Impact of the tsunami of 26 December 2004 on the coral reef environment of Gulf of Mannar and Palk Bay in the southeast coast of India

A. K. Kumaraguru*, K. Jayakumar, J. Jerald Wilson and C. M. Ramakritinan

Centre for Marine and Coastal Studies, School of Energy, Environment and Natural Resources, Madurai Kamaraj University, Madurai 625 021, India

The live coral cover of 48.5% in the Gulf of Mannar was reduced to 36% after the tsunami of 26 December 2004. Corals showing partial bleaching, infestation with disease, silt-smothered live corals, recently killed corals, broken corals, upturned corals and sea grass damage were found in many places around the 21 islands. The coral cover under stress was 6.7%, which included corals showing partial bleaching and those infested with pink line disease syndrome. The silt-smothered coral cover was 30%. Damage to corals due to tsunami was 6.7% that included recently killed corals, upturned corals and broken corals. Sea grass damage was also found in low quantities. Landscape alterations revealed that Shingle, Mulli, Valai, Thalaiyari, Upputhanni, Van, Kasuwar and Karaichalli islands experienced more shore erosion compared to the other islands. Uprooted trees were found in all the islands. Corals lying closer to the shore in all the islands were affected by sedimentation.

The live coral cover of 26.7% in the Palk Bay was reduced to 19.2% after the tsunami. The coral cover under stress was 2.8%, which included those showing partial bleaching and those with infestation of pink line disease. Silt-smothered coral cover was 10.5%. Unlike the islands in the Gulf of Mannar, there was no change in landscape structure in the Palk Bay region. Only inundation of sea water was noticed in some places. There was substantial increase in sedimentation rate after the tsunami in the Palk Bay showing 12, 54 and 13 mg/cm^2/d during Nov. 2004, Dec. 2004 and Jan. 2005 respectively.

Keywords: Coral bleaching, coral disease, Gulf of Mannar, Palk Bay, sedimentation, shore erosion, smothered corals, tsunami.

THE Indian Ocean undersea earthquake of magnitude 9.3 in the Richter scale[1], that occurred on 26 December 2004 has devastated the coastal areas of all the 13 coastal districts of Tamil Nadu, including Nagapattinam, Kanyakumari, Cuddalore, Chennai and Kanchipuram and the Union Territory of Pondicherry. The reported[2] height of the tsunami waves in Tamil Nadu was between 7 and 10 m. The killer waves, on their way, gorged beaches, crushed coral reefs, smashed thousands of hectares of mangrove forests and refashioned coastlines[3–6].

In some coastal areas, destruction was less because of the coral reefs and mangrove forests, which acted as barriers to dissipate the energy of the waves. While the entire Tamil Nadu coast was affected, major parts of Palk Bay and Gulf of Mannar coasts were not affected mainly because the island nation Sri Lanka has acted as a shield, bearing the brunt of the tsunami force and deflecting the waves towards the north and south of its coasts. The defused waves from the deflection were further muffled by the chain of 21 islands and the coral reefs around them in the Gulf of Mannar, thus protecting Tuticorin and Ramnad districts. Although the coastlines of these districts were protected from the catastrophe, water flooding in several places was noticed by coastal people.

Tsunamis can have serious negative impacts on coral reefs[3,5]. Although reefs in deeper water or at a distance from the coastline may escape unharmed as the tsunami passes over as a pressure wave with only slight changes in water depth, near-shore reefs stand to take a considerable pounding.

The corals of Gulf of Mannar and Palk Bay have already faced two catastrophic bleaching events, one[7] in 1998 and the other[8] in 2002 and have been recovering slowly. The major issue causing concern for the coral reefs was the backwash of mud and other sedimentation-related stress created after recession of the tsunami[9]. Satellite images of regions of the Andaman and Nicobar Islands have shown that a huge amount of sediment has been washed from the land into the sea. Coral reefs are built by coral polyps and symbiotic algae, zooxanthellae, which need pristine waters to thrive. If they are deprived of sunlight because of sedimentation-related turbidity, it will be difficult for corals to survive. So, there was an urgent need to assess the impact of the tsunami of 26 December 2004, not only on the landscape of the islands, but also on the corals of Gulf of Mannar and Palk Bay.

Material and methods

The Gulf of Mannar has a chain of 21 islands along a stretch of 140 km between Rameswaram and Tuticorin (Figure 1 and Table 1). The islands have fringing coral reefs and

*For correspondence. (e-mail: akkguru@eth.net)

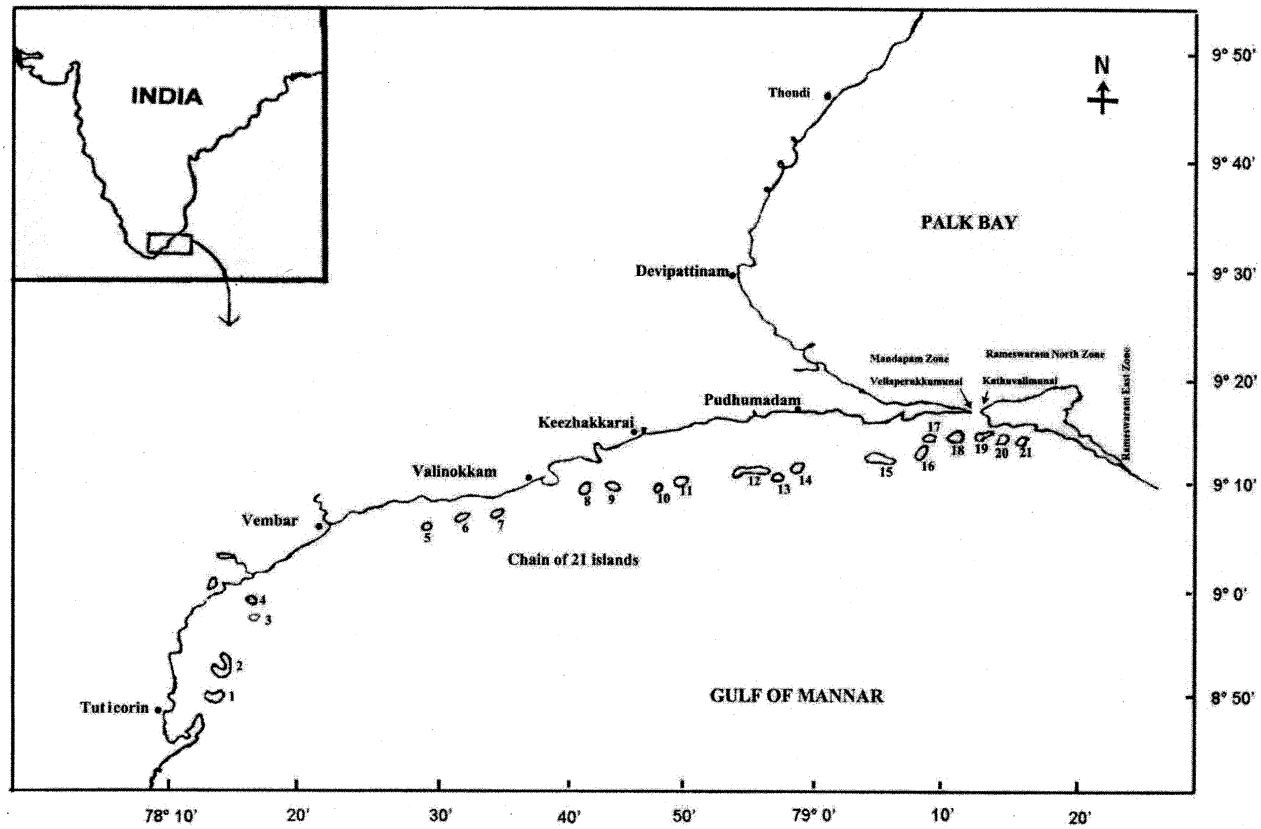

Figure 1. Study sites in the Gulf of Mannar and Palk Bay regions.

patch reefs rising from shallow areas of the sea floor. Fringing reefs are found within 100 m from the shore around the islands. They are not continuous but distributed and occur around all the islands. Patch reefs rise from depths of 2 to 5 m and are 1 to 2 km in length with widths of as much as 50 m.

