Appraisal of tsunami inundation and run-up along the coast of Kanyakumari District, India – GIS analysis

OCEANOLOGIA, 49 (3), 2007.
pp. 397–412.

KEYWORDS
Tsunami
Kanyakumari
Inundation
Geospatial technology
Evaluation

Nainarpandian Chandrasekar*
Jeyakodi Loveson Immanuel
Jeyaraj Dajkumar Sahayam
Manoharan Rajamanickam
Sakthivel Saravanan

Centre for GeoTechnology, School of Technology,
Manonmaniam Sundaranar University,
Tirunelveli – 627 012, India;

e-mail: ncsmarine@yahoo.co.in

*corresponding author

Received 23 February 2007, revised 9 July 2007, accepted 16 July 2007.

Abstract

On 26 December 2004, a tsunami severely affected almost all the coastal villages of Kanyakumari District, India. It was one of the worst affected coastal sectors of South India. An attempt has been made here to assess the impact of the tsunami hazard on coastal landforms and the level of inundation using GIS techniques. The areas of inundation were surveyed and mapped by fixing regular transects along the coastal regions. The percentage of inundated area in the total area was estimated. It was found that inundation was higher on low-lying coasts and relatively less on elevated coasts. In some cases, the extent of inundation was a few kilometres in relation to other coasts, but the percentage of inundated area in the total coastal area was high. The extent of inundation along the study area varied from 50 m to 450 m. Inundation was minimal in coastal villages like Kanyakumari, Agastheeswaram, Madhysoodhanapuram and Dharmapuram, but extensive at Colachel. The percentage of inundated area in the total area ranges from 8% (Dharmapuram) to 39% (Colachel). The degree of inundation was controlled by coastal geomorphological features such as sand dunes, cliffs, coastal vegetation, nature and configuration of the beach, not to mention the angle and velocity of the invading tsunami surge.

1. Introduction

A tsunami is a natural coastal hazard generated in the deep ocean as a result of an earthquake, volcanic activity, submarine landslide or meteoritic impact. It propagates across the ocean from the point of origin at a steady speed and transforms into a series of giant waves. These waves suddenly increase in height, causing severe damage to the coastal zone. One such event happened on 26 December 2004 as a result of an earthquake (magnitude > 9 on the Richter scale) focused along the subduction zone of the India Plate with the Burma Micro Plate off the island of Sumatra, Indonesia (Park et al. 2005). It caused immeasurable loss of life, property, etc., along the coastal regions of Indonesia, Thailand, Sri Lanka, India and Africa. It also altered coastal landforms and shorelines in the affected areas. Tsunamis are frequent events in the so-called ring of fire around the Pacific Ocean and in the coastal regions of Japan but are rare occurrences on Indian Ocean coasts (Kumanan 2005).

Much research has been carried out to determine the impact of tsunamis on coastal environments such as the nature of inundation, run-up level, erosion, deposition, vegetation, etc. in damaging the coast. Alami & Tinti (1991) evaluated the tsunami hazard along the Moroccan coast by comparing tsunami data with the set of available earthquake data. Minoura et al. (1994) studied the sediments deposited by tsunamis in the lacustrine sequence of the Sanriku Coast, Japan, and inferred the probable source of those sediments deposited on the coast. Dawson (1994) suggested that the geomorphological processes associated with tsunami run-up and backwash are highly complex. He showed that coastal landscapes might be greatly altered not only by direct tsunami run-up orthogonal to the shoreline but also by episodes of vigorous backwash and by water flow sub-parallel to the coastline. In order to assess the future risks, Jaffe & Gelfenbaum (2002) used tsunami deposits to create geological records of not only of a single tsunami but also of the effects of past tsunamis. Raval (2005) reported severe destruction along the coast of Nagapattinam, South India, primarily because of its geographic setting, which has favoured much inundation. Narayan et al. (2005a) found that the elevated landmass (medu) played a key role in preventing inundation and minimising damage along the coast of Tamilnadu. Mohan (2005) reported that elevated coastal dunes and beach ridges along the coastline could act as barriers to minimise the rate of inundation along the northern parts of the Tamilnadu coast. Narayan et al. (2005b) found that the degree of inundation was strongly scattered in direct relationship to the morphology of the seashore and run-up level on the Kerala coast. Kurian et al. (2006) investigated the inundation characteristics and geomorphological changes resulting from the 26 December 2004 tsunami along the Kerala Coast, India. They noted that river inlets had been conducive to inundation; the devastation was extremely severe there, as the tsunami had coincided with the high tide. Chandrasekar et al. (2006b) reported that the extent of inundation depends mainly upon the nature of the coastal geomorphology. Chandrasekar et al. (2005) and Mujabar et al. (2007) found that beach morphology and sediment volume along the southern Tamilnadu coast were modified by the tsunami inundation. In recent years, advanced scientific techniques like GIS and Remote Sensing have been applied to comprehend and model the various aspects of tsunamis. Walsh et al. (2000) compiled a tsunami hazard map based on the modelled inundation for the Southern Washington Coast. Papathoma et al. (2003) estimated the tsunami vulnerability for the Herakleio coast in Crete. Bandibas et al. (2003) developed new software – Geohazard View – for the interactive management of geological hazard maps. Keating et al. (2004) modelled the inundation of the Kealakipapa Valley, Hawaii, using a 10 m tsunami wave model. Imamura (2004) introduced a new information system – TIMING (Tsunami Integrated Media Information Guide) – for monitoring tsunamis in Japan for advanced and real time information. Chandrasekar & Immanuel (2005) categorised the tsunami hazard for certain beaches of South India using GIS techniques. Chandrasekar et al. (2006a) applied geospatial technologies to evaluate the impact of tsunamis on certain beaches in South India and compiled a hazard map. In this paper, we have attempted to map the extent of inundation at village level and to find a relationship between the extent of inundation and the run-up level.

