Assessment of Tsunami Impacts on the Marine Environment of the Seychelles

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ABSTRACT

The tsunami that hit the Seychelles islands on 26 December 2004 had traveled approximately 5000 km from the epicenter, offshore Sumatra, in less than seven hours, and had a wave-height of 2.5-4 m at first landfall. This study was conducted as part of the official UNEP Tsunami damage assessment to affected countries of the Indian Ocean, in February 2005. Two major patterns in coral reef damage were noted, dependent on the geographic location of each island, direction of exposure at each site, and reef substrate. The northern islands clustered around Praslin (including Curieuse, La Digue, Felicite and the rocks of Isle Coco and St. Pierre) showed very high levels of damage (approaching 100%) on carbonate reef substrates. By contrast, sites around Mahe showed much lower levels of impact, generally below 10%, due to the shelter provided by the outer northern islands and dissipation of wave energy as the tsunami traveled over the greater distance of shallow water from the outer edge of the banks to Mahe. Granitic surfaces and reefs suffered little damage due to their density and hardness. On solid carbonate reef surfaces attached corals showed little breakage and mechanical damage or overturning. However the majority of true coral reef sites in the granitic islands have a reef framework that was only loosely consolidated due to coral mortality during the 1998 El Niño and subsequent bioerosion. This reef matrix was not robust enough to resist the tsunami waves, either from direct impact of the force of water, or movement of rubble and rocks. In these areas significant reef rubble was moved by the wave and consequently associated live coral colonies were also displaced and damaged. Thus > 50% of substrate damage and >25% of direct damage to corals in northern and eastern-facing carbonate framework sites was recorded, <10% damage in shallow carbonate substrate sites in central, western and southern locations, and < 1% damage on all granitic substrate sites. Coral reefs are very important to the economy, society and infrastructure of the Seychelles – all the damaged northern sites are prime tourist locations for the country, and the most highly damaged terrestrial locations are adjacent to degraded reef areas. Though impacts from the tsunami was less than other threats, such as coral bleaching, they highlight the differential vulnerability of different locations and the need to implement strong measures for reef and coastal conservation.

INTRODUCTION

Background

The Seychelles comprises 115 islands covering a land area of 455 km^2 in the western Indian Ocean, between

Obura, D.O., Tamelander, J., & Linden, O. (Eds) (2008). Ten years after bleaching - facing the consequences of climate change in the Indian Ocean.CORDIO Status Report 2008. Coastal Oceans Research and Development in the Indian Ocean/Sida-SAREC. Mombasa. http//:www.cordioea.org

Figure 1. Map of the inner granitic islands (Mahé and the Praslin-La Digue group showing study sites visited during this survey. Sites visited included: Prasling-Curieuse-La Digue - 1. Isle Coco, 2. Felicite, 3. La Digue, 4. Madarin/Red Point, 5. Grande Anse, 6. Coral Gardens, 7. Baie Launay, 8. St. Pierre, 9. Anse Petit Cours. Mahé – 1. Anse Cimetiere/ Moyenne/ Grand Rocher, 2. Airport, 3. Baie Ternay, 4. Anse Royale,

4 and 11°S (Fig. 1). Forty-one islands comprise the inner granitic group of mountainous islands, within a radius of 50 km from the main island Mahe, with Mahe, Praslin and La Digue being the largest and most important for towns and settlement. The outer islands are all coralline and built of old reef carbonate growth, and rise to only a few meters above sea level.

The tsunami

The tsunami wave that hit the Seychelles islands on 26 December 2004 had traveled approximately 5000 km from the epicenter, offshore Sumatra, in less than seven hours. At 13.00 hours waves ranging from 2.5m to 4m in height hit the east coast of Praslin, La Digue and Mahé islands. The effects were felt all along the east coast of Mahé, propagating over a 30 minute period. Refracted waves hit the west coast of Praslin and Mahé 30 minutes to 1 hour after the respective east coasts were hit. Another wave occurred at 17.00 hours, followed by two smaller waves at 22.00 hours and 05.00 hours (on 27 December). The second wave had more or less the same effect as the first because, although smaller, it occurred at high tide. The two smaller waves caused damage only on the west coast of Praslin. The surges caused by the waves flooded the low lying areas of Mahé, Praslin and La Digue and caused widespread damage to beaches, coastal vegetation, roads, bridges, other infrastructure and houses. The flooding continued for a period of about 6 hours. Two people lost their lives.

The tsunami was followed on 27 December 2004 by extreme weather with rainfall reaching 250 mm in the northern and central areas of Mahé. Torrential rains continued for several days. Runoff from the hills formed virtual rivers that swept across the country, causing widespread landslides, tree and rock fall in the northern and central part of Mahé and in other areas, with associated further damage to infrastructure, dwellings and the vegetation on slopes. The rainfall caused more widespread damage to land areas of the Seychelles, thus hampered immediate mitigation and focus on tsunami impacts. Together, these almost simultaneous incidents caused serious damage to the infrastructure of the Seychelles.

The coastlines of the Seychelles granitic islands are of two types: 1) granitic rock which is often steeply sloping or accidented with large boulders and rockfalls; 2) coralline coastlines backed by flat coastal plains and fronted by fringing coral reefs (of either old or recent construction). On the coralline coastlines, the fringing reef crests break waves sufficiently to enable the coastal plains to form from sediment accumulation. Between the reef crest and shoreline, sheltered lagoons may be present, backed by fine sand beaches. Channels in the fringing reefs allow the passage of water in and out of the lagoons with the tides. The flat land, calm lagoons and ocean access of the coralline shorelines have attracted settlement and development, supporting a large proportion of agriculture, urban development and tourism of the Seychelles.

