

ISLAND RESOURCES FOUNDATION

CORAL HARVESTING AND SAND MINING MANAGEMENT PRACTICES

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SUMMARY

This study addresses the coastal resource management problems associated with sand mining and coral harvesting in tropical areas. Customary sand and coral extraction techniques, large and small scale use practices, impacts on local environments, and alternative harvesting approaches to various marine minerals are reviewed. Specific examples of adverse effects on the environment from excessive, badly sited, ill-planned or un-monitored coral harvesting and beach, dune, and marine sand mining activities are presented and analyzed. These examples are based on existing documentation and, in some instances, were corroborated by site visits to areas where large scale, hydraulic dredging strategies for marine sand had been employed or land-based beach or dune sand mining were common practice.

Study findings suggest the following.

(1) The mining of beach and dune sand should be discouraged except under special circumstances, with careful advance planning and monitoring.

(2) Coral reefs, marine sand deposits, sand beaches and dunes are each a part of dynamic natural coastal systems which provide barriers to potentially damaging storm-driven waves and swells. Modifications to them resulting from poorly planned or sited sand and coral mining activity can, over time, diminish their protective capacity causing loss or damage to shoreline areas and facilities.

(3) Marine sand mining (especially by hydraulic dredging) should be confined to coastal waters sufficiently deep, open and distant from adjacent coral reefs and beaches to minimize coastal impacts.

(4) Sand and coral mining projects require antecedent impact assessments, baseline site studies and monitoring. Ideally, they should be preceded by a comprehensive sand and coral resource assessment, as part of a sand and coral management planning strategy. Post-mining site re-surveys and impact assessments are recommended.

(5) The commercial harvesting of deep "precious coral" species requires specialized management strategies because of their exceptionally slow growth rates.

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1. INTRODUCTION

Coastal and nearshore marine minerals of most developing countries represent both a traditional and expandable resource of economic value and strategic significance. For centuries, coastal minerals of both geological and biological origin have served as sources of building materials (rock and coral), lime (derived from coral and calcareous sands) and currency (shells and corals). More recently, as the economies of many of these countries have grown and diversified, marine minerals are being heavily exploited for uses as fuel (oil and gas), rare metals extraction (placer deposits), jewelry and tourist curios (coral and shell), and, on a much larger scale using new technologies, for construction aggregate.

Coastal areas are not only a source of valuable and useful minerals; they also represent a zone where massive amounts of sedimentary materials are often dredged or dug from one location and moved to more preferred locations as fill or discarded spoil. Harbors are often built, improved, or expanded by deepening the seaward portion, approach channels and turning basins. Excavated material is sometimes discarded but more customarily is used as fill to expand landward portions of harbors for new docks, warehousing and cargo handling facilities or waterfront renewal areas. Sea sand is occasionally dredged from "offshore" and transplanted "onshore" to restore, improve or even create a beach in a process called beach nourishment. Sometimes sand is extracted from offshore deposits and used solely as fill to create new "flat land" by covering over coastal swamplands, mangrove areas, or shallow lagoons. In these instances where "sand" is used for fill, the value of the dredged or mined material is derived largely from its mass and accessibility rather than its compositional quality.

As the uses for coastal minerals have expanded and demand continues to grow, their often unquantified, unmanaged, and unmonitored extraction has resulted in significant modifications to coastal regimes--often with considerable environmental damage and occasional economic loss. Examples of these impacts include coastal erosion, loss of habitat, declining water quality and reduced biological productivity. Due to the biological and physical processes characteristic of tropical coastal areas, these

natural systems are slow in returning to pre-existing conditions or sustain irreversible impacts (see Section 4).

The principal causes of adverse environmental impacts associated with coastal mineral resource extraction include: 1) the failure to account for the relevant biological, geological and physical parameters which characterize the mining and emplacement or disposal sites; 2) failure to discern the pathways and linkages between the biotic (living) and abiotic (non-living) components associated with the activity; 3) failure to employ proper technologies; and 4) failure to develop and adopt sand and coral resource management strategies which allow for environmentally sustainable mining activities.

Though coastal and marine mining as an extractive or harvesting process implicitly involves environmental disturbance, many of its associated impacts can be reduced if not eliminated. It is the purpose of this case study to demonstrate the consequences of poorly planned or executed marine mining activities and to identify possible alternative extractive or harvesting strategies which minimize some of the negative environmental effects and which also minimize costly ex-post-facto remedial engineering interventions.

Sources of information for the case study were derived from a systematic review of the literature, reports from expert consultants, and visits to various sand mining and dredging sites in St. Lucia, the Virgin Islands, and Puerto Rico in the Caribbean and Fiji in the South Pacific. The discussion on coral harvesting per se is based on selected examples described in the literature, due to the absence of extensive hard coral block extraction activity at the beach and nearshore sand mining sites visited.

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2. STATEMENT OF THE PROBLEM

Substantial portions of the nearshore marine areas and coastal zones of most developing countries are simultaneously 1) a target of expanding development initiatives and 2) a source of large volumes of mineral materials required for development activity or generated by that very development as a secondary product requiring "disposal". Unfortunately, the development process is rarely planned or scheduled to permit the "materials" needs of one scheme to be filled in a timely fashion by the mineral materials excavated in another. Locational separation of the source (or borrow site) and the emplacement (or spoil site) often exacerbates the problem. High transport costs complicate moving low unit value, high volume materials (like sand) even moderate distances.

Marine mineral material serves many different purposes and may be harvested:

- as aggregate for concrete by small and large scale users;
- for the sole purpose of later extracting small quantities of some valuable trace mineral, leaving vast amounts of waste materials called "tailings";
- because it is simply in the way and needs to be moved (e.g., harbor, canal, marina, and ship channel sediments);
- for its bulk and cheapness as "fill" (in coastal storm defense systems, causeways, roads, airports);
- for beach enhancement and storm damage repair to shorelines;
- because, in tropical areas, it is needed for its chemical and physical properties, e.g., as coral construction block, for lime production, cement manufacture, or to sell as an export (precious coral, shells, aggregate).

The most commonly harvested marine mineral is sand. In non-tropical countries, sand is an erosion product of the land areas. Rivers and streams transport sand and other sediments to the sea where they are subsequently distributed somewhat unevenly by waves and currents along the shorelines as beaches, dunes, sand spits, barrier islands, and submerged layers of sediments on coastal shelves and platforms and in estuaries and harbors. By way of contrast, in tropical countries with

sea coasts and coral reefs, sand is formed in the sea biogenically. Like its terrestrially derived temperate counterpart, this carbonate sand often ends up distributed unevenly on adjacent coastal areas. Sometimes both types are intermixed in varying proportions.

Regardless of the origin of the sand or its composition, all nations have it and mine it by various methods as a mineral. It is a basic material, and developing and developed countries alike confront coastal sand supply, distribution and resource management problems for a variety of reasons:

- Sand is a vital component of various coastal processes and habitats, and is difficult to "harvest" without disrupting one or the other or both.
- Sand, although a renewable resource, is replaced only on a long-term basis or cycle due to low natural production rates.
- Sand deposits are usually in the "wrong" place when needed (i.e., often "underwater" or distant from intended use sites).
- Marine sand can be expensive to harvest or "mine"--and if large volumes are involved, the process requires specialized, elaborate and costly hydraulic dredging or excavating equipment (which is always at risk and subject to damage or loss on open coastlines under even moderate storm conditions).
- Demand cycles for marine sand and aggregate mining activity vary widely which makes advance planning difficult.
- The scale and method of extraction and the mode of transport and emplacement also vary widely, and each step poses the risk of inadvertent, undesirable environmental effects.

Unfortunately, the development planning and resource management approaches used in many developing countries are not sufficiently responsive to the complexity of local demand factors, site selection and harvesting practices. There is a need for antecedent and post-audit environmental impact assessments. The least damaging extraction and emplacement strategies need to be selected when addressing coral and sand mining requirements.

3. THE RESOURCE

3.1 Coastal Minerals

The coastal plain and adjacent nearshore submerged continental shelf constitute a zone abundant in useful mineral resources. The area serves as a sink for terrestrial alluvium and marine minerals transported onshore to beaches by wind-driven waves and tidal currents. Typical nearshore marine minerals include bauxite, phosphates, placer deposits, and aggregate (sand, gravel, shell). Beneath the sea bed of submerged coastal shelf areas may be found such economically valuable and extractable resources as petroleum and natural gas, as well as surface minerals which have been reworked downward. Dissolved minerals are present in the waters overlying the marine portion of the coastal area, of which salt (sodium chloride), the most prevalent, is commonly harvested by solar evaporation of sea water in low lying coastal areas around the world.

3.1.1 Placers

The two categories of hard minerals of greatest economic importance which occur in the coastal area are placers and aggregates. Placers are deposits of minerals and heavy-metal ores such as gold, magnetite and chromite concentrated by the mechanical sorting action of currents (Press and Siever, 1972). Due to their high specific gravity, these minerals settle rapidly near the mouths of rivers whenever stream flow energy levels fall below critical points determined by the minerals' respective specific gravity. Subsequent sorting by local waves and currents removes the lighter elements leaving behind the heavier minerals. Cronan (1980) suggested that mid-latitude and high energy tropical beaches are the most favorable environments for these deposits.

The existence of offshore or nearshore placer deposits is highly correlated with drowned river valleys and submarine terraces formed by global changes in sea level (eustatic), the submarine erosion of mineralized outcrops and occasionally nearby terrigenous sources.

3.1.2 Aggregate

Aggregate is a technical term for deposits of sand, gravel or occasionally shell. When harvested, sorted by size and washed free of clay and organic material, these materials are capable of being bound together by cementing agents for use in the construction industry. Coastal aggregate deposits, especially those of temperate zone continents and even some larger islands, are essentially the products of terrestrial erosion. They are most often associated with river beds and mouths, sand beaches and shallow offshore platforms and shelf areas.

A second major source of aggregate characteristic of many tropical coastal areas is carbonate sand derived from nearshore coral and algal communities (Figure 1).

Corals are living systems of invertebrate coelenterates which live as colonies within a self-made external supportive structure composed of calcium carbonate. A characteristic feature of one group of corals, the hermatypic corals, is the presence of symbiotic algae (zooxanthellae) which appear to serve the corals in respiration and skeletal growth (Stoddart, 1969). Many species of hermatypic or stony corals are noteworthy in that they are the principal species in forming a large and diverse but interrelated community termed a coral reef. These communities, composed of a complex assemblage of marine life, represent a reservoir of calcium carbonate, stored in the form of shells and skeletons of organisms that inhabit the reef. Due to physical and biological forces that erode and transform these organisms' skeletal remains, calcareous sand is continually being generated, and some is subsequently transported to shore by the prevailing wind-driven waves and currents.

Marine calcareous algae, often occurring both inshore of and associated with the adjacent reef, are a second significant source of carbonate sands in tropical waters. Decay of carbonate plates and nodules connected with these algae also contributes to the sand budget of tropical coastal areas. Hubbard, *et.al.* (1981a) estimates that the calcareous algae and other associated members of the coral reef community (molluscs, sea urchins, etc.) may even surpass corals in production of calcareous material that becomes carbonate sea sand.

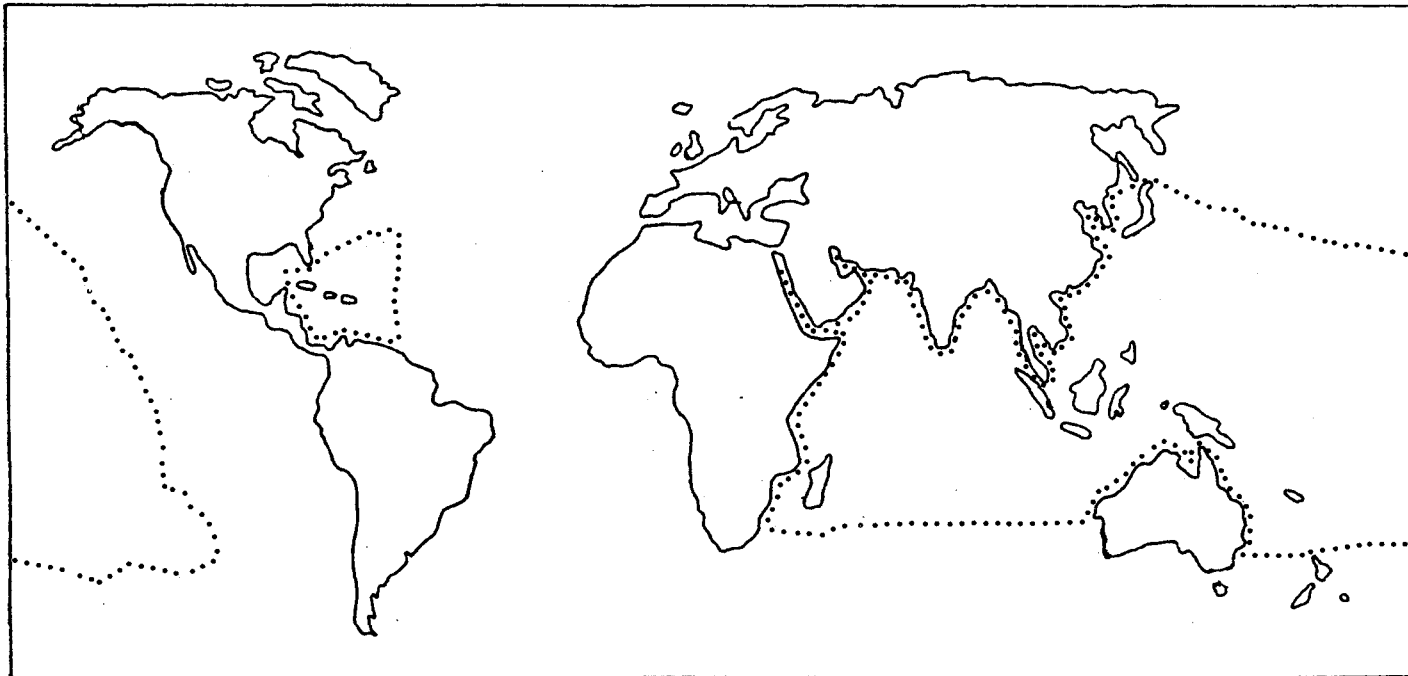


Figure 1. Geographical distribution of hermatypic corals where ten or more genera have been recorded (Source: Stoddart, 1969).

3.2 Uses

3.2.1 Placer Deposits

Industrial scale exploitation of marine placer deposits is rare among less developed countries (LDC's), due in part to limited financial and technical resources for geological surveys. Placer mining is usually of small scale and conducted through a joint venture with a second country or firm willing to invest resources in exchange for a percentage of the profits. However, increased awareness of the importance of strategic metals by the developed world, together with a desire by LDC's to diversify their economies, could result in an expansion of current activities. The ongoing United Nations program strategy to support regional Coordinating Committees for Offshore Prospecting (CCOP) is currently assisting a number of Asian and Pacific coastal and insular developing countries in the achievement of this objective.

3.2.2 Aggregate Materials

In contrast to the limited distribution of placer deposits, sand and gravel are generally plentiful and widespread. Despite this abundance, however, local scarcities do occur. Due to the low unit value and the high unit transport cost of aggregate, economics dictate that mining should occur in close proximity to the site of intended use. This is especially true when extremely large volumes of sand and gravel are extracted for fill, beach nourishment or remedial shoreline stabilization. In coastal areas, this constraint is complicated by the recent rapid growth of urban centers which has exhausted traditional nearby mining sites.

One response to this scarcity has been to exploit adjacent sandy beaches and dune systems. However, despite the short term advantages in convenience and reduced costs associated with this alternative, there are hidden long term consequences (habitat destruction, coastal erosion, and reduced natural hazard protection against storm waves).

Customary extraction patterns reflect two distinct use categories with very different scales of operation. In one category, a few--even a few hundred--persons remove sand and aggregate from a beach, dune,

reef flat or lagoon system on a modest scale over a long span of time. This first approach requires one kind of resource management strategy. The second category involves massive, capital intensive, mining or dredging operations removing millions of cubic yards of material over a period of a few months from a single location on a one-time development project basis. Such a scale and intensity present a very different kind of resource management problem.

As awareness of the problems associated with beach sand extraction has grown, increasing interest has been diverted to offshore mining as a viable alternative. This technique has proven to be economically feasible in many coastal sites. Today the most active aggregate mining countries are Japan, the United States, the United Kingdom, Australia, and the Netherlands (Cruickshank and Hess, 1975). Established marine sand mining enterprises from these countries often are intermittently involved as contractors in developing country projects, using massive, sea-going dredging vessels and equipment. Such marine dredging endeavors, often harvesting large volumes of material, require different kinds of equipment, involve different kinds of impacts, and necessitate very different resource management strategies from terrestrial sand mining activities.

3.2.3 Coral Harvesting

In many developing countries coral chunks or "heads" are mined from the living reef or from the landward rubble zone behind the reef to provide a source for building "blocks" and the production of lime (Mahadevan and Nayar, 1972). Typically, coral is cut or sawn into blocks before being allowed to dry and harden by exposure to sun and air. Once blocks are set they are often covered with some form of waterproofing which also serves as decoration (Phelan, 1952).

Coral-based lime production is a centuries old traditional industry in many parts of the coastal tropics. The process only requires the application of heat (900°C.) to coral or algal limestone traditionally worked in an easily constructed basalt kiln. The calcined (burnt) limestone is then removed, slaked, graded, sacked and stored until needed.

Typical industrial and domestic uses of the lime include application in mortar and cement and as a clarifying agent, neutralizer and soil conditioner.

The use of both coral sands and coral blocks for building and construction purposes became quite common in the Caribbean and South Pacific theatres of World War II where construction of airbases and defensive fortifications required the use of locally available building materials on many of the resource-poor islands. Their use is still common today throughout most smaller offshore tropical island areas when populations are clustered along shorelines.

3.3 Methods of Extraction

Onshore sand harvesting from beaches and associated beach berms and dunes is convenient and inexpensive. As a result, it has been a traditional practice for centuries and is still common in some countries, especially in more remote coastal areas. Methods of extraction range from a hand shovel and wheel barrow or truck to various types of mechanical front-end loaders, back hoes, draglines, power shovels and bulldozers. For many people and rural villages, beaches are the only source of affordable and accessible sand (Figure 2).