The study area (Latitude $08^0 04' 30''$ and $08^0 12' 30''$N and Longitude $77^0 15' 45''$ and $77^0 33' 58''$E) is situated in the southernmost part of the Indian Peninsula (Fig. 1). The Bay of Bengal, the Indian Ocean and Arabian Sea border the study area but the major part of it faces the Arabian Sea. It comprised 12 coastal villages in Kanyakumari District, Tamilnadu State, India (Fig. 1). A small number of rivers, along with several creeks and streams, control the drainage system. The River Palaiyar debouches into the Arabian Sea near Tamaraikulam. The River Valliyar flows between Kadiapatnam and Manavalakurichi and drains into the Arabian Sea. The only perennial stream in South Indian, the Tamirabarani, debouches far to the west of Colachel into the Arabian Sea. The Panniyar and Pampuar are the few notable creeks that flow across Rajakkamangalam and Colachel respectively. Most of the coastal villages have sandy, pocket-type beaches.

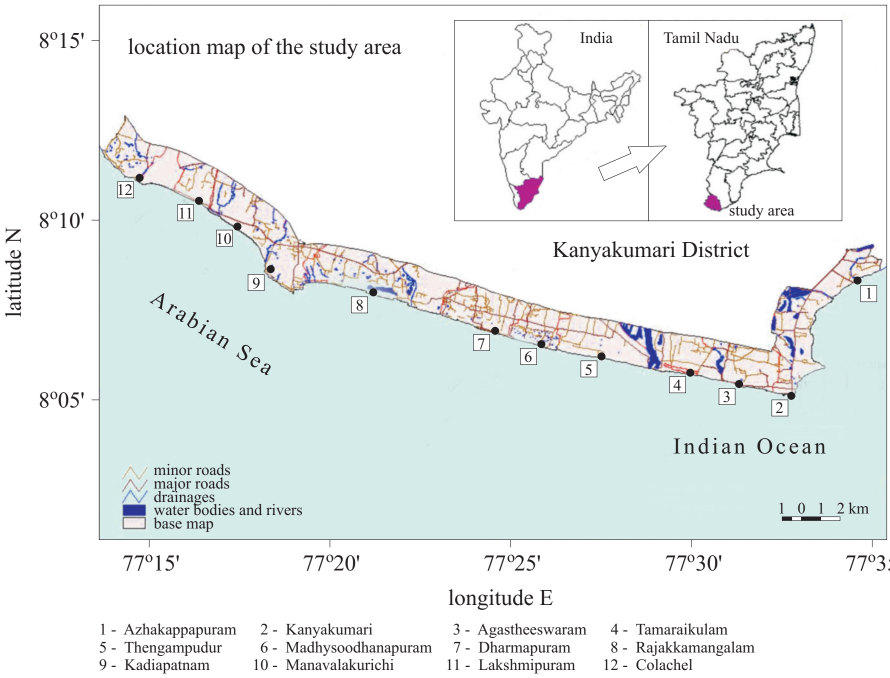

Fig. 1. Map of the study area

The coast at Kanyakumari, Agastheeswaram and Kadiapatnam consists of rocky cliffs. Mangroves (at Managudi, for example), salt marshes and coconut plantations are further features in the study area. The coastline between Kanyakumari and Kadiapatnam consists of sheet rocks. Well-developed sand dunes are present along the coastline near Tamaraikulam and Thengampudur. A high wave energy condition prevails in the study area. Beach placers in this region are intensively mined. The study area experiences not only direct waves from their point of generation but also waves diffracted from the southern tip of Sri Lanka (Fig. 2).

2. Material and methods

The base map for this area was drawn at a scale of 1:8000 based on cadastral maps of each coastal village and was superimposed on the toposheets; high-resolution satellite imageries were interpolated onto the base map.

Tsunami (wave) height, run-up elevation and inundation distance were measured according to Figure 3. Tsunami inundation was greatest in the embayments. Run-up is the difference between the elevations of maximum tsunami penetration and sea level just before the tsunami attack;