Fringing coral reefs around the central granitic islands have allowed the development of fine sand beaches and lagoons, and settlement of the sheltered coastal plains behind them. Channels through the fringing reefs provide access to the ocean from safe harbours for artisanal fishing boats and pleasure craft. The same coral reefs provide the primary infrastructure that supports Seychelles' tourism industry, providing beaches and sites for snorkeling and SCUBA diving. Due to stresses from development and overfishing, and then the mass coral bleaching of

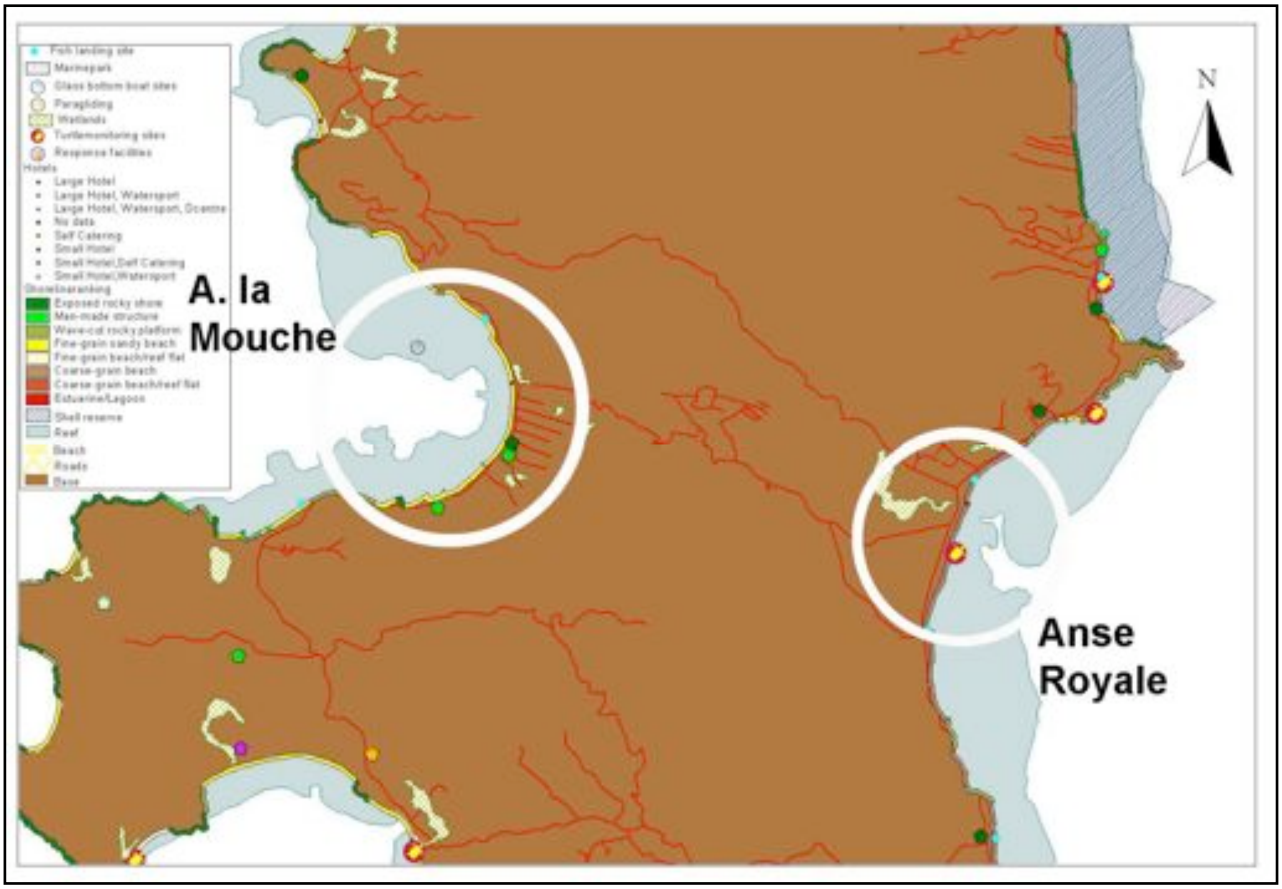

Figure 2. Map of central-southern section of Mahe Island showing areas of maximum terrestrial impacts at Anse Royale and Anse la Mouche channels in the fringing reefs (reefs shown in blue) approach closest to land. Map source: Seychelles Ministry of Environment.

coral reefs in the Indian Ocean in 1998 that caused 80-90% mortality of corals, many of the granitic islands' coral reefs are significantly degraded.

Terrestrial Impacts

Impacts of tsunami waves are strongly affected by the shape and bathymetry of reefs and channels to the open sea –reef crests, complex coral reef surfaces and granitic shorelines absorb and dissipate the wave energy, while deep channels allow focusing of the waves closer to land and lead to higher wave heights. The importance of the coral reefs is shown by the locations of major terrestrial and coastline damage, and the influence of these marine ecosystems on shoreline vulnerability (Fig. 2). The major locations of terrestrial damage, at Anse Royale and Anse Mouche, on Mahe, and to the seawall in Curieuse Marine Park, are located on fringing reef coastlines. Significantly, shoreline damage was focused where deep channels lead through or up to the fringing reefs, focusing and amplifying the wave energy to these points. Thus the combined shelter and ocean access that have allowed coastal development just above the high tide line adjacent to fringing reefs contributed to the high vulnerability of these to the tsunami. This vulnerability will also extend to other wave- and storm-related threats, and intensification of these threats through sea-level rise and changes in storm patterns.

METHODOLOGY

As part of the UNEP fact-finding mission, the IUCN Global Marine Program and CORDIO were requested to assess the tsunami impacts on the marine environments of the Seychelles, undertaken from February 3rd-13th, 2005. The study included stakeholder consultation and site visits to eight of the inner islands of the Seychelles (Fig. 1). It was not possible in the time available to include outer atoll islands.