Coral harvesting of dead coral blocks, taken from back-reef areas, is normally done by hand from the shallow rubble zone, "lagoon" or reef flat. Where coral heads deposited by storm waves have become "cemented" to the substrate or in cases of living corals mined directly from the reef, long handled tongs, steel pry bars, dynamite, wire rope, and power winches are the principal means of harvest. Small scale entrepreneurs use boats to transport the coral blocks ashore for processing, direct use or sale. The cumulative environmental impact of these practices, however, can be costly (see Section 5) and, in combination with a rising demand for aggregate and building material, has forced most countries to look to offshore sand resources and a dredging strategy.

In contrast to beach sand and coral mining, marine dredging represents a more technically-demanding extractive process; the required equipment is cumbersome, costly and complex where large quantities of



Figure 2. Illegal beach sand mining, St. Maarten, Netherlands Antilles.

sand are involved; the process is often at risk due to adverse weather conditions; and the impact to coastal ecosystems can be severe. Despite these constraints, dredging is a proven strategy for harvesting marine aggregate and sedimentary material for fill and construction use. Dredging is also used to create canals, harbors, ship channels, turning basins, marinas and underwater trenches for pipelines, tunnels and power cables, where the dredged material is only a by-product.

The prevailing methodology for the extraction of nearshore or off-shore non-fuel minerals (especially aggregate) involves two types of dredge systems, mechanical and hydraulic. The most common mechanical types are the dipper dredge and various bucket dredges.

The dipper dredge is basically a barge-mounted power shovel (Figure 3a). It is equipped with a power-driven ladder structure and operated from a barge-type hull. A scoop-like bucket is firmly attached to the ladder and is forcibly thrust into the bottom material to be removed. Dipper dredges normally have a bucket capacity of 8 to 12 cubic yards and a working depth of up to 50 feet. There is a great variability in production rates, but 30 to 60 cycles per hour are common.

Customary use of the dipper dredge is for excavation of hard, compacted materials, rock or other solid materials after blasting. Although it can be used to remove most bottom sediments, the violent scooping action of this type of equipment may cause considerable bottom sediment disturbance and resuspension during any digging of fine-grained material. In addition, a significant loss of the finer material will occur from the open bucket during the hoisting process. Scow-type barges are required to move the dredged material to a disposal area, and production is relatively low when compared to cutterhead dredges. The dipper dredge is not recommended for use in dredging fine grain or contaminated sediments.

Bucket dredges involve a crane which may be permanently or temporarily barge mounted. If a wheeled or crawler type crane is employed, it can work from shore or from a self-built temporary causeway. A drop-able bucket on the end of a wire is used to excavate bottom material. Different types of buckets can fulfill various types of dredging re-

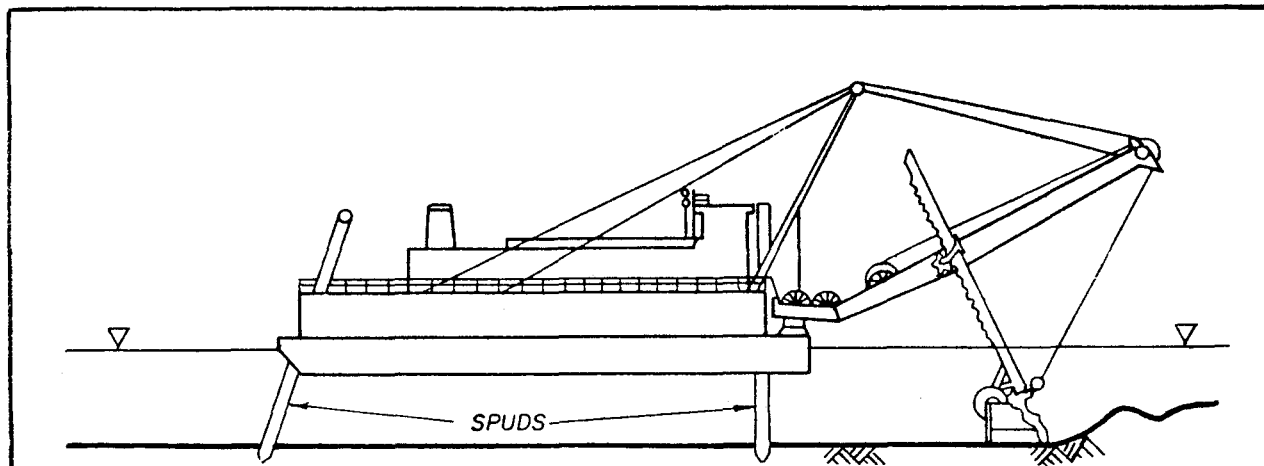


Figure 3a. Dipper dredge.

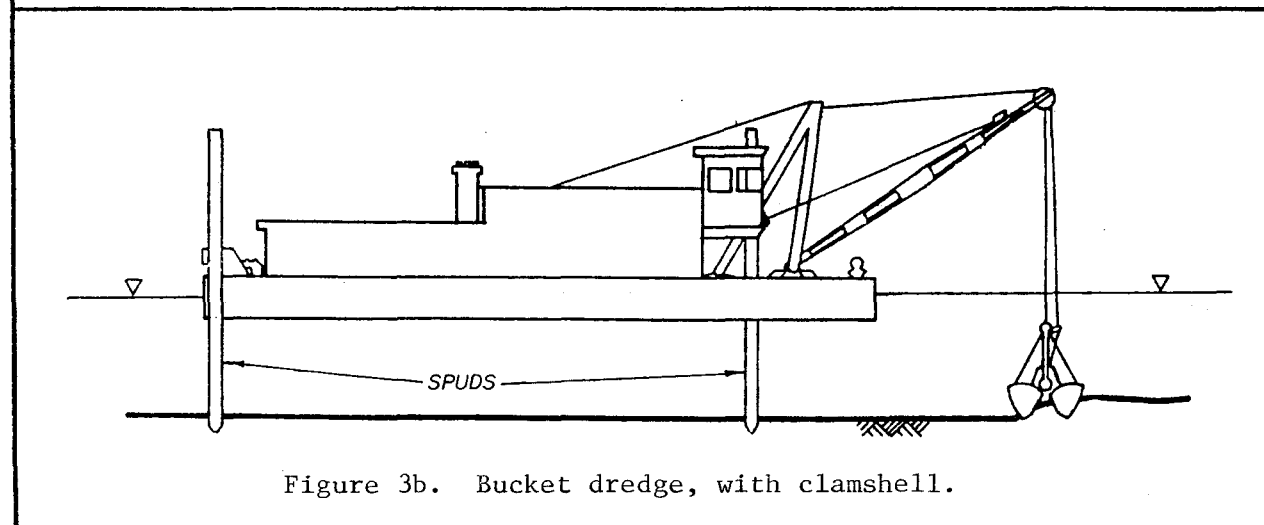


Figure 3b. Bucket dredge, with clamshell.

(Source: U.S. Army Corps of Engineers, 1983.)

quirements. The most common buckets used are the clamshell and dragline types and can be quickly changed to suit operational requirements. The clamshell is worked vertically and "grabs" the sediment, while the dragline is worked horizontally and scoops up sediment (Figure 3b).

The material excavated is placed in scows or hopper barges that are towed to the disposal areas. Bucket dredges range in capacity from 1 to 12 cubic yards. Twenty to thirty cycles per hour are typical, but large variations exist in production rates because of the variability in depths and materials being excavated. The effective working depth for a bucket clamshell dredge is limited to about 100 feet and somewhat less for a dragline.

Bucket dredges may be used to excavate most types of sea bed materials except for the most cohesive, consolidated sediments and solid coral and rock. Bucket dredges usually excavate a heaped bucket of material from off the bottom, but during hoisting turbulence washes away part of the load. Once the bucket clears the water surface, additional losses may occur through rapid drainage of entrapped water and slumping of the material heaped above the rim. Even under ideal conditions, substantial losses of loose and fine sediments will usually occur. To minimize the turbidity generated by a clamshell operation, watertight buckets have been developed.

In contrast to the mechanical dredges, hydraulic sand and gravel harvesting systems are a relatively recent innovation which first became operational on a large scale in the early 1960's. The two most prominent types used in coastal waters are the cutterhead-suction and trailing suction hopper dredges. Both are capable of moving large volumes of aggregate at a rapid extraction rate.

The cutterhead-suction dredge uses a spiral shaped cutter to force its way through hard consolidated material including some coral but excluding rock (Figure 3c). Once material is broken up by the hardened teeth of the rotating cutterhead, it is sucked as a slurry (approximately 80 percent water) into the open mouth of the dredge by a suction pump. Then, it is pumped to the shore emplacement or spoil area using a semi-flexible floating pipeline or, less commonly, to an adjacent barge.

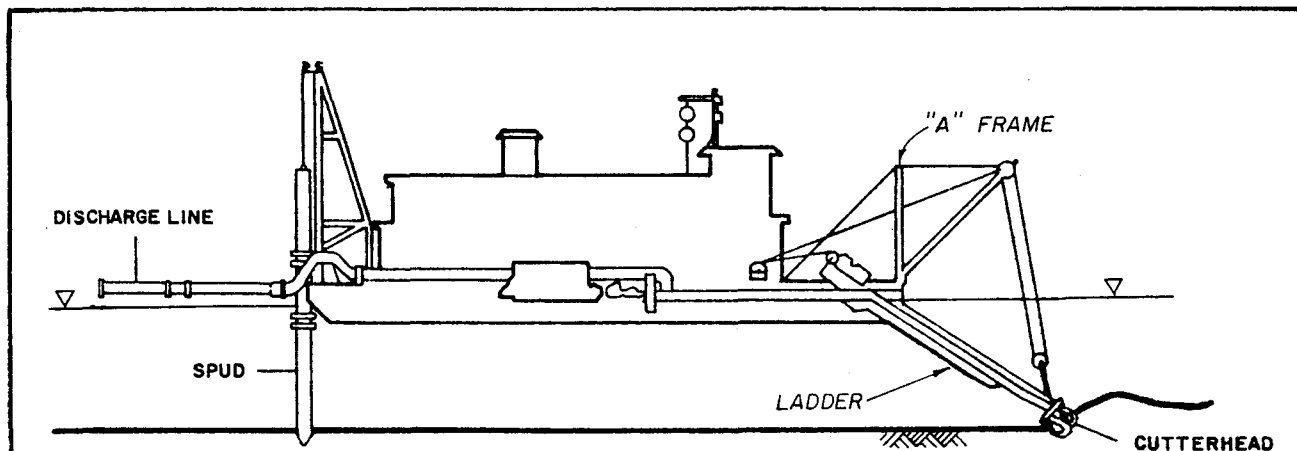


Figure 3c. Hydraulic pipeline cutterhead dredge.

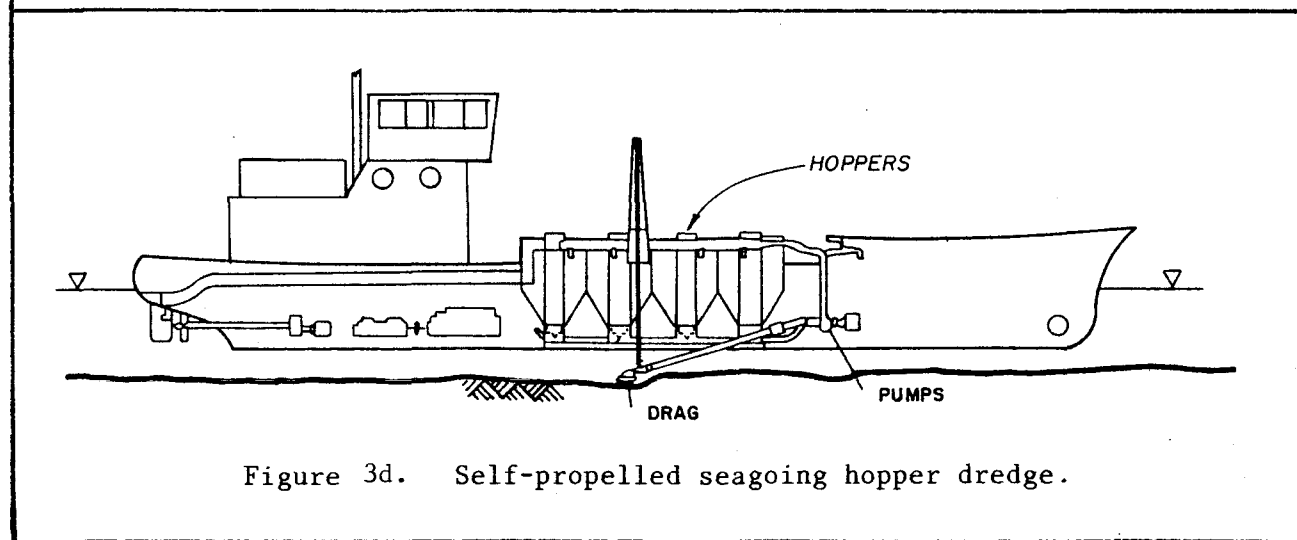


Figure 3d. Self-propelled seagoing hopper dredge.

(Source: U.S. Army Corps of Engineers, 1983.)

Operations of the cutterhead dredge are restricted to moderate sea conditions, especially if a floating pipeline to a shoreline dredge spoil discharge area is deployed. Such discharge pipes often range from 8" to 36" in diameter. A 24" dredge can discharge approximately 1,500 cubic yards per hour, depending on the material, pump size, pipe line distance, pipe-joint leakage factors, and elevation of the spoil area above sea level.

The trailing-suction hopper dredge is unique among the various dredge types in that it is a self-propelled, sea-going vessel, and it makes sequential shallow cuts over a large area (Figure 3d). It functions principally like a wet vacuum cleaner, by dragging a suction pipe or dragarm across the bottom which is "trailing" from the dredging vessel above. Material collected as a slurry is pumped into the ship's hoppers and periodically transported to shore. Hopper dredges are self-unloading. They can either dump the material in submarine storage pits located nearshore to be used at a later date or pump the material directly ashore. One significant advantage of the hopper dredge is that it allows operations in more exposed, heavier sea conditions due to the flexible linkage between the trailing suction pipe and the ship.

Hopper dredges are classified according to hopper capacity: large-class dredges have hopper capacities of 6,000 cubic yards or greater; medium-class hopper dredges have hopper capacities of 2,000 to 6,000 cubic yards; and small-class hopper dredges have hopper capacities of from less than 2,000 to 500 cubic yards. During dredging operations, hopper dredges travel at a ground speed of from two to three mph and can dredge in depths from about 10 to 80 feet. They are equipped with twin propellers and twin rudders to provide the required maneuverability.

The comparative advantages and disadvantages of dredge types are presented in Table 1.

Table 1. Comparison of dredge types commonly used for extraction of coastal area marine minerals.

DREDGES	WORKING DEPTH (in meters)	ADVANTAGES	CONSTRAINTS
Dipper- (single open scoop or bucket w/teeth on leading edge)	0-20	Can excavate bulky consolidated, hard materials (debris, rock, coral)	High sediment discharge Low productivity Requires calm sea conditions
Bucket (Dragline)- (single open flat scoop, not illus- trated)	0-20	Low mobilization costs Barge or shore develop- ment option	High sediment discharge Low productivity Limited range Softer materials only
Bucket (Clamshell)- (double-sided close- able "bucket")	0-40	High flexibility Handles variable conditions Low mobilization costs	High sediment discharge Low productivity Not suitable for hard surfaces
Hydraulic/Cutter Head Suction	0-30	High production capacity Can work semi-consolidated materials (coral, algae sand, hard pan, clay)	Requires calm sea conditions Relatively shallow depths High mobilization costs
Hydraulic/Trailing- Hopper Suction	6-30	High production capacity Handles exposed conditions Self-propelled with hopper dumping capacity	Requires softer uncon- solidated bottoms High mobilizations costs Deep draft vessel

Sources: Euroconsult, 1981; Bhatt, 1979; Clark, 1977; U.S. Corp. of Engineers, 1971, 1973, 1978, 1983.

4. ENVIRONMENTAL CONTEXT

4.1 Coastal Dynamics

In order to understand the potential impacts associated with marine mining it is helpful to summarize certain physical processes characteristic of coastal areas. A more detailed presentation can be found in the Coastal Erosion Case Study.

The coastal zone is a dynamic system where the land, air, sea and human activity meet at a common high-energy interface. The major physical forces which drive the system are wind, waves, tides and currents which in turn are generated by gravity, the rotational force of the earth and solar radiation. One element in this system, the sand and other sedimentary material, exists in a continuous state of flux between erosion, transport or deposition phases. To help understand sediment flux as it pertains to sand, the concept of a "sand budget" was devised. Bowen and Inman (1966) divided the budget into credits and debits, the net difference being evident on the shoreline as either deposition or erosion.

In temperate latitudes the primary sources of new beach sand supplies are terrestrial material requiring river or stream transport prior to coastal deposition. Supplies of beach sand attributable to terrestrial origins may be augmented from offshore sources as well. On tropical coastlines, carbonate sands derived biologically from reefs and algal flats in offshore and nearshore areas can equal or surpass terrestrial sources. Carbonate sand precipitation from salt water also represents an additional source of sand for tropical beaches (Komar, 1976). On the debit side, physical factors contributing to the erosion of a beach include abrasion, chemical breakdown, wind and wave transport (Figure 4).