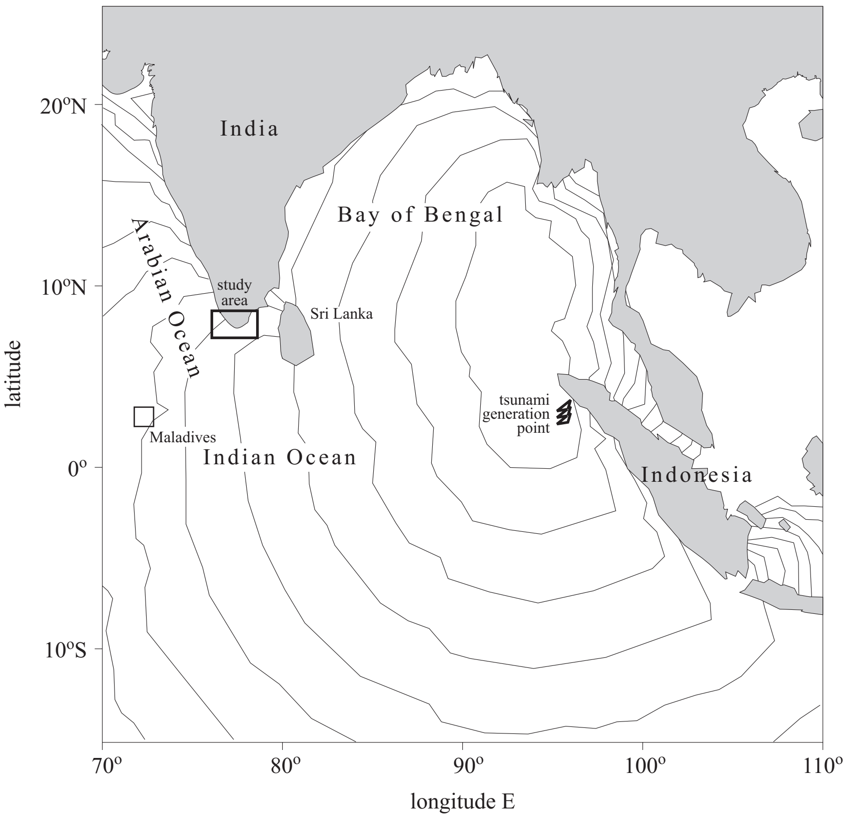

Fig. 2. Map showing the propagation of the tsunami along the Indian Ocean

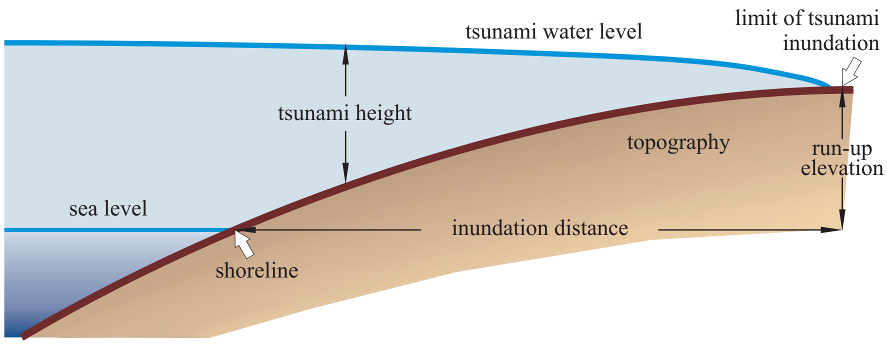

Fig. 3. Measurement of inundation distances and run-up elevation (method adopted from USGS survey team – weblinks)

the inundation distance is the horizontal distance of the point of penetration (on land) from the seashore. With reference to local water level at the time of the survey, cross-sectional profiles were taken from the water line to the inundation limit. During the field survey, various indicators like wave heights, water stains on buildings, salt burnt trees, and broken branches of trees and debris on the trees were also used to measure run-up elevation. Heights were assessed manually. The hypothesis of tsunami height was set up by measuring wave heights at intermediate points along the coastline and collecting additional data on sediment deposit profiles (USGS: http://walrus.wr.usgs.gov/tsunami/Sumatra05/heights.html). The survey was done using a hand-held GPS, levelling and surveying equipment, with regular intervals in each transect following standard procedures. The field data were superimposed on the Satellite images (LISS 4 and PAN merged data) and interpreted using GIS techniques (ArcGIS-9.1).

3. Results

The extent of inundation along each coast in the study area is shown in Figure 4 and Table 1. The maximum inundation distance of 450 m was recorded on the coast of Colachel. The extent of inundation was also high in the coast of Tamaraikulam (350 m), Rajakkamangalam (300 m), Lakshmipuram (300 m) and Manavalakurichi (250 m). Azhakappapuram experienced the low inundation of 40 m.