Two survey methods were used. The first was developed as a rapid assessment tool by the SCMRT-MPA in conjunction with the Marine Unit in the Department of Environment, and conducted by staff and rangers at MPA and other sites on Mahe, Praslin and Curieuse (SCMRT 2005 a,b,c). Four observers conducted approximately 10-minute samples, each assigned some of 7 coral taxa/groups (*Acropora*, other branching corals, foliose, massive, encrusting, fungids and soft corals). Colonies were recorded as damaged or undamaged (broken or overturned) along with general observations on the status of the reef. Colonies completely missing due to wave damage were not possible to differentiate using this method. Because the main coral reef areas in the Seychelles were significantly affected by high mortality in 1998 and had weak eroded frameworks at the time of the tsunami, it is likely that many coral heads were completely removed from the study sites, and thus not recorded. Surveys were conducted in 3 periods covering Mahé (30 December 2004), Curieuse (5 February) and Praslin (5 February).

The second method used was an ICRI/ISRS (International Coral Reef Initiative/International Society for Reef Studies) methodology for assessment of damage from the tsunami to coral reefs, developed during January 2005 (ICRI/ISRS 2005), using a 0-5 semi-quantitative scale (Table 1). This method recorded a broader variety of variables including damage to live corals, damage to the substrate and debris from the terrestrial environment. The method is based on samples of $10m^2$ areas of the bottom, selected haphazardly during swims across the sample area.

Table 1. Classes used for estimation of benthic cover and the incidence / abundance of tsunami damage indicators. Based on Australian Institute of Marine Science long term monitoring programme and English et al. 1997.

Class	*Range (%)*	*Desc*
0	0	None
1	1-10	Low
2	11-30	Medium
3	31-50	Common
4	51-75	High
5	76-100	Extreme

Details of the method can be obtained from the authors and the UNEP website (http://www.unep-wcmc.org/latenews/emergency/tsunami_2004/coral_ass.htm).

RESULTS

In general, the extent of the damage caused by the tsunami will mainly depend on the slope and topography of the seabed. On gradually sloping shorelines, the energy of the wave appears to build up, sucking water away from the shore, followed by powerful flooding waves and surge transporting vast amounts of water and unconsolidated rubble. Direct damage of the tidal waves results from the massive water flows and associated kinetic energy while indirect effects include sediment deposition and land-based pollution (nutrients, pesticides, industrial and urban chemicals, biological material) brought by the backwash. Increases in turbidity and organic carbon, as a result of this pollution, may result in oxygen depletion, potentially detrimental to fish, corals and seagrasses.

Primary Impacts to Coral Reefs

Coral reef damage in the inner Seychelles islands was limited principally to physical breakage due to the tsunami waves, surge and, potentially, backwash. Damage was documented to reef substrates, mobilization of sand and rubble, and damage to live corals. Limited damage from siltation and debris was noted, and no evidence of coral diseases or other effects of pathogens or pollutants was seen. Types of damage are summarized below. The assessment focuses on damage to coral reef habitats, but also mentions associated habitats and species.

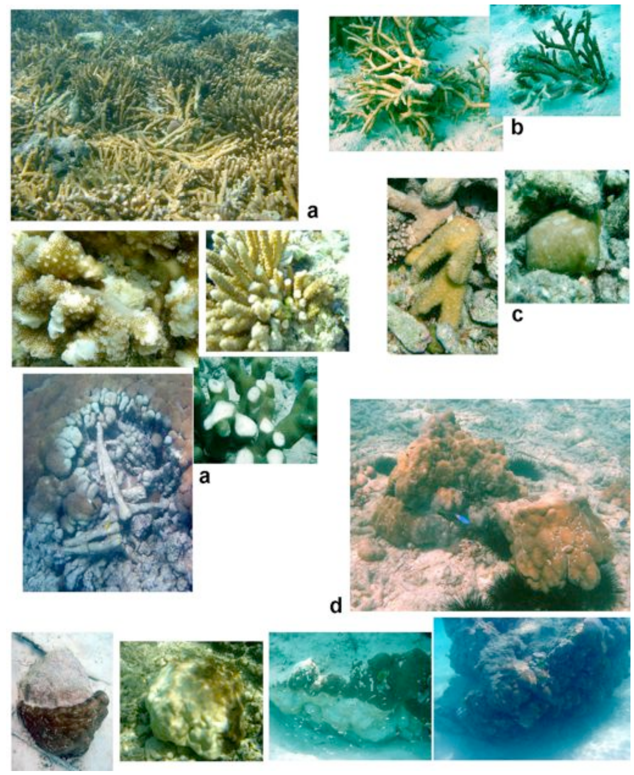

Figure 3. Mechanical damage to corals occurred by breakage of predominantly branching corals and overturning and smothering of massive corals. A) *Acropora* and *Pocillopora* were highly susceptible to breakage, though *Porites* and columnar corals like *Goniopora* also suffered damage. Coral fragments suffered mortality due to partial smothering in sand (b) and in mobile rubble (c). Overturning of massive corals (d) occurred where their bases were only loosely attached, and in sediment where mobilization of sand away from one edge of a large colony could lead to tipping, of boulders > 2 m in diameter. Mortality of massive coral surfaces buried in sand was one of the most significant mortality agents noted.

Mechanical damage to corals (Fig. 3)

Mechanical damage to corals was documented as breakage of branches and overturning. *Acropora* and *Pocillopora*, being the two main genera of branching corals on Seychelles' reefs were the most frequently observed to be damaged. *Pocillopora* occurs as individual heads up to 30 cm in diameter, and damage was observed as broken branches off a parent colony, and loose branches in the rubble. By the end of these surveys (on February 12, some 48 days or 7 weeks after the tsunami), most broken sections of Pocillopora had not fully healed with incomplete tissue growth over the break. *Acropora* was present as

