Review

Impacts and Recovery from a Large Tsunami: Coasts of Aceh

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Abstract

The impacts of the 26th December 2004 Indian Ocean tsunami were examined on three separate coastal sectors in the west, north and east of Banda Aceh. The most vulnerable coasts are the soft coasts, such as mangroves, and the least vulnerable are the rocky headlands with the sandy coasts occupying a broad intermediate position. The extent of impact for each category of coasts appears to vary with the tsunami wave height and other characteristics. Coastal recovery was remarkably rapid, especially for sandy beaches. In some cases, foredunes returned to the coast. The impacts and recovery processes provide valuable lessons for coastal management, for example, in the replanting of mangroves and other coastal vegetation in the modified coastal environments and the questionable construction of seawalls on accreting coasts. In years to come, the tsunami impacts would disappear, except for modifications by human activities.

Keywords: coastal geomorphology, tsunami impacts, coastal recovery, coastal management, Aceh

Introduction

Geomorphological studies on tsunamis have been limited [1] but became increasingly prominent after the 26th December, 2004 Indian Ocean tsunami. Much of the earliest geomorphological information on the coastal impacts of the Indian Ocean tsunami is scattered in various reports on the tsunami-affected countries [2-8]. More details on the geomorphological impacts of the 2004 tsunami on coasts came from academic studies focusing on the processes relating to erosion, transportation and sedimentation and, in particular, the interpretation of sedimentary deposits left behind by the tsunami. The studies dealt with the coasts of Indonesia [9-11], India [12-16], Maldives [17, 18], Thailand [19-22], and a number of other countries [23-28]. Contamination in sedimentation was first examined in one study [22]. Studies on geologic and geomorphic imprints and sedimentation have been conducted on other recent tsunamis in the Asian region [29-31].

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Geomorphologically, tsunamis erode the surface, transport materials, and deposit materials, leaving both distinctive depositional and erosional features on the coastal landscapes. In particular, large tsunamis produce significant geomorphological changes in a matter of a few minutes in coastal environments [10, 11, 22, 28]. Erosion is more evident and large-scale erosion can be considered as general scouring, while local scouring is caused by water as it moves around obstacles. The tsunami waves move faster into estuaries, rivers, and inlets, resulting in materials transported inland or left in lagoons and estuaries.

The impacts of tsunamis on a coast give rise to several related geomorphological questions. Firstly, what is the severity of impact and extent of change caused by a tsunami on a coast? The extent of alteration depends on the height or energy of the tsunami wave and the character of the pre-existing coast. It is expected that many tsunamis could not have any impact on the coast if their wave height is lower than ordinary waves or even storm surges. The 2004 Indian Ocean tsunami with a maximum water height of 50.9m in Sumatra, 19.6m in Thailand, 11.3m in Sri

Lanka, 9.6m in India and 4.4m in the Maldives [32] would create a wide range of impacts.

Secondly, what coasts would recover from the impacts of a tsunami? Most noticeable are the depositional coasts with beaches that were eroded at the shoreline and had deposition inland. Beaches were reported to recover within less than a year in Sri Lanka [27], while some effects are still noticeable one year later in the Andaman Sea [22]. In Aceh the tsunami impacts on the coasts were still noticeable in the last field trip in August 2008.

Thirdly, how long would the tsunami impacts remain on the coastal landscapes? While the immediate impacts of tsunami are evident, normal coastal processes would superimpose their imprint on the tsunami coast. Over time, the resulting coast will not show the impact of the tsunami but it may not be the same coast in form or space before the tsunami. Without being informed, one could not know the impact of the tsunami, except where human interference, e.g. seawall, resettlement, replanting, etc, has taken place.

As the lower end of tsunami impacts are merged with those of storm surges, it would be more likely that these impacts are not distinguishable. For most tsunamis, it is not surprising that their impacts have been determined by buried tsunami deposits or exposed megaclasts and other features if not covered by vegetation [33]. Thus, we have the curious issue of the tsunami as a geomorphic agent in rapidly altering coasts over geologic time but leaving practically little or no evidence of its changes.

Fourthly, how significant are tsunamis as a geomorphic agent? It seems that "[t]here has been little appreciation in the literature that coastal landscapes may reflect tsunami processes rather than those induced by wind-generated waves and wind" [33: 98]. "Tsunami[s] have for the most part been ignored in the geological and geomorphological literature as a major agent of coastal evolution" [33: 100]. The impacts of tsunami on coasts have been underestimated according to a worldwide survey on sedimentologic and geomorphic imprints [1]. But one could argue that on a large scale, coastal evolution depends on three driving mechanisms: sea level change, sediments and tsunami [34].