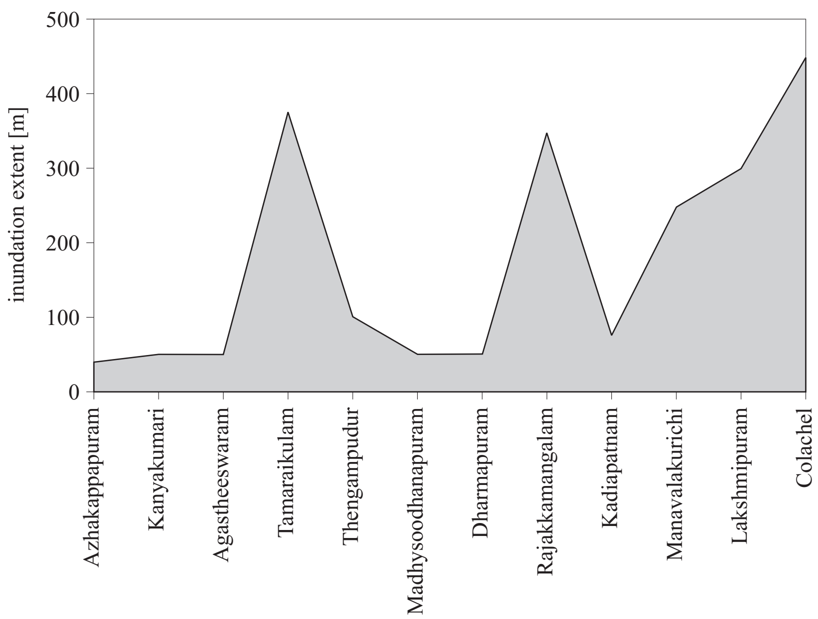

Fig. 4. Inundation due to the tsunami along the study area

Table 1. Inundation extent and run-up level along the study area

Location	Inundation extent [m]	Run-up level [m]
Azhakappapuram	40	1–2
Kanyakumari	50	1–2
Agastheeswaram	50	1–2
Tamaraikulam	375	4–6
Thengampudur	100	3–4
Madhysoodhanapuram	50	2–3
Dharmapuram	50	2–3
Rajakkamangalam	350	3–4
Kadiapatnam	75	2–3
Manavalakurichi	250	3–4
Lakshmipuram	300	4–5
Colachel	450	5–6

The inundated area in the total coastal area is given in Table 2 and shown in Figure 5. Rajakkamangalam has the largest coastal area (20.85 km^2), Colachel has the smallest (3.25 km^2). The inundated area was large in Thengampudur (3.85 km^2) but much smaller (c. 1.03 km^2) in Dharmapuram. It seems obvious that the most seriously inundated beaches were smaller in total coastal area and vice-versa. This statement may not be strictly applicable to all the coastal villages; on an overall perspective, however, it is clear that highly inundated areas suffered less damage to property and life loss due to their being inhabited, whereas areas only slightly inundated sustained severe damage to property and loss of life as they were situated close to the high-tide zone.

Table 2. Total coastal area and inundated area of the study area

Location	Total coastal area [km^2]	Inundated area [km^2]
Azhakappapuram	9.85	0.8
Kanyakumari	11.09	1.4
Agastheeswaram	9.12	1.56
Tamaraikulam	15.61	2.27
Thengampudur	12.77	3.85
Madhysoodhanapuram	14.8	1.05
Dharmapuram	11.38	1.03
Rajakkamangalam	20.85	2.22
Kadiapatnam	19.36	2.03
Manavalakurichi	12.32	1.43
Lakshmipuram	8.7	1.56
Colachel	3.25	2.07

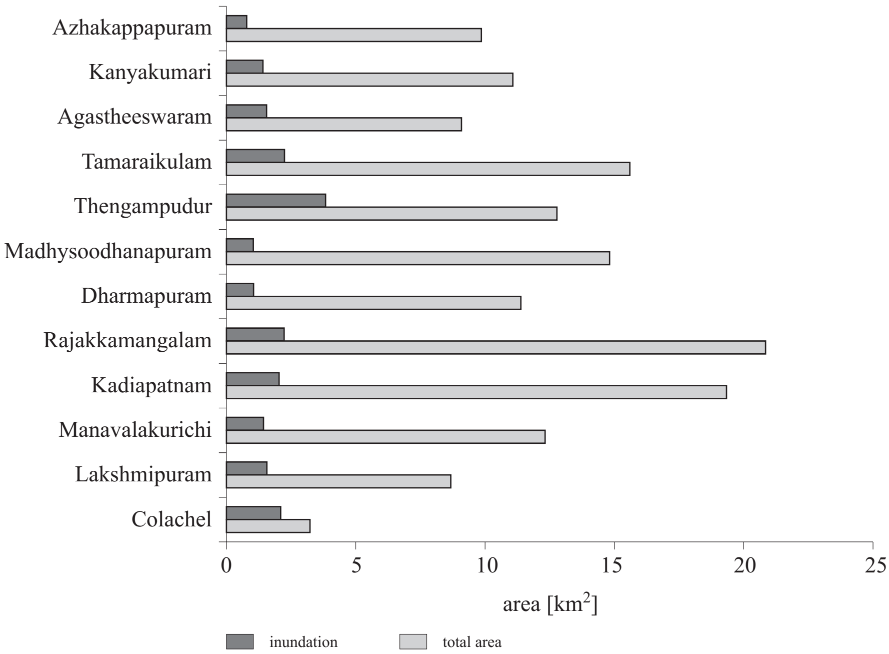

Fig. 5. Total coastal area and inundated area in different locations of the study area

The percentage of inundated area in the entire coastal area is shown in Figure 6 and Table 3. The percentage of inundation was much higher (39%) along the coast of Colachel, and a low inundation percentage (7%) was recorded at Madhysoodhanapuram. It is quite interesting to note the very high level of inundation. The percentage of inundation in the total coastal area seems to be relatively less than that of the coasts where the extent of inundation was low. The coasts of Tamaraikulam, Manavalakurichi and Lakshmipuram attest to this: the extents of inundation there were 375 m, 300 m and 250 m respectively, but the corresponding percentages of inundation were 23%, 15% and 10%. These figures are quite similar to those from coasts that experienced less inundation.

Figure 7 shows the relationship between the extent of inundation and the run-up level along the study area. In the present study, it was found that the extent of inundation was directly proportional to the run-up level. Substantial inundation coupled with a steady rise in the run-up eventually resulted in the utmost devastation in the respective coastal zone. There was total devastation of the coastal configuration and landforms, and the possibility of escaping from the risk was close to zero.