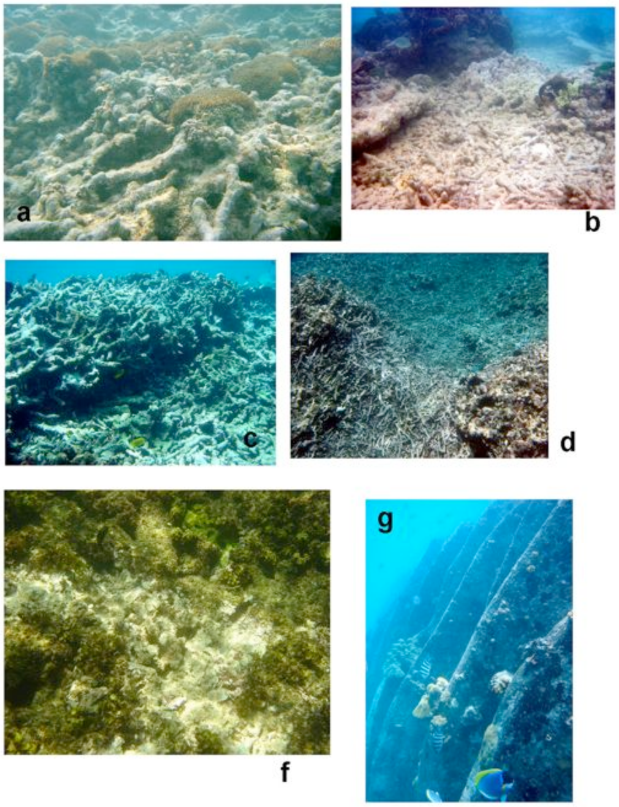

Figure 4. Mechanical damage: a) coralline subtrates showing poorly consolidated framework of branches and rubble, with corals growing on top. This framework was easily damaged (b, c, d) by wave and surge energy, and battering with rubble and rock pieces. F) Damage to consolidate coralline rock shown by scars where protruding corals or rocks torn off. g) No damage was recorded on any granite substrates.

individual colonies and as fields or thickets of staghorn morphologies. The former suffered breaks similar to *Pocillopora*, while for the latter a field could be entirely flattened, with scattered branches in the rubble in all directions, or in a consistent direction.

Mechanical damage to substrate (Fig. 4)

No damage occurred on any granite substrates, nor was there any clear indication of movement of granite rocks and boulders larger than 50 cm or so. Carbonate reef substrates showed considerable signs of damage. In areas of hard old reef framework, minor damage was noted by the presence of scars where rocks and perhaps corals were torn off, but the intensity of damage was low and restricted to areas shallower than 50 cm (e.g. Anse Royale). Coral reefs that were healthy before the 1998 coral bleaching event but suffered high mortality have shown only partial recovery since then, with the result that the reef framework is mostly made up of loosely consolidated coral skeletons and branches. Just before the tsunami, these had a varying degree of live coral attached to the reef or growing on loose rubble pieces of different sizes. These reefs showed severe physical damage by the tsunami waves with widespread rubble, loose rocks, overturned corals and eroded craters showing evidence of movement. Without definitive data before the tsunami it was hard to determine absolute levels of mechanical damage to substrates, however in general it appeared high, and in some cases (e.g. the northerly-exposed sites of I. Coco and St. Pierre) rubble movement and total damage may have been as high as 100%. Before the tsunami many of these areas had low coral cover so damage to coral was minor; however damage to the reef matrix was very high.

Movement of substrate (Fig. 5)

Movement of loose rocks and rubble was a major factor in exacerbating damage to reef substrates and to corals. Granite rocks were too dense and rounded, and showed no evidence of having been moved . Carbonate rocks were extensively moved, in all sizes from small rubble, through large dead *Acropora* tables to massive *Porites* heads over 1 m across. The low density of carbonate skeletons and the often irregular shape of rubble fragments contributed to their ease of movement by waves. In some cases, massive *Porites* heads 2 m in diameter and greater were toppled, though this was likely due to sediment movement, another form of damage described below. In some areas, such as Grand Anse, Curieuse, whole areas of the bottom looked whiter (observation by MPA ranger, Paul Lavigne), due to the overturning of rubble revealing their whiter undersides (with darker algal growth on the upper surfaces).

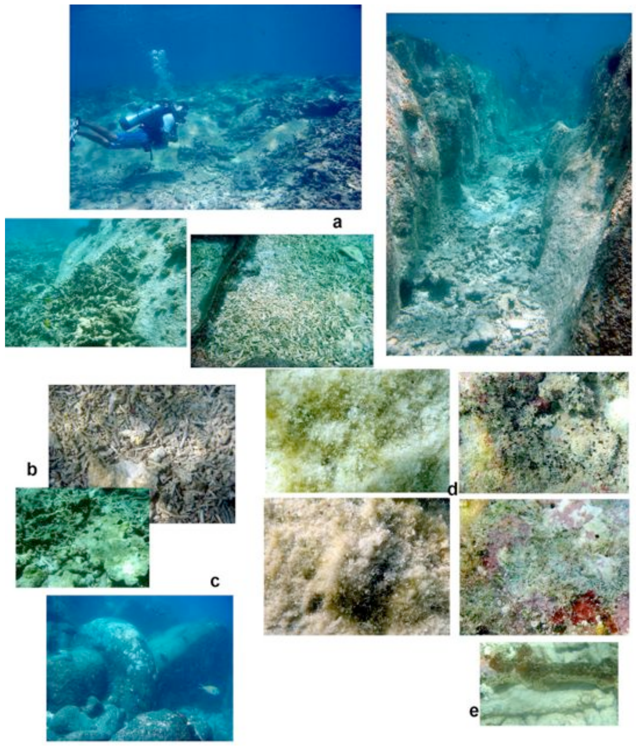

Figure 5. Movement of substrate: a) in areas with rubble and unconsolidated coral framework, extensive movement of broken rubble and pieces occurred, shown by drifts of rubble against immovable granite bedrock. b) detail of coralline rubble showing predominance of branching pieces as well as large flat plates, e.g. from dead *Acropora* tables. c) granite boulders were not moved, being too dense and rounded. d,e) impact of rubble movement visible in algal growth covering the rubble – lower sides (right hand panels and upper branch in e) having coralline algae and other encrusting/boring organisms, upper sides (left hand panels and lower branch in e) covered with fine white sand and short algal filaments representing a few weeks of algal growth. This gave a white appearance to many highly disturbed areas.

