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Inundation characteristics and geomorphological impacts of December 2004 tsunami on Kerala coast

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Inundation characteristics and geomorphological changes associated with the December 2004 tsunami along the Kerala coast are presented here based on post-tsunami surveys, tide data and beach profile measurements. Maximum inundation and damage was caused in the zones adjoining Kayamkulam inlet in southern Kerala. Arrival of the tsunami coincided with the high tide in this sector, resulting in maximum devastation. Impact of the tsunami was not felt in the afternoon in northern Kerala due to the ebb or low tide and maximum inundation along that sector is reported during midnight, coinciding with the next high tide. Beach profile measurements confirm erosional tendency of the tsunami, which deposited huge quantities of black sand in the hinterland regions of the worst-affected Kayamkulam inlet area.

Keywords: Beach erosion, inundation, Kerala coast, run-up level, tsunami.

THE December 2004 Sumatra–Andaman earthquake generated a tsunami of unprecedented proportions, that devastated the shores of many Asian countries. The tsunami affected many parts of the Kerala coast[1], located in the shadow zone with respect to the direction of propagation of the tsunami, and in that sense its severity was rather unexpected. Nearly 200 people were killed and hundreds injured in addition to the loss of houses and properties worth several crores of rupees. Although there are reports of some previous tsunamis (1881, 1833, 1941, to mention a few), generated by earthquakes in the Andaman–Sumatra region, there is no documented evidence of any such events affecting the Kerala coast. A 1945 earthquake of M 8.0 in the Mekran coast is believed to have generated significant tsunami run-up in some parts of Gujarat[2,3], the only documented report of any tsunami affecting the west coast. To the best of our knowledge, the 2004 tsunami is the first of its kind to have affected the Kerala coast (Figure 1).

A significant observation associated with the 2004 tsunami effects along the Kerala coast is its localized amplification in some regions and totally subdued effect elsewhere. Understanding the spatial pattern of the tsunami and its effects on the coastal morphology has important implications for assessing future scenarios of inundation. Since most evidence left by tsunamis is perishable, it is important to carry out post-tsunami surveys to measure the run-up heights, inundation limits, arrival time of waves and assess the impact on the coastal life and property, flora and fauna, geomorphology, etc. Such information is important for future hazard assessment, and to develop inundation models. Tsunami-mitigation strategies have to be formulated based on such database[4]. Here, we report post-tsunami observations along the 560-km long stretch of Kerala coast as well as geomorphological changes in the shores of the Kayamkulam inlet region, where the effect of the tsunami was most severe. We use these observations to analyse the impact of the tsunami with respect to wave propagation and tidal characteristics of the region.

During the post-tsunami days, starting from 27 December 2004, field visits were conducted at different locations of the Kerala coast. The *Post-Tsunami Survey Field Guide* published in the website of International Tsunami Information Centre (ITIC)[5] was taken as a guide in the field trip. Sea level variations were studied from data available for Cochin and Neendakara (near Quilon). For Cochin, the tide gauge record available in the NIO website, which is based on data from the tide gauge at Cochin Port, was used. Sea-level data for Neendakara are observations by the Hydrographic Survey Wing of the Government of Kerala

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Location no.	Time of maximum inundation (h)
1	2145
2	2130
3	+0030
4	2145
5	2130
6	2130
7	2200
8	2345
9	2330
10	1800
11	2140
12	+0200
13	2300
14	2020
15	1600
16	1430
17	2400
18	1400
19	1300
20	1240
21	1130
22	1430
23	1400
24	1300
25	1400

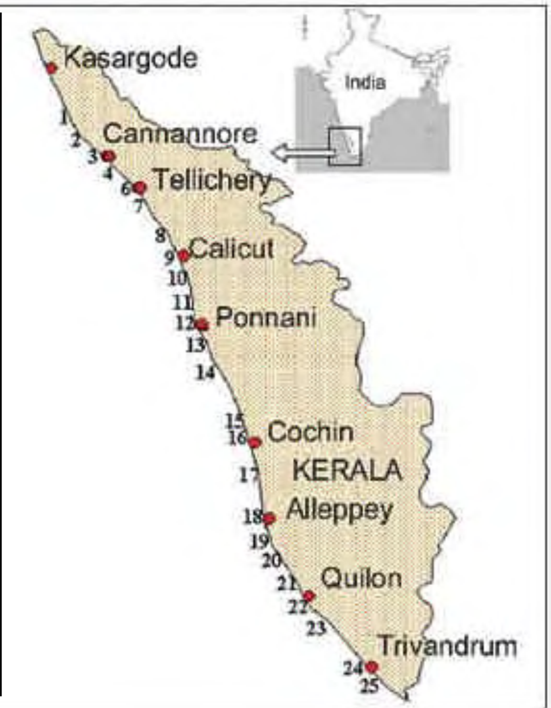


Figure 1. Time of maximum inundation at different locations of the Kerala coast.