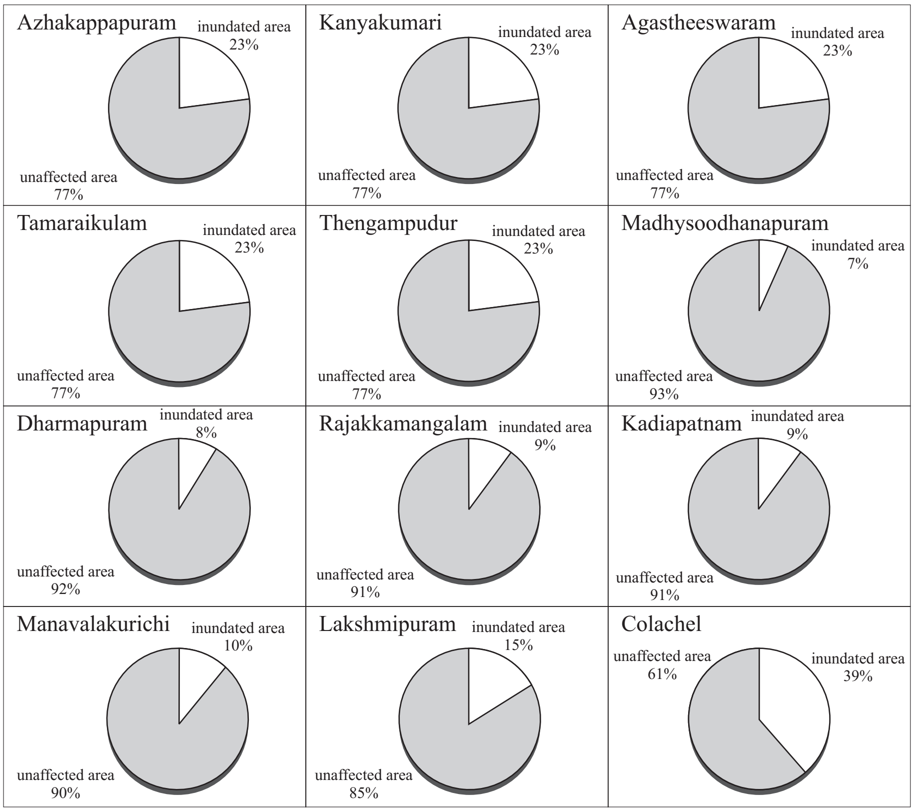

Fig. 6. Percentage of the total coastal area inundated

Table 3. Percentage of inundated and unaffected area

Location	Inundation extent [m]	Inundated area [%]	Unaffected area [%]
Azhakappapuram	40	23	77
Kanyakumari	50	23	77
Agastheeswaram	50	23	77
Tamaraikulam	375	23	77
Thengampudur	100	23	77
Madhysoodhanapuram	50	7	93
Dharmapuram	50	8	92
Rajakkamangalam	350	9	91
Kadiapatnam	75	9	91
Manavalakurichi	250	10	90
Lakshmipuram	300	15	85
Colachel	450	39	61

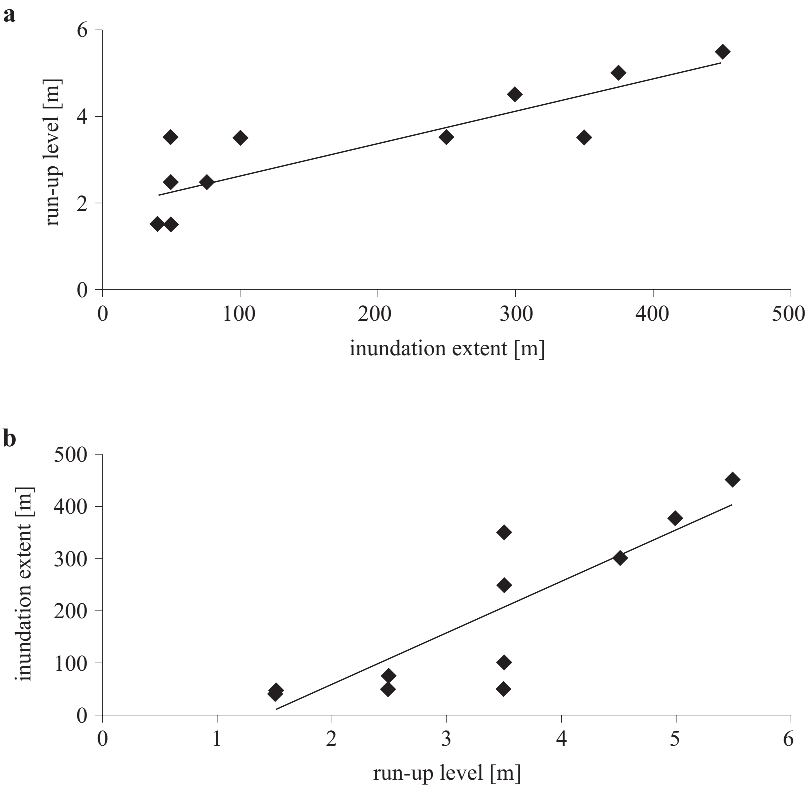

Fig. 7. Relationship between inundation extent and run-up level (a)–(b)

4. Discussion

The extent and tendency of inundation along the study area seem to vary from coast to coast: each beach exhibited its own resistance towards the uprushing tsunami surge.