In addition to these local inputs and outputs, the longshore transport of sand is significant in many cases. Herbich (1975) defined littoral (longshore) transport as the movement of sediment along the coastal area by currents created mainly by waves and tides. Such transport is primarily due to the presence of a longshore current formed by wave trains breaking at an angle to a beach. Water "piles up" on the side of the small angle formed between the wave and beach creating a current

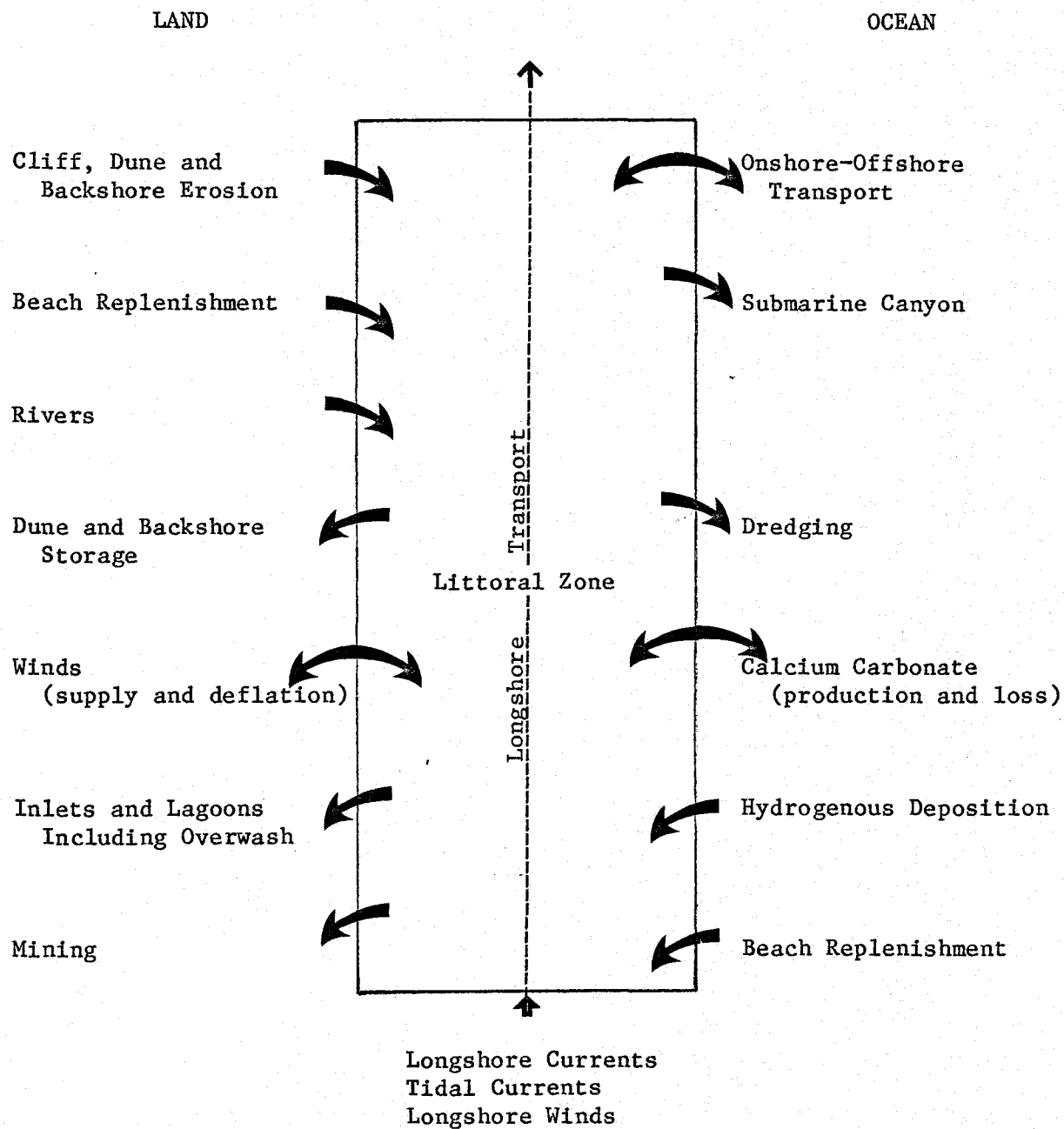


Figure 4. Sources of credits and debits to the littoral sand budget (Source: Modified after U.S. Army Corps of Engineers, 1974).

transporting water parallel to the coast in the same direction as the angle. Wind driven longshore currents when combined with wave action may have much the same effect (Komar, 1976).

The rate of sand transport is generally correlated with the angle and height of wave attack as measured from the beach. The greater the angle and height, the higher the rate. Conversely, littoral wave trains breaking more or less parallel to the beach result in little or no sediment transport and signify a relatively static situation. The volume of transported sediment depends on several factors including the velocity of flow, sediment characteristics and the slope of the bottom.

Given the importance of wind and wave forces in driving coastal processes, it is clear that seasonal variation will significantly affect beach dynamics. Whereas solitary storms passing near a coastline have been known to create or destroy entire beaches and sand cays (Stoddart, 1963), other seasonal changes are less drastic and more regimented. Beaches on northwestern United States coasts are typical of the latter, where summer shorelines characterized by sand beaches and wide back berm features contrast dramatically with the pebble and boulder beaches of the winter. This transformation is caused by the seasonal offshore transport of sand to submarine bars during the winter months due to high energy wave conditions. Under calmer conditions, sand is retransported onshore once again covering the rubble and boulder beach area before the cycle is repeated (Bascom, 1964).

While this seasonal sand transport pattern affects whole coastlines, there are localized sand transport patterns or "cells" which differ significantly in their characteristics. Inman and Chamberlain (1960) identified discrete sand transport cells along the southern California coast, each cell consisting of a beach situated between two rocky promontories. Beach sand, originating from upland areas near the first promontory, is transported "down current" where, upon reaching the second promontory, it leaves the cell as it is transported offshore.

A second type of littoral cell has been described (Inman, et.al., 1963) for a carbonate beach site on the eastern coast of Kauai, Hawaii. Offshore reefs and reef flats are periodically interrupted by shallow

depressions or channels running perpendicular to the shoreline. These channels (most in-flowing, a few out-flowing) serve as traps for calcareous sands originating from the reef. Incoming swell drives sand closer to shore, serving to replenish the beach. Sand reaching the shore is subsequently moved by longshore transport to eventually be lost to the beach/reef system upon reaching a deeper inlet with a seaward flowing bottom current. Storage sinks for sand involved in the process can either be temporary (like beaches, dunes, sand bars and cays), semi-permanent features like inshore lagoons, or permanent repositories like offshore canyons.

4.2 Biological Impacts

Coral and sand mining activity involves an adverse impact on coastal or marine habitats and biological communities either directly or indirectly. Operational design, scale and duration of the activity are very significant factors as each materials handling phase--extraction, transport, and emplacement--can generate undesirable effects. Biological communities on the sea bed or lagoon/bay floor, in the water column above, or on the beach at the site of the emplacement or effluent run-off (if "hydraulic" dredging is involved) are usually affected. Organisms occurring at some distance from the mining sites may also be threatened since water-borne fine sediments associated with one or more of the extractive phases can be transported considerable distances down-current before finally settling out.

Additionally, the indirect biological or environmental effects associated with marine mining activities are often more complex and of greater significance than the direct impact of removing relatively small areas or volumes of material from the sea bed or beach system. These include:

- reduction of feeding and respiratory efficiencies and induced mortalities in bottom-dwelling, non-mobile organisms, such as bivalve molluscs and corals, attributed to increased sedimentation;
- reduction of primary productivity (i.e., photosynthesis)

due to reduced light transmission caused by turbidity in the water columns;

- introduction of abnormal volumes of organic material and nutrients, increasing biological oxygen demand and, in turn, reducing oxygen levels and productivity;
- re-introduction of toxic substances uncovered by mining activities in the water column, posing the risk of incorporation into the food web;
- inadvertent destruction of adjacent habitat critical to life cycles of certain organisms;
- disruption of migratory routes of motile marine organisms.

With few exceptions, a concentration of re-suspended sediments and their later deposition are the primary agents causing the biological effects cited above. Point sources of sediment vary with the existing method of extraction. For all marine dredging strategies, concentrations of re-suspended material may occur at the bottom of the water column where the cutterhead or bucket stirs it up. Mechanical dredges such as the clamshell, bucket or dipper also create a "rain" of particulates in the water column as material is brought to the surface. Hydraulic dredges also lose some sediment in pumping the material ashore when floating discharge pipe joints flex and leak due to wave action or faulty design.

Fine sediments can be lost in any barge loading process, a problem common to all dredges discharging into self-contained or along-side barges. However, hydraulic cutterhead dredges which use suction to draw up a water-sand slurry to be pumped ashore are the worst contributors as finer silt and clay sized components are often discharged at three different locations--the excavation site, along the discharge pipe, and at the spoil area ashore. This problem can be mitigated if the spoil area is "diked" and settling ponds with weirs (small dams) are employed to reduce the "fines" carried back into coastal waters by the effluent.

Any dredging operation piping into a series of large settling ponds (low energy level, long residence or settling time) is going to have less suspended sediment in the final overflow to the sea than a dredge pumping

into a series of small hoppers or barges (high energy level, brief residence time). However, fine sediments discharging from a mobile hopper dredge or anchored cutterhead tend to be dispersed by current action over a large area, whereas shore based dredge spoil areas tend to concentrate discharges of fine sediments in one coastal location. For land fill purposes, the grain size of dredged material is not critical, but for construction sand or beach nourishment only a small amount of the very fine sediment can be accepted (see Section 7.1).

The degree of impact from sand mining-induced sedimentation is dependent on the sensitivity of the exposed community to stress as well as the quantity and size characteristics of sediment and rate of sedimentation. Non-motile benthic communities which filter their food are generally the most vulnerable to high rates of sedimentation. Coral reefs and marine grass beds are two tropical marine communities which are particularly sensitive to both high rates of sedimentation and abnormally high turbidity which reduces light penetration (Table 2).

In fact, sediments deposited on some coral species are likely to kill them within only a few days if the layer of material is thick enough and within weeks even if it is thin but continually replaced by recurring deposits (Johannes, 1975). Hubbard and Pocock (1972) demonstrated that coral species exhibited varying tolerances to sediment size and attributed this ability to the respective coral polyp's size and inherent filtering ability.

Other effects on corals attributed to sedimentation include reduced rates in growth (possibly due to declines in photosynthetic rates of the symbiotic zooxanthellae, Goreau and Goreau, 1959) and reduced species diversity (Brock, et.al., 1966). The quantity and size characteristics of sediment--and thus its biological impact--vary with distance from the point of suspension in the water column, which in turn is dependent on current velocity. The greater the current speed, the farther heavier sediments are carried from the source. Conversely, low velocities usually mean only finer sediments will be carried outside of the immediate area of the mining site. Particle shape can also affect distance traveled. For example, plate-like, flat or irregularly-shaped calcareous

Table 2 a, b. Documented stresses, effects and impacts from mining activities to marine grass and coral reef communities.

a. Marine Grass Communities.

STRESS	EFFECT	IMPACTS	REFERENCE
Sedimentation	Suffocation	Reduced distribution	vanEepoel (1971)
		Reduced productivity	Odum (1963)
	Reduced light transmission	Reduced density	Thayer (1975)
Resuspension of subsurface materials	Increased BOD*	Reduced density	Thayer (1975)
	Changes in Redox** potential	Reduced density	Thayer (1975)
	Reintroduction of toxics	Reduced density	Thayer (1975)

b. Coral Reef Communities.

STRESS	EFFECT	IMPACTS	REFERENCE
Sedimentation	Suffocation	Death	Brock (1966)
	Reduced light transmission	Reduced growth rate	Goreau and Goreau (1959)
		Reduced depth range	Goreau and Goreau (1959)
		Reduced species density	Brock (1966)
	Increased BOD*	Reduced species diversity	Brock (1966)
Modification of reef topography	Alter current regime	Reduced larval settling/survival rates	Hubbard (1972)
Weakening of substrate under-pinnings	Toppling of corals	Death	Maragos (1982)

* Biological oxygen demand

** Reduction - oxygen

fragments derived from Halimeda (a calcareous alga) travel farther at the same velocities than round sand particles of the same weight characteristics. This may seem like a trivial factor, but it can dimensionally affect the area of corals damaged or killed by nearby dredging activity.

Additional environmental effects commonly associated with the resuspension of sediments are increased biological oxygen demand (BOD) and the re-introduction of toxic contaminants and clays into the water column. When small organic particles in various stages of decomposition buried by overburden are again exposed to an oxygen-rich, sea water environment, the rate of decay is accelerated. The result of this decaying process is a local reduction of dissolved oxygen. When significant quantities of these organics are involved (especially in coastal embayments and lagoons with poor water circulation), oxygen levels can be reduced to a point detrimental to sessile and pelagic organisms. Similarly, when buried layers of clay are uncovered by dredging, there is a risk of continuing resuspension of very fine material from the newly exposed deposit. Continued resuspension of fine sediments in the vicinity of coral reefs may prevent substrate consolidation and subsequent recolonization by many benthic organisms (especially the planktonic larvae of corals, as well as other reef invertebrates) which require hard bottom to establish themselves.

These impacts are significant in evaluating differences between available dredging technologies. Most mechanical and hydraulic dredges working from anchored positions (Figure 5a) leave a borrow pit or dredge hole (actually a depression) as a result of the extraction activity. If the pits are deep enough and occur in waters characterized by reduced circulation, they act as sinks or traps for fine particulate matter both during and after dredging. When organics are involved, these pits often become severely oxygen depleted; further, due to the trapping of fines, their bottoms are characterized by a semi-fluid anoxic sediment, with perpetually turbid water, which inhibits colonization and leaves the pits as semi-permanent features of the local sea bed. Some marine sand dredge pits, as in the U.S. Virgin Islands and St. Lucia, have not recovered after forty years (vanEepoel, et.al., 1971 and

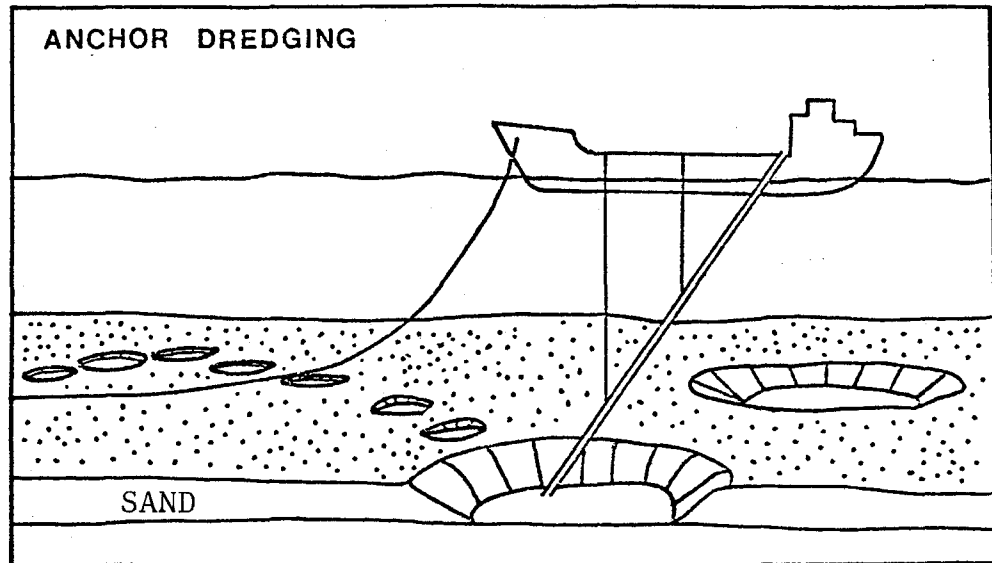


Figure 5a.

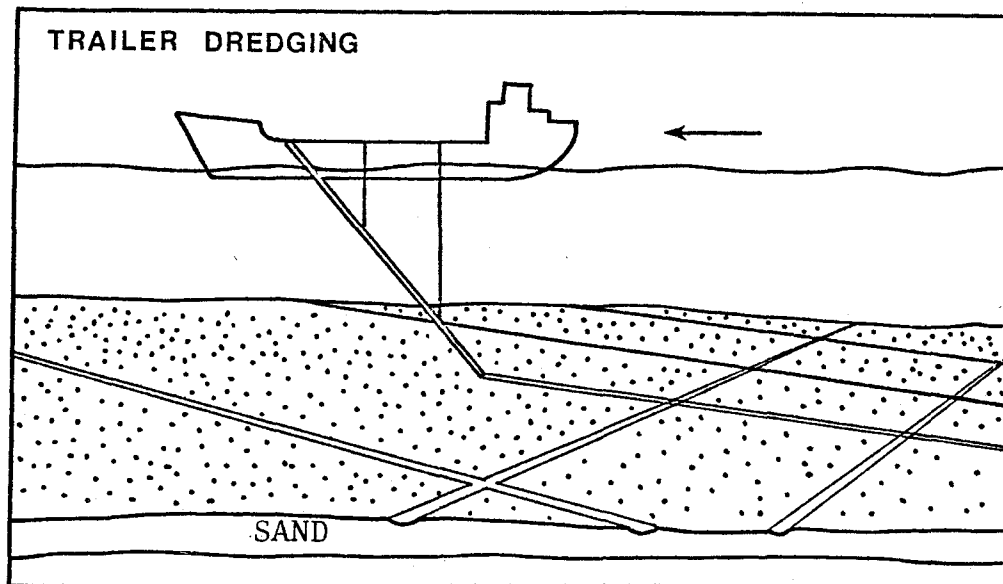


Figure 5b.

Figure 5. Two common approaches to hydraulic dredging, resulting in very different kinds of benthic impacts (Source: ICES, 1975).

Deane, et.al., 1973).

Turbidity and oxygen depletion can be ameliorated by dredging in deeper water with better circulation where currents and waves can more readily transport coarser sand, by dredging shallower borrow pits, by filling deep borrow pits with solid nontoxic waste materials to provide a hard substrate for re-colonization, or using a hopper trailer dredge which leaves long but shallow channels during the sand extraction or harvesting process (Figure 5b).

4.3 Physical Impacts

Marine mining activity, whether on the shoreline or on the adjacent submerged shelf, incurs a risk of altering physical processes (especially beach dynamics and coastal current and wind driven wave and swell patterns) which may adversely affect coastal systems. Even slight modifications in nearshore bottom contours by small scale long term or large scale short term dredging activity may induce slight changes in wave height. These changes result in significant changes in delivered energy impinging upon adjacent beaches, reefs, sea grass beds, and other shoreline areas. What often follows next is a slow erosion, slumpage or continuing "draw down" of existing beach sand, to refill the adjacent dredge hole or borrow pit that was too close to shore. Shore based sand mining that reduces beach berm and dune mass and height also poses risks of increased storm wave damage to inland areas and reduces the supply of naturally stored sand available for equilibration of the system.

4.4 Toxic Sediments

Another consideration in assessing alternative approaches, optimum mining site and mining technologies is the possibility of re-introducing previously buried toxic substances into the environment. This is especially true where mining occurs in areas adjacent to large urban centers, industrial sea ports or dump sites. Many toxic materials are non-biodegradable and as such continue to persist in the sedimentary environment. Nearshore bottom areas act as more or less benign sinks for these and other pollutants where they become smothered by subsequent sediment

deposition. When these polluted bottom sediments are disturbed by mining or other similar activity, they become re-exposed and open up the risk of pollutant re-introductions into the water column at concentrations higher than when they were originally introduced. Incorporation of pollutants into local food webs is possible, creating the potential for reaching toxic levels in any of several critical organisms including man. One solution to this problem is to relocate any dredging operation to an alternative, nearby site where prior core borings have established the absence of buried layers of organic or silty sediment, toxic or otherwise.