A related aspect to the above question is the role of tsunami within the magnitude and frequency concept [35]. While tsunamis are considered "common, high-magnitude phenomena" [33: 100], they have been have described as "high-magnitude and high-frequency events at geological timescales" [1: 85] and also as "high magnitude-low frequency events in coastal evolution" [1: 89]. This paper treats tsunamis as high-magnitude and low-frequency events in which the post-tsunami coast is subject to normal coastal processes but it may not take the development pathway as it did prior to the tsunami.

Finally, there are implications for coastal management as to whether a coast is recovering or a new coast has been created by a tsunami. The coastal condition provides valuable information for the rehabilitation of ecosystems, e.g. the restoration of mangroves and other coastal vegetation. For example, in Aceh, replanting was unsuccessful in a number of areas because of a failure to recognize the retreat of the shoreline or suitable hydrological and sedimentological situations for planting of mangroves. Also, the construction of seawalls was carried unnecessarily when beaches are recovering or new beaches built on coast [36].

Coastal Types and Forms

Whereas the characteristics of tsunamis are influenced by wave height (extreme, large, moderate), direction, and nearshore bathymetry [11, 27, 30, 37], their impacts depend on overall coastal variables such as the erodability of coasts (e.g. rocky coasts or coasts of unconsolidated material) and coastal features. Dunes and beach ridges prevent tsunami flow from penetrating inland [28]. In Sri Lanka, the dunes are significant where tsunami heights were moderate (<4-7m) [27]. Coastal vegetation belts can also reduce tsunami impacts.

Local factors at the coast are important in influencing the tsunami impacts, e.g. varying shelf topography, morphology, coastal habitats and vegetation, sediments, infrastructure and others for the Andaman Sea coast [22] or the width of reef flat, height of beach berm, and orientation to tsunami approach for the atolls of the Maldives [27]. In contrast, differing coastal types (morphology, topography, habitats), the sheltering effect of islands and the extensive human change to the North Coast are important factors in Aceh.

Information, even qualitative, is scarce on the impacts of tsunamis on coastal types and their subsequent recovery. The IUCN considered eight coastal types for the assessment of tsunami impacts: open (straight) sandy, open (straight) rocky, barrier, embayed, coral reef, archipelago, tidal flat and estuarine and deltaic coasts [38]. One textbook cited sandy barrier coasts, deltas and alluvial plains, two types of rocky coasts and atolls separated by deep channels as the major coastal landforms created by tsunamis [33]. Another study attributed cobble deposits, embayments and absence of fringing reefs on the windward reefs of Netherland Antilles to the impacts of tsunami [39]. For the Indian Ocean tsunami, one study has examined the general impacts on a variety of coastal environments in Sumatra, Sri Lanka and the Maldives [27]; another emphasized the coastal habitats and morphology of the coast [22]; and a third indicated that coastal landforms can be changed by tsunami flows [28]. On some coasts, the rapidity of change or coastal sensitivity is increased by the impact of a tsunami. For example, tsunamis increase the rapidity of change or the coastal sensitivity of soft coastal landscapes, e.g. beaches, dunes and mud flats [40].

This study examines the impacts of the 26th December 2004 Indian Ocean tsunami on the coastal types of Aceh to gain some insights into the impacts, the extent of recovery and new forms created. It is supplemented by photographs to fill the illustrative gap on these significant geomorphological aspects of impacted, recovered or new coasts.

Study Area

The study focuses on three coastal sectors of Banda Aceh totaling about 65km, extending west to Pulot village and east to Kuala Lho Me. The West Coast, North Coast and East Coast are approximately 20km, 25km and 20km, respectively (Fig. 1). They vary in geological structure and relief, coastal types, and coastal processes. For each coast, its orientation, offshore topography and coastal forms are important factors in influencing the extent and impacts of the tsunami.

The North Coast is low-lying and consists of undifferentiated alluvium. The West Coast is of high relief and consists of massive Palaeozoic limestones at headlands and alluvium in the bays and estuaries. The East Coast has moderate relief with volcanics and fringed by alluvium; coralline limestone is at one headland, Ujung Batee Kapal [41]. The study area is subject to monsoonal climate with Northeast Monsoon from December to March and Southwest Monsoon from May to September, and thus a strong seasonal impact is evident on the beaches and river mouth bars.