4.1. Inundation distance

The extent of inundation on each coast along the present study area is shown in Figure 4 and Table 1. The inundation extent and run-up level seem to be directly proportional to each other. Narayan et al. (2005a) reported that the extent of inundation ranged from 20 m to 7000 m along the Tamilnadu coast, with the run-up varying between 1 m and 12 m. Rasheed et al. (2006) observed that along the Kerala coast, the inundation distance was between 60 m to 600 m, and the run-up between 2 m and 5 m. The inundation extent along the study area varied from 40 m to 450 m, whereas the run-up level ranged from 1 m to 6 m.

It is obvious from the inundation level that the uprushing tsunami surge had no difficulty in capturing more of the low-lying coast than of the elevated coast due to the increasing gradient and rock exposures in the latter. This will have checked the sea water during its uprush, whereas there were no such obstructions on the low-lying coast to attenuate the tsunami surge. This observation is supported by Mohan et al. (2005), who concluded that the intensity of the tsunami was greater in areas with a shallow near-shore bathymetry and flat onshore topography. The presence of offshore shoals, deeper near-shore bathymetry and elevated onshore topography with dune ridges prevented greater tsunami inundation. The observation made in this study matches that of Raval (2005) on tsunami devastation on the Nagapattinam coast, Tamilnadu: the impact of the tsunami there was primarily due to its coastal setting, which was conducive to much inundation and run-up. Moreover, the Colachel coast experienced waves both diffracted from Sri Lanka and deflected from the Maldives, which are located southwest of Colachel (Fig. 2). These two types of waves will have caused the utmost destruction on the Colachel coast, whereas the Azhakappapuram coast was slightly in the shadow zone of Sri Lanka. Moreover, the beaches along the coast exhibit significant rock exposures, which will have brought down the rate of inundation (Chandrasekar 2005). Tamaraikulam also experienced very considerable inundation, for example, the Palaiyar River mouth (Chandrasekar et al. 2006a), which enabled the uprushing tsunami to capture much of the coastal zone. Rajakkamangalam and Manavalakurichi were also very seriously inundated as they lie close to the mouths of the Rivers Panniyar and Valliyar respectively. Kurian et al. (2006) reported similar conditions along the Kerala coast, where the devastation was greater along beaches adjoining river inlets because of the serious inundation these were subject to. Grauert et al. (2001) and Goff el al. (2006) have stated that severe inundation in the river inlet/mouth could not only affect the adjoining coast but also alter the pattern of the river inlet/mouth itself by depositing tsunami-borne sediments there or by eroding the sediments from the estuarine waters or by redistributing the sediments. Further studies could be attempted on the sedimentology of the tsunamites along the river inlet/mouth of the study area to confirm the above findings. Cliff coasts, like those at Kanyakumari, Agastheeswaram and Kadiapatnam, experienced less inundation; this will have been impeded by the rock exposures with very steep faces. Narayan et al. (2005b) and Mohan et al. (2005) confirmed the above fact when they observed that the inundation was very slight on elevated landmasses and beyond dune ridges. Figure 8 illustrates the village level mapping of the areas of inundation. It clearly depicts the areas of inundation on the respective coasts. It could

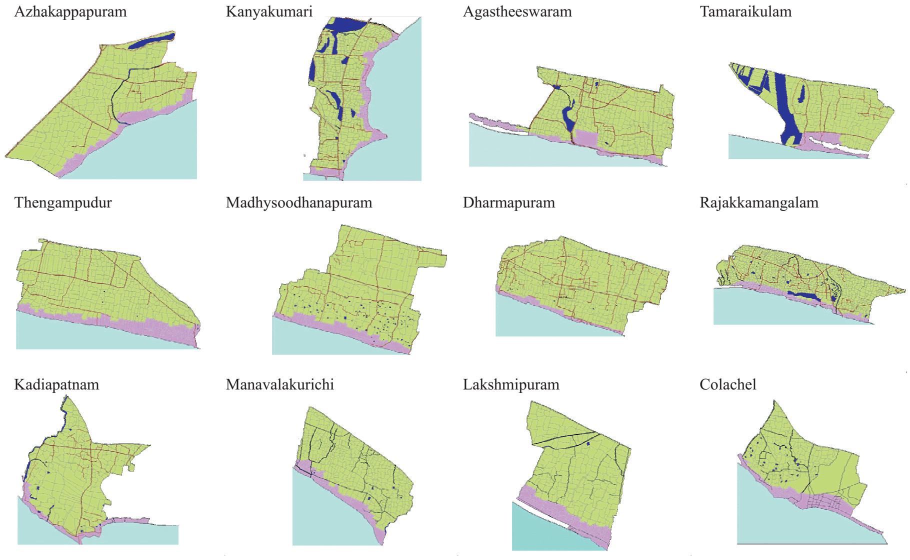

Fig. 8. Village-wise mapping of areas of inundation (areas shaded in pink denote the inundated area)

serve as a guide for compiling a vulnerability map based on inundation and also to identify risk-free zones for the construction of buildings and settlements in the future.