5. SITE EXAMPLES

The foregoing overview established the physical and biological context in which most sand and coral mining activities take place, without accounting for a "human intervention" factor in the "sand budget ledger".

Such intervention can take the form of mining or dredging (a debit) or nourishment (a credit). Similarly, biological processes can also take the form of debits (die off, loss of productivity) and credits (habitat creation). Failure to account for these dynamics in the planning and management of mining activities may result in significant, inadvertent modification to coastal and nearshore environments. The indirect or deferred economic costs associated with these modifications, as demonstrated by the following case studies, can be considerable. In each case, inadequate attention to project design, environmental planning and monitoring resulted in serious damage, often with significant economic costs.

5.1 Coral Harvesting and Mining

One of the utilitarian functions of living fringing and patch-type coral reefs, in situ dead coral reefs, sea grass beds, beaches and coastal rubble, and sand or lagoonal-shelf deposits is to buffer adjacent tropical shorelines. These formations create a natural breakwater system, protecting coastlines from attack by high energy, storm-driven waves and swells. When this "breakwater" effect is diminished by natural or man-induced removal or degradation, incoming oceanic waves and swells, occasionally heightened by abnormally high storm tides, can pass unimpeded to break directly on the shoreline. This can accelerate normal erosional processes and raise the risk of severe damage to human life, coastal villages, roads, tourist facilities, beaches and harbors.

Given the role of coral reefs in providing storm buffering, there are sound economic reasons to draw up environmental guidelines for mining coral and coral sand resources. The following three site examples illustrate this point.

5.1.1 Bali, Indonesia

Sengkidu Beach is on the east coast of Bali, fringed by a barrier coral reef lying approximately 150 meters offshore. The reef was mined for construction block and coral material to use in the production of lime; and subsequently Praseno and Sukarno (1977), employing remote sensing techniques, identified zones of coral depletion and demonstrated cause and effect linkages between mining practices and shoreline erosion. They calculated that approximately 100 meters of beach had eroded over a relatively short period of "some decades." Beach loss at the time of the study was beginning to translate into economic losses, and adjacent plantations and lands bordering a nearby rural village were increasingly at risk (Figure 6).

5.1.2 Sri Lanka

The island of Sri Lanka (formerly Ceylon) (Figure 7) provides another example of modern coral mining practices which have resulted in significant economic costs. Coastal erosion there is not a new phenomenon but has been cited in references dating back to the pre-Christian era (Swan, 1974). Although some long-term erosion occurs on the eastern and north-western coasts, it is most acute along Sri Lanka's southwestern coast, attributed, in part, to the coastline's continuing adjustment to the physical forces associated with the southwest monsoon (Swan, 1965).

High population densities have also created severe pressures on Sri Lanka's coastal and coral reef and sand resources. Human activities which have adversely affected coastal systems are (1) residential and recreational development; (2) salt evaporation pans (salterns); (3) mineral extraction; (4) coastal land put into cultivation; and (5) fishing (Amerasinghe, 1978).

The activity most harmful to shoreline and beach stability is the widespread mining of coral and coral sands for lime production, cement manufacture, and other purposes. Coral material is harvested from both coastal quarries and offshore using dynamite, crowbars and boats. Erosion is further accelerated by mining natural replenishment sands for use as construction aggregate, for lime production and as placers

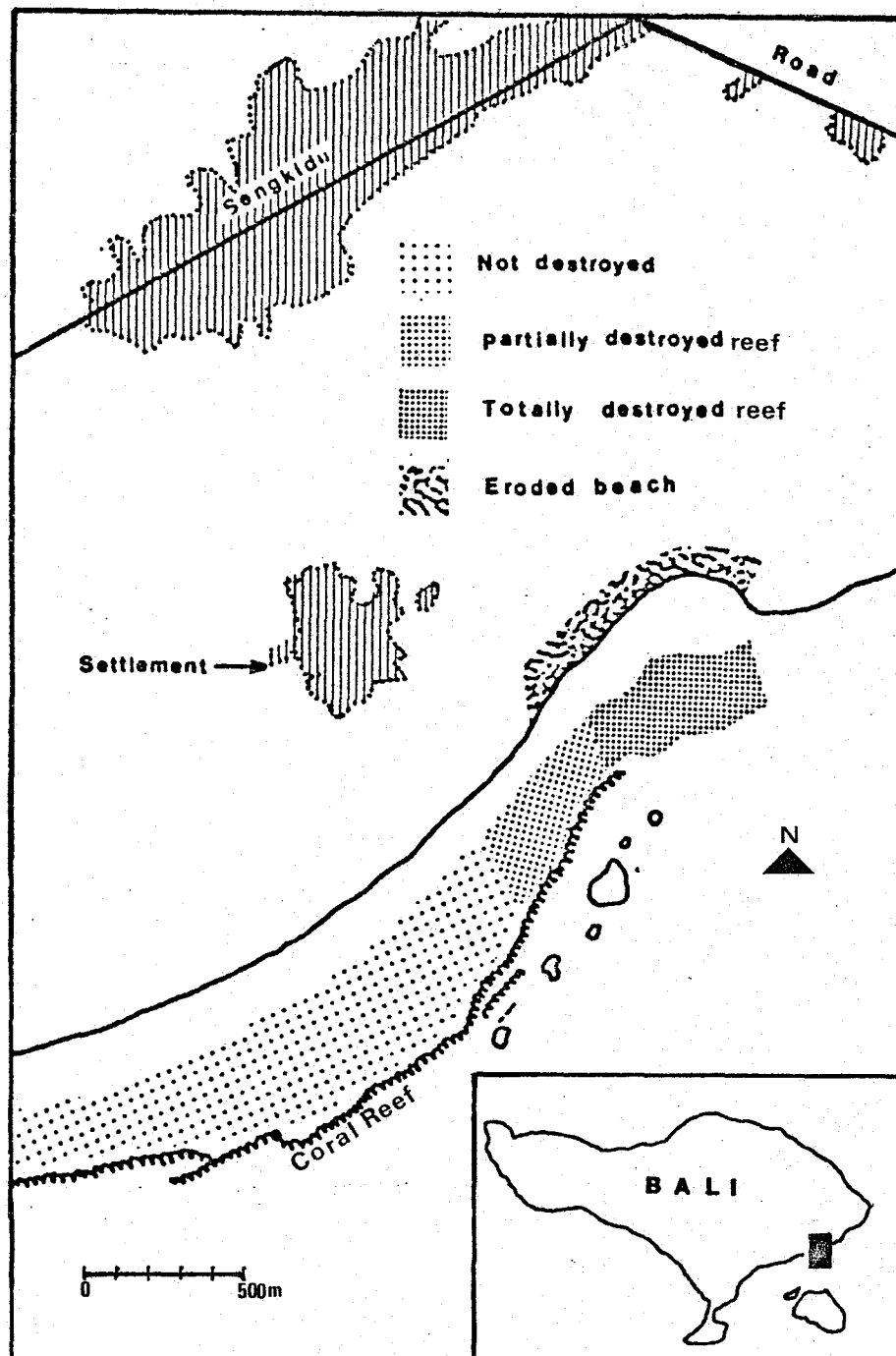


Figure 6. Coral destruction and subsequent beach erosion in Sengkidu Beach, Bali, Indonesia. (Source: Modified after Praseno and Sukarno, 1977.)

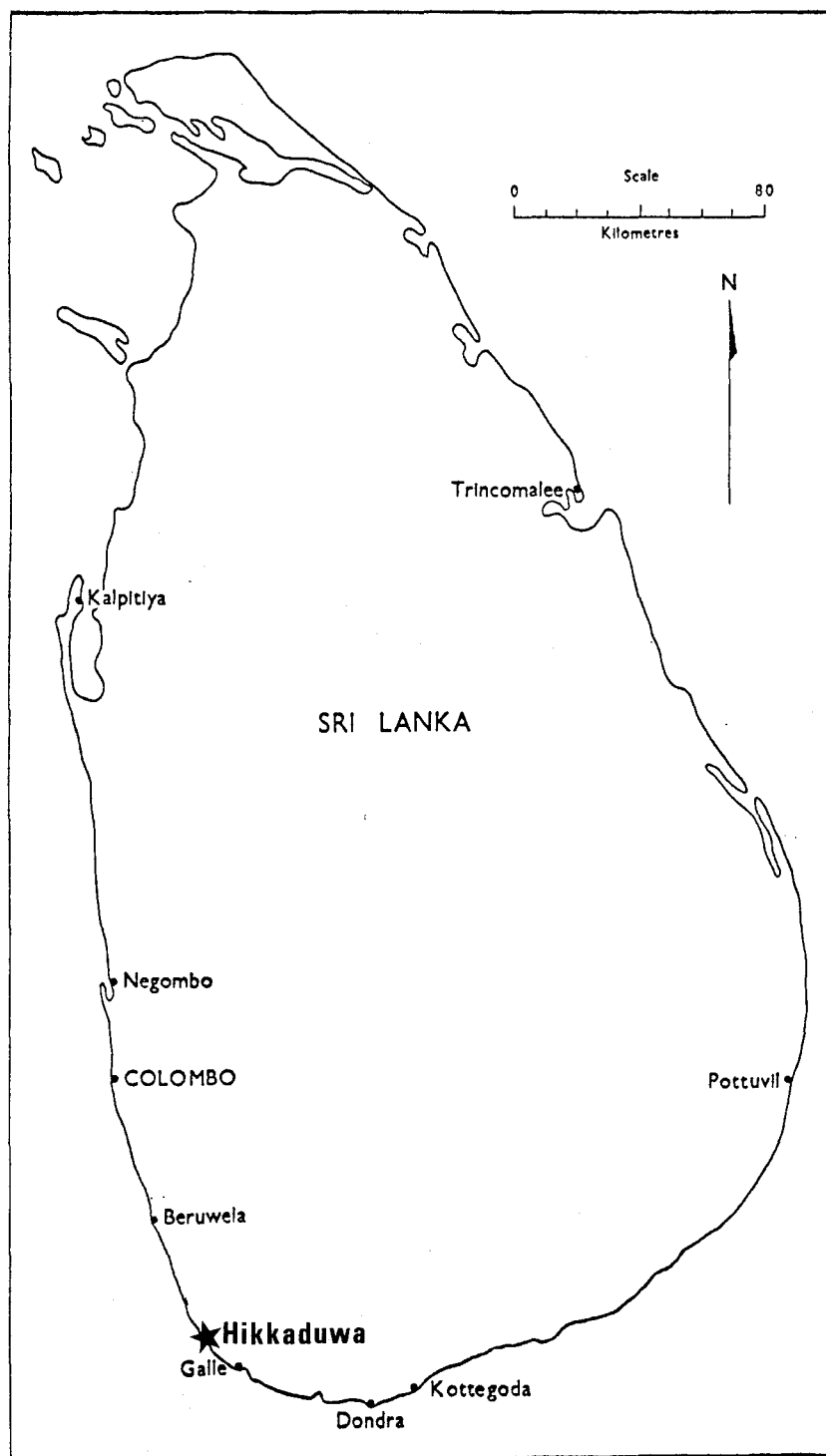


Figure 7. Sri Lanka, showing location of Hikkaduwa coastal erosion site.

(ilmenite, monazite, rutile) (Pattiaratchi, 1964).

The net effect of these practices combined with existing physical conditions has been to create zones of critical coastal erosion throughout the southwestern coastal regions of Sri Lanka.

One such zone is Hikkaduwa, some twenty miles north of Galle (Figure 7). This area is characterized by a low-lying coastline underlain and fringed by a coral reef. Swan (1974) suggested the area was somewhat erosion resistant until 1915 when a storm cut off the headland at Telwatte Point from the mainland. Despite gradual losses of beaches in the area, the existence of offshore coral reef systems played a mitigating role by moderating the seasonal forces contributing to erosional processes. However, concentrated exploitation of the offshore coral reefs have degraded the coastal defenses resulting in accelerated erosion along a six mile stretch of coastline from which an estimated 75,000 tons of coral is mined annually (Amerasinghe, 1978 and Soysa, *et.al.*, 1982). According to Linsky (Valencia, 1981), the resulting "... loss of beach from direct wave action has been estimated at 300 meters over 50 years with a net dollar loss of over US \$3 million" (Figure 8). In response to the problem, the government has constructed an expensive series of groins with little success as beach

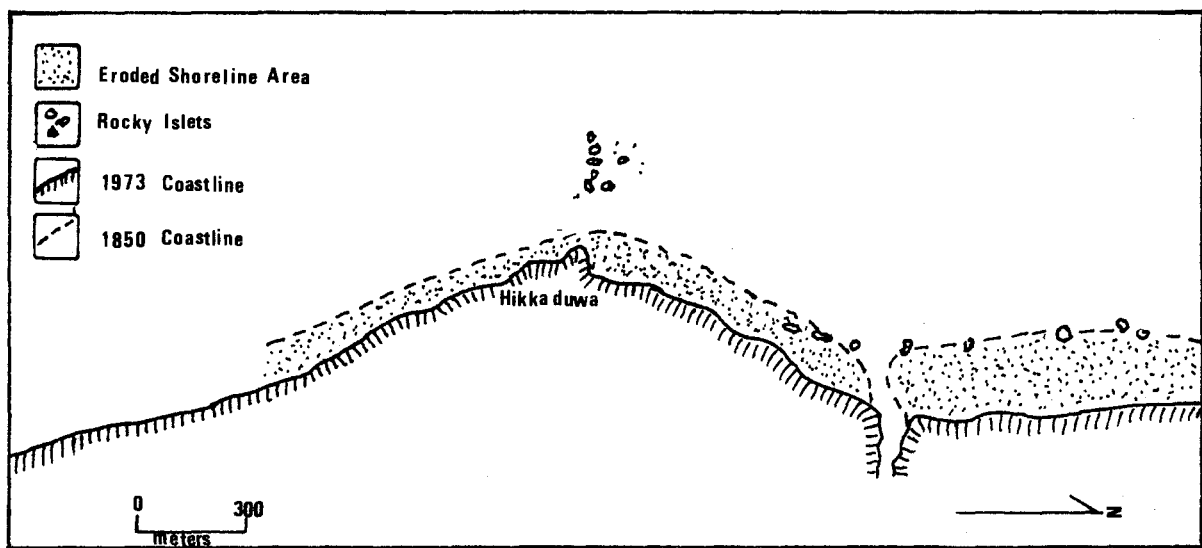


Figure 8. Erosional changes in Sri Lanka's southwest coast, adjacent to Hikkaduwa. (Source: Modified after Swan, 1974.)

areas remain exposed to the unmoderated influences of offshore wave attack (Swan, 1974).

5.1.3 Tarawa, Kiribati

The construction of expensive restorative structures to reverse erosional impacts to beach systems is not unique to Sri Lanka. These trends are also illustrated by the Tarawa Atoll site example, a reverse "L" shaped assemblage of very small islands situated in the former Gilbert Islands, now named the Republic of Kiribati (Figure 9). Situated on the equator in the central-Pacific, Kiribati has a population of 56,000, concentrated on sixteen atolls with a combined land area of only 280 square kilometers.

The Tarawa Atoll has a total land area of only 21 square kilometers, divided into rural and urban concentrations in the north and south portions respectively. The lagoon opens to the west, measures 350 square kilometers and is enclosed to the east and south by a chain of small, low-lying islands characterized by sloping beaches, limestone rock outcrops and mangroves (Bolton, 1982). Offshore, turtle grass beds and numerous coral patch reefs (living and dead) are scattered throughout the area before the coral barrier reef is met at the atoll's edge (Zann, 1982).

As in most atolls, Tarawa has a high coastline length to land ratio signifying a scarcity of land. This is particularly critical in south Tarawa where a high birth rate and in-migration from Kiribati's other populated atolls have resulted in a dramatic contrast in human densities between the north and the south ($144/\text{km}^2$ vs. $2,700/\text{km}^2$).

Stress imposed by human activity is especially critical for the atoll's marine resources because of their significant economic utilization: fishing, dredging, breakwater and causeway construction, waste disposal, and coral and sand extraction.