from a tide staff maintained by them. For field surveys, 83 locations spread all over the Kerala coast, reported to have been affected by the tsunami, were visited. At each location, local people were also interviewed to collect eyewitness reports on tsunami inundation characteristics for the location of visit as well as adjoining areas. Considering the geomorphic set up of the Kerala coast, run-up was estimated as the elevation at local maximum of the horizontal inundation measured relative to mean water level at each location (p. 13, ITIC tsunami glossary). Field signatures such as trapped floating objects in plants/trees/buildings, flood mark or damaged windows and doors of buildings, etc. were relied upon to locate the maximum inundation level and elevation was measured using level and staff method. Information such as arrival time and height of different waves, inundation characteristics, nature of damage and causalities, etc., as listed in the *Field Guide* was also recorded. Beach profile measurements were made at nine stations on both sides of the Kayamkulam inlet, where the reference stones were intact and pre-tsunami beach profile changes could be documented.

Damage due to the tsunami was maximum in sectors adjoining Kayamkulam inlet in southern Kerala. Towards north and south of this zone, damage was less extensive. A brief description of damage due to tsunami along the coast is given below (locations mentioned in the text are keyed to Figures 1 and 2).

In the southernmost Pozhiyur to Vizhinjam sector there was no damage, but just 1 km south of Vizhinjam harbour, some country boats were damaged. Water level increased more than 0.50 m above the wharf, causing severe damage to fibre boats berthed in the area. However, in Poonthura, Beemapally, Valiathura, Sankumugham and Veli areas further north, water level increased only up to the monsoonal berm and no damage was reported. No damage was reported also from the Veli–Paravur sector. In the coastal stretch between Mayyanad and Eravipuram near Quilon, sea walls collapsed due to the tsunami. Further north, near Thangassery, the tsunami caused severe damage to the harbour area, which is protected by two breakwaters. Areas north of the harbour were also affected, despite protection by the sea wall. John Brito colony, south of Sakthikulangara harbour area was also badly hit, killing one person and washing away 46 houses; country boats and other fishing vessels were damaged inside the harbour.

The sector immediately to the north of Sakthikulangara till Kovilthottam is well protected by the sea wall, and hence there was no hinterland inundation. However, at Kovilthottam, hinterland inundation took place through a gap in the sea wall and caused some damage. In the sector north of Kovilthottam, till Cheriazhikkal, damage was minimal in spite of higher inundation, probably due to the good quality of construction of houses. Further north, the damage was extensive (Figure 3). Many houses collapsed completely and almost all other houses were partially damaged. Many deep pits were formed on the eastern side of the coastal road. In the Alappad Panchayat, which covers the Kovilthottam–Kayamkulam inlet barrier beach sector,