4.2. Percentage of inundation

The percentage of the total coastal area inundated is shown in Figure 6 and Table 3. The inundation of seawater caused by the tsunami waves could not travel far on beaches which are well above the mean sea level (MSL), such as those at Muttom, Kadiapatnam and Mandakadu (Chandrasekar 2005). But inundation did occur on the beaches of Tamaraikulam, Manavalakurichi and Lakshmipuram, which are located below the mean sea level. It was also confirmed that the huge tsunami wave flowed around natural barriers, flooding low-lying areas behind them.

The Sri Lankan landmass stood in the path of the tsunami waves from the Indian Ocean to the Kanyakumari coast. The diffracted waves struck the coast of Kanyakumari with a low tsunami wave height and were not able to inundate the inland areas because of the presence of the elevated rocky coast (Minoura et al. 1994, Besana et al. 2004, Keating et al. 2004). At present, the study shows that considerable erosion has taken place in Colachel, Periyakadu, etc.

4.3. Correlation between inundation and run-up

Figure 7 shows the relationship between inundation extent and run-up level along the study area. Severe inundation and run-up may affect the coastal topography by transporting offshore sediments onto the beach and redistributing the sediments within the beach. Shuto (2001) observed similar conditions along the Japanese coast, where tsunamis have caused severe erosion and have altered the coastal topography in many locations. Narayana et al. (2005) studied the nature of the sedimentation induced by this tsunami along the Kerala Coast of India and found that the tsunami surge had transported and redistributed the black sands (heavy minerals) from the continental shelf to the coast. Most of the beaches along the study area are already known to have potential heavy mineral reserves. The high inundation and run-up in the study area also enriched the significant amounts of heavy minerals on the beaches. As a result, resources in existing enrichment zones were further enriched, so these deposits now have to be reassessed for future mining purposes. Goff et al. (2006) reported that the 1975 Kalapana tsunami produced waves that deposited a discontinuous basalt boulder and carbonate sand veneer on the Halape –Apua Point coast of the island of Hawaii. These deposits were found up to 320 m inland. So it has been demonstrated that tsunamis have the potential to transport, redistribute and deposit sediments far into the hinterland. Most of the beaches in the study area have a lengthy and wide backshore. Both the Government Sector and the Private Sector are actively involved in sand mining in the study area, especially near Kadiapatnam and Manavalakurichi. The considerable inundation and run-up replenished the heavy minerals in the already mined area; it has now become a future mining development site.

From the above study, it is evident that low-lying coasts were the prime victim of the tsunami surge, as they were unable to put up any resistance against the accelerating tsunami surge. Elevated beaches with rocky exposures experienced only minimal inundation owing to the steep slope; this will have retarded the progress of the seawater into the backshore. The percentage of inundation was found to be similar on the entire coast irrespective of its extent. Coasts with high inundation were affected comparatively less, even though their total area is similar to that of the low inundation beaches. The vulnerability of a particular coast depends mainly on the percentage of inundation and not on the extent of inundation. Village–level inundation mapping gives a bird's eye view of the inundation induced by the tsunami. It could serve as a tool for the preparation of a hazard map and for selecting suitable sites for future construction. In addition, this study could be used to understand or delineate the impact of inundation in damaging the coastal environment. Risk-assessment maps could also be prepared using various parameters observed in the present study by applying geospatial technologies to create preparedness among the coastal community.

Acknowledgements

The authors wish to thank Dr. M. Prithiviraj, SERC and Dr. Bhoop Singh, National Resources Data Management System (NRDMS), Department of Science and Technology (DST), Govt. of India, New Delhi for providing financial assistance in the form of research projects to carry out these works (Ref. No. ES/11/936(5)/05 and SR/S4/ES-135-5.1/2005).

References

Alami S. O. E., Tinti S., 1991, *A preliminary evaluation of the tsunami hazards in the Moroccan coasts*, Sci. Tsunami Hazards, 9 (1), 31–38.

Bandibas J., Warita K., Kato H., 2003, *Interactive presentation of geological hazard maps using geohazardview*, J. Nat. Disaster Sci., 25 (2), 75–83.

Besana M. G., Ando M., Mirabueno M. H., 2004, *The May 17, 1992 event: Tsunami and coastal effects in Eastern Mindanao, Philippines*, Sci. Tsunami Hazards, 22 (2), 61–68.

Chandrasekar N., 2005, *Tsunami of 26th December 2004: Observation on inundation, sedimentation and geomorphology of Kanyakumari Coast, South India*, Proc. 22nd IUGG Int. Tsunami Symp., Chania, Greece, 49–56.

Chandrasekar N., Immanuel L. J., 2005, *GIS supported categorisation of tsunami experienced beaches along the southern east coast of India: Usage in mitigation activities*, Proc. Nat. Sem. on GIS Application in Rural Development, Hyderabad, India, 349–362.

Chandrasekar N., Immanuel J. L., Rajamanickam M., Sahayam J. D., Singh D. S. H., Rajamanickam G. V., 2006a, *Geospatial assessment of Tsunami 2004 damages along the rocky coast of Kanyakumari, India*, [in:] *Geomatics in tsunami*, S. M. Ramasamy, C. J Kumanan, R. Sivakumar & Bhoop Singh (eds.), New India Publ., New Delhi, 135–146.

Chandrasekar N., Immanuel J. L., Sivasubramanian P., Rajamanickam G. V., 2005, *Impact of tsunami between the coast of Thoothukudi and Periyathalai*, [in:] *Quaternary climatic changes and landforms*, N. Chandrasekar (ed.), M.S Univ. Publ., 299–314.