The islands in the Gulf of Mannar are classified based on their proximity to the mainland, into four major groups. They are Tuticorin group, Vembar group, Keezhakkarai group and Mandapam group. The islands are Van, Kasuwar, Vilanguchalli and Karaichalli in Tuticorin group; Upputhanni, Puluvuni challi and Nallathanni in Vembar group; Yanaipar, Pallimunai, Poovarasanputti, Appa, Thalaiyari, Valai and Mulli in Keezhakkarai group and Musal, Manoli, Manoliputti, Poomarichan, Pullivasal, Krusadai and Shingle in Mandapam group (Figure 1). A survey of reefs in each island in the Gulf of Mannar was done. Palk Bay region is also one of the coral-rich areas of India. Rameswaram Island separates Palk Bay from the Gulf of Mannar. The Palk Bay reefs are generally patchy type and are scattered in a stretch of 25–30 km and are in less than 200 m width. Coral reefs in the Palk Bay lie in an east-west direction along the mainland from Mandapam to Rameswaram Island (Figure 1). The eastern half extends from Rameswaram to Pamban Pass and is known as 'Kathuvalimunai Reef' and the western half is known as 'Vellaperukkumunai Reef'. In the Palk Bay region, there is an ongoing study to monitor corals. Three zones, viz. Rameswaram East (Zone-I), Rameswaram North (Zone-II) and Mandapam (Zone-III) were being monitored for biophysical status of the reefs.

The biophysical status of corals was assessed using Line Intercept Transect (LIT) method[10] (Figure 2 *a*). In general, coral community characterization is done using life-form categories such as live coral cover, coral bleached, dead coral rock, dead coral with algae, algae alone, sea grass, and sand and rubble, which provide a morphological description of the reef community. However, the coral life-form categories after tsunami were assessed according to the guidelines of ICRI/ISRS[11] for rapid assessment and monitoring of coral life-forms. The life-form categories observed were live coral cover, coral showing partial bleaching, coral infected with diseases, silt smothering on the live coral surface, recently killed coral, broken coral, upturned coral, seagrass damage, filamentous algae, and thick and turf algae. The monitoring was done after tsunami during January 2005, around the 21 islands of the Gulf of Mannar and in the Palk Bay regions.

The life-form categories were recorded on data sheets by swimming along lines, which were placed roughly

Table 1. Islands in the Gulf of Mannar

Island	Location		Approximate area (km^2)	Approx. distance from previous island (km)
	Lat N	Long E		
Tuticorin group				
Van	08°50′	78°13′	0.245	0
Kasuwar	08°52′	78°13′	0.241	3.0
Vilanguchalli	08°56′	78°14′	NA	6.0
Karaichalli	08°57′	78°15′	0.166	2.0
Vembar group				
Upputhanni	09°05′	78°30′	0.377	19.0
Puluvini challi	09°06′	78°35′	0.126	3.0
Nallathanni	09°06′	78°35′	1.248	3.0
Keezhakkarai group				
Yanaipar	09°09′	78°42′	0.229	12.0
Pallimunai	09°09′	78°44′	0.134	3.0
Poovarasanputti	09°09′	78°49′	0.008	1.5
Appa	09°09′	78°49′	0.410	8.0
Thalaiyari	09°11′	78°54′	0.945	8.0
Valai	09°11′	78°56′	0.127	0.2
Mulli	09°11′	78°56′	0.170	5.0
Mandapam group				
Musal	09°12′	79°05′	1.836	9.5
Manoli	09°13′	79°07′	0.353	4.5
Manoliputti	09°13′	79°07′	0.037	0.2
Poomarichan	09°14′	79°11′	0.187	6.5
Pullivasal	09°14′	79°11′	0.482	0.3
Krusadai	09°15′	79°12′	0.740	0.5
Shingle	09°15′	79°14′	0.191	1.5

NA, Not available – submerged bank.

parallel to the shore line at depths of 3–5 m. The LIT length used was 20 m at each site. Altogether 84 sites in the Gulf of Mannar region (four LITs for each island – lagoon side–2 and seaward side–2) and 12 sites in the Palk Bay region (four LITs in each zone) were marked and monitored. Identification of coral species was expanded to include taxonomic data in addition to life-form categories.

In the Palk Bay region, the chosen three zones were already being monitored for sedimentation. Sediment traps were already in place in the selected locations of each zone. The traps were custom-made (Figure 2 *c*) following the design described by Gardner[12]. Four traps were deployed in each location. The identified location was already marked with a permanent transect[10] for monitoring the corals at periodic intervals. A particular coral of distinct size and dimension was chosen in each of the 20 m permanent transects and the traps were laid in all four directions with at least 1 m distance from the chosen coral (Figure 2 *b*). A steel rod with four PVC containers (11.5 cm in height and 5 cm in diameter) at one end was fixed on the sea floor at a depth of 3 and 1 m away from the permanent transect. In each location, four steel rods were placed at right angles to one another to cover all four directions. Thus, 16 PVC containers were placed in each location for collecting sedimented silt.

A general survey of the shores of each island in the Gulf of Mannar was done, especially on the peripheral margins of the tideline to find out any visible indications of landscape alterations caused by tsunami flooding.

Results

Gulf of Mannar

Results of the study indicated that there was a slight reduction in live coral cover. Corals showing partial bleaching, infestation with disease, silt smothering live corals, recently killed corals, broken corals, upturned corals, seagrass damage, filamentous algae, and thick and turf algae were found in many places around the 21 islands in the Gulf of Mannar.

Tuticorin group of islands

Biophysical status of reefs: The live coral cover of 42% observed during pre-tsunami in November 2004 was reduced to 31% during post-tsunami in January 2005 (Figure

3 *a*). The life-form cover showing partial bleaching and infestation with disease was alive but under stress, and hence was considered as a separate life-form category. These corals may live through the stress and become normal in due course. A large percentage of corals was smothered by silt which was under stress, as manifested by lesions on their surface. The recently killed corals, up turned corals and broken corals made up only a small percentage (Figure 3 *a*). The filamentous algae, and thick and turf algal covers were also in small quantities (Figure 3 *a*).