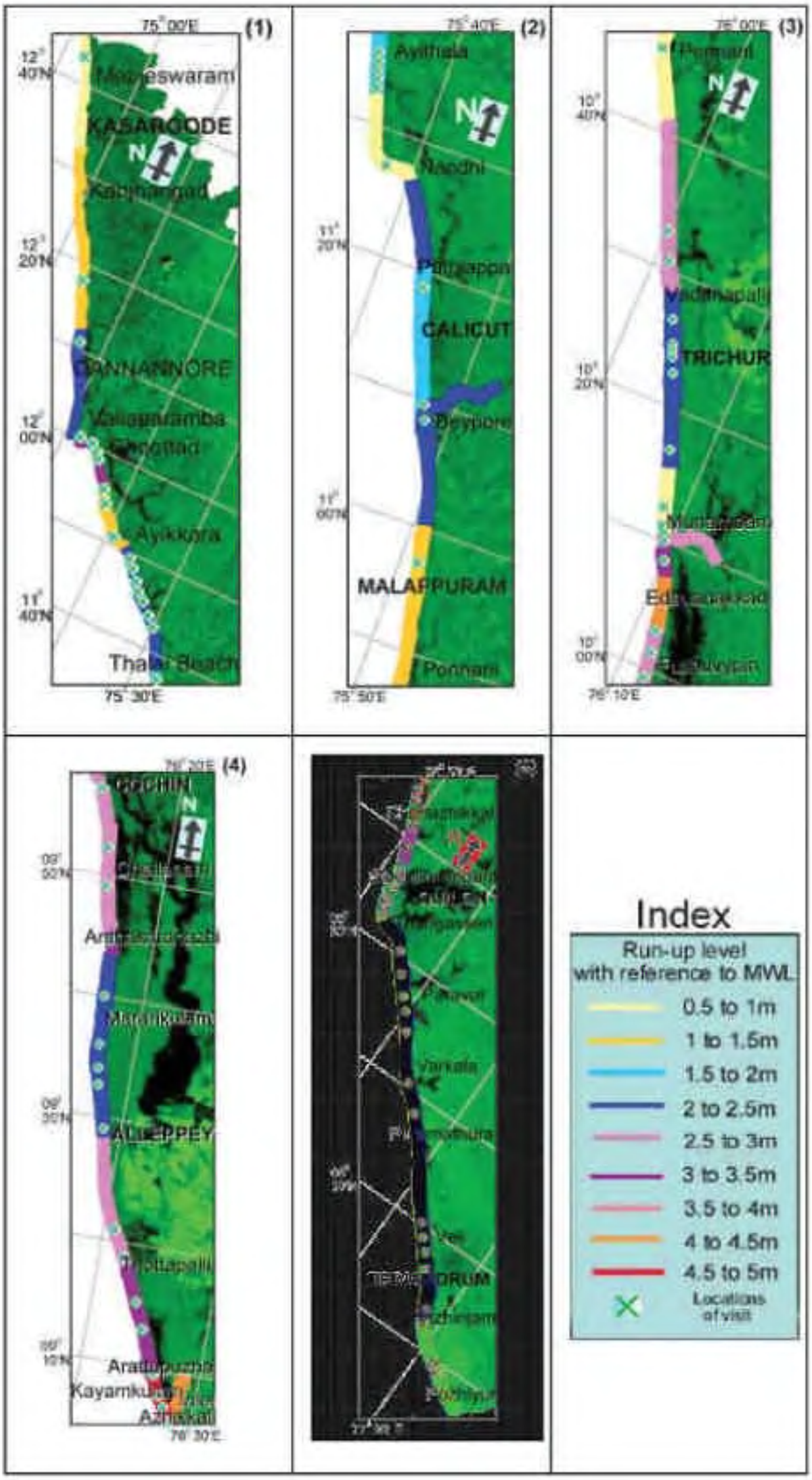


Figure 2. Run-up level along the Kerala coast; panels 1–5 cover the whole coast starting from Manjeswaram in the north to Pozhiyur in the south; locations of field visit are also marked.

132 people were killed, mostly women and children, who were trapped in collapsed houses. More than 1250 people were injured and 2400 houses completely damaged. The flood water that inundated the whole barrier beach flowed

Figure 3. Total devastation caused by tsunami at Azhikkal region, south of Kayamkulam inlet. ***a***, Deep scouring on the side of the coastal road; ***b***, Damaged concrete house; ***c***, Totally devastated fishermen colony and ***d***, Remains of collapsed houses, including a lorry carried in.