Sedimentation/siltation (Fig. 6)

The tsunami waves, compounded by heavy rainfall and rough seas in the following week, mobilized extensive amounts of marine and terrestrial sediment. Missing sediment was commonly noted in many reef habitats, where old rubble that had likely been buried in sediment for many years was exposed. These areas were distinguishable because they lacked mature algal communities of filamentous, turf or coralline algae. At distinct reef channels, such as in Baie Ternay, erosion of sediment from the channel edges was noted, up to an estimated 70 cm of sediment lost.

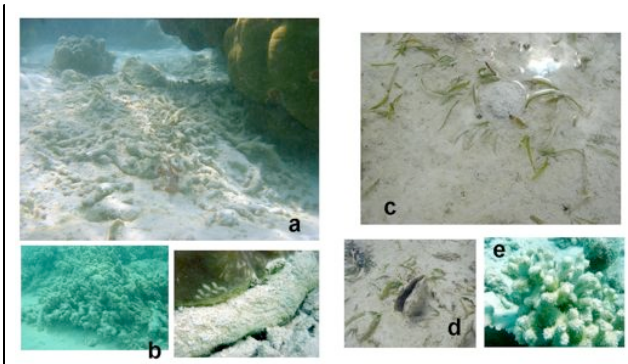

Figure 6. Sedimentation damage: extensive sediment movements occurred due to the surging of waters back and forth by the tsunami, resulting in exposure of buried rubble around many coral bommies, reef structures and channels (a, b). Mobile sediment was deposited over shallow seagrass beds causing high mortality of seagreass and pen shells (d). Fine silt released into the water column by the waves deposited slowly on many rock surfaces, including rubble and newly dead coral surfaces (e).

Silt deposition on rock surfaces was noted, in layers up to 2-3 mm thick on surfaces that often had a cover of thin algal filaments. However, because of the time since the tsunami waves, it is possible that more silt had built up because of subsequent factors, or some had been lost. Heavy sedimentation on a seagrass bed was also noted (see above). Interestingly, high siltation was noted only for white carbonate silt, not darker terrigenous soil, suggesting little impact of the heavy rains following the tsunami.

Curieuse Wall and Mangrove Forest

Extensive damage was done to the causeway/wall enclosing a shallow lagoon previously used for turtle farming, and a mangrove forest area in the Marine Park at Curieuse Island. The mangrove forest developed over the approximately 100 years that the causeway has been in place, and is one of the largest in the Seychelles, containing 7 of the 9 species found in the islands. More than one half of the wall was knocked inwards by the tsunami waves, with the principal damage occurring where a channel leads up close to the wall and from this point east to the Park HQ beach. At the time of this study, no damage had been noted to the mangrove forest, as it is sheltered from the winds of the northwest monsoon. However, a wide channel on the beach and near shore was created by the large volume of draining water. This may further develop into erosion of the leading edge of the mangroves, with consequent loss of habitat area and species. The loss of mangrove forests could have major consequences on local marine biodiversity as these areas provide habitats for many juvenile and adult crustacean and fish species. The mangrove forest is one of the primary attractions for visitors to Curieuse Marine Park, accessed using a boardwalk that was also damaged by the tsunami. Without repair to the wall, further damage to the boardwalk will occur during the southeast monsoon and the combined loss of mangroves and boardwalk may significantly reduce financial income from the Marine Park, which subsidizes other protected areas that cannot support themselves.

Site Damage Summaries

Northern islands, north-east exposure

Several sites were surveyed around Curieuse Island, in the Marine Park, including Grand Anse, Baie Launay and sites to the north and west. Overall 8.1% of coral colonies showed signs of tsunami damage and extensive rubble movements were noted on shorelines facing east, south and north. On a deeper site at 8 m east of Curieuse (Coral Gardens), many massive corals were overturned and exposed due to their eroded bases and weak framework. Many live coral colonies (*Acropora*, *Pocillopora* and *Tubipora*) were washed up on the beach. Other damage included broken *Acropora* stands in Resort bay, and damaged turtle nests (see later section).

The coral reef at I. Coco was the farthest-east reef surveyed, and faced directly the path of the oncoming tsunami. St. Pierre is more sheltered, but both sites share a morphology of exposed granite rocks on their seaward side, and an extensive development of reef corals and carbonate framework in the shallows and in the lee of the islands. In both areas, corals on granite substrates showed little damage. However the reef frameworks of dead staghorn *Acropora* exhibited a near-total devastation. Signs of damage included: mobile rubble pieces and broken coral fragments, the accumulation of large amounts of carbonate rubble in drifts up the sides of granite boulders and in depressions, loose dead *Acropora* tables (their large surface area making them easy to move) and craters/ depressions in the branching framework where back and forth movement of such pieces by the waves caused erosion of circular depressions. There were also erosion gullies through the framework where large sections of rubble framework may have been transported to deeper water. Damage to the reef framework was consistently estimated at > 50%. Corals close to the bottom on granitic surfaces showed evidence of breakage, likely due to rubble movement along the bottom.

The bay at La Reserve/Anse Petit Cours is west-facing. It was surveyed for two reasons: first, the shoreline and hotel suffered extensive damage, and second, this reef area suffered some of the lowest mortality of coral during 1998. Reef structure is slightly similar to Baie Ternay, with an extensive area of shallows leading out from the beach, and a sloping reef with high coral cover to a sand base at 6 m leading into deeper water. The island shoreline leading west from the bay is steeply sloping, with a fringe of coral growth at 1-10 m depth. Coral diversity was observed to be higher than other locations. Extensive rubble damage was found in the shallows, and because of the higher abundance and diversity of corals, higher levels of breakage of live coral. In particular, flattened areas of staghorn *Acropora* were common (e.g. *A. austera*), and damaged stands of the extensive columnar growth forms of *Goniopora*. Because of the sloping sand base, many *Porites* colonies in waters > 6 m were toppled, due most likely to erosion of sand from under one side and tumbling of the colony/ boulder.