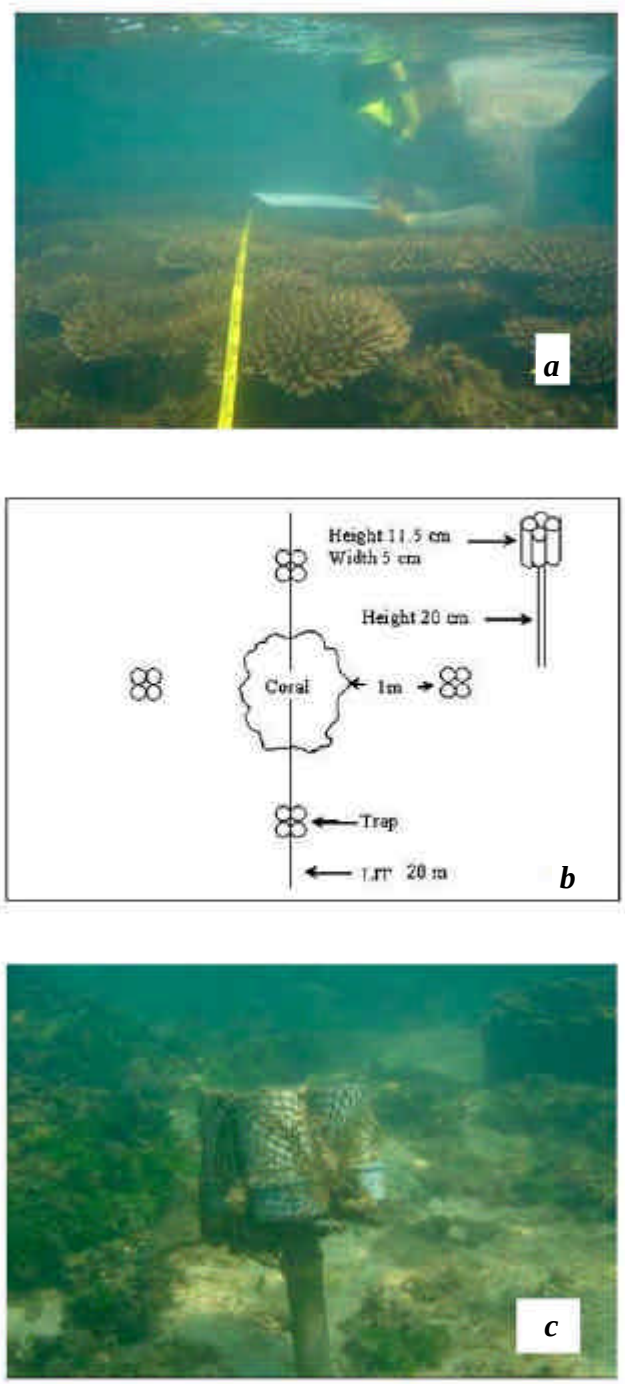

Figure 2. ***a***, Underwater coral reef survey using Line Intercept Transect. ***b***, Schematic diagram of sediment traps laid in coral reef. ***c***, Custom-made sediment trap placed in coral reef area.

Major physical changes: The peripheral landscape of Van island has changed after the tsunami. The southern side of the island was eroded (Figure 4 *a*) up to 8–10 m and coral rubble was spread over the shore of the island. More than 6–8 m along the northern side of the island was totally eroded. The northwestern tip of the shore was inundated. Earlier, the width of this tip used to be 40 m and this has gone down to 10 m after the tsunami. The sea on the northeastern side has cut through the low-lying sandy shore and reached the other side, making a passage forming a narrow canal of water. Corals of the families Acroporidae, Poritidae, Pocilloporidae and Faviidae showed signs of stress caused by sedimentation. Coral species *Pocillopora verrucosa*, *Turbinaria crater* and *Acropora intermedia* showed partial bleaching and deposition of silt.

The southeastern tip of Kasuwar island was eroded to an extent of 6–8 m and the shore sand was deposited near the blunt end, increasing the height of the island in that location. Widespread scattering of coral rubble was found all along the shore. Water has entered through the southeastern shore and filled the pool in the island. Corals of Acroporidae, Poritidae, Faviidae, Pocilloporidae and Oculinidae showed partial bleaching and sedimentation stress.

The northeastern corner of Karaichalli island was eroded up to 8–10 m and the broad end of the northeastern corner became a blunt end after erosion. Coral rubble was scattered over the entire northeastern and northwestern sides of the island. Shore erosion was widespread all along the western side of the island to an extent of 6–7 m. Sea water had entered through the southeastern shore and eroded the island, and the coral rubble was lifted and spread over the island. The entire stretch of the southeastern shore was eroded to an extent of 5 m. Shore erosion has also occurred throughout the southwestern side to an extent of 5–6 m. The sudden surge of sea water flow has broken the middle region of the shore, paving the way for entry of water into the island.

Coral species *A. intermedia* was found uprooted and washed ashore from the southern side of the island. Other species such as *Porites solida*, *P. lobata*, *Favites abdita*, *Goniastrea* sp., *Symphyllia recta* and *Acropora hyacinthus* showed signs of partial bleaching. Coral species *Acropora humilis* and *Pocillopora damicornis* were buried in sand and silt on the southern side of the island.

The corals of the submerged bank of Vilanguchalli island were affected by sedimentation and most of the reef areas were hit by mass deposition of sand and silt on the corals. Some of the massive coral forms such as *Porites lobata*, *Favites pentagona*, *Favia stelligera*, *Favia pallida*, *Turbinaria crater* and *Acropora hyacinthus* showed small patchy lesions. Coral species *A. intermedia*, *A. hyacinthus*, *P. damicornis* and *T. crater* were broken, uprooted and upturned in a number of locations around this island.

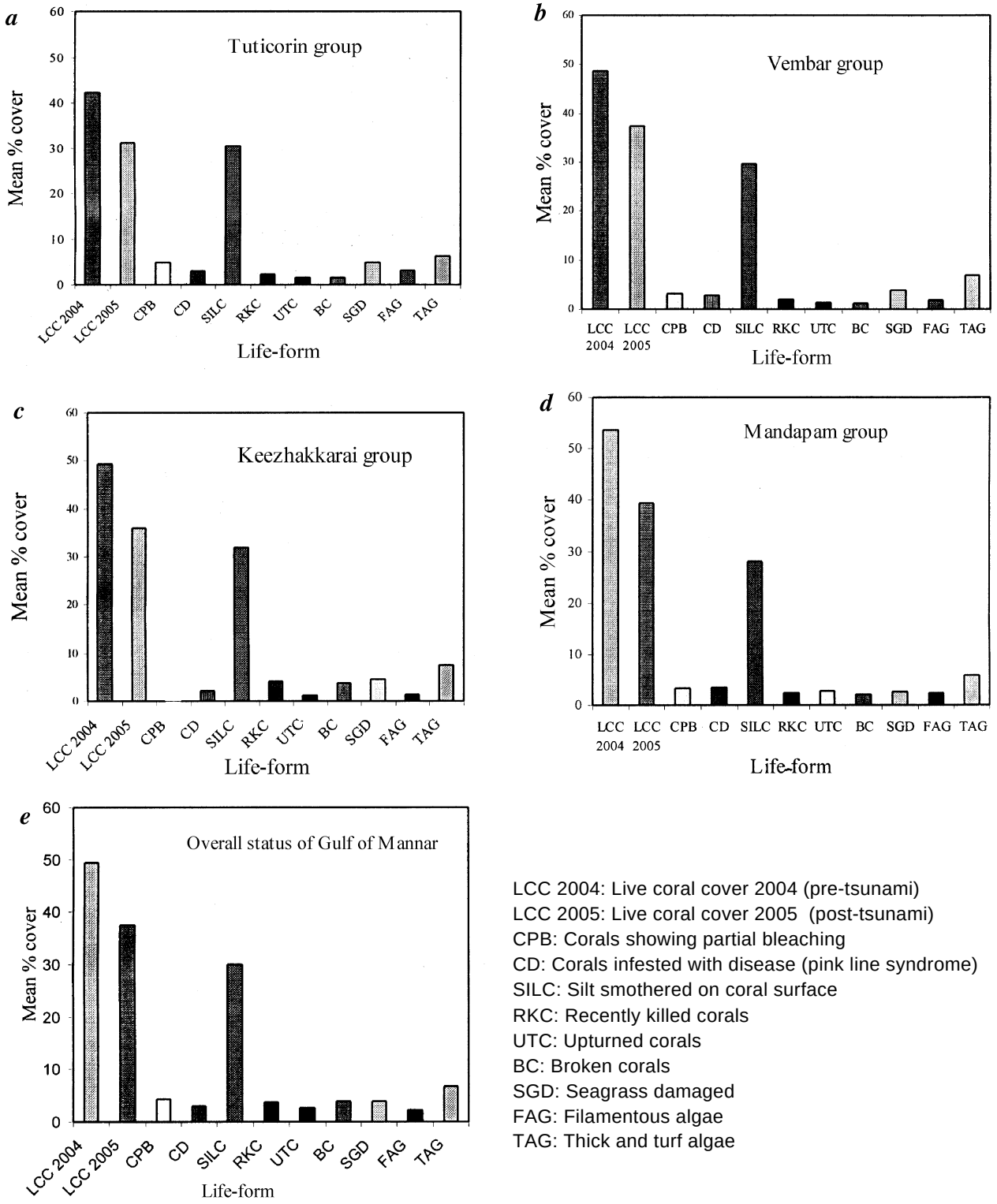

Figure 3. Biophysical status of coral life-form categories in the four groups of islands in the Gulf of Mannar during pre- and post-tsunami periods.

Vembar group of islands

Biophysical status of corals: The live coral cover of 49% around Vembar group of islands has been reduced to 38% after the tsunami (Figure 3 *b*). Life-forms such as corals showing partial bleaching and coral infested with diseases were live, withstanding the stress. Corals smothered by silt, recently killed corals and broken corals were

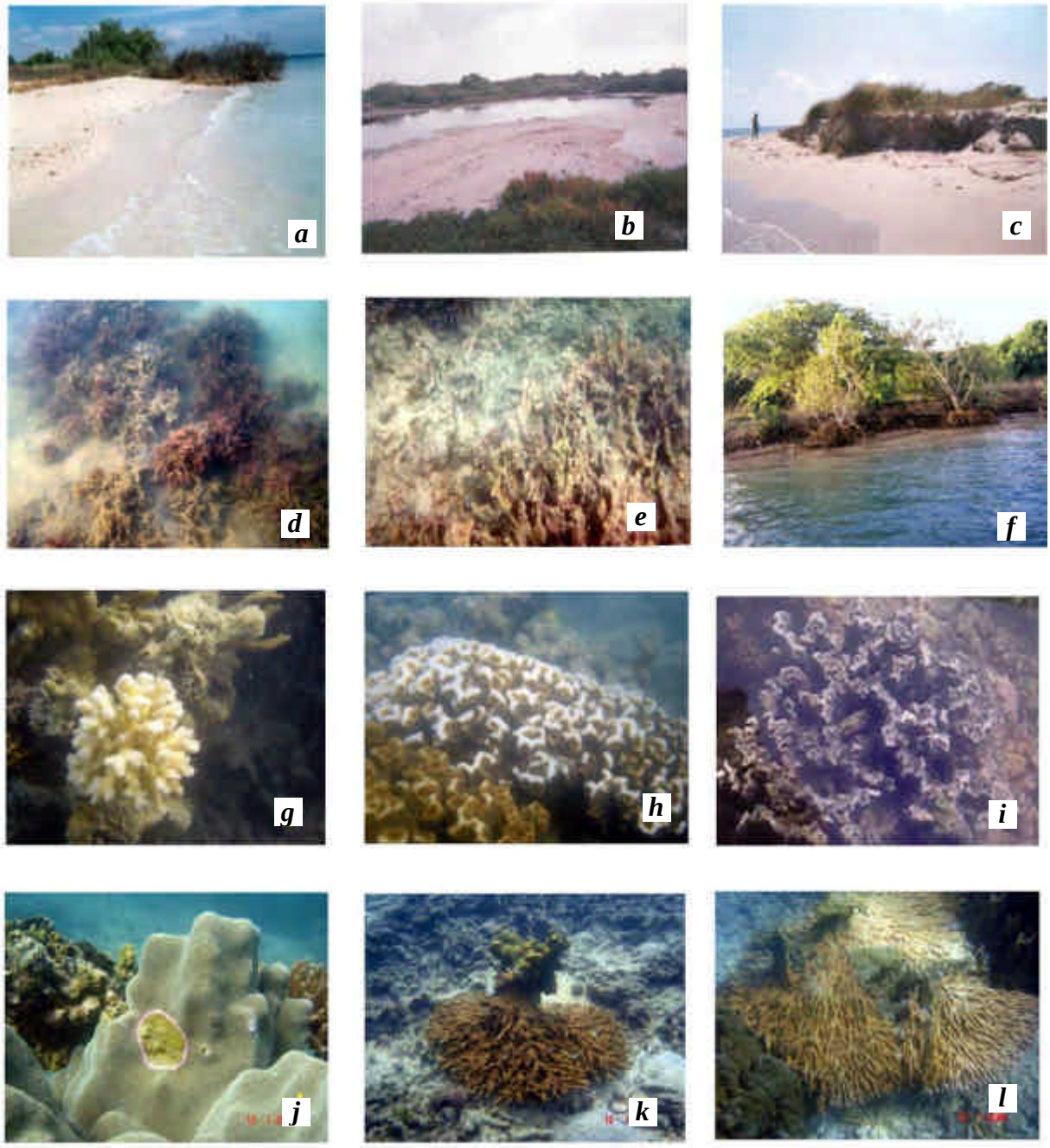

Figure 4. ***a***, Eroded island shore (Van); ***b***, Sea water inundation (Mulli); ***c***, Eroded island shore (Appa); ***d***, Corals buried with eroded sand (Shingle); ***e***, Sedimentation on corals (Shingle); ***f***, Uprooted mangrove trees (Krusadai); ***g***, ***h***, Corals showing partial bleaching (Manoliputti and Manoli respectively); ***i***, Sedimentation on corals (Musal); ***j***, Coral with pink line disease (Palk Bay–Zone-I); ***k***, Uprooted coral (Palk Bay–Zone-II); ***l***, Broken coral (Palk Bay–Zone-III).

minimum. Besides these, upturned corals were also observed to a lesser extent. Filamentous algae, and thick and turf algal covers were in small quantities (Figure 3 *b*).

Major physical changes: The Upputhanni island in Vembar group showed shore erosion to an extent of 15 m in the northeastern tip, and hence the northeastern shore has been reduced to a small bend. The entire northern shore was eroded to an extent of 6 to 8 m. The northwestern tip of the island showed erosion of 12 m width and changed the elongated tip to a blunt end. Coral rubble has been spread over the entire southeastern coast of the island. *P. lobata*, *T. crater*, *F. abdita* and *A. hyacinthus* have suffered due to sedimentation stress.

Shore erosion has taken place at the southeastern end of the island to an extent of 7–9 m, and mangrove trees

were flooded by sea water. Large quantities of marine algae were washed ashore along with coral rubble, which was conspicuous throughout the middle portion of the southern shore of the island. The creek that lies on the southern side in the middle of the island showed no alteration. *A. digitata* and *A. hyacinthus* were either broken or tilted at their base, although to a small extent. The basal portions of the massive coral forms *P. lobata*, *P. solida*, *P. lutea*, *Favia speciosa* and *F. pallida* were eroded to a depth of 15 to 20 cm throughout the southern side of Upputhanni island. These corals also showed lesions on their surfaces. Silt deposition on the corals *P. damicornis* and *P. verrucosa* caused bleaching of the whole colony. Corals of the southern side of Upputhanni island, viz. *P. lobata*, *P. solida*, *P. lutea*, *Galaxea fascicularis*, *Goniastrea* sp., *F. pallida*, *F. abdita*, *A. digitata* and *A. nobilis* were smothered by sand and silt. *Galaxea astreata* and *P. verrucosa* have collapsed on the sliding sandy slope.

In Puluvunichalli island, the northeastern shore was eroded up to an extent of 4 m width and coral rubble was spread over the length of the entire shore. The northern shore that faces the mainland experienced soil erosion. *P. lobata*, *T. crater* and *F. abdita* showed signs of stress caused by sedimentation. Sea water has entered the island at the northeastern end causing inundation. Lesions caused by sedimentation were also observed in the corals. The southern and western sides of the island did not show any sign of disturbance due to the tsunami and corals of Acroporidae, Poritidae, Faviidae, Oculinidae and Mussidae were normal and healthy. However, *P. verrucosa* and *A. nobilis* showed partial bleaching due to siltation on their surface.

The northwestern end of the shore of Nallathanni island was eroded to an extent of 4 m in width and sea water had entered the island. Acacia trees were inundated by sea water due to shore erosion. *P. lobata*, *P. solida*, *T. crater*, *F. abdita* and *A. hyacinthus* showed signs of lesions caused by sedimentation. The western end of the island was eroded to an extent of 5–6 m in width and the shape has changed to a blunt end. The northern side of the shore, which is 2 km in length, has encountered an erosion of 3 m width throughout the entire stretch and hence the sea water has inundated Acacia trees along the shore.

Keezhakkarai group of islands

Biophysical status of reefs: The live coral cover of 49 % has been reduced to 36% after the tsunami, with a loss of 13% (Figure 3 *c*). Corals living under stress included those with partial bleaching and with disease. Silt-smothered corals constituted 32%. Damaged coral cover included recently killed corals, upturned corals and broken corals. Filamentous, and thick and turf algal covers were also seen in small quantities (Figure 3 *c*). Damage to seagrass was also observed.

Major physical changes: Mulli island in Keezhakkarai group showed extensive alteration in its landscape and damage to reef structure. The entire stretch on the eastern side of this island was eroded to an extent of 10–12 m in width and the northeastern shores were also eroded up to 6 to 8 m in width to a stretch of 100 m. The displaced coral rubble and sand have been washed ashore towards the western side. These washings have fallen on the branched Acroporid corals *A. intermedia*, *A. humilis*, *A. hyacinthus* and *A. digitata*, and on other species such as *Galaxea* sp., *Favia* sp. and *P. damicornis*, causing severe stress which might lead to the death of these corals in due course. *P. lobata*, *P. solida* and *F. stelligera* showed signs of lesions caused by sedimentation on their surfaces. Mangrove trees in the northeastern side of this island were uprooted. Sea water entered the low lying open area of the northern side of this island and formed a pool of sea water (Figure 4 *b*).

The eastern side of Valai island was eroded to an extent of 12–14 m in width and in a stretch of 100 to 120 m, and the mangrove trees found along this side were also uprooted. Shore erosion was more prominent at the western end of this island. Thus the western tip of this island showed soil erosion in a stretch of 70–80 m to a width of 3 to 5 m. Earlier, the western end of this island had 2 m width with 1 m height of sand mass in a stretch of 70 m. This sand mass was completely eroded and washed down the seaward side and formed a new channel of 10–12 m width. The depth of this channel was 2–2.5 m during high tide. Corals of Poritidae, Faviidae and Acroporidae showed settled sediments on their surfaces.

In Thalaiyari island, the northern side of the shore was eroded up to an extent of 5–7 m width in a stretch of 100 m. Earlier, the eastern end of this island had a small and narrow channel through which sea water used to pass through during high tide. The width and depth of this channel before the tsunami were about 2 m and 1 m respectively. The seaward side of Valai and Thalaiyari islands has a shallow water area during high tide. Coral species closer to the shore, particularly those of Faviidae, Poritidae and Pocilloporidae, showed sedimentation stress.

Appa island showed shore erosion on the extreme corner of the northeastern side. The northwestern side of this island was eroded up to an extent of 6–8 m in width and eroded sand was displaced to the northern side of the island (Figure 4 *c*). Similarly, the southern side of the island was also eroded up to 2 m in width. Most of the Acacia trees lying in the southern side of the shore were uprooted. Coral rubble mounds lying near the southwestern side of the island were spread out widely and moved to an extent of 2–3 m due to strong tidal waves. Sea water had entered the southern side of the island.

In Poovarasanputti island, live corals on the eastern and western sides were smothered by silt and sedimentation stress, causing considerable damage to corals. Some broken corals of *A. hyacinthus* and *A. cytherea* were noticed

along the southern side of the bank. In Pallimunai island, the northeastern shore was eroded to an extent of 2 m in width. *A. intermedia*, *A. formosa*, *A. humilis*, *P. damicornis*, *Galaxea* sp., *Goniastrea* sp. and *Favia* sp., lying near the northeastern shore were found buried under the eroded shore sand.

In Yanaipar island, the southeastern shore was eroded to an extent of 2–3 m in width and corals lying near the shore, viz. *A. formosa*, *A. intermedia*, *A. hyacinthus*, *P. verrucosa* and *P. damicornis* were buried under the eroded shore sand. The massive coral species *P. lobata*, *P. solida*, *F. abdita*, *F. pentagona*, *F. pallida* and *F. stelligera*, found closer to the shore, showed signs of disturbance due to sedimentation on their surfaces.

Mandapam group of islands

Biophysical status of reefs: The live coral cover of 54% that existed in the pre-tsunami period was reduced to 39% after the tsunami (Figure 3 *d*). The percentage cover of corals under stress in the post-tsunami period was 6.7, which included corals showing partial bleaching and those infested with disease. The percentage cover of silt-smothered corals was 28, which was the least among the four groups in the Gulf of Mannar. Tsunami-related damage to corals included upturned corals, recently killed corals and broken corals (Figure 3 *d*). Seagrass damage was found to be minimum in this group of islands. Moderate quantities of filamentous, and thick and turf algae were also observed.

Major physical changes: Shingle island has had an alteration of its landscape. The tsunami has caused shore erosion to an extent of 10–14 m in width on the northwestern corner of the Shingle island and has eroded and displaced the shore sand to the western side under which corals were submerged (Figure 4 *d*). Corals of branched types were tilted due to flooding. The floated shore sand, mainly composed of fine coral sand, has fallen on live corals and has buried, up to 15 cm height, *A. intermedia*, *A. digitata* and *P. verrucosa*, posing a threat to their normal living condition. The southeastern side of this island had uprooted mangrove trees. The uprooted massive coral heads were moved towards the northern side of the island. The same observation was reported by local fishermen who found unusually massive coral heads entangled in their shore seines.

Corals of Acroporidae and Pocilloporidae are generally tolerant to sedimentation. However, the stress caused by heavy sedimentation in due course may result in the death of corals (Figure 4 *e*). Sedimentation was observed in the lagoon side on *P. lobata*, *F. abdita*, *F. pentagona* and *F. stelligera*. These coral species have come under stress due to sedimentation and as a result showed partial lesions. Mangrove trees were uprooted in some places and coral rubble, lying along the high-tide mark, was lifted away and strewn all around the shore of Shingle island.

In Krusadai island, the northeastern corner of the shore had eroded to an extent of 5 m in width and some mangrove trees in this island were also uprooted (Figure 4 *f*). Coral species found near the seaward side (southern side) closer to the shore, particularly *A. hyacinthus*, *A. digitata*, *Montipora foliosa*, *F. stelligera*, *F. abdita*, *Galaxea* sp., *P. lobata* and *P. solida* showed stress due to sedimentation and partial lesions on their structures. The channel lying between Krusadai and Pullivasal islands did not show any change.

In Pullivasal island, corals are present only on the seaward side (southern side) and belong to Acroporidae, Faviidae and Poritidae. *P. lobata* and *A. hyacinthus* showed partial bleaching. In Poomarichan island, coral species of Acroporidae, Poritidae, Faviidae and Oculinidae are sparsely distributed and they did not show any change due to the tsunami.

In the northeastern corner of Manoliputti island, the shore was eroded to an extent of 4–6 m in width and mangrove trees were uprooted. However, there was only little impact on the coral species of Pocilloporidae, Poritidae and Faviidae, as indicated by partial bleaching (Figure 4 *g*). Other coral species of Acroporidae, Oculinidae, Mussidae and Agariciidae were normal and healthy. The channel lying between Manoliputti and Manoli islands was found deepened by about 1.0 to 1.5 m for a short stretch. The northern end of the island was eroded up to 3 m in width.

Around Manoli island, some mangrove trees near the edge of the sea were uprooted in some parts of the island. Corals closer to the shore in this island comprised species of Acroporidae, Faviidae, Mussidae, Merulinidae, Oculinidae and Agariciidae, and they were normal and healthy. However, some coral species of Pocilloporidae and Poritidae showed partial bleaching in their structures (Figure 4 *h*).

P. lobata, *F. pallida* and *Galaxea* sp. were found upturned in the waters between Manoli and Musal islands. Broken pieces of corals of *A. intermedia* and *A. digitata* were found near the seaward side of Musal island. Sedimentation was found on corals (Figure 4 *i*).

Overall status of Gulf of Mannar

The overall status of coral life-form categories estimated during the pre- and post-tsunami periods is given in Figure 3 *e*. The overall status of live coral cover of 48.5% in the Gulf of Mannar observed during the pre-tsunami period was reduced to 36% after the tsunami. The mean cover of corals under stress was 6.7%, which included those showing partial bleaching and those infested with pink line disease syndrome. The percentage cover of silt-smothered corals was 30 (Figure 3 *e*). Damage to corals due to tsunami was 6.7%, and included recently killed corals, upturned corals and broken corals. Seagrass damage, filamentous, and thick and turf algae were also found.

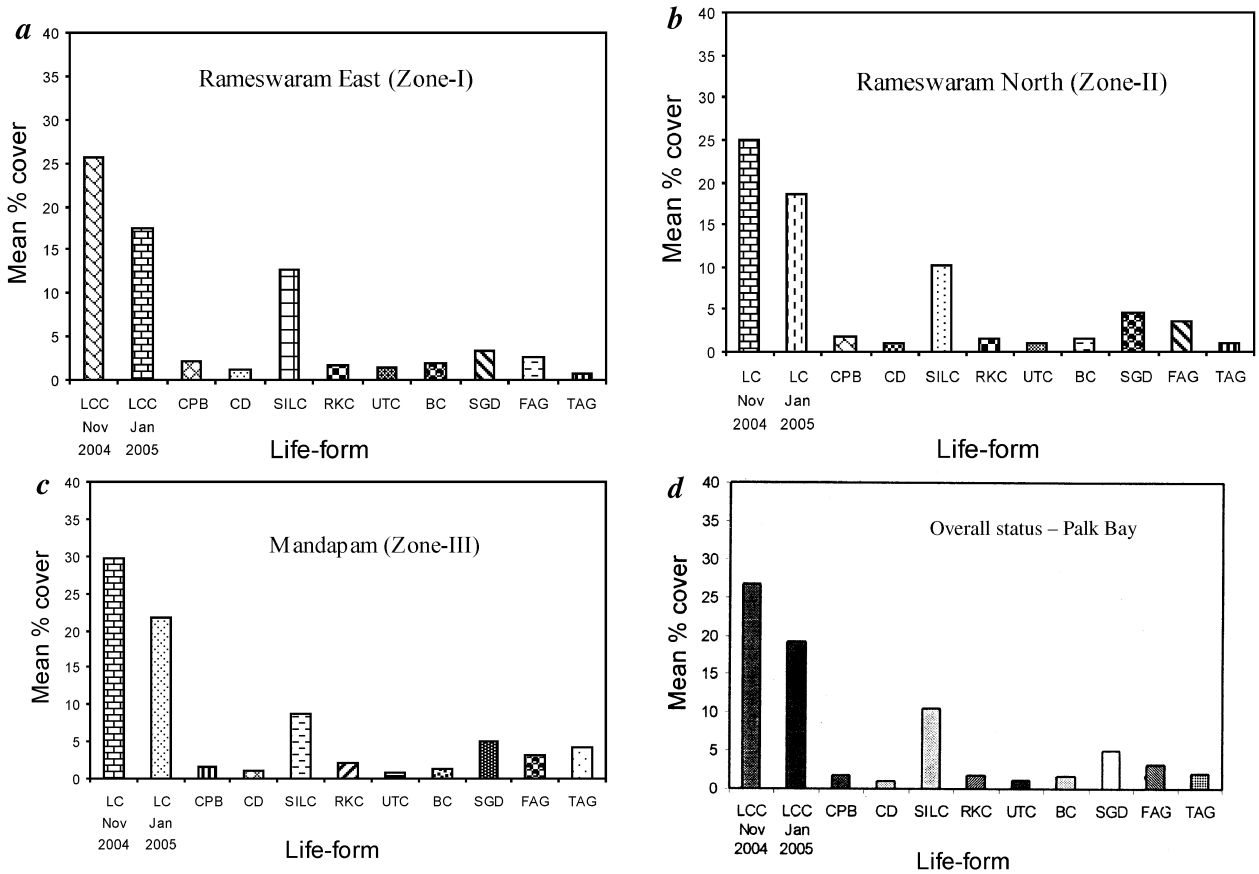

Figure 5. Biophysical status of coral life-form categories in the three zones of Palk Bay.

Landscape alterations revealed that Shingle island in the Mandapam group, Mulli, Valai and Thalaiyari islands in the Keezhakkarai group, Upputhanni island in the Vembar group and Van, Kasuwar and Karaichalli islands in the Tuticorin group showed more erosion of their shores compared to the other islands. Uprooted trees were also observed in all the islands. Corals of all the islands lying closer to the shore were affected by sedimentation.

Palk Bay

The pre- and post-tsunami observations indicated that there was a reduction in live coral cover. The biophysical status of coral life-form categories, viz. live coral cover, coral showing partial bleaching, coral infected with diseases, silt smothering live coral surface, recently killed coral, broken coral, upturned coral, seagrass damage, filamentous algae, and thick and turf algae in the Palk Bay region indicated differences.

Rameswaram East (Zone-I)

Biophysical status of reefs: The biophysical status of life-form categories during the pre-tsunami (November 2004) and post-tsunami (January 2005) periods is given in Figure 5 *a*. The pre-tsunami live coral cover of 25.6% had decreased to 17.5%, with a loss of 8.1%. Corals living under stress showed partial bleaching and infection with disease (Figure 4 *j*). Silt-smothered corals made up 12.6%. The damaged coral cover included recently killed corals, upturned corals and broken corals. Filamentous algae, thick and turf algal cover and damage to seagrass were also found in Zone-I (Figure 5 *a*).

Major physical changes: Zone-I of Palk Bay includes the area between Agnitheertham and Olaikudah regions facing east on Rameswaram island. The beaches of these areas are rocky in nature. Therefore, no shore erosion was found in this zone. However, the water level rose up to 2 m in height. Zone-I has mostly massive type of corals with huge structures. Only few corals of tabular and branched types were uprooted and broken due to the tsunami. Corals of Acroporidae, Mussidae, Pocilloporidae, Oculinidae, Faviidae and Poritidae were affected.

Sedimentation rates in Zone-I are given in Figure 6. The mean sedimentation rates were 5, 64 and 15 mg/cm^2/d during November 2004, December 2004 and January 2005 respectively. Thus, sedimentation rate was higher during the tsunami strike in December 2004 compared to that either before or after the tsunami.

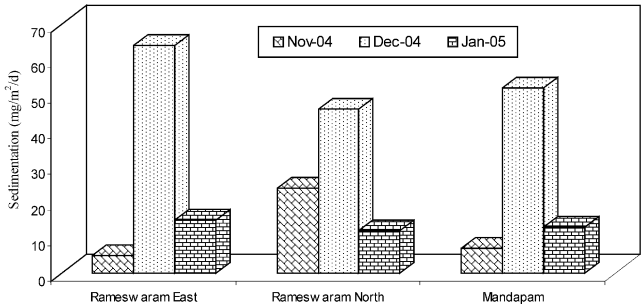

Figure 6. Sedimentation rate in the three zones of Palk Bay.

Rameswaram North (Zone-II)

Biophysical status of reefs: The biophysical status of life-form categories during the pre-tsunami (November 2004) and post-tsunami (January 2005) periods is given in Figure 5 *b*. In Zone-II, the pre-tsunami live coral cover of 24.9% has decreased to 18.5%, with a loss of 6.4%. Corals living under stress included those showing partial bleaching and infection with disease. Silt-smothered corals constituted 10.2%. The damaged coral cover was 4.0%, which included recently killed corals, upturned corals (Figure 4 *k*) and broken corals (Figure 3 *b*). Filamentous algae, and thick and turf algal cover were 3.5 and 1.1% respectively. Damage to seagrass (4.6 %) was also found in Zone-II.

Major physical changes: Zone-II of Palk Bay includes the area between Vadakadu and Pamban. The shores are facing the northern side on the island. The region between Vadakadu and Ariyankundu is on sandstone rocks and the region between Villunditheertham and Pamban is sandy beach. Shore erosion was not observed here. Sea water level rose up to 2 m. Inundation of sea water was noticed to an extent of 20–25 m towards the shore. Similar to Zone-I, some tabular and branched corals were uprooted in Zone-II. Corals of Acroporidae, Pocilloporidae, Oculinidae, Faviidae and Poritidae were among them.

Sedimentation rates of Zone-II are given in Figure 6. The mean sedimentation rates were 24, 46 and 12 mg/cm^2/d during November 2004, December 2004 and January 2005 respectively. Similar to Zone-I, sedimentation rate was higher in December 2004 after the tsunami.

Mandapam (Zone-III)

Biophysical status of reefs: The biophysical status of life-form categories during pre-tsunami (November 2004) and post-tsunami (January 2005) periods is given in Figure 5 *c*. In Zone-III, the pre-tsunami live coral cover of 29.8% has decreased to 21.7%, with a loss of live coral cover of 8.1%. Corals living under stress were 2.5%, showing partial bleaching and infection with disease. Silt-smothered corals constituted 8.8%. The damaged coral cover included recently killed corals, upturned corals and broken corals (Figures 4 *l* and 5 *c*). Filamentous algae, thick and turf algal cover, and damage to seagrass were also found in this zone.

Major physical changes: Zone-III of Palk Bay includes the area between Thonithurai of Mandapam and Vedhalai region. The beaches are sandy, facing north. Shore erosion was not observed in this zone. However, inundation of sea water was noticed to an extent of 20–25 m towards the shore, up to a height of 2 m. Similar to Zones-I and II, tabular and branched corals were uprooted and percentage of coral damaged and uprooted was more in this zone. Corals of families Acroporidae, Pocilloporidae, Oculinidae, Faviidae and Poritidae were affected.

Sedimentation rates in Zone-III are given in Figure 6. The mean sedimentation rates were 7, 52 and 13 mg/cm^2/d during November 2004, December 2004 and January 2005 respectively. Similar to Zones-I and II, sedimentation rate in Zone-III was also higher during December 2004 after the tsunami.

Overall status of Palk Bay

The overall status of coral life-form categories estimated during the pre- and post-tsunami periods in the Palk Bay region is given in Figure 5 *d*. The live coral cover of 26.7% observed in the Palk Bay during the pre-tsunami period was reduced to 19.2% after the tsunami. The mean cover of corals under stress was 2.8%, which included corals showing partial bleaching and those infested with pink line disease. Silt-smothered coral cover was 10.5%. Damaged corals due to tsunami included recently killed corals, upturned corals and broken corals. Seagrass damage, filamentous algae, and thick and turf algal cover were also seen (Figure 5 *d*).

Unlike the islands in the Gulf of Mannar, there was no change in landscape structure in the Palk Bay region. Only inundation of sea water was noticed in this region. Corals of all the islands in the Gulf of Mannar were affected by sedimentation due to the tsunami. The overall mean sedimentation rates in the Palk Bay region were 12, 54 and 13 mg/cm^2/d during November 2004, December 2004 and January 2005 respectively, indicating substantial increase in sedimentation after the tsunami.

Discussion

The post-tsunami status assessment of the islands and coral reefs around them in the Gulf of Mannar indicated that the margins and peripheral landscape of the islands were altered to a certain extent. Corals of Shingle, Mulli, Van, Karaichalli and Vilanguchalli islands have been

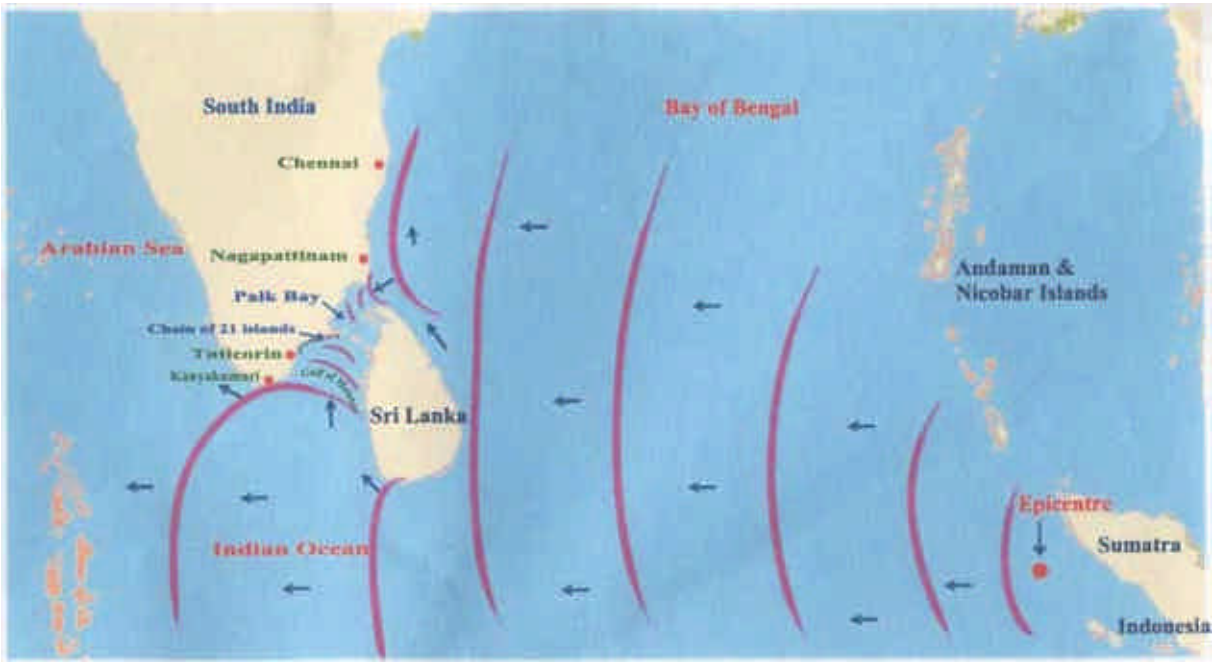

Figure 7. Flow of tsunami in the Gulf of Mannar and Palk Bay (based on simulation by Wikipedia, 2004).

disturbed by the tsunami. The height of the waves in the coastal areas of Tamil Nadu, particularly in Nagapattinam and Kanyakumari districts has been reported as 7 to 9 m causing enormous damage to life and property[2].

In Tamil Nadu, the waves struck the shores of Kanyakumari in the south and Nagapattinam and other districts in the north with full force, as there was no hindrance on their path. On the other hand, the coastal districts between the above two, viz. Pudukottai, a coastal district in Palk Bay, and the districts of Ramanathapuram, Tuticorin and parts of Tirunelveli in the Gulf of Mannar were not affected as the height of the waves was only 1 to 2 m with much less energy. This was obviously due to the barricade-like protection given by the island nation Sri Lanka (Figure 7). It appears that only the deflected waves after hitting Sri Lanka[2], and losing much of their energy, have entered the Palk Bay and Gulf of Mannar. Besides, the 21 islands and coral reefs around them in the Gulf of Mannar, stretching from Rameswaram in the north to Van Island in the south near Tuticorin, have acted like baffles dissipating the energy further (Figure 7).

The deflection and redirection of the waves and along with them the water mass, could be the reason for the sea water receding to unusual levels in some places before flooding back to normal. For instance, in Tiruchendur coast, located 30 km south of Tuticorin, pilgrims taking holy bath in the sea observed the water level receding up to a distance of about 50 m from the normal low tide mark. Similarly, in the southern side of Dhanuskodi (Gulf of Mannar coast), such an observation was made by fisherfolk and tourists. However, in some other places like Rameswaram (Palk Bay coast), the water level had slowly raised and flooded the roads, although not alarmingly.

The reef platforms along the periphery of the 21 islands in the Gulf of Mannar belong to the Pleistocene and modern times, and extend from Tuticorin in the south to Adam's bridge in the north[13]. They form a discontinuous chain of islands[14], lying close to the mainland at a distance of 5 to 10 km, and can be called 'Mannar Barrier'[15]. This barrier protects the low lands of coastal Ramanathapuram and Tuticorin districts from cyclonic effects. The reefs present may not be older than 4020 ± 160 years[16] and in any case less than 9000 years, similar to most of the modern reefs around the world[17,18]. The deflected waves which entered the Gulf of Mannar from the south have hit the islands from different directions, depending not only on the hydrodynamics of the water mass, but also on the nature and direction of spread of the island land mass. Therefore, different islands have their shores eroded in different directions, either on the lagoon side or on the seaward side or both in some cases.

The deflected waves as they moved from south to north (Figure 7) have caused erosion of the shores mostly on the lagoon side of the islands, changing even the peripheral contours in some islands. The lagoon side of most of these islands has lesser coral reef formation compared to the seaward side. At the same time, the erosion of the shores on the seaward side has been limited, since this side has a massive network of fringing and patch reefs. However, this has led to some impact on corals such as sedimentation of silt, partial bleaching, lesions on the surface of corals and coral disease (pink line syndrome) in some cases.

The erosion of the shores was greater along the lagoon side of the islands of Shingle, Krusadai, Manoliputti, Thalaiyari, Valai, Pallimunai, Yanaipar, Nallathanni, Puluvuni challi and Upputhanni. However, Van, Kasuwar and Karaichalli islands in the Tuticorin group have shown shore erosion on both sides, since the entry of deflected waves must have hit these islands first with greater force before moving on towards north to the other islands. Besides, the coral cover on the seaward side must have not only reduced the force, but also altered the course of flow of the water mass. Among all the islands, Shingle and Mulli had more erosion because they both have narrow stretches of seaward and lagoon side land masses characterized by irregular contours. This probably enabled the waves to strike all around the islands, resulting in substantial change in contour of the periphery, besides damaging the corals.

Shallow reefs close to the shoreline can help in protecting the coast by absorbing some of the energy. Reports from the 1883 tsunami following the eruption of Krakatoa volcano, have indicated that even giant coral heads weighing several tons were tossed hundreds of feet inshore[19], indicating that some amount of energy was still absorbed by the coral reefs. The degree and nature of the impact may vary depending on the shore topography and hydrodynamics of the wave itself. Thus, in the present study also, uprooted, upturned and smothered corals were found in many places as a result of the flow of water mass in different directions.

The morphology of coral islands is dynamic, since they are mostly made of sand and influenced by natural and anthropogenic agents. The natural disturbances include erosion, accretion, wave, current and sea-level variation. Anthropogenic disturbances include construction of breakwaters, discharge of industrial effluents, mining of coral reefs and trawling operations for fishing. Destruction of coral reefs by various anthropogenic activities such as siltation, logging and illegal mining has been reported[13,20–24]. Coral mining during the past several decades in the Gulf of Mannar, especially around the Tuticorin group of islands, for building construction, and industrial and chemical processes, has caused considerable damage and is a cause for concern[25,26]. Keezhakkarai and Mandapam group of islands have been facing erosion already along the northern sides, i.e. on the lagoon side. The tsunami has aggravated the situation and thus intensified the pressure on these islands, as evident from the submerged trees and sharp-edged coasts after erosion.

Detecting coastal environmental changes in the tropics poses unique challenges. Although subtle changes induced by human activities can be detected easily, natural variability is commonly difficult to distinguish. However, in many cases the induced changes associated with resource extraction and other human activities are so rapid that they can be quantified easily by geoindicators such as changes in the coral reefs[20,21,25], mangroves, shoreline position and sediment sequences[27,28]. The after-effects of the recent tsunami on the coral reefs as manifested by high sedimentation, siltation and smothered corals indicate the potential threat posed not only to the fragile coral reef ecosystem, but also to the coastal region of the mainland.

Ramesh *et al.*[29] reported the annual sediment deposition in the Gulf of Mannar sea floor as 1.73 cm/yr. The sedimentation rate in the Palk Bay is already high and the higher sedimentation level observed after the tsunami may aggravate the existing pressure on the fragile coral-reef ecosystem. In coral-reef ecosystems, sedimentation acts as a major limiting factor controlling the distribution of reef organisms and overall reef development[30]. The reduced level of light due to suspended sediment in the water column can reduce coral growth[31] and can have an impact on natural zonation patterns[32]. Excessive sedimentation can also discourage the settlement of coral larvae. Therefore, sedimentation and siltation resulting in smothered corals caused by the tsunami have been a potential threat to these already impacted ecosystems in the Palk Bay and also in the Gulf of Mannar.

Past experience indicates that damage caused by man may be irreversible but damage suffered by corals after a natural event such as a tsunami will be rectified over time. Corals will survive if protected from the destructive activities of man, because corals impacted by natural disasters have shown good resilience, as observed in the case of coral bleaching events of 1998 and 2002 in the Gulf of Mannar and Palk Bay regions[7,8].

The indiscriminate removal of corals during the last several decades has led to the loss of not only a number of coral species and coral grounds, but also the protection they have been providing from natural calamities such as cyclonic storms and rarely in a case like the recent tsunami. The Gulf of Mannar appears to have had a barrier reef ecosystem originally, perhaps a long time ago, as suggested by Bakus[15], and has been lost over time largely due to anthropogenic causes. Therefore, it is time that rejuvenation and rehabilitation of corals and coral reefs are done in a systematic manner so that a natural barrier reef may develop in the next few decades, which will be of service not only to the fishing industry but also to the coastal population. The idea of constructing seawalls along the beaches may not serve the purpose in the long run. Instead, developing a barrier reef ecosystem at least in the Gulf of Mannar and Palk Bay regions will help boost the environmental, social and economic conditions of the coastal people. Being one of the world's most productive ecosystems, coral reefs are vital to the coastal populations. Hence, it is imperative that their socio-economic role is taken into account and ecological measures implemented accordingly.

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