The coasts of Aceh are influenced by semi-diurnal tides with a tidal range of slightly more than 1m at Banda Aceh. Wave conditions vary widely. The North Coast, which is protected by Pulau Weh, is the most sheltered and has a wave height mainly <1m from the northwest. The most exposed is the West Coast as it is open to the Indian Ocean swell with wave height of 1-2m and even more from the dominant southwest direction. The East Coast is in between with waves from a wider sector from NW to NE and wave height predominantly <1m [42].

The coasts in the study were impacted by different tsunami heights according to various field surveys. An international team found that most wave heights exceed 15m with some above 30m on the West Coast, a majority below 10m and few above 10m at Banda Aceh on the North Coast, and just above 5m at Kreung Raya Port on the East Coast [43]. Comparable maximum run-up heights of 25+ m at Lhoknga on the West Coast, 8m between Banda Aceh and Kreung Raya on the North Coast, and 5+ m south of Kreung Raya on the East Coast were given in another study [44]. The Russian team found heights mostly more than 10m with the highest at 34.9m [45]. The highest was 48.8m at Banda Aceh [46], a value comparable to the maximum water level cited by the National Geophysical Data Center [32]. To summarize, the West Coast was impacted by the highest wave height, sometimes exceeding 30m, the North Coast by height around 10m, and the East Coast by heights of about 5m. These different wave heights have implications on the impacts and recovery of various coastal types in the study area.

Field trips were conducted in May 2005, July 2006, March 2007, and August 2008 to examine the impacts and recovery of the coasts of Aceh from the 2004 tsunami. Not all locations were covered in all four surveys (due to lack of accessibility), but field observations could determine how the tsunami has impacted and the coasts recovered. The preliminary results of the survey in May 2005 were reported earlier [47]. This study extends the duration and other locations of observation not covered in the first survey to obtain a better idea of recovery and coastal evolution. The observation from May 2005 to Aug 2008 provided a better sense of recovery and the permanence of landforms created by the tsunami. However, a full picture will not be known until monitoring continues for many more years.

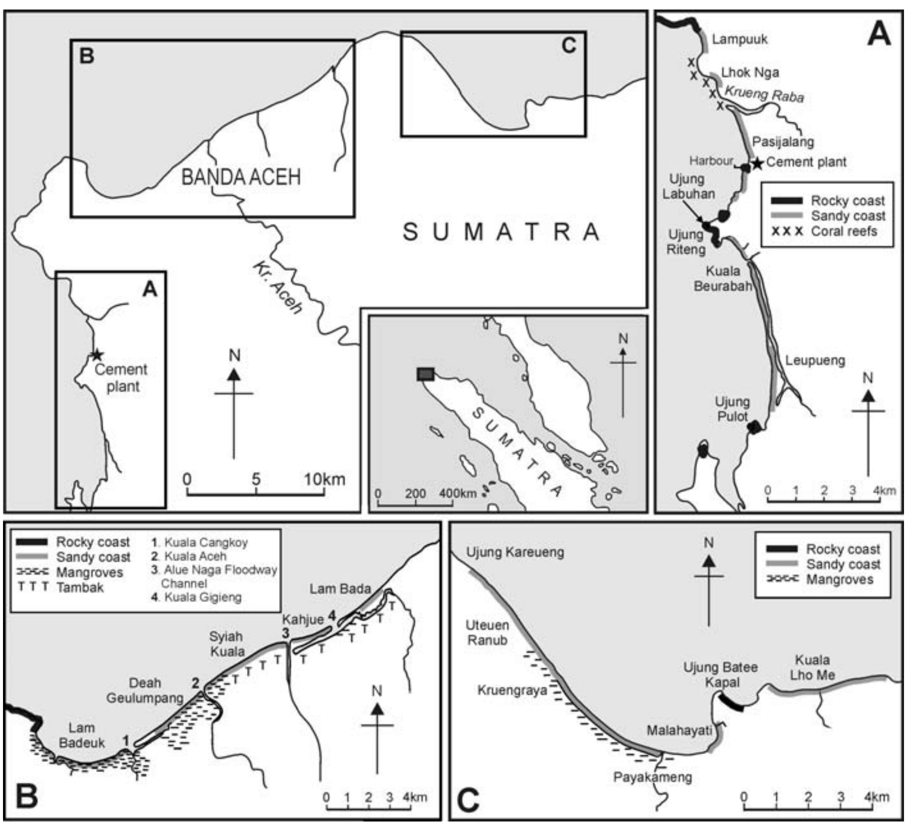

Fig. 1. Study area: Pre-tsunami major coastal types. A. West Coast. B. North Coast. C. East Coast.