Chandrasekar N., Saravanan S., Immanuel J. L., Rajamanickam M., Rajamanickam G. V., 2006b, *Classification of tsunami hazard along the southern coast of India: An initiative to safeguard the coastal environment from similar debacle*, Sci. Tsunami Hazards, 24 (1), 3–24.

Dawson A. G., 1994, *Geomorphological effects of tsunami run-up and backwash*, Geomorphology, 10 (1–4), 83–94.

Goff J., Dudley W. C., deMaintenon M. J., Cain G., Coney J. P., 2006, *The largest local tsunami in 20th century Hawaii*, Mar. Geol., 226 (1–2), 65–79.

Grauert M., Bjorck S., Bondevik S., 2001, *Storegga tsunami deposits in a coastal lake on Suouroy, the Faroe Islands*, Boreas, 30 (4), 263–271.

Imamura F., 2004, *Risk evaluation and real time information for tsunami disaster mitigation*, Proc. Wave, Tide Observations and Modelings in the Asian-Pacific Region, 93–100.

Jaffe B. E., Gelfenbaum G., 2002, *Using tsunami deposits to improve assessment of tsunami risk*, Proc. Conf. Solutions to Coastal Disasters '02, ASCE, 836–847.

Keating B., Whelan F., Brock J. B., 2004, *Tsunami deposits at Queen's Beach, Hawaii-initial results and wave modeling*, Sci. Tsunami Hazards, 22 (1), 23–43.

Kumanan C. J., 2005, *Global scenario of tsunamis*, [in:] *Tsunami: The Indian context*, S. M. Ramasamy & C. J. Kumanan (eds.), Allied Publ., Chennai, 15–26.

Kurian N. P., Pillai A. P., Rajith K., Krishnan B. T. M., Kalaiarasan P., 2006, *Inundation characteristics and geomorphological impacts of December 2004 tsunami on Kerala coast*, Curr. Sci. India, 90 (2), 240–249.

Minoura K., Nakaya S., Uchida M., 1994, *Tsunami deposits in a lacustrine sequence of the Sanriku coast, northeast Japan*, Sediment. Geol., 89 (1/2), 25–31.

Mohan V. R., 2005, *December 26th, 2004 Tsunami: A field assessment in Tamilnadu*, [in:] *Tsunami: The Indian context*, S. M. Ramasamy & C. J. Kumanan (eds.), Allied Publ., Chennai, 139–153.

Mohan V. R., Gnanavel D., Sriganesh J., Kulasekaran J., Srinivasalu S., 2005, *The 26th December, 2004 Tsunami run-up and inundation and their relationship with geomorphology in Tamilnadu, India*, http://www.sthjournal.org/tsabst/mohan.pdf#search=%22geomorphology%2Btsunami%22

Mujabar P., Chandrasekar N., Saravanan S., Immanuel J. L., 2007, *Impact of the 26 December 2004 Tsunami on beach morphology and sediment volume along the coast between Ovari and Kanyakumari, Tamil Nadu, South India*, Shore & Beach, 75 (2), 22–29.

Narayan J. P., Sharma M. L., Maheswari B. K., 2005a, *Effects of medu and coastal topography on the damage pattern during the recent Indian Ocean tsunami along the coast of Tamilnadu*, Sci. Tsunami Hazards, 23 (2), 9–18.

Narayan J. P., Sharma M. L., Maheswari B. K., 2005b, *Run-up and inundation pattern developed during the Indian Ocean tsunami of December 26, 2004 along the coast of Tamilnadu (India)*, Gondwana Res., 8 (4), 611–616.

Narayana A. C., Tatavarti R., Shakdwipe M., 2005, *Tsunami of 26th December 2004: Observations on Kerala coast*, J. Geol. Soc. India, 65 (2), 239–246.

Papathoma M., Dominey-Howes D., Zong Y., Smith D., 2003, *Assessing tsunami vulnerability, an example from Herakleio, Crete*, Nat. Hazards Earth Syst. Sci., 3 (5), 377–389.

Park J., Anderson K., Aster R., Butler R., Lay T., Simpson D., 2005, *Global Seismographic Network records the great Sumatra-Andaman earthquake*, EOS Trans. AGU, 86 (6), 57–64.

Rasheed A. K. A., Das V. K., Revichandran C., Vijayan P. R., Thottam T. J., 2006, *Tsunami impacts on morphology of beaches along South Kerala Coast, West Coast of India*, Sci. Tsunami Hazards, 24 (1), 24–34.

Raval U., 2005, *Some factors responsible for the devastation in Nagapattinam region due to tsunami of 26th December 2004*, J. Geol. Soc. India, 65 (5), 647–649.

Shuto N., 2001, *Tsunami induced topographical change recorded in documents in Japan*, ITS Proc. Sess., 3 (3–6), 513–522.

Walsh T. J., Caruthers Ch. G., Heinitz A. C., Myers E. P., Baptista A. M., Erdakos G. B., Kamphaus R. A., 2000, *Tsunami hazard map of the Southern Washington Coast: Modelled tsunami inundation from a Cascadia Subduction Zone earthquake*, Washington Div. Geol. Earth Res. Rep. GM-49, 12 pp.