Mahe, north-east exposure

Among all sites on Mahe, damage to coral reefs was highest at Anse Cimetiere with at least 27% of colonies showing signs of physical and mechanical damage. The damage to this site is likely underestimated as most of the coral colonies that were damaged were completely destroyed and therefore were not included in the sampling methodology employed by SCMRT. Historical data of this site show that the reef slope has experienced an 80% reduction of coral cover as a result of the tsunami, from 20% to < 5%.

The coral reef of Baie Ternay Marine National Park, on the northwest tip of Mahe Island, was among the most damaged sites on Mahe (Fig. 7), and illustrated the different types of damage (above) based on habitat and depth. It is a highly enclosed bay, with a reef crest dividing the inner seagrass/beach area from the outer deep bay, the reef crest being just below the surface and reef growth down to 8-10 m. Damage to corals was negligible below about 3 m, but > 10% of vulnerable branching corals at the reef crest were broken. A large proportion of the reef crest is dead branching corals from 1998, however the sheltered bay has enabled complete consolidation of branches and rubble by coralline algae, which prevented re-breaking of the framework by the tsunami. See 'seagrass' section, below, for a description of sedimentation impacts, and beaches around the east and west boundaries of Baie Ternay were built up by sand deposition. Overall, compared to long term damage caused by coral bleaching during the El Niño of 1998, damage from the tsunami event was minor.

Figure 7. Aerial photograph of Baie Ternaie, western point of Mahe, showing major habitats and illustration of primary points of damage: green – shallow seagrass, extensive smothering by sediment and mortality of seagrass and pen shells; black – reef crest and shallow rock/rubble/sand environments with high pre-existing coral mortality from 1998, showing mechanical damage to corals and substrated; red – main coral reef and growth areas, good recovery from mortality in 1998, minor damage to corals little to no damage to substrate; blue – channel, extensive sand-scouring and transport of sand out of channel.

The reef at Anse Royale is an old carbonate platform dominated by fleshy algae (*Sargassum*, *Turbinaria*) due to its highly exposed position to waves from the east and long term degradation from coastal land use. Tsunami damage was surveyed from a depth of 6 m, but was limited to the shallowest 50 cm at the reef crest where scars on the framework show where rocks (or perhaps corals) were ripped off.

Mahé, south-west exposure

Damage to granite reefs at the southern-most point of Mahe and in Port Launay was negligible. In the large bay of Anse la Mouche/Anse Copra corals grow in typical sheltered backreef areas, dominated by opportunistic species on eroding substrates in the shallows, and deeper reefs dominated by large massive corals. The area is impacted by eutrophication from land and overfishing, with large sea urchin populations. Damage was patchy, with some areas showing no damage. However in some locations on the deeper reefs below 5 m staghorn *Acropora* coral heads were broken by the waves. In the shallows large massive corals were toppled as their bases are highly bioeroded and likely also be sediment displacement from underneath. In the shallows small branching corals were completely undamaged. Overall, coral damage was less than 5%. A layer of sediment appeared to have been removed from the reef, with extensive fields of fine rubble visible in the channels between coral heads.