Mining of coral is a traditional activity in Kiribati. Ironically one of the primary uses of coral is for the construction of barriers to protect shorelines from erosion. Howarth (1982) in a survey of South Tarawa's two major islands (Betio and Bairiki) identified eighteen

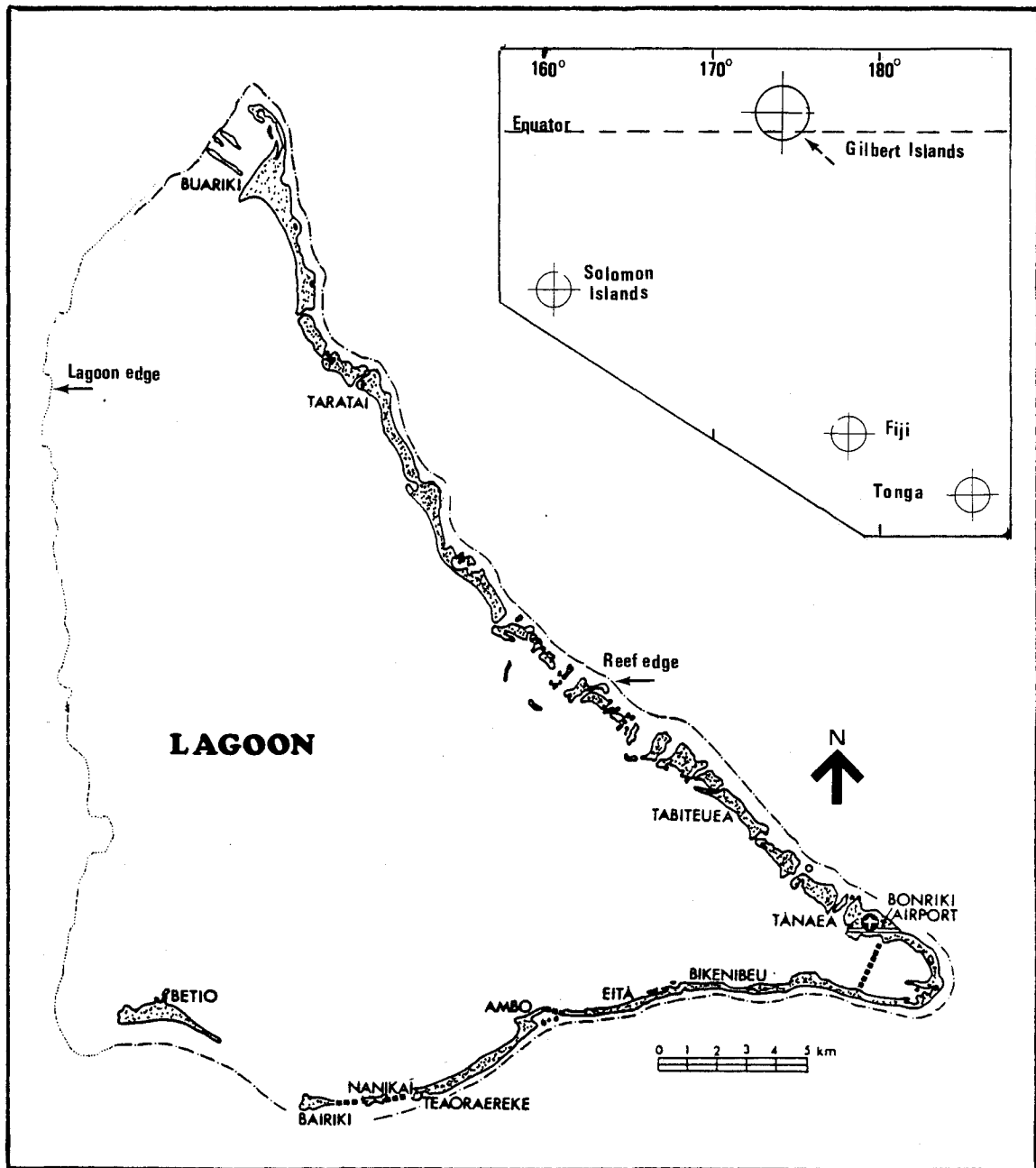


Figure 9. Tarawa Atoll, Republic of Kiribati (Gilbert Islands).
(Source: Modified after Howarth, 1982.)

coastal protection zones using coral and/or concrete blocks enclosed by heavy wire mesh baskets (gabions) for shoreline protection.

Coral mining and other man-induced impacts on the coral reefs have produced major environmental problems. In a recent survey of corals in or near the islands of Betio and Bairiki, Zann (1982) found no living coral cover greater than forty percent cover of the bottom, and most sites on the lagoon side indicated ten percent or less cover. One result of the presence of a diminished living reef (partially created by the mining practices) has been increased erosion undermining coastal protective structures and creating new sites at risk. In a second irony, once coral populations were depleted, the traditional source of coastal protective structures (gabions) disappeared, and alternative sources of materials were required.

Howarth (1982) compared the number of gabions employed between September 1978 and August 1982 (Table 3a) and calculated that approximately 110 additional gabions a year were being built for coastal protection (Table 3b). Based on the price of the coral substitute, concrete blocks at 85 cents per block, the approximate cost for a four cubic meter gabion was US\$213 (Table 3c). At the average annual production rate for gabions this represented an annual expenditure of US\$23,430/year for preventative coastal erosion structure production (Table 3d).

Table 3a. Gabions known to be erected between September, 1978 and February, 1982, indicating the increased need for coastal protective structures. (Source: Howarth, 1982.)

Coastal Defense Zone	September/October 1978		February 1982	
	2x1x1	2x1x0.5	2x1x1	2x1x0.5
Betio	216	69	565	114
Bairiki	30	0	29	31
Total Gabions	246	69	594	145
Equivalent 2 x 1 x 1 meter gabions	281		666	

Table 3b. Average number of gabions constructed annually in South Tarawa Atoll. (Source: Howarth, 1982.)

Total No. of Gabions in February 1982	Total No. of Gabions in October 1978	=	Average No. of Gabions Constructed Year
Interim Period of Time			
606	- 281		
3.5		=	110 gabions/year

Table 3c. Costs of constructing a 2m x 2m x 1m gabion with concrete block in US \$. (Source: Howarth, 1982.)

	1982
Basket	83
Labor	12
Blocks @ 0.85 cents	106
Plant Hire	12
TOTAL COST PER BASKET	US\$213 (approximately)

Table 3d. Annual capital expenditure on gabion construction in South Tarawa Atoll. (Source: Howarth, 1982.)

Ave. No. of Gabions	x	Cost per basket	=	Total annual capital expenditure for gabion construction
110		\$213	=	\$23,430/year

5.2 Beach Sand Mining

5.2.1 St. Lucia

In many tropical countries, coral exploitation for construction block and lime production is overshadowed by mining coastal sand for aggregate on an even larger scale. This practice is especially prevalent in developing countries where scarce technical and financial resources prohibit the exploitation of inland sand deposits. St. Lucia, an island situated in the West Indies, is one such area where mining sand and aggregate from beaches has been a convenient and traditional practice.

Vigie Beach, located on the northwest leeward coast of St. Lucia, is a small crescent-shaped beach measuring 20-30 meters in width and extending approximately 5,000 feet between two basaltic headlands (Figure 10). No rivers enter the area, and the principal sources of sand appear to be nearby offshore calcareous algal and fringing coral reef communities supplemented by incidental erosion from the adjacent headlands (Edmunds, 1983). Waves approach from the north/northeast and vary in strength between seasons, driving an offshore-onshore sand transport cell. Long-shore transport appears to be insignificant. These characteristics suggest that the beach system is relatively self-contained and dependent on sand in the system rather than on continuous replenishment from outside, upstream sources to replace losses, whether natural or man-made.

Due to the proximity to Castries, St. Lucia's capital, Vigie Beach and the narrow low lying neck of land to Vigie Point have been exposed to a variety of uses. For example, the city cemetery is located immediately behind the beach. Vigie Airport, running diagonally behind the cemetery, was built in 1943 and subsequently expanded to its present length of 5,700 feet. The only access road to the airport terminal parallels the beach (running between the cemetery and the airport runway) and also provides the access to Vigie Point. Vigie Beach has been a traditional recreational area for local residents of Castries, and since the early 1960's has served two major hotels, one at either end of the beach (Figure 10).

In addition to these activities, the beach has also served as the primary source of sand for the city and its citizens. There is little

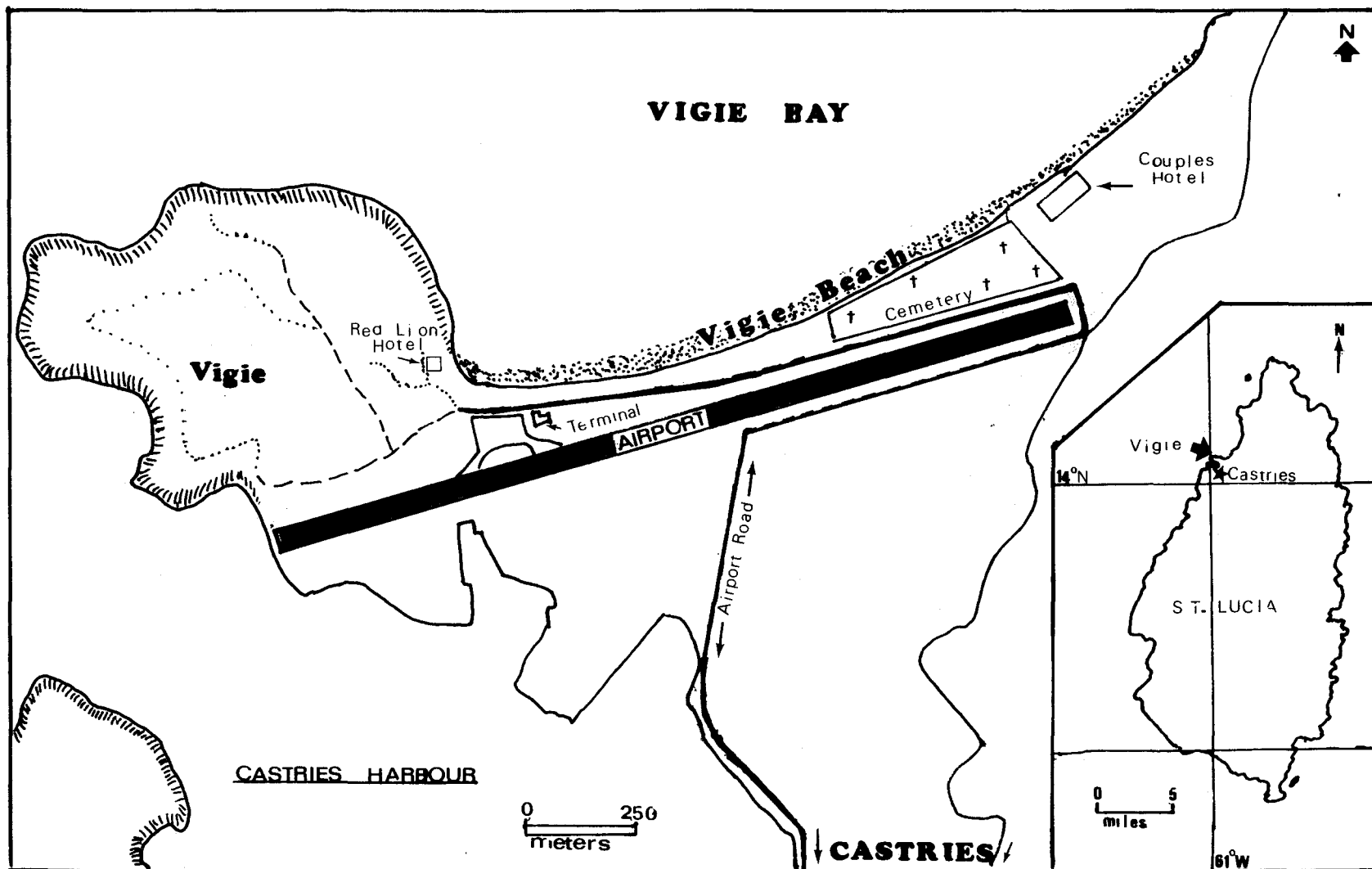


Figure 10. Location map of Vigie Beach, St. Lucia, showing interrelationship of threatened areas and facilities because of excessive beach sand mining.

data to indicate beach mining was a problem in Vigie prior to 1948. Up until that date, domestic and commercial building construction was based on lumber as a basic material, and there was little need for aggregate. However, in 1948 a catastrophic fire destroyed a large portion of Castries and in the subsequent reconstruction period concrete block and reinforced poured concrete replaced lumber as a building material. Vigie Beach became the principal source of sand for cement block manufacture and concrete. Despite early indications of beach erosion, sand mining continued unimpeded until 1963. By that year the condition of Vigie had deteriorated to the point that the government introduced a Beach Protection Ordinance which placed the mining of sand under licenses administered by the Ministry of Communications and Works. The law suffered from several weaknesses: it exempted the officers of the Crown, the Castries Town Council (one of the primary users) and the neighboring village councils; it only applied to Vigie and one other beach; and, finally, it was inadequately enforced. Sand mining continued unabated at Vigie Beach even though it was officially illegal for some users.

Exceptionally heavy swells during the winters of 1963/64 and 1964/65 exacerbated the erosion process which was further accelerated by continuing illegal sand mining. Visible narrowing and deterioration of Vigie Beach, and other St. Lucia beaches also locally mined for construction sand, led to public outcry and to the passage of the Beach Protection Act of 1967. This Act, still technically in force today, placed the administrative responsibility for all sand mining under the Director of Public Works (DPW). By doing so, the new legislation effectively broadened the scope of the 1963 Act while providing a mechanism to establish volume and time limits on beach mining activities.

Despite the passage of the 1967 legislation and its ostensibly more stringent constraints regarding sand extraction at Vigie Beach (and elsewhere), regression continued and was accelerated by the unusual winter storms of 1967/68 and by ongoing, although reduced, illegal sand extraction.

The potential economic consequences of continued beach regression began to appear critical. The estimated volume of sand mined from the

Vigie site during the period 1960-1970 had totalled 110,000 cubic yards (Table 4a). An analysis of aerial photographs between the period 1941-1970 indicated beach regression had reached 80 feet (Table 4b). A comparison of documented erosion (lost beach area) and estimated sand removal (Table 4c) suggests that beach recession was caused entirely by mining of sand for the building industry (Deane, et.al., 1973). By 1970, an estimated 10.1 million dollars of real estate alone was at risk (Table 5a). In addition to loss of land value, there were other significant issues. The city of Castries was threatened with loss of its airport access road and its principal cemetery, the city and country were threatened with a loss of tourist revenues derived from visitor use of two major Vigie Beach hotels, and the local population was faced with the loss of a traditional recreational site.

In response to these concerns and in an attempt to reduce the rate of beach and beach berm erosion threatening both the cemetery and the only access road to the airport and Vigie Point, the government elected to construct a 300 foot long strip of gabion mattresses (a system of rectangular wire mesh baskets filled with stone) on the face of the eroding beach berm near the road. This emergency measure cost approximately US\$25,000--a not inconsiderable sum in 1970 for a small island government with many other public development priorities.

By 1973, the beach front of the Red Lion Hotel (at the southern end of Vigie Beach) had eroded down to a pebble and cobble beach, resulting in a reduction in tourism and lost revenues. In an attempt to restore the beach, the government used rock from a nearby quarry to build a rubble stone groin adjacent to the hotel at a cost of approximately US\$5,000.

Three years later abnormally heavy sea swells from a winter storm overwashed the diminished beach and flooded the Couples Hotel. Continued flooding prompted the government to build a new set of gabion mattresses costing another US\$5,000 on the eastern end of the beach. As the situation continued to deteriorate the government recognized that the "patchwork" strategy was ineffective and temporary, so another approach was needed. The new strategy was offshore sand mining for beach nourish-

Table 4a. Estimates of sand mined from Vigie Beach, St. Lucia
(1960 - 1970). (Source: Deane, et.al., 1973.)

LOCATION OF SAND SOURCE	ESTIMATED VOLUME OF SAND MINED (Cubic Yards)				
	1960-62	1962-65	1966-68	1969-70	TOTAL
Vigie Beach	70,000	35,000	3,000	2,000	110,000

Table 4b. Beach loss from erosion at Vigie Beach, St. Lucia
(1941 - 1970). (Source: Deane, et.al., 1973.)

BAY	STATION	COASTAL EROSION (Ft.)			AVE BEACH LOSS PER YR. (1941-1970) (Ft.)
		1941-51	1941-66	1941-70	
Vigie	1	16	65	80	2.66 ft.
	2	0	48	50	1.66 ft.
	3	14	54	54	1.80 ft.

Table 4c. Comparison budget of sand losses, Vigie Beach, St. Lucia.
(Source: Deane, et.al., 1973.)

LOCATION	Estimate of Sand Used By Building Industry (1960-1970) (Cu. Yds.)	EROSION 1941-1970 (Cu. Yds.)
Vigie Beach	110,000	104,000

Table 5a. Current value of real estate at risk due to Vigie Beach erosion. (Source: Edmunds, 1983.)

TYPE OF REAL ESTATE	VALUE (US \$)
<u>Hotel</u>	
Red Lion	\$ 2,000,000
Couples	3,500,000
<u>Other</u>	
Public Road	384,615
Vigie Airport:	
Runway Costs	2,115,305
Buildings	576,923
Land	1,538,461
TOTAL	\$10,115,384

Table 5b. Estimated costs of protective/restorative activities to protect Vigie Beach and property at risk from the threat posed by coastal erosion. (Source: Edmunds, 1983.)

Activity	Location	Date	Estimated Cost (US \$)
Gabion Mattress	Adjacent to Public Road	1970	\$ 25,000
Stone Groin	Red Lion Hotel	1973	5,000
Gabion Mattress	Couples Hotel	1976	5,000
Beach Nourishment	Couples Hotel/Cemetery	1980	434,245

ment, selected in part because of the temporary presence of a large Jamaican-owned suction dredge working in Castries Harbor. The scope of the beach replenishment project was limited by government access to external funding which in the end amounted to US\$434,000. By mid-May of 1980 the work had been completed, and a total of 289,000 cubic yards of sand was deposited on the beach in a zone extending from the Couples Hotel 1,600 feet to the southwest, building up the area adjacent to the cemetery which was most seriously threatened by erosion.

Although no data exist to determine the effects of dredging on offshore algal and coral communities, there was evidence that a considerable portion of the new beach sand put in place washed out subsequent to emplacement, a process attributed to "fines winnowing" (Edmunds, 1983).

Total investment of public funds to protect and restore Vigie Beach following long term beach sand extraction activities was estimated to be US\$469,245 (Table 5b). Since sand cost US\$1.87 per yard in 1980 to place on the beach, the overall restoration costs of US\$469,245 represents slightly more than twice the adjusted market value of sand previously removed, legally or illegally. It was a costly lesson in beach dynamics and resource management. Unfortunately, the beach berm is still being under cut, and beach sand draw down continues although perhaps at a slower pace than previously recorded.

There is a further irony to the situation stemming from the existence of large but as yet undeveloped pumice "sand" deposits in St. Lucia, a volcanic island. Up until recently, these resources, which are relatively close to Castries, have been rejected as too costly to develop (primarily costs associated with an access road) and because greater care is required to mix cement when lighter pumice sand is used. Nevertheless, the events detailed above contributed to the establishment of a Regional Beach Erosion Control Project, which undertook the testing of pumice as an alternative source for aggregate. Upon finding that pumice blocks were structurally superior to those made with beach sand, the government began considering greater use of the resource, and an experimental project is underway using pumice as a substitute for beach sand. The extraction of beach sand at Vigie has ceased, but the future

of the beach itself remains in doubt. It was a costly lesson.

5.2.2 Puerto Rico

In contrast to the leeward beach situation at Vigie in St. Lucia, many windward or more exposed insular and continental shorelines function differently. With high energy beach systems, they exhibit very different kinds of sand budgets, higher onshore-offshore sand and rubble exchange rates, and large scale sand sinks or reservoirs of material behind the beach itself.

Sand blown from exposed, generally windward beach foreshores and berms often develops into sand dune systems behind the berm crest itself. Salt-tolerant vegetation subsequently takes root and helps stabilize these sand dunes. Dunes, in turn, serve both as a secondary barrier protecting inland areas against seasonal storm waves impinging on the beach and as a reservoir of sand for the beach itself when it is attacked by storm waves, swells and tides generated by hurricanes or cyclones (Figure 11).