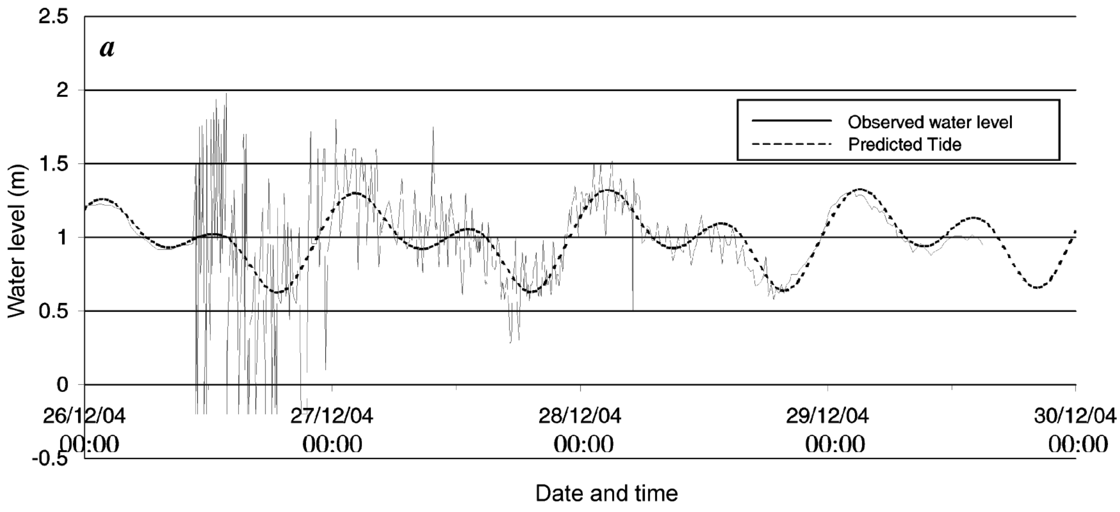
Figure 4. Devastation caused by tsunami at Valiazhikkal region, north of Kayamkulam inlet and Edavanakkad, north of Cochin. ***a***, Deep trench formed close to the coastal road immediately to the north of Kayamkulam inlet; ***b***, Roof of a newly constructed house grounded due to wall collapse; ***c***, Boulders of sea walls thrown inland at Edavanakkad and ***d***, Deep trench formed close to the coastal road at Edavanakkad.

Figure 5. Examples of tsunami inundation from northern Kerala. ***a***, Collapsed embankment at Choottad, Cannannore; ***b***, Country boats thrown inland at Kadalur point, Calicut; ***c***, Damaged railway footbridge at Thalassery and ***d***, Collapsed laterite banks at Kadalur point, Calicut.

towards TS canal, which runs parallel to the shore. Water rushed through Kayamkulam inlet and together with the overflow from the barrier beach, water level rose to about 4.5 m, causing severe damage in the adjoining areas of Kayamkulam backwaters. Another notable feature of the tsunami onslaught in the area was the deposition of black sand in the sector north of Cheriazhikkal up to the inlet, with maximum thickness of about 1 m. The devastation was quite extensive in the sector immediately to the north of Kayamkulam inlet also (Figure 4 *a*, *b*), though not as much as at Alappad, probably because this area was not as thickly populated. Just north of the Kayamkulam inlet, a deep trench was formed adjacent to the coastal road. As in the case of the southern part of the inlet, here also extensive deposits of black sand were found in the hinterland area. Maximum damage was observed in the Tharayilkadavu area, about 4 km north of Kayamkulam inlet. Many houses were completely damaged and 30 people died in this area. More than 800 houses were completely damaged and about 1500 were partially damaged. The incidents at Tharayilkadavu and Alappad show that the breakwater constructed for fishing harbour interfered with the tsunami. No serious damage was reported along Arattupuzha–Thottappally–Alleppey sector further north.

Inundation and loss of life and property were much less in the sector from Alleppey to south of Anthakaranazhi inlet. In Arattuvazhi, about 3 km south of Anthakaranazhi, inundation caused damage to many houses. Further north, in the zone around Anthakaranazhi inlet, three deaths were reported in addition to damage and loss of fishing gadgets. In the zone north of Anthakaranazhi up to Cochin inlet, there was no significant inundation or damage. However, at Puthuvype, just north of Cochin, many shops arranged for a beach carnival were damaged. Further north, in the Edavanakkad region, inundation was high causing widespread damage in the area (Figure 4 *c*, *d*). Many houses were completely damaged and five people were killed, a number that would have gone up, had the area been more densely populated. Deep pits were formed along eastern side of the coastal road. Huge boulders of sea wall of this area were thrown far inland by the tsunami. The impact clearly shows that even the sea wall cannot protect a coast from the tsunami. There was a reduction in the inundation further north, till Munambam inlet, where the waves entered upstream up to about 500 m and flooded up to a level of 2.5 m in the eastern parts, causing extensive damage to houses. Further north, in the Ponnani, Calicut, Cannannore and Kasaragode coasts, inundation was low. However, the flood waters caused some damage at a few locations (Figure 5) along the northern Kerala coast.