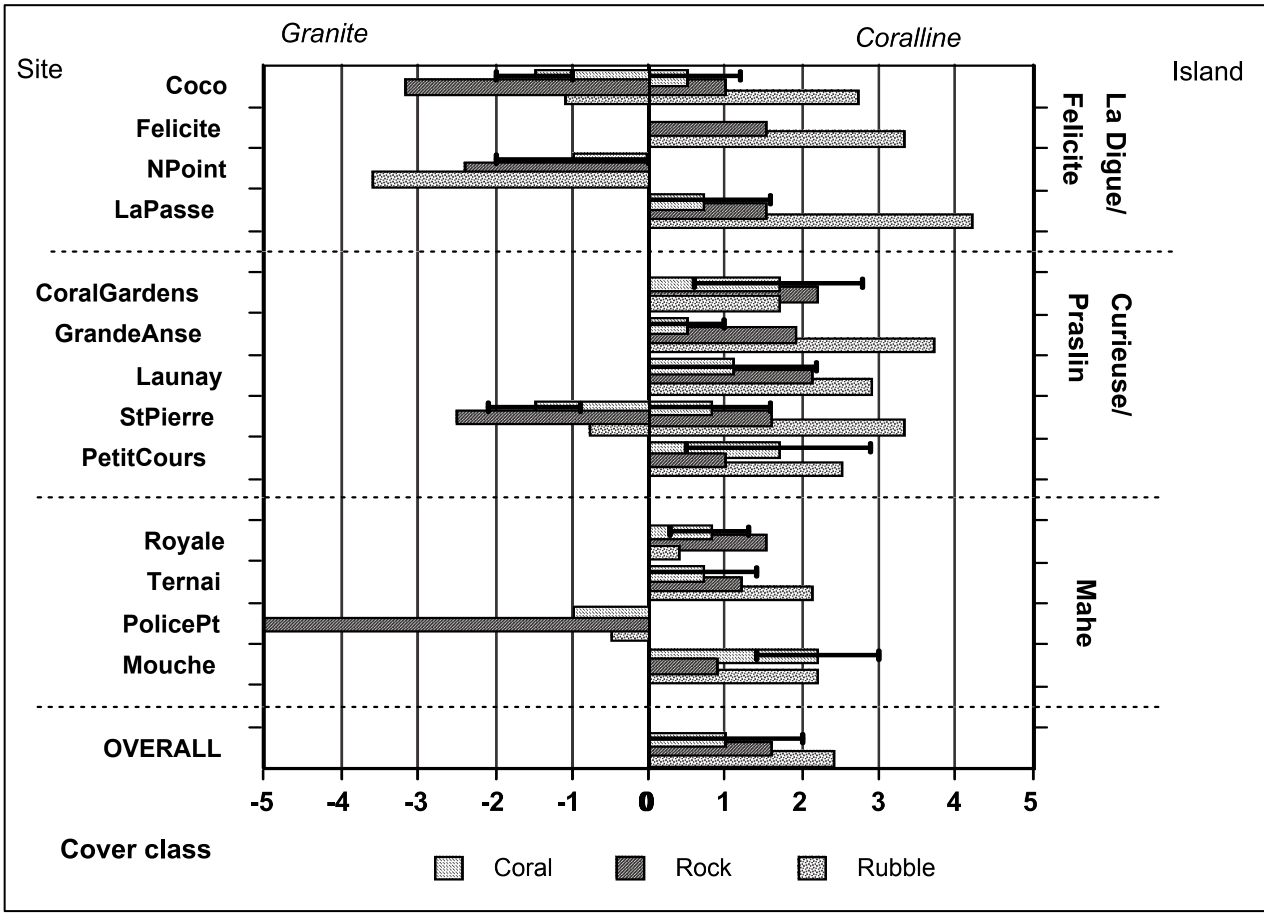

Figure 8. Benthic cover status at study sites on Mahé, Praslin and La Digue, separated by granitic or coralline substrate type.

Damage to Seagrass Beds

Damage to seagrass beds in the Seychelles was low, with only one definite case of damage recorded at Baie Ternay Marine Park (above). Suspension of sediment and erosion of the reef channel resulted in the burial and smothering of the shallow seagrass area between the reef crest and beach inside the bay. Some of the seagrass areas appeared to be recovering as the excess sediment is being removed by normal tidal and wave action, exposing smothered seagrasses (though some still living) and dead pen shells. Mortality of pen shells (*Pinna* sp.) living in the seagrass beds was high, with many of the shells now exposed 1-2 cm above the substrate. This may indicate a minimum depth of newly deposited sand, and (unsuccessful) attempts by the bivalves to burrow upwards to avoid smothering. At the boundary between seagrass beds and the channel, undercutting of the seagrass bed and exposure of roots occurred.

Marine Turtles

The impact of the tsunami on nesting sea turtles in the Seychelles seems to have been relatively minor and what impact there was appears to have been restricted to the inner islands. No obvious damage to nesting beaches was reported from any of the following sites in the outer islands (pers. comm. Jeanne Mortimer): Aldabra (Terence Mahoune), Farquhar atoll (Antonio "Mazarin" Constance), and D'Arros/St. Joseph (Jean-Claude Camille; pers. obs., J.A. Mortimer). Bird Island reported "large tides" but no apparent damage to any monitored turtle nests (Margaret Norah). Aride Island reported two nests destroyed by the tsunami (Dylan Evans). Within the Marine Parks, no apparent damage was reported on the beaches of Ste. Anne Island (Jude Bijoux), but at Curieuse nests were lost at Anse Cimitiere but not at the most important nesting beach Grand Anse (Alain Cedras). At Curieuse, erosion at Grande Anse is the norm at this time of year, but the problem appears to have been exacerbated by the tsunami. At Intendence beach on Mahe no nest damage was recorded (Anders Dimblad).

DISCUSSION

Two major patterns in coral reef damage were noted, controlled by the geographic location of each island and exposure direction of each site, and reef substrate. The northern islands clustered around Praslin (including Curieuse, La Digue, Felicite and the rocks of Isle Coco and St. Pierre) showed very high levels of damage (approaching 100%) on carbonate reef substrates. By contrast, sites around Mahe showed much lower levels of impact. The limited damage on Mahe is due to the shelter provided by the outer northern islands, and energy dissipation of the tsunami traveling over the greater distance of shallow water from the outer edge of the banks to Mahe.

Granitic reefs suffered less damage than reefs with a calcium carbonate substrate (Fig. 8). Granitic surfaces were either immovable as they form the bedrock of the islands, or in the case of boulders and rocks, are too dense and of a compact shape to be displaced by the force of the tsunami. Even on carbonate rock surfaces that were consolidated and firm, attached corals showed little breakage and mechanical damage or overturning. However the majority of true 'coral reef' sites in the granitic islands have a reef framework that is loosely consolidated due to mortality during the 1998 El Niño and subsequent bioerosion. This reef matrix was not robust enough to resist the tsunami waves, either from direct impact of the force of water, or movement of rubble and rocks. In these areas significant reef rubble was moved by the wave and consequently associated live coral colonies were also displaced and damaged. We documented > 50% of substrate damage and >25% of direct damage to corals in northern and eastern-facing carbonate framework sites), <10% damage in shallow carbonate substrate sites in central, western and southern locations, and < 1% damage on all granitic substrate sites. Given the importance of coral reefs to the economy and social structure of the Seychelles (e.g. all the damaged northern sites are prime tourist locations for the country) this provides a strong threat to the country and requires action for mitigation.

An important correlation between coral reef location (coastal geomorphology) and shoreline damage was noted. Most damage to shorelines occurred where fringing reefs and bays with extensive coral development occur – e.g. Anse Petit Cours (Praslin), the causeway (Curieuse), Anse Royale (Mahe) and Anse la Mouche (Mahe). At these locations, development immediately above the high tide line was made possible by the protection offered by fringing reefs. However the reefs offered only limited protection from a wave the size of the tsunami, and maximum damage occurred where reef channels cut in closest to land (the causeway at Curieuse, Anse Royale, Anse la Mouche). Thus the vulnerability of the low coastal plains to wave damage was clearly shown by the tsunami. While fringing coral reefs protect these shorelines during regular conditions, their protection was limited during this extreme event.

Along with the high vulnerability of coral reefs in the northern islands, the Curieuse Marine Park suffered damage to its infrastructure (UNEP 2005). The wall protecting the mangrove forest and artificial lagoon was damaged, which will expose the high-diversity mangrove stand to erosion during the southeast monsoon. Additionally, infrastructure of the MPA was damaged, including boat engines, electrical equipment and physical facilities on land.