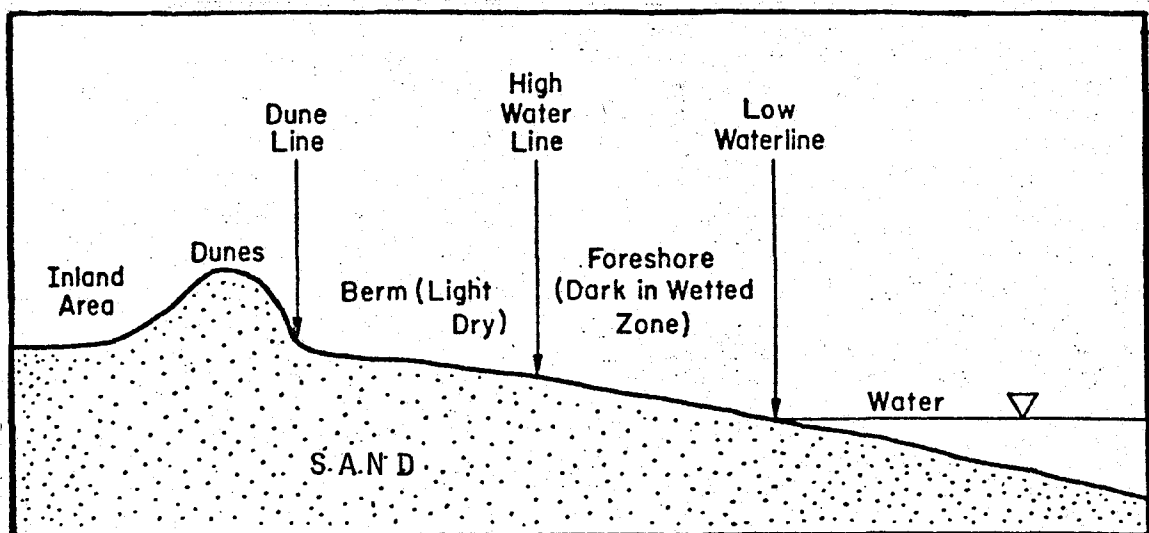


Figure 11. Idealized cross-section showing beach, dune line, and water line. (Source: Nichols and Cerco, 1983.)

Unfortunately, dune systems are also easily accessible, naturally stock-piled sources from which semi-sorted, pre-washed sand is readily obtained. Quite often, this happens without a formal government permit and with little regard for environmental consequences.

An instructive example of this exists on the north coast of Puerto Rico and has been addressed recently in an intensive policy and management study which focused on three major dune sand mining areas on the more exposed Atlantic coast of the island (Nichols and Cerco, 1983). Sites were selected by the Puerto Rico Department of Natural Resources as the most representative heavily mined areas (Figure 12).

Construction of a major international airport for the island east of its capital city of San Juan at Isla Grande in the 1950's required enormous volumes of fill. Some of the material was taken from nearby Playa de las Tres Palmetas at Carolina, east of the airport site. Within a few years, high levels of erosion were reported for the Carolina beach area. During the 1960's and early 1970's the Hatillo beach area to the west also experienced an intense large scale removal of dune sand, some by permit and some illegally. In the 1970's the Isabella beach dune areas were also harvested for large volumes of sand. Again, some mining was by permit; some was not. The justification for the dune/beach sand mining was always "development" and the long term impact remained an unknown--at least until the mid-seventies when studies by government resource managers and technical consultants (see below) suggested limits to sand extraction quantities were required to prevent further damage to Puerto Rico's sand beaches and dune systems.

The Environmental Quality Board of Puerto Rico raised the issue of excessive sand mining and long term sand resource planning as early as 1971 (PREQB, Annual Report, 1972). Preliminary guidelines for sand extraction in Puerto Rico were provided by one consultant (Hernandez-Avila) as early as 1973 based mainly on qualitative observations giving insights into sedimentary processes active in the dunes. Noticeable effects of storm waves on beach erosion and alterations of dune height and width at Playa de las Tres Palmitas, Carolina by a sand extraction episode were recorded by Cintron and Pool (1976). The problem of dune protection and

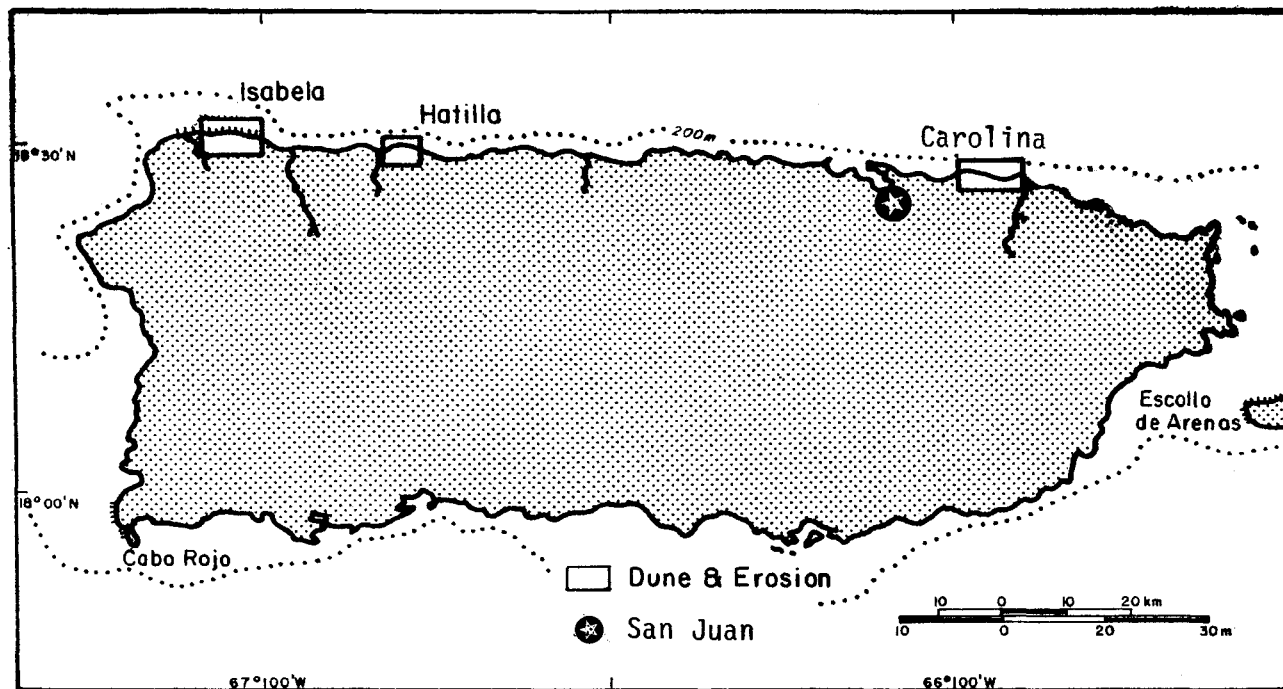


Figure 12. Location of dune erosion sites on the north coast of Puerto Rico (Source: Modified from Nichols and Cerco, 1983).

sand extraction was subsequently documented by NOAA under Puerto Rico's Coastal Zone Management Program in 1978 (NOAA, 1978). Two years later, the history and magnitude of sand extraction and estimates of Puerto Rico's total sand resources were provided by Castillo and Cruz (1980); the hazard of coastal flooding was documented in a government study (PRDNR, 1980); and three pertinent sand dune management studies from outside Puerto Rico also became available (Armon, 1980; Cullen and Bird, 1980; and Gares, *et.al.*, 1980).

Due to increasing concern expressed by resource managers and planners over the growing evidence of impacts attributable to excessive sand extraction, the Puerto Rico Department of Natural Resources began to assemble all the available data needed to define the dimensions of the problem and to establish both a technical and policy based solution.

This took time, in part because as in most sand resource management matters the government had to address not only traditional, ongoing and new kinds of legitimate and illegal sand uses but also had to project future needs and assess those needs within the context of the associated environmental constraints. It was a difficult task.

Every prospective user of sand confronting changed controls, limits, licensing or fees wants to know why there are new "unfair" and "costly" rules which did not apply yesterday to someone else. It was necessary in Puerto Rico to build a solid government position for a new beach resource management strategy, based on sound scientific data, because of the presence of resource users accustomed to fewer restrictions. When data was collected and analyzed as part of a management planning project under the Department of Natural Resources, it produced findings which suggested there was real cause for concern. By coincidence, the outcome of the study was reinforced by exceptionally severe storm damage at the three study beach areas during the course of site assessment field work in 1982 (Nichols and Cerco, 1983).

It has been documented that over a thirty year period (1950 to 1980) sixteen million cubic meters (approximately 21 million cubic yards) of sand had been mined from Puerto Rico's north shore dunes and beach areas. Of this total, eleven million cubic meters (14.3 million cubic

yards) were extracted for fill and construction use from the three key beach areas of Carolina, Hatillo and Isabella (Castillo and Cruz, 1980).

The sand used, in this case, was not "free" but had a deferred cost.

Nichols and Cerco (1983) summarized the situation well:

Along the north coast, sand dunes once provided protection against storm surges, waves and flooding. They not only offered natural protection for human life and property but served as a source of sand to buffer beach erosion. Today, after several decades of massive sand extraction few natural dunes remain. By removing back-up dunes and lowering fore-dune crests, storm waves now [1983] overtop and breach the remaining ridge and flood lowlying areas landward. Where dunes have been completely destroyed, ocean front property, settlements and mangrove habitats are exposed to the full force of ocean storm waves....

The size, height and stability of residual dunes at Isabella, Hatillo and Carolina [are now] inadequate in many places for long term protection of life and property. As a result of high northern swells, October 11-13, 1982, dune ridges collapsed, were breached at 23 points [and are] insufficient to protect the coast from wave run-up of a one in 20-year hurricane.

Given the deteriorating status of the dunes in response to man-induced and natural processes, the task now is to maintain the dunes in their best achievable condition.... If the dunes are to serve both as a sand and recreational resource as well as a barrier for storm protection, they must be understood....

This case confirms that some environmental management lessons come at a price. Fortunately, some of these lessons are transferable and may reduce the risk of replication at other locations. Conclusions drawn in the Nichols and Cerco (1983) post-audit of the Puerto Rican experience are instructive for most sand dune mining activities. The problem is how to continue to mine sand from dunes while minimizing the risk of future storm damage to property and human life, thus lessening the need for costly protective structures and other remedial measures.

At the outset, the operating characteristics and natural functions of beach and dune areas must be addressed. These were identified by Nichols and Cerco:

- The dune and beach system is dynamic. Dune sand is continually exchanged between the beach or nearshore zones.
- Dunes constitute a natural reservoir of sand. When the dune face is eroded during storms, the sand released nourishes beaches and reduces erosion effects.
- Dune width and dune height provide a volume and mass of sand that reduces the landward extent of overtopping, overwash and flooding of zones behind the dunes.
- The life expectancy of protection depends on the lateral erosion rate and the dune height in relation to the heights and frequency that storm surge and runup attain.
- Over the long-term the dune/beach system can migrate landward in response to storms, erosion, rising sea level and a negative sediment budget [especially when accelerated by sand mining activity] (Nichols and Cerco, 1983).

Since the type and status of dunes vary widely, both naturally and as a result of previous sand extraction and other development activities, different management approaches may be needed. These include: (1) prohibiting all dune sand mining; (2) letting the natural process prevail, while mining some sand on a sustainable yield basis; (3) modifying the natural processes to maintain or restore the dunes for protection while mining sand on a managed by-product or secondary yield basis; (4) optimizing sand extraction and subsequently rebuilding the dunes artificially.

For most developing countries, option (1), no dune (or beach) sand mining, is unacceptable. If option (2) is chosen and natural processes are allowed to prevail, the coast must be managed in a manner that is compatible with beach and dune migration trends and historical erosion rates. The approach permits some sand extraction or development but controls it to minimize interference with natural processes and to provide a degree of protection (Nichols and Cerco, 1983).

To manage the beaches and dunes so that natural processes prevail and critical existing sand dune reservoirs are kept more or less intact, a beach/dune management zone needs to be defined (see Nichols and Cerco for the procedure). By establishing a dune management or setback zone,

future sand extraction and vehicular activities, as well as development, can be directed inland away from the more active portion of the dunes. No sand mining would be allowed from the primary shoreward dune and "protection" would have precedence over "sand mining."

Should option (3) be selected to encourage the natural processes (a) to provide sand for harvesting and (b) to maintain and/or restore dunes previously damaged by a combination of sand mining and storm action, the management strategy involves:

- building up dune gaps and washover zones through fencing and planting appropriate vegetation and/or;
- building up dune gaps, washover zones and elevations of sand mining borrow pits to appropriate design heights (50 year or 100 year storm) by large scale sand nourishment from offshore using a hydraulic dredge;
- establishing a set back zone landward of surviving dunes, into which dunes can migrate and recover;
- regulating all sand mining and restricting it to carefully selected undamaged accreting and residual back dune areas behind the primary shoreward dune (which would not be mined except under special circumstances where accretion rates exceed required storm protection requirements).

Option (4), emplacing protective engineering structure in dune gaps and washovers resulting from excessive sand extraction, can only be justified where the value of existing property and facilities is very high. It is a proven high risk, short sighted approach leading to potentially disastrous and costly consequences, as illustrated by both the St. Lucia and Puerto Rico examples. Engineering structures are no substitute for natural sand dunes along open stretches of coastline.

5.3 Marine Sand Mining

5.3.1 U.S. Virgin Islands

Over the past two decades, many developing countries have stopped or reduced the practice of harvesting beach sand for construction purposes. To a degree, this is attributable to increased awareness of negative

environmental impacts associated with coastal sand and coral mining activity. More significant is the simple realization that there are socially and economically valuable alternative uses for beaches, i.e., for local recreational uses and development of waterfront resorts, hotels, condominium sites and other tourist attractions. But when a government declares beach sand extraction illegal or restricts traditional harvesting practices and therefore the supply of sand, it will sooner or later be forced to identify and regulate the mining of alternative sources of aggregate.

This was the situation in the U.S. Virgin Islands in the 1960's when external factors began to stimulate economic growth in three sectors, government operations, export manufacturing and tourism. In tourism, growth rates were exponential, both in number of arrivals and in accommodations. Between 1960 and 1970, visitor arrivals increased tenfold. As the employed labor force tripled, the stock of housing doubled, real per capita income rose ten percent annually, and electric and water consumption averaged 20 percent per year growth (McElroy, 1978).

Environmental stresses from such massive social changes quickly became apparent. Open spaces were replaced by suburban sprawl, shorelines were altered by hotel, marina and industrial expansion, and previously undisturbed ecosystems became sites of residential clusters, government facilities, commercial buildings and road networks (McEachern and Towle, 1974). Much of this activity required sand for a variety of purposes for land fill, for increasing beach width or length, for building docks, and for construction of hotels, houses and other facilities. Between 1960 and 1970 the consumption of sand tripled along with the price which went from \$1.00 to \$3.00 per cubic yard. In the context of a growing beach-oriented, tourism-based economy, traditional sand removal from beaches began to be publicly questioned. It was eventually legally challenged and, in 1973, prohibited by law, resulting in a sharp increase in more costly imports of sand (at \$5.00 to \$7.00/cubic yard) from other islands such as Puerto Rico, the British Virgin Islands, Anguilla, Barbuda, and even the distant Bahamas. Other alternatives were examined which included large scale offshore marine sand dredging to provide the

needed construction sand and fill material.

Marine sand mining has a long history in the U.S. Virgin Islands. As early as 1935, over one million cubic yards of material was dredged from the bottom of Lindbergh Bay on the southwestern coast of St. Thomas. Fill was placed in a nearby, swampy area for the construction of the present airport runway, leaving a large, deep excavated turbid basin in the bay bottom. As a result of the ensuing turbidities, benthic grasses once found to a depth of 10 meters are now absent in depths exceeding 2.5 meters. Dredging effects were compounded by large quantities of fine terrigenous clays washed into the bay as a result of continuing construction on nearby hillsides (vanEepoel, et.al., 1971). The extensive sump resulting from dredging activities still, nearly 50 years later, collects fine sediments which then are available for resuspension and redistribution throughout the bay system. This periodically increases turbidity and limits the regrowth of coral and sea grasses. Adjacent Lindbergh Bay Beach, a public recreation area, remains popular with local residents (not tourists), more for its accessibility by public bus transport than its marginal water quality.

Between 1961 and 1981, over 2.2 million cubic yards of aggregate (principally sand) were extracted for local construction activity from Christiansted Harbor, St. Croix, the most southerly of the Virgin Islands (Hubbard, et.al., 1981a). Over 200,000 cubic yards of sand was harvested from each of eight other bays in the Virgin Islands (Brewers, Water, Crown, Cruz, Great Cruz, Vessup, Long, and Turners) during the 1960's and early 1970's. One area in particular, Water Bay, was the focus of repeated sand mining activities between 1960 and 1971 and was selected as the "case study" site.

5.3.2 Water Bay, St. Thomas

Situated on the northeastern shore of St. Thomas, Water Bay opens to the east facing the Leeward Passage, an inter-island channel from the Atlantic Ocean to the Caribbean Sea. It is bounded on the north by Coki Peninsula, on the west by Pineapple Beach, and on the south by the island land mass proper, ending at Footer Point. Prior to dredging, Water Bay

supported marine flora and fauna characteristic of most West Indian shallow water marine communities dominated by turtle and eel grass flats interspersed with small patch reefs. The sublittoral area of the Bay was approximately twenty hectares with a relatively even bottom and gradual slope to seaward (Figure 13).

Part of the Bay's southern shore is the bold slope of Mt. Pleasant, which rises steeply to a 200 foot elevation. A small indentation between Footer Point and Mt. Pleasant is known as Sugar Bay, behind which there is a lowland area which was at one time used as a public garbage dump. Until 1969 Sugar Bay had a rather nice beach; the story of its disappearance is instructive.

