing systems which use water flush toilets. Given the dispersed nature of these structures, small scale solutions will be most cost effective. These could take the form of standard settling tanks and sand filters, but instead of letting the nutrient rich waste water effluents soak down into the beach they could be used for irrigation of inland vegetation. The dwarf forests of the island are clearly severly limited by lack of water, organic matter, and nutrients, and should grow prolifically on clarified secondary sewage effluent if this is supplied via pumps for spray irrigation or drip irrigation inland. The nutrients would then be trapped in the land vegetation, which would become more lush as they perform biological tertiary sewage treatment and prevent reef eutrophication. It is recommended that a pilot project be initiated to determine if this is a cost effective coastal zone protection and land restoration measure which should be required of all multi-unit water flush systems.

A somewhat different situation exists in Grand Turk because the groundwater is brackish and very close to the surface over most of the island. There is likely to be little or no groundwater flow to sea except through tidal exchange with the salinas, and as a result virtually all sewage nutrients must be accumulating in the groundwater. This represents a considerable potential resource for those trees with roots capable of reaching them and tolerant of salt levels. The fastest growing tree on the island appears to be *Casuarina equisetifolia*, locally known as cedar. This tree is salt tolerant, fixes nitrogen from the atmosphere and adds it to the soil in organic form. Its wood grain is not straight enough for lumber, but the wood is so dense and dry that it can be burned green, and it is regarded as the world's best charcoal wood (Casuarinas: Nitrogen-fixing trees for adverse sites, 1984, National Academy of Sciences, Washington DC). The only caution is that care must be taken not to import another species, *Casuarina cunninghami*, which has been introduced into Florida where it is generally thought to be *C. equisetifolia*, but which is a dangerous weed which can spread out of control. *Casuarina* could be planted as a source of fuelwood to replace the charcoal currently being imported on a large scale from Haiti. Given the deforestation situation in Haiti, it is shocking that they are exporting charcoal, and it would be wise for Turks and Caicos to end this unsustainable trade and replace it with locally generated energy, or better yet, with windmill or photovoltaic electricity, which should be cheaper than the current fossil fuel electricity generating plants.

In addition there are a large number of other economically valuable plants capable of growing in brackish and saline waters which could play an important role in purifying groundwater and increasing sustainable biological productivity. Many of these are listed in books such as Plants for Arid Lands, Dryland Management: Economic Case Studies, and books on new arid zone crops such as jojoba and guayule, which I will bring next time to the Turks and Caicos. A further possibility worth exploring is the use of the salinas to grow saltwater grains. Several recently "rediscovered" plants traditionally grown by Mexican desert Indians, including the grass *Distychlis*, are capable of producing high quality food grains and I have information on seed sources and contacts for research advice. It is recommended that the Agriculture Division explore the a pilot project to experimentally test the applicability of many of these potentially useful or valuable arid zone plants in the Turks and Caicos Islands.

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