Tsunami damage to coral reefs in the Seychelles was severe on the northern carbonate-framework reefs, but minor elsewhere. These damages, occurring while reefs were still recovering from 80-90% mortality of corals during 1998, point to a critical vulnerability of the coral reefs of the Seychelles. The El Niño in 1998 created extensive rubble fields from death and breakage of the fast growing branching corals (*Acropora* and *Pocillopora*) that dominated the shallow waters of Seychelles reefs (Jennings et al. 2000). At the time of the tsunami, the primary reef carbonate frameworks in the granitic islands were relatively weak physical structures, consisting of attached and loose calcium carbonate pieces of varying sizes. These may become strongly consolidated by coralline algae growth over 5-10 years under good conditions (e.g. observation from Baie Ternay). The chemical and biological consolidation into a rigid reef framework, such as that found on some fringing reef sites (e.g. Anse Royale) may take hundreds to thousands of years. Only 6 years after the bleaching, the loosely consolidated reef frameworks were not able to resist the force of the tsunami, resulting in severe movement of rubble and breakage.

In the short to medium term, any mitigation activities will have to deal with the problem of loose reef frameworks and the long time needed for reef matrix consolidation, in order to promote coral reef recovery and growth. In the medium to long term, damage from the tsunami should be considered in the context of Seychelles as a Small Island Developing State. As such, it has a particular vulnerability to shocks and threats due to its small size, from natural disasters to economic and global political influences. While damage from the tsunami was not catastrophic to coral reefs, it significantly worsened the catastrophic impact of coral bleaching 6 years previously, with impacts focused on the most vulnerable, and most valuable, coral reef areas. On these reefs, the tsunami set back biological recovery of corals by 6 years. Because of the extensive physical damage to the reef matrices, however, the set back to overall reef recovery may be much longer than that.

The interaction of these two types of threats in the medium to long term will be particularly important for the Seychelles – physical exposure to extreme waves events, and their increasing severity due to climate change – rising sea level, northwards migration of the cyclone belt in the southern Indian Ocean, and increasing severity and frequency of major storms. While the occurrence of another tsunami cannot be predicted, the increasing severity of the threat from waves to the Seychelles is clear. Broad principles reflecting the importance of coral reefs to Seychelles were used to develop recommendations for mitigation:

I. Improve capacity for assessment of coastal health and vulnerability to waves and storms, using on bathymetry, coastal topography and coral reef status;
II. Improve watershed management that minimizes downstream and marine impacts of water use and treatment, to maximize the recovery potential of coral reefs impacted from multiple threats including eutrophication, overfishing and coral bleaching;
III. Integrate ICZM and Marine Protected Area management frameworks covering all of Seychelles' coastal and EEZ waters, recognizing the coastal protection benefits of healthy coral reef ecosystems.

As part of the UNEP assessment mission, a number of short to long term recommendations were made to respond to the tsunami damage. Briefly, these included:

1. Mitigation of tsunami damage and enhancement of coral reef recovery - rehabilitation and restoration technologies for coral reefs are in their infancy, but studies should be initiated to address the key factors of substrate stability, water quality improvements to enhance coral survival and enhancement of natural recruitment and survival of small corals.
2. Assess and replace lost infrastructure of Curieuse Island Marine Park, in particular to protect the mangrove forest.
3. Development of coral reef and environmental monitoring capacity at SCMRT-MPA and strengthening of the Seychelles Coral Reef Network to ensure complementarity among

monitoring programmes in the Seychelles.

4. Development of a shoreline vulnerability model and planning capacity.

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REFERENCES

ICRI/ISRS 2005. Tsunami Damage to Coral Reefs. Guidelines for Rapid Assessment and Monitoring. April (2005). Victoria, Seychelles. 30 pages. http://www.unep-wcmc.org/latenews/emergency/tsunami_2004/coral_ass.htm.

IOC-WESTPAC (2006). Post-disaster assessment & monitoring of coastal ecosystems. In: Proceedings of the conference on biological and cultural diversity in the Indian Ocean & Asian waters, Phuket, Thailand, 20–24 February 2006. Intergovernmental Oceanographic Commission (UNESCO)—Sub-Commission for the Western Pacific; 2006. /http://westpac.unescobkk.org/S.

Jennings, S., Marshall, S., Cuet, P. & Naim, O. (2000). The Seychelles. In: McClanahan, T.R., Sheppard, C.R.C. & Obura, D.O. (Eds) Coral Reefs Of The Indian Ocean: Their Ecology And Conservation.

Kathiresan, K., Rajendran, N., (2005). Coastal mangrove forests mitigated tsunami. Estuarine, Coastal and Shelf Science 65, 601-606.

Kerr, A.M., Baird,A.H., & Campbell. S. (2006). Comments on "Coastal mangrove forests mitigated tsunami" by K. Kathiresan and N. Rajendran [Estuar. Coast. Shelf Sci. 65 (2005) 601e606]. Estuarine, Coastal and Shelf Science 67 539-541.

Obura, D.O. (2006). Impacts of the 26 December 2004 tsunami in Eastern Africa. Ocean & Coastal Management 49: 873–888.

Russell, M., Skewes, T., & Engelhardt, U. (2005). Australian Government assistance to the Seychelles tsunami relief effort. Ausaid/Seychelles Ministry of Environment and Natural Resources/Seychelles Fishing Authority. April 2005.

SCMRT-MPA/DE (2005). Preliminary report on the state of coral reefs around Mahe after the December 26th tsunami event. The Seychelles Centre for Marine Research and Technology—Marine Parks Authority (SMCRT-MPA) and the Marine Unit, Nature and Conservation—Ministry of Environment and Natural Resources, Department of Environment.

UNEP. (2005). After the tsunami. Rapid Environmental Assessment. Division of Communications and Public Information. United Nations Environment Programme (UNEP). February 2005.