The seabed of Water Bay was dredged for sand on five separate occasions between 1961 and 1971 (Table 6). In 1961, as part of a resort development project at Pineapple Beach, 50,000 to 100,000 cubic yards of sand were first dredged from the shallow area near the beach to provide adequate depth for a boat dock, for beach improvement and for construction and fill use. An area contiguous to the original mining site was subsequently mined in 1965 for additional construction material and fill for a swamp adjacent to the already existing hotel on Pineapple Beach. After 9,000 of a scheduled 25,000 cubic yards were extracted by a suction dredge working over a large area only six to eight feet deep, the hotel owners ordered the contractor to stop. Mounting complaints of water quality by hotel guests using the beach had reached booking agents on the U.S. mainland, who threatened to refuse to book further guests at the Pineapple Beach Resort until swimming and snorkeling conditions improved. Rather than risk the possibly irreparable loss of visitors and potential repeat customers, the hotel owners elected to absorb the added costs of hauling the required fill material.

Four years later, however, a 1967 U.S. Department of the Interior permit to dredge 600,000 cubic yards of sand from Water Bay (issued to a local concrete ready-mix company) was announced and activated by the contractor. The same hotel, perceiving that its investment was again threatened, joined forces with the environmental community to oppose the action. The owner/manager of the Pineapple Beach Resort facility re-

Figure 13. Water Bay, St. Thomas, U.S. Virgin Islands, showing bathymetry and shoreline swamps prior to dredge and fill operations (1960-1971). (Base map from NOAA Chart No. 938.)

Table 6 . History of marine sand mining, Water Bay, St. Thomas, U.S. Virgin Islands. (Sources: vanEepoel, 1969; Grigg and vanEepoel, 1972.)

Year	Dredging Location	Quantity (yd ³ sand)	Dredge Type	Purpose
1961 -62	Pineapple Beach (nearshore)	50,000 to 100,000 (est.)	Dragline	Construction aggregate/ beach nourishment/ dock access
1965	Pineapple Beach (nearshore)	9,000	Sand sucker	Land fill
1969	Sugar Bay (nearshore)	100,000	Hydraulic cutterhead	Fill/Aggregate
1970	Inner Bay	50,000 (+)	Hydraulic cutterhead	Aggregate - off site use
1971	Outer Bay	450,000 (+)	Hydraulic cutterhead	Aggregate - off site use

sponded to the proposed scheme as follows in a letter to the government:

It came to my attention during the first week of January 1969 that a large dredging operation was contemplated in the vicinity of the Water Bay Area, St. Thomas, V.I.... Since we had the previous experience of a business loss on dredging only 9,000 cubic yards we [know] that dredging ... [additional sand] would cause a very sizeable operating loss we could not afford.... The greatest asset we have is our beach. By July 1969 we will have a total investment of approximately four million dollars in Pineapple Beach Club and the Condominiums. Our entire investment would be in jeopardy if the beach [is] damaged....

I feel confident that this government does not want to be responsible for permitting a dredging operation to operate in an area that would cause immediate financial loss in the daily operations and possibly cause irreparable damage to one of the most popular beach resorts in the Virgin Islands.

I don't feel that the Government of the Virgin Islands would want to be a party to the substantial adverse publicity that such an abusive operation would receive not only locally, but throughout the travel industry....

The author of this letter also requested that an investigation be conducted by the government to assess the potential effects of removing 600,000 cubic yards of sand from Water Bay.

The proposed scheme involved 50,000 cubic yards of sand as fill for a former garbage dump and 550,000 cubic yards of construction sand to be hauled away from the site. Despite the previously cited protests, the contractor's hydraulic cutterhead dredge was in place and commenced pumping sand from Water Bay in early April 1969. Within thirty days over 100,000 cubic yards of sand were dredged from directly in front of Sugar Bay Beach on the south coast of Water Bay and deposited ashore filling the former swampy garbage dump site. Because the dredge was urgently needed at another nearby site and to allow time for the deposited material to settle, dredging activity was stopped temporarily.

Within months from the cessation of dredging activities, Sugar Bay Beach literally disappeared and was replaced by the underlying pebble and cobble-dominated substrate. Sugar Bay Beach was originally two hundred

meters long and approximately ten meters in width. Surveys conducted a few months after the 1969 dredging indicated the beach materials had slumped into the adjacent dredge pit. The pre-existing sand berm had been eroded back, forming a three foot vertical wall several feet above sea level, exposing the seagrass tree root systems (Figure 14). Slump-off resulted in high water turbidities from both the exposed remnant of the beach as well as the newly eroded deposits. Additional turbidity was caused by exposed layers of mud opened during the removal of overlying sand deposits. Serious impacts on Water Bay life forms have resulted from chronic resuspension of mud fines, clays and organic materials (vanEepoel, 1969; Grigg and vanEepoel, 1970).

Reef die-off and reduction in sea grass densities were attributed to increased rates of sedimentation resulting from the dredging operations. Grigg and vanEepoel (1970) estimated that approximately ninety percent of undredged Water Bay corals on the southeast shore and 20-25 percent of corals on the northern shore were killed by the sand extraction activity (Figure 15). Two emergency groins costing approximately \$10,000 were installed by the contractor in 1969 at either end of Sugar Bay after the beach disappears. However, they failed to have any positive effect and, subsequently, also washed away.

This then was the setting which preceded a resumption of sand mining in the fall of 1970 (a continuation of the 1969 dredging activity under the same permit). By this time a number of technical reports and scientific studies had become public, documenting the impact of sand mining operations at Water Bay and elsewhere in the Virgin Islands (vanEepoel, 1969; Grigg and vanEepoel, 1970). Researchers described the 1969 mining activities at Water Bay, though of a short term nature, as a "major ecological disaster for sublittoral flora and sessile fauna" in the immediate area of dredging (vanEepoel, 1969). Therefore, as mining activities recommenced, they came under increased public and private scrutiny. Tourism and hotel industry spokesmen lobbied for a monitoring regime, arguing that further "Sugar Bay disasters" would affect the value of their properties.

Until 1969 applications for required dredging permits (then issued



Figure 14a. Sugar Bay Beach (1969), before offshore dredging in Water Bay, St. Thomas, U.S. Virgin Islands.



Figure 14b. Sugar Bay Beach (1970), after offshore dredging in Water Bay, St. Thomas, U.S. Virgin Islands.

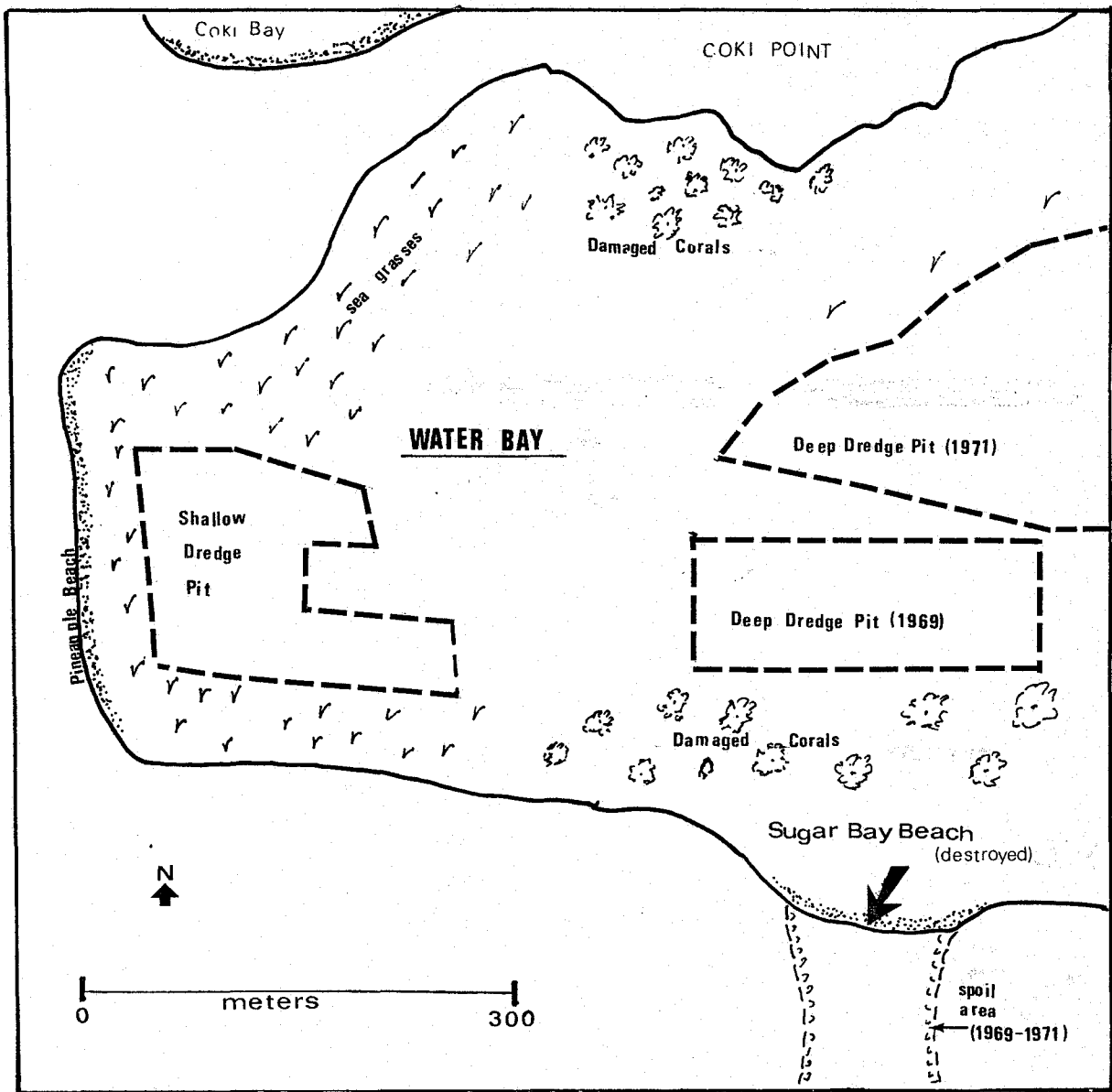


Figure 15. Water Bay, St. Thomas, U.S. Virgin Islands, showing dredge sites and adversely impacted areas including Sugar Bay Beach.

by the U.S. Department of the Interior) were seldom scrutinized. When approved, they were subject to little monitoring or enforcement and were issued as open licenses for extended periods. However, as a pre-condition to recommencing mining activities at Water Bay in 1970, the following requirements were imposed by the local Virgin Islands government:

- Dredging had to be transferred to deeper areas at the entrance to Water Bay;
- Prior to dredging, core borings in the remaining seabed mining areas were to be taken to determine quality and depth of bottom and to assure that no disturbance of clay and organic "fines" would occur;
- A sediment discharge settling basin on the inshore disposal site, equipped with proper weirs to extend residence time, was to be maintained;
- Dredging in waters less than 35 feet in depth was prohibited;
- A surveillance program was to be established to ensure the adequate protection of the environment.

However, despite these required modifications and systematic attempts by local scientists to monitor the renewed dredging activity, conditions at Water Bay worsened during final stages (1970-71) of the now accelerated effort by the contractor to dredge the remainder of the total 600,000 yards approved under the original 1967 permit. Matters finally came to a head when the Governor of the Virgin Islands requested that the U.S. Department of the Interior withdraw the dredging permit. Cancellation was ordered on November 3, 1971, long after damage was done.

The positive legacy of the Water Bay experience was the establishment of a new territorial policy regarding beaches and dredging and a monitoring program to prevent future similar occurrences. The negative legacy is the number of dredge pits which still exist in Water Bay with unconsolidated bottoms acting as chronic sources of turbidity and preventing recolonization near the mining site (Grigg and vanEepoel, 1972; Insular Environments, 1975; Island Resources Foundation resurvey of site area, 1983). Sugar Bay's former sandy beach continues to be a narrow strand of rubble and shows no signs of natural recovery nearly fifteen years later.

6. ALTERNATIVE MANAGEMENT APPROACHES

6.1 Coral Mining

6.1.1 Stony (Hard) Corals

Most "hard" or stony corals (scleractinians) have rather slow growth rates, ranging from one-tenth of a centimeter to ten centimeters per year in length (Stoddart, 1969). For this reason, they are often seen by more conservative scientists and managers as non-renewable marine resources since natural production rates are frequently exceeded by even very low levels of harvesting. When hard corals are exploited commercially, and, therefore, in effect treated as renewable resources, their slow growth rates suggest the need for careful resource management plans to control their harvesting for lime manufacture or, in the case of smaller, more delicate corals, as tourist curios and in the ornamental export trade (Wells, 1981).

Unfortunately, no comprehensive management strategies or regulations are known to exist for small stony corals, although some countries have export restrictions (Wells, 1981). The state of Hawaii, where extensive coral harvesting occurs, currently manages corals by establishment of a restricted zone (within 1,000 feet of shore and under 30 feet in depth) where the harvesting of coral and sand is prohibited; collecting for research purposes is excepted.

Grigg (1976) proposed the following minimum requirements: commercial "fishing" licenses; collection of catch/effort data; establishment of minimum size limits significantly above the determined age of reproductive maturity; establishment of a monitoring program focused on heavily harvested reef areas; and a public information program to educate users on the importance of coral conservation. He also recommended the prohibition of all forms of random dredging for corals due to catch inefficiency (losses) and destructive impacts on the slower growing, deeper corals and their hard bottom habitats.

The need for sound management strategies for coral harvesting cannot be overemphasized due to the resource's slow rate of natural replenishment. Excessive exploitation implies a long recovery period and, translated into economic terms, a prolonged period of reduced harvests.

Because of these considerations, the U.S. Western Pacific Regional Fisheries Management Council (based in Hawaii) proposed that prior to the commercial harvesting of any virgin stocks in the region, a resource assessment should be completed to include total area of the bed, density estimates, and species present (U.S. Dept. of Commerce, 1979).

6.1.2 Precious Corals

Certain types of rare, slow growing corals are referred to as "precious corals" because of their special color, shape, hardness, texture, ornamental value and widespread commercial use by the handicrafts and jewelry industry (Poh, 1971; Wells, 1981). Wholesale prices for raw (dockside) precious coral can range from \$50 to \$500 per kilo, depending on the species, size, quality and color of the specimen (Eade, 1980). Ninety-five percent of the world's harvest of this resource comes from the Pacific. The most commonly harvested precious coral species are of the genera Corallium (white, pink, red, gold, and bamboo coral) and Antipathes (black and wire). They are only found in isolated colonies on hard substrates in water depths of between 30 and 500 meters.

Precious coral mining dates back to 100 A.D. in the Mediterranean region. In the Pacific the earliest recorded activity dates to the early nineteenth century in Japan but fell into temporary decline and was only recently revived by the Taiwanese in the mid-1950's. Today the sector is dominated by Japan, Taiwan, the Philippines and Hawaii (Grigg, 1970, 1976; Wells, 1981).

Harvesting techniques are of two types: non-selective use of a tangle net dredge (like an enormous industrial floor mop) which is dragged on deep coral beds to break off and ensnare specimens, or the use of one or more costly, more selective techniques (SCUBA, camera-assisted grabs, and minisubmarines with power driven cutting devices).

The non-selective, tangle net dredge approach has the obvious advantage of comparatively low capital and operational costs (boat, net, winch, and crew), continuous operation, and simplicity. The principal disadvantages of the technique are: damage to the substrate, low catch efficiency and removal of immature under-valued specimens. Conversely,

selective direct harvesting for deep-water species incurs high capital costs, has depth limitations and is technologically more complex. These factors, however, are offset by the fact that environmental degradation is minimized and a high catch efficiency assured.

Precious corals grow even more slowly than most hard corals (Noome and Kristensen, 1976). Since harvesting activity is expanding and prices continue to rise, the need for proper management of this rather exotic but valuable resource is obvious. The traditional approach to the management of precious coral resources has been by rotation of harvesting effort from bed to bed as dictated by the economics of a slow-growing species. This strategy, first documented in the Mediterranean in the nineteenth century, was self-imposed and based on traditional nine year cycles. Within the past two decades, more "scientific" approaches to coral management have evolved. Growth rates for black coral and the deeper-water species of Corallium were estimated to be six and one cm./year, respectively, and have been used to determine a maximum harvesting pressure which the coral population could sustain for an indefinite period of time, or maximum sustainable yield (MSY). In the case of black coral (which is more accessible), this was determined to require limiting annual harvesting to an area measuring two to four percent of the total bed (U.S. Dept. of Commerce, 1979).

The MSY determined for black coral has been adapted by the Western Pacific Regional Fishery Management Council (WPRFMC) to other slow-growing coral species, at least until data become available to support a more species-specific management approach. To implement the MSY through subsequent regulations the WPRFMC employed the concept of three discrete management units: established beds (determined by a history of exploitation); conditional beds (those beds whose location and area are approximately known and optimum yield determined by analogy with established beds); and exploratory beds (all remaining areas).

Based on these management units, regulations were formulated and proposed in a draft management plan for precious coral. These encouraged use of more selective approaches to harvesting and establishment of weight quotas and size limits for pink and black coral species.

In addition to these operational regulations, permits were required and refuge areas established for purposes of providing research control areas and reproductive reserves.

6.2 Beach Sand Mining

Information available on successful management strategies for mining beach sands is marginal. Campbell (1978) recommended that where physical or economic constraints require harvesting sand from beaches, a rigorous monitoring program be initiated prior to and during mining. The program would include an official responsible for regulating the removal of sand and confine all extractive activities to designated, pre-selected sites situated between high and low tides and rotated over time from beach to beach to allow for the rejuvenation of the mined area. Sites should also be confined to accreting beaches, and limited harvesting would be allowed only after a sand resources survey had been completed, calculating the sand budget and the effects of any sand mining "debit" factors. For detailed beach dune sand mining management requirements, the reader is referred to Nichols and Cerco's report on Puerto Rico (1983).

6.3 Marine Sand Mining

One alternative to mining beach sand and nearshore deposits is to identify suitable reserves for mining farther offshore. Areas where sand extraction causes minimal impact to the adjacent environment are channels and submarine canyons on the edge of some continental or insular shelf areas. These features act as sinks for the sand and are the terminal points for the sand transport cells (described in Section 4.1). Channels which have continued to receive sand over geological time have built up huge reservoirs of sand capable of sustaining most aggregate demand for extended periods. Nevertheless, care should be taken to avoid mining in proximity to the zone of active transport into the area for fear of accelerating up-drift erosion.