North Coast

The pre-tsunami North Coast within Banda Aceh was a low-lying coast punctuated by estuaries, lagoons, sand spits and small barriers. It was cut by two major artificial outlets (Krueng Aceh and Alue Naga Floodway channel) and two natural outlets (Kuala Cangoy and Kuala Gigieng) which separate a number of barriers and beaches at Lam Badeuk, Deah Gelumpang, Syiah Kuala, Kahjue and Lam Bada (Fig. 1) [48].

The North Coast had been substantively modified by human activities. Mangroves behind the barriers and around estuaries had been replaced by aquaculture (tambaks or fish ponds and shrimp ponds) and paddy cultivation. The settlements were subject to periodic flooding by tides. The major coastal types of the North Coast were beaches and low barriers under a low wave energy environment.

Although the tsunami waves were not the highest on the North Coast, their impact was a virtual destruction of the low-lying coastal landforms - barriers and barrier islands, gentle beaches, mangroves - and the human landscape. The entire coast was most severely impacted by inundation and with subsidence [51], the coastline retreated further inland up to several hundred metres [52]. Inundation was observed 3-4km inland [44]. Vestiges of concrete buildings, cement floors, ponds, and paddy fields remained and were flooded by seawater. Ponds and paddy fields were characterized by their remaining embankments at right angles to the coast.

The barriers and low-lying beaches fronting the North Coast were completely destroyed except for sectors towards the east. The most dramatic retreat of the sandy coast was at Syiah Kuala. The sand spit east of Kuala Cangkoy at Ulee Lheue was washed through in several places [44]. Towards the east, remnants of the barrier east of the Alue Naga Floodway Channel remained at sea in May 2005. Part of the lagoon remained at Kuala Gigeng, having been extended at its widest in the Banda Aceh area.

Over a period of four field visits, the beaches built slowly on a much retreated coastline and were increasingly better from west to east. Beach formation ceased east of the Alue Naga Floodway Channel after the completion of a rubble seawall from the western end of the town to the floodway. The coastal seawall, which stands at 2m high with a 5-m wide base and a 2-m wide horizontal crest, was built to prevent flooding that occurs with high tides or with heavy rainfall [36].

The structure prevented beach formation outside the wall as observed at Krueng Bau (east of Lam Badeuk). A small sandy tombolo between a remnant terrain and the seawall was evident in March 2007 but it disappeared when observed in August 2008. Deah Geulumpang beach could not recover further with the completion of seawall when observed in August 2006 (Fig. 2).

Immediately east of the Alue Naga Floodway Channel is Kahjue Beach, which is an example of a beach where coastal processes operate without the interference of the seawall. It benefited from the movement of onshore material and longshore drift from east to west (Fig. 3). Further to the east at Lam Bada Beach, foredunes of almost 1m in height have formed as a result of more sediments and strong wind from the Northeast Monsoon (Fig. 4). The foredunes are colonized by a herbaceous herb *Sesuvium portulacastrum* and a sand-binding creeper *Ipomoea pes-caprae.*

In summary for the North Coast, the main coastal types before the tsunami consisted of gentle beaches fronting barriers and spits washed by low wave energy waves. In the post-tsunami phase, recovery was possible if sediments were brought in from the nearshore zone or from alongshore drift. Wind has helped to create low foredunes which are being colonized by vegetation. A major intervention to coastal recovery has been the construction of a coastal seawall from the western end of town to the Alue Naga Floodway Channel behind which flooding occurs.

Fig. 2. Deah Geulumpang Beach in its early stage of recovery ceased to recover further when enclosed behind a rubble seawall that stretches from the east of the town to the Alue Naga Floodway Channel, March 2007.

Fig. 3. Kahjue Beach, east of the Alue Naga Floodway Channel, continues to recover as it is not enclosed by the rubble seawall, March 2007.