Plot of sea-level variations (raw as well as tide-filtered) at Neendakara during 25–29 December 2004 is presented in Figure 6 *a*, *b*. Till 10:30 h on 26 December 2004, the water-level variations were basically of the semi-diurnal tidal oscillations varying between 1.22 and 0.58 m above the chart datum. However, by 10:45 h (i.e. four hours after the earthquake occurred) the first tsunami wave was felt, with the water level going up to 1.5 m and the waves were



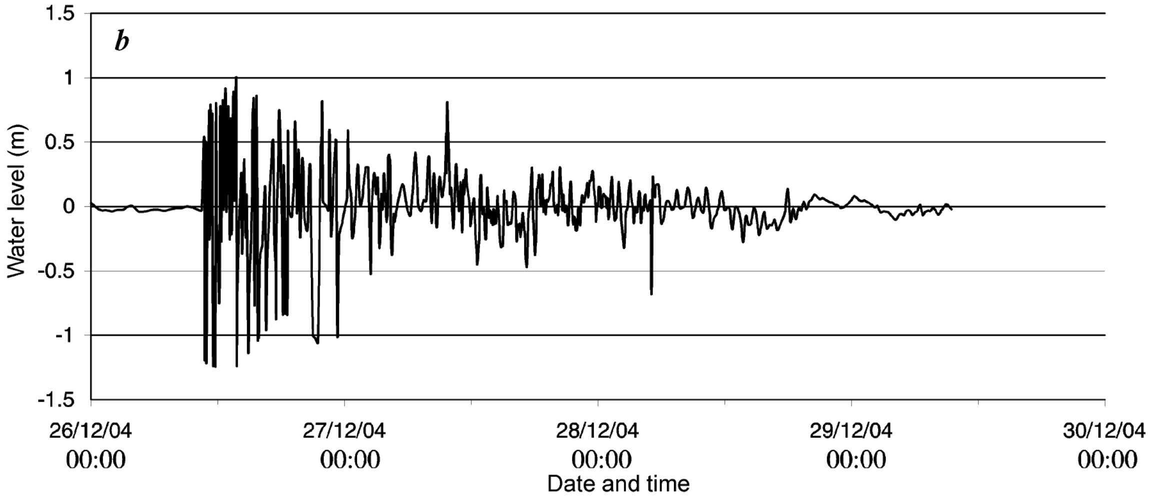


Figure 6. Water-level oscillations at Neendakara, near Quilon (data source: Chief Hydrographer, Govt of Kerala). ***a***, Raw data and predicted tide using MIKE21 tools. ***b***, Tide-filtered water-level oscillations due to tsunami.

found to be overriding the tidal oscillations thereafter for two days. A major peak was seen at around 11:30 h, but the highest waves were seen between 12:30 and 13:30 h. Inundation and damage due to the tsunami had taken place in the Quilon sector during this time interval. The oscillations though with reduced amplitude, continued in the afternoon and evening also. However, the water level did not go up considerably, presumably due to the prevailing low tide. Due to the same reason, there were many occurrences of levels below the chart datum till around 21:30 h. Though the water-level oscillation due to the tsunami was reduced by evening, two high waves, one at around 21:30 h and another around 23:10 h were noticed (Figure 6 *b*). In consonance with the tidal flood around that time, the level of water went up, with peaks of up to 1.7 m. After midnight, the oscillations were considerably reduced though it continued till 28 evening.

The sea-level variations at Cochin for the period 25–29 December 2004 are presented in Figure 7. The pattern is similar to what was observed for Neendakara, except that the time of peaks and amplitudes is different. This is not surprising because Cochin is around 140 km north of Neendakara and the tide gauge is located considerably inside with reference to the inlet. The first wave arrived in Cochin at 11:10 h on 26 December. Thereafter, there was a drastic fall in the water level. There was a group of three high waves following it between 13:30 and 14:30 h, the time when most of the damage occurred in this region. As in the case of Neendakara, the oscillations continued thereafter with reduced amplitude, but the higher levels were not forthcoming due to the lower tides in the evening. By midnight, the amplitude of the oscillations went down considerably. On 27 and 28 December, oscillations similar to what was seen at Neendakara continued.

Thus the water-level recordings at both the locations show that inundation due to the tsunami was higher due to the coincidence of its occurrence with the high tide. The devastating effect of the tsunami would have been