6.4 New Technologies

One result of increased concern over environmental degradation associated

with marine mining activities has been a focus on the development of new technologies designed to ameliorate undesired impacts. One such technology, the Submarine Sand Recovery System (SSRS), was developed and tested in Hawaii. The novel feature of the SSRS is the use of a suction probe which burrows beneath surface layers to extract sand, thereby reducing sediment loads. Designed to be used in thick sand deposits, the basic system consists of a small barge or boat, a vacuum pump, a flexible hose connecting the pump and suction head and a submerged plastic pipeline to facilitate direct pumping of sand to shore (Casciano, 1976). Sand is pumped shoreward as a slurry into a settling basin.

The SSRS was tested off the coast of Hawaii in fifty to sixty feet of water at a distance of 300 feet from shore inside a fringing coral reef. It is instructive to compare two post-operations environmental assessments, one completed four months after mining activity ceased (Maragos, 1977) and a second approximately five years later (Maragos, 1982). Interestingly, some of the significant near-term impacts (destruction of benthic molluscs, localized damage to corals, sea urchins trapped in sand pits) appeared to have no long-term consequences. The sand craters which were originally six meters deep and filled with "fines" had all but disappeared as adjacent sands migrated to fill the conical pit. However, this sand migration caused the undermining of an adjacent coral reef. As a result, a ribbon of coral collapsed along the reef edge, measuring 1-3 meters wide for a distance extending 200 plus meters along the reef-sand deposit interface.

Maragos (1977) recommends that a buffer zone 100 meters in width be established between any proposed mining activity and adjacent coral reefs and should be proportionally widened if the mining exceeds 10,000 cubic yards or creates a crater deeper than seven meters. The Water Bay experience reported in Section 5.3 suggests that Maragos' recommendations are appropriate, except that sand mining near a beach area should take place outside the ten meter depth contour with a buffer zone of at least 200 meters from the nearest beach.

7. ATTEMPTS AT RESTORATION

7.1 Beach Nourishment

Beach nourishment has become an increasingly popular strategy to mitigate erosion impacts on beaches, increase recreational space, and compensate for other causes of beach loss. Nourishment involves placing sand on an eroding beach, taken generally from offshore areas using any one of several extractive technologies. This is a potentially attractive strategy, but there are complications. First, the source of the original erosion must be identified and arrested and the beach stabilized or else the new sand will erode with the old. Secondly, a degree of short term biological disruption is to be expected at both sites of extraction and deposition. Finally, the emplacement of new beach sand may create longer term turbidity and sedimentation problems from fines washing out as sediment stabilization takes place over time.

Matching textural and size characteristics between existing beach and mined sand will reduce the rate of erosion. Analytical techniques are now available to identify this information. New fill must be able to withstand both storm surge as well as the moderate wave action typical of the beach if the threat of erosion is to be reduced.

Walton, et. al. (1977) described a beach nourishment project on Carolina Beach, North Carolina. There 2.5 million cubic yards of fill were placed on an eroding beach, of which 1.2 million cubic yards (or forty-six percent) were lost in two years due to erosion. New fill was deposited and a groin built, but both measures proved ineffective as total losses surpassed fifty percent. Loss of the beach was attributed to the mining of the fines and their subsequent displacement seaward by wave action and the cessation of upbeach littoral drift from the creation of the Carolina Beach Inlet (a man-made cut completed in 1952).

Where erosion persists after new fill is deposited on the beach, vegetation techniques are occasionally employed for purposes of stabilization. Best results have occurred in areas where some vegetation already exists or has existed in the past (Davis, 1975).

Where significant littoral movement occurs without natural replenishment, construction of groins may be necessary to contain fill. This

technique was successfully employed in Key West where fill placed on a rocky shore to create a 3,000 foot beach in 1960 was protected by four previously installed rock groins. Erosion over a six year period was estimated to be only thirty-seven percent, attributed primarily to wind transport (Walton, et. al., 1977).

However, a word of caution about groins is appropriate. In the cases of Water Bay (St. Thomas, U.S. Virgin Islands), Vigie Beach (St. Lucia)--see Sections 5.2 and 5.3--and on numerous other occasions, hastily installed or badly sited groins have failed to accomplish their purpose (beach sand accretion or stabilization) and either further damaged the site or were themselves damaged or destroyed. The decision to use groins depends on the particular physical characteristics of the proposed replenishment or stabilization site. Groin construction which fails to account for local beach sand transport patterns and seasonal variations can result in major adverse modifications to adjacent beach areas. The construction of these structures should be recognized as a complex task requiring a sound environmental and engineering plan.

7.2 Dredge Pit Stabilization

There is little information relative to the success of restoration attempts of dredge pits. One technique which has been attempted is the construction and emplacement of artificial reefs at the bottom of the borrow pits. Artificial reefs were first defined as man-made or natural objects placed in selected areas of the marine environment to provide or improve rough bottom habitat for purposes of increased productivity (Parker, et. al., 1974). Since 1974 artificial reefs have been used to accomplish commercial and recreational fisheries enhancement and solid waste disposal. In the only known use of these structures to fill dredge pits, Penn (1983) utilized an assortment of materials (rubber tires, concrete, car bodies) in Laucala Bay, Fiji to fill old dredge sites and to facilitate the development of a benthic community. Based on preliminary findings, he noted that car bodies were particularly conducive to settlement due to their rough metallic edges. There is no evidence that this attempt effectively stabilized the dredge pit.

Important considerations in the use of this technique are the existence of toxic substances in the materials (gas, oil, lead, copper); the location and site stability (bottom type, current and wave action); and the availability of suitable materials.

As an alternative to the use of artificial substrate to stabilize bottom, there have been numerous attempts at transplanting both sea grasses and corals to disturbed areas, including old sand and coral mine sites.

Sea grasses have demonstrated a capacity to bind bottom sediments with their root systems, reduce wave erosion through the protective covering afforded by their blades, and increase rates of sedimentation by current retardation attributed to their leaf structure (Thayer, et.al., 1975). Because of these characteristics, marine grasses have been the object of numerous replanting efforts. Of the approximately 125 attempts at sea grass restoration, the majority have occurred in the Gulf of Mexico and Caribbean regions. Despite these attempts in a history that dates back to 1945, problems continue to exist. Penn (1983), in an attempt to restore dredge pits in Fiji with sea grasses, cited high death rates attributed to herbivorous fish and turtles and the cost as the major constraints. Lewis, et.al., (1981), in a comprehensive experiment testing various combinations of grass species and techniques, achieved only mixed success in his attempts to restore a ten hectare borrow pit created in the Florida Keys over thirty years ago. However, even in the most successful combinations of sea grasses and transplanting techniques, costs ranged from \$27,000 to \$86,000 per hectare, suggesting --if only in economic terms--the importance of impact assessment and sound mining practices designed to preserve habitat rather than requiring its later, more costly restoration.

7.3 Coral Restoration

Even less is known about re-introduction of corals in previously disturbed areas. Maragos (1974) attempted to transplant two common species of corals in Hawaii to a degraded bay hoping to provide a site of settlement for coral larvae and to restore the bay's fauna. Based on the

experiment, he concluded coral transference may be an effective procedure for preserving and creating coral reefs, provided the original sources causing die-off were removed and allowance was made for the current and wave energy tolerances of coral species. In a related experiment, Maragos estimated that coral recovery may entail a 30-50 year time frame. Factors known to influence the period required for recovery are: extent of initial damage, condition of substrate availability of coral larvae, the role of grazers, competition from other species, and food availability (Pearson, 1981).

8. LESSONS LEARNED

8.1 Coral Mining

- Coral communities serve as one of the principal sources of sand for beaches and nearshore areas in tropical waters. Biological and physical weathering of these highly productive communities provide a major source of sand to nearby coasts, often surpassing the inputs from terrigenous sources.
- Coral reefs act as barriers for coastal beaches, communities and facilities, protecting them from the natural hazard of damaging storm-driven, high-energy ocean swell and waves. Removing or modifying some coral reefs can initiate or accelerate abnormal coastal erosion processes, resulting in economic loss and expensive restorative measures. Site examples from Indonesia, Sri Lanka and the Republic of Kiribati demonstrate the indirect economic costs associated with coral mining in terms of loss of shoreline land, declining coastal land values, and the increased need for costly remedial engineering work in affected coastal areas.
- Living corals are slow-growing colonial organisms which cannot sustain localized commercial exploitation without their rapid depletion. There was no evidence in the three site examples described (based on the literature) that the exploited reefs have demonstrated any signs of recovery. For environmental planning purposes, these organisms should be treated as non-renewable resources. No effective exploitive management strategy has yet been developed, nor are restorative techniques sufficiently well known to permit significant commercial harvesting. Even non-commercial artisanal harvests of coral should be monitored closely, as extraction rates, although low, may still exceed natural re-generation.

8.2 Beach Sand Mining

- Adverse effects of excessive beach mining may be deferred for years before they become evident due to seasonal and other ephemeral factors affecting beach dynamics. In both the St. Lucia and Puerto Rico examples, large scale changes in beach dynamics were delayed

several years. In the case of St. Lucia, a major tropical storm was contributory in accelerating the effects of chronic sand mining on Vigie Beach. In Puerto Rico, widespread erosion on Carolina Beach was not reported until several years after initiation of mining activities.

- Many small scale beach sand cells with few outside sources of sand renewal cannot support intensive extraction pressures. St. Lucia's Vigie Beach appears to be an excellent example of this beach type. Natural inputs could not compensate for extraction pressures, and sand had to be replaced finally through costly beach nourishment.
- Beach dunes play a critical role in shore protection; their removal or degradation could signify large scale economic loss associated with storm surges, waves and flooding. The three beaches described in Puerto Rico demonstrate that reduced size, height and stability of dunes resulting from mining activities increased natural hazard risk.
- Preservative and restorative responses to beach degradation are costly, often offer only temporary relief, and may themselves have adverse environmental impacts at both site of extraction and deposition. In St. Lucia the "ineffectiveness" of a patchwork strategy at Vigie Beach, involving experiments with gabion mattresses, rock groins and eventually beach nourishment, was demonstrated.
- Long term economic losses resulting from beach sand exploitation must be analyzed against shorter term economic gain--the balance may justify the development of alternative sources of aggregate. If the total costs associated with the mining of Vigie Beach could have been predicted, coupled with the long term aggregate needs of Castries, the development of nearby terrestrial pumice sand resources, as an alternative to beach sand, might have been selected when this option was first considered more than a decade ago.

8.3 Marine Sand Mining

- High turbidity and increased sedimentation associated with marine sand mining can result in severe degradation of benthic communities

(marine grass beds and coral reefs), especially those requiring consistently good light penetration and non-turbid water. Surveys conducted in Water Bay (St. Thomas, U.S. Virgin Islands) after sand mining documented significant coral kill (ranging from 20 to 90 percent) directly related to proximity to the dredge sites.

- Mining too close to shore can affect coastal nearshore processes, resulting in major changes such as the loss of an adjacent beach, alteration of berm and coastal vegetation die-off. The Water Bay site history documents the loss of Sugar Bay Beach by its slumping into the adjacent dredge pit. Other changes included reduction in height of the back berm and die-off of exposed coastal vegetation.
- Failure to define the characteristics of the target materials for mining through pre-dredge boring at the site can result in the exposure of highly erodible substrates beneath sand deposits which may later act as chronic sources of turbidity. Exposed layers of mud directly underlying sand deposits mined in Water Bay created a source of chronic water turbidity. The continuing suspension of mudfines, clays and organic materials may have played a significant role in the observed coral die-off and prevention of recolonization of both the dredge pits and adjacent impacted areas.
- Sand mining often conflicts with other coastal uses and, if beaches and water quality are degraded, may result in economic losses. Water Bay provides an excellent example of resource use conflict which first became apparent during an initial hotel-sponsored dredging operation. That activity ultimately conflicted with the desire of resident and prospective hotel visitors to have access to undisturbed water quality at the beachfront, and when subsequent dredging activities were proposed for an adjacent area, opposition arose from the hoteliers who recognized the economic consequences (i.e., reduced occupancy) of indiscriminate or badly sited dredging operations and argued publically for environmental controls.
- Mining in shallow protected waters can leave bottom "borrow" pits as semi-permanent features which act as traps for fine sediments and become chronic sources of resuspended material. Some of the

traps identified in the Water Bay case study, originally dredged in the 1960's, still show little evidence of filling or of recolonization.

- Although restorative techniques exist, in general, they are expensive, technically demanding, and only partially serve their objectives. In the final analysis, careful planning and management of mining activities is far preferable to restoring degraded sites.

9. GUIDELINES

- (1) Commercial mining of living coral reefs should be restricted and in most cases prohibited. Corals are slow growing organisms. Since effective management strategies have yet to be discovered, living reefs do not appear to be able to sustain extractive pressures. Their importance as productive marine systems, artisanal and commercial fishing sites, recreational attractions, and natural breakwaters seems to far outweigh the value derived from their direct exploitation for construction material or other consumptive uses. Zoning allowable uses for coral reef system "exploitation" is a desirable strategy, demarcating protected areas and sites and sectors for artisanal harvesting, fishing, diving and mining activities. Permits are useful but require performance and practice monitoring. An alternative to harvesting the living reef for meeting these local needs is the rubble lagoonal area and algal reef flats behind the reef crest. Caution is, however, required as this zone also serves as a wave energy absorption barrier, and excessive dead or live coral harvesting can have seriously damaging effects on adjacent shorelines. Mining of the rubble area and reef flats should be discouraged in areas adjacent to eroding shorelines and more vulnerable beaches.
- (2) Precious corals, which grow much slower and deeper than most reef corals, require special management approaches as they come under pressure from commercial harvesting activity. Commercial tangle net dredging for precious corals damages both the substrate and immature specimens and should be gradually phased out in favor of more selective harvesting methods which should be encouraged. Extraction activity should not exploit more than four percent of known bed area per annum. Weight quotas and size limits should be applied and a permitting systems established for commercial uses.
- (3) The mining of beach sands should generally be discouraged. When the scarcity of accessible alternative sand resources dictates the need for beach and dune mining, extraction should proceed slowly and be carefully monitored and regulated, employing such management

tools as periodic beach profiling and rotation of sites, licensing of commercial users, and quantity quotas as needed, based on site-specific sand budgets. Preferred sites include accreting (growing) beaches, multiple dune systems, or other stable reservoir areas known to be the terminus of sand circulation cells or sinks.

When sand mining is terminated, beach berm and dune sites (especially on windward shorelines) should be replanted with appropriate stabilizing vegetation to prevent further sand loss due to wind erosion.

- (4) The mining or dredging of offshore sea bed sand and aggregate is the preferred alternative to beach and dune mining, providing adequate site selection strategies, antecedent impact assessments, and controls are employed to prevent or minimize potential adverse effects on coral reefs and coastal areas. Waters should be sufficiently deep and open to currents in order to speed the dispersion of suspended sediments and leveling of dredge sites upon completion of operations through natural movement of bottom sediments. Preferred marine sand deposits are stable reserves at the ends of the submarine sand circulation pattern, such as near the heads of submarine canyons where sands are known to be drifting deeper and are no longer a part of the local circulating sand budget. Windward facing bays and beaches are more unstable than leeward systems, and wind and wave approach angles can be important factors in choosing a sand mining site.

- (5) Mining activities for sand and aggregate should be preceded by a country-wide, systematic resource inventory to provide a rational strategy for selecting appropriate sites and extraction technologies and to link the mining project with local supply and demand options.

The inventory should include:

- identification of existing, high quality sand "reservoirs";
- identification and classification of marine sediments scheduled for removal by dredging as waste material or spoil;
- characterization of the deposits (depth, sediment sizes and proportions, extent of coverage);

- characterization of the local environment of each site to include identification of the existing sources and sinks of the particular sediment deposit (sand, aggregate, silt), relevant processes linking the two (current regime and transport units), marine communities potentially affected by mining activities, potential for reintroduction of toxic substances, and storage options;
 - economic and environmental assessment of exploiting alternatives to coastal/marine sources (pumice, quarry fines, river sand).
- (6) Marine sand mining sites, except those in major harbors and ship channels, should be located as far as possible from living coral reefs and sandy beaches. A minimum buffer zone of 100 meters between the dredge borrow pit edge and the nearest coral reef is recommended (more if the mining exceeds 10,000 cubic yards or the pit is deeper than seven meters). Any nearshore marine mining adjacent to a beach should take place outside the ten meter depth contour and have a minimum 200 meter buffer zone separating the dredging site and the beach's edge at low tide. Special monitoring of the current borne plume of fine sediments generated by any marine dredging is important if there are sensitive marine habitats (e.g., coral reefs) in the area. The plume shape and axis can change dramatically due to ephemeral wind, wave, and current factors and can necessitate prompt reduction in plume densities and dimensions by reduced extraction rates or even temporary shut-down.
- (7) Marine mining site selection, especially for sand and aggregate, should be based on a thorough analysis of the available environmental information and relevant socio-economic data necessary for assessing alternative locational, dimensional and technological options. In the absence of an antecedent, comprehensive sand resource inventory (Guideline 5) there is a need to elicit coastal current data from local fishermen, divers and others who traditionally use the area, also encouraging their participation in future "monitoring" strategies regarding impacts. Final site selection should consider issues such as biological productivity,

alternative present and future uses, and shoreline spoil disposal and emplacement problems.

- (8) Once site selection has been completed, a more comprehensive baseline study and project management plan for the specific location is desirable in order to establish detailed operational guidelines for the contractor. An understanding of the precise physical, biological and biochemical characteristics of a site and environmental quality tolerances of specific biotic communities (which may have been subjected to prior stress) are required if monitoring activities with clearly identified standards are to be effective.
- (9) A monitoring program should be developed adhering to pre-determined environmental quality standards. Monitoring parameters should include: environmental factors most likely to be affected by mining activities and tolerance ranges of potentially affected biotic communities to environmental disruptions. Once the parameters are identified, standards should be set using the baseline and other pre-existing information. Standards, if exceeded during operations, would warrant a modification or temporary cessation of activities. An assessment of available extraction and control options should be completed to determine the most appropriate system for site conditions. Whenever possible, full scale mining operations for large projects should be preceded by a pilot mining phase in order to test impact assessment, monitoring procedures, and control strategies.
- (10) Follow-up (post-audit) environmental assessments should be completed after any temporary or final cessation of mining operations. Follow-up assessments are required to confirm volumes harvested and to gauge the degree of impact on and recovery of the site and adjacent habitats after cessation of activities. They also represent a means to fill a critical data gap in the understanding of specific types of mining activities carried out in local waters, essential to the development of improved, practical standards and more cost efficient strategies for future dredging or mining operations appropriate to the area.

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