Fig. 4. The recovery of Lam Bada Beach has progressed well with the formation of low foredunes colonized by *Sesuvium portulacastrum* (foreground) and *Ipomoea pes-caprae*, August 2008. Landwards of the foredunes are planted Casuarinas.

West Coast

In contrast to the East and North coasts, the West Coast is exposed to high swell waves from the Indian Ocean, reaching up to more than 2m. Before the tsunami, it was predominantly a sandy coast of bays and barriers between headlands and estuaries. The rocky headlands appear as a result of massive limestones extending as spurs or isolated hills near the coastline, particularly in the northern half of the West Coast. Beaches backed by high fossil dunes and beach ridges were found at Lhok Nga. South of Kreung Raba, barriers and lagoons dominated; the barrier at Leupung was 6km long [49]. The barriers were directed north as a result of stronger longshore drift from south to north during the Southwest Monsoon. Beaches were subject to seasonal changes. The coral reefs off the southern headland of Lampuuk and at Lkok Nga build beaches with distinct coral sand. Mangroves were limited and confined to estuaries and behind the barriers. Several major coastal types could be distinguished on the pre-tsunami coast (Fig. 1).

Fig. 5. The high coastal dune belt at Lampuuk was eroded and scoured severely to expose underlying layers of fossilized layers, August 2008.

(a)

(b)

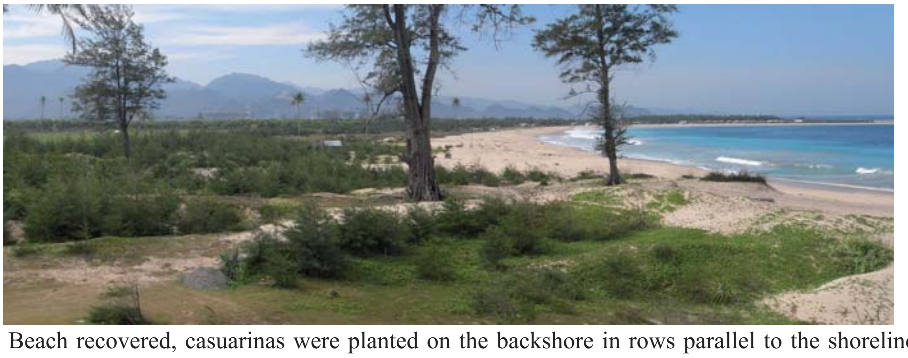

Fig. 6. As Lampuuk Beach recovered, casuarinas were planted on the backshore in rows parallel to the shoreline, March 2007 (a). Some of the more seaward rows did not survive but the rest flourished well, August 2008 (b).

Of the three coasts, the West Coast received the maximum destruction as it faced directly the direction of the tsunami waves and was not protected by nearby islands. The fringing reefs at Lhok Nga and Leupueng did not stop the large tsunami waves. Previous studies recorded severe erosion and subsidence with a coastal retreat of up to 60-100m inland in Lhok Nga and extensive sand sheets reaching 5km inland [10]. The erosive impacts included coastal retreat, vertical erosion, erosion of rivers and cliffs and boulder deposits [11]. At one location, continuous soil stripping was up to 50m inland from the shoreline [9].

Lampuuk beach with its 15-m high dunes was affected severely. Sand was removed inland and offshore and the tsunami waves penetrated into the river on the northern end of the beach. The beach ridges and dunes were stripped of vegetation and lowered in height; the overlying material of the dunes removed to expose underlying cemented layers, also noted in an earlier study [11] (Fig. 5). While the beach ridges and dunes could not regain their height, the beach recovered rapidly and its backshore planted with casuarinas. Further inland, the tsunami-flooded area is being reduced (Fig. 6). The stream near the northern headland is still blocked by a sand bar.

Another indication of rapid coastal recovery is immediately south of Lampuuk at Lhok Nga beach, where there were low dunes before the tsunami. The beach has recovered through the migration of bars welded to the beach to reduce the depression on land. Foredunes have re-established due to strong winds from the southwest (Fig. 7).

The barriers along the West Coast were completely removed or partially destroyed. In the former case, the coast retreated to the landward side of the lagoon. At the northern half of Leupueng new beaches are being formed on the much retreated coastline. The remnant barrier in the south recovered through bars migrating landward; a 95-m wide berm and a 20-m wide foreshore were recorded in August 2006 and casuarinas have been replanted (Fig. 8). Some winding streams previously influenced by spits and barriers now reached directly to the sea.

Despite being impacted severely, coastal recovery has been remarkably rapid on the West Coast. Overwashes were an important process in the recovery as first observed in May 2005 at the beginning of the Southwest Monsoon. South of Ujung Riteng, overwashes up to 22m wide were plastered on a 15-m wide foreshore in August 2006. Through overwashes and normal progradation the beaches subsequently recovered. Almost all beaches were wider than before except where the pre-tsunami beaches were very wide [50].

In contrast, recovery on coral beaches has been poor. To date, the coral beaches have not fully recovered, due to lack of material or of sufficient size to be washed on to the reef flat. Also, the hard surface of the coral flat is not conducive for deposition of materials.

On coral beaches, the tsunami waves damaged the coral reefs, removed coral beaches, and distributed materials over a wide area. Boulders were recorded in several sectors with the maximum boulder measuring 7.2m and weighing

(a)

(b)

Fig. 7. In May 2005, Lhok Nga Beach was in an early stage of recovery with sand moving landward to reduce the depression and the flooded area (a). By March 2007 the flooded area has been greatly reduced, the beach well recovered and low foredunes formed (b).

(a)

(b)

Fig. 8. In May 2005, the barrier at Leupueng was barely recovering with the lagoon remaining wide (a). By Aug 2008, the lagoon had decreased its width and the barrier had widened and was planted with casuarinas (b).

an estimated 85 tons [11]. In May 2005 the largest coral boulder measured about 1x2x3m and estimated around 15.6-16.2 tons assuming that the specific gravity of coral is below that of limestone at 2.6-2.7 (Fig. 9). This boulder had been dislodged from the reef flat and has not moved from its position.

The tremendous force of the tsunami waves is evident on rocky headlands which took the full force as the tsunami hit the coast. Basal stripping of the forested slope produced a distinct and characteristic trimline in the headlands. I propose to name this type of headland as the "Dayak" headland, after the coiffure of the Dayaks (a general term referring to the indigenous non-Muslim groups in Kalimantan/ Borneo) (Fig. 10). This "Dayak" headland does not correspond to any existing model of hardrock headland in which the vegetation cover has an important role [33]. Laser measurements of the headland immediately north of the harbour indicated the trimline to be at 20.5m, compared to 25m in another study [44].

Fig. 9. The largest boulder reported in this study has fresh (whitish) marks indicating that it was clearly dislodged and moved to the coral flat by the tsunami waves, March 2007.

In summary, the west coast of rocky headlands, beaches and barriers, and coral reefs saw a much varied response to the tsunami. Sandy coasts were eroded landward with the destruction of some barriers. Coastal recovery was rapid for the sandy coasts and some new beaches were formed on a much retreated coastline. Rocky headlands bear the distinctive "Dayak" haircut trimline.

East Coast

The pre-tsunami East Coast consisted of bays with lower dunes and beach ridges between three broad headlands. Like the West Coast, the beaches were also subjected to seasonal changes. Malayalati Port is in the largest bay where a narrow belt of mangroves had developed behind a barrier. Unlike the general situation on the east coast of Sumatra, the estuaries have a substrate of sand [53] and the sandy sheltered bays are colonized by *Sonneratia alba*.

In general, the erosional impacts of the tsunami on the East Coast were far less severe that those on the West and North coasts, although the extent of inundation was 1 km at Kreung Raya, south of Uteuen Ranub [44]. The reduced tsunami impact was perhaps due to a combination of factors: the lower tsunami wave heights and thus lower erosive impact, the coastline not facing the direction of tsunami waves, and the nature of the coastal forms. Subsidence was evident on the East Coast by a belt of submerged mature *Sonneratia alba* 40-100m from the present shoreline at Kuala Lho Me. At Payakameng the landward retreat of the holes of the mangrove mud lobsters (*Thalassina anomala*) into the vegetable gardens of the villages could be a further indication of subsidence of the land [47].

Coastal recovery began particularly with the onset of the Northeast Monsoon towards the end of 2006. Although the low dunes and beach ridges were eroded, coastal recovery took place along the entire East Coast. The main process of recovery is in the landward movement of nearshore material, leading to the gradual disappearance of the elongated depression as materials were added to the tsunami-impacted sandy coast (Fig. 11). At Kuala Lho Me, the beach ridge had been eroded and with subsidence, the *Sonneratia alba*, are now in a much seaward position. The beach is recovering as sediments are brought down to the coast by the stream (Fig. 12).

In summary, of the three coasts, the East Coast had the least impacts. Beaches were not eroded severely and recovered. Mangroves were eroded but mature trees survived.

Coastal Management

The impacts of the 26th December 2004 Indian Ocean tsunami on the various coastal types of Aceh offer valuable lessons for coastal management. The same coastal type can be impacted differently and coastal recovery varies with coastal type. High dunes and beach ridges did play an important role in protecting the coast. Some mature mangroves were relatively unaffected if tsunami waves were low. However, the nearshore coral reefs were damaged and with the removal of sand from the reef flat and the backshore, beach recovery is much more difficult compared with sandy coasts. Even with the complete removal of some barriers, beaches can form on a much retreated coastline.

(a)

(b)

Fig. 10. The hill north of the harbour on the West Coast showed its characteristic trimline, May 2005 (a). By August 2008, vegetation had re-established at the trimline to make it less distinctive.

Fig. 11. South of Uteuen Ranub, beach recovery is still in progress and is also affected by seasonal changes, March 2007.

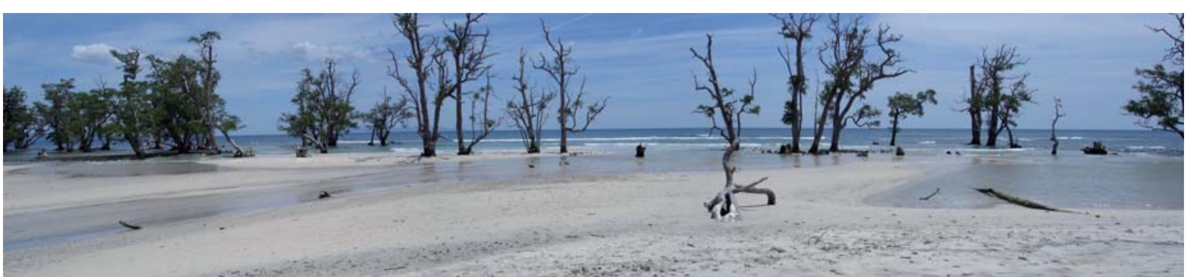

Fig. 12. At Kuala Lhok Me, subsidence has resulted in mature *Sonneratia alba* lying 40-100m from the shoreline at high tide. The beach is recovering from sand brought down by a stream from a coastal sector where active rehabilitation of the coast for shrimp ponds is taking place, August 2006.

In the post-tsunami phase the replanting of mangroves and other coastal vegetation was considered a good practice in tsunami mitigation measures. Not all replanting programmes were successful. For example, in the rush to plant coconuts on the recovering Lhok Nga beach, the young coconut seedlings were rapidly dessicated by dry conditions from the blowing sand of foredunes (Fig. 13). The failure of some mangrove replanting on the North Coast and West Coast was caused by problems of local hydrology and sediment transport (Fig. 14). The success of replanting requires many physical factors including knowledge of modified previous environments and the involvement of coastal communities [36].

Seawall construction to protect the eroded coast in the post-tsunami phase is questionable in some cases. On coasts where subsidence has occurred and flooding is common, seawalls to prevent flooding (with complementary flood alleviation schemes) seems logical, such as at Pulot village on the West Coast (Fig. 15). However, where beach recovery is evident and the beach is wide enough to protect the coast, there is less necessity for a seawall, such as south of Ujung Riteng, where the seawall approaches the base of the headland (Fig. 16), and north of the cement plant at Pasijalang (Fig. 17). In August 2006, the beach at Pasijalang had a 47-m berm colonized by *Ipomoea pes-caprae* and has replanted coconuts. Although the rubble seawall on the North Coast was meant to keep out high tides and floods, it restricts the discharge of floodwater and seawater. An alternative protective barrier could be provided by the rehabilitation of mangroves and other coastal vegetation [36].

Coastal protection works and mitigation measures should be carried out with a better understanding of the tsunami impacts and coastal recovery. More field research is required to provide a better understanding of effective mitigation measures and thus reduce the wastage of funds.

Discussion

This study provided illustrated examples of several coastal types impacted and recovered from a large tsunami. Quantitative statements relating tsunami waves to the impacts of coastal types are not possible. For example, no relationship has been established between coastal retreat and wave height [11].

Several qualitative statements relating to tsunami impacts to coastal types are possible. Firstly, the most vulnerable coasts to a tsunami are "soft" coasts, such as mangroves, and the least vulnerable are the rocky headlands with the sandy coasts occupying a broad intermediate position. Secondly, the extent of impact for each category of coasts appears to vary with tsunami wave height and other characteristics, but this is difficult to determine. One area of controversy relates to the effectiveness of mangroves to protect the coast from tsunami impacts [54-59].

Fig. 13. An early attempt to plant coconuts at the Lumpuuk dunes failed because of burial from sand, May 2005.

Fig. 14. At Krueng Bau, replanted mangroves faced problems of sedimentation and barnacle infestation, March 2007.

(a)

(b)

Fig. 15. Remaining coconut tree stumps were indicative of severe erosion to the coast at Pulot village, May 2005 (a). By August 2006, a rubble seawall had been built to protect the road which was occasionally affected by high tides (b).

Fig. 16. South of Ujung Riteng, the beach is recovering and wide enough for protecting the road. A rubble seawall constructed up the headland in the south is unnecessary and interferes with beach recovery, March 2007.

Fig. 17. North of the cement plant, Pasijalang Beach has recovered well enough to have casuarinas planted on its backshore and is used for local recreation. The construction of a rubble seawall almost along the berm crest would not be useful, March 2007.

Field observations in Aceh and elsewhere (Thailand, Sri Lanka, and Tamil Nadu) suggest that mature mangroves and coastal vegetation can be effective against tsunami wave heights of about 5m, close to a value cited elsewhere [53, 60]. Few coastal ecosystems can be effective against tsunami waves of 10m or more.

In terms of coastal recovery, rocky headlands will be colonized by vegetation and soil formation would take place over a much longer period. Mangrove coasts may not recover at all to their former state as their topography has been greatly altered and hydrologic and sedimentary conditions differ from their previous state. For example, mangroves could not recover to their previous state on the severely altered North Coast.

For sandy coasts, the most vulnerable are spits and barriers, some of which may disappear completely. Beaches can recover due to the fact that normal coastal processes take place after the tsunami. An important factor is the source of sediments as the tsunami moved some sediments inland which were thus lost permanently. Some sediments moved seaward and these could migrate landward through bars. Also, longshore drift would be interrupted by changes in estuaries and inlets and coastlines may take a longer time to reach a new equilibrium.

Beach recovery takes place through overwash facies from stronger waves during onshore monsoons and progradation facies of normal waves. The rate of recovery depends on the availability of material from the nearshore zone. New beaches can form on the landward side of lagoons where barriers have been removed. If sediments are available, barriers can recover.

Conclusions

Several generalizations can be made on the impacts of a large tsunami on coastal types. All coasts will be impacted but in different degrees depending on the character of the coasts and the nature of a tsunami's erosive power. The majority of coasts, with the exception of mangroves, will usually recover. A minority of new coastal forms will be created.

Although some tsunami impacts still remain after a year [22] long-term impacts will be minor except in cases of vertical uplift or subsidence where coasts required a longer time to adjust to the sea level [27]. In the examples from the West Coast [50] and also on the North Coast, some new beaches have been created or have recovered on a much retreated coastline. Thus, in countries with earthquake-prone coasts, such as Japan, Indonesia, and the Philippines, this raises the intriguing issue of whether their coasts are being renewed and shaped periodically in decades or hundreds of years by tsunamis.

A related question is then whether a category of tsunami-dominated coasts can be as important as wave-, tide-, and fluvial-dominated coasts. Geologically speaking, the answer would be affirmative as the tsunami-dominated coasts would probably be at the top of a hierarchy of coastal types but eventually masked by the other coastal processes. The possible exception would be the boulders left behind by extreme tsunamis.

Finally, the tsunami impacts and subsequent coastal recovery provide valuable immediate lessons for mitigation measures to be implemented: for replanting mangroves, location of housing, vegetation belts, etc. In years to come, few will recognize the coasts of Aceh as impacted by the Indian Ocean tsunami, except where modifications have been done by human activities. Eventually, much coastal evidence of the tsunami impacts would disappear rapidly except in extreme cases, e.g. Krakatau. In geomorphological processes, tsunamis are low frequency but high magnitude events that wrought changes to the coastal landscapes that in time become part of the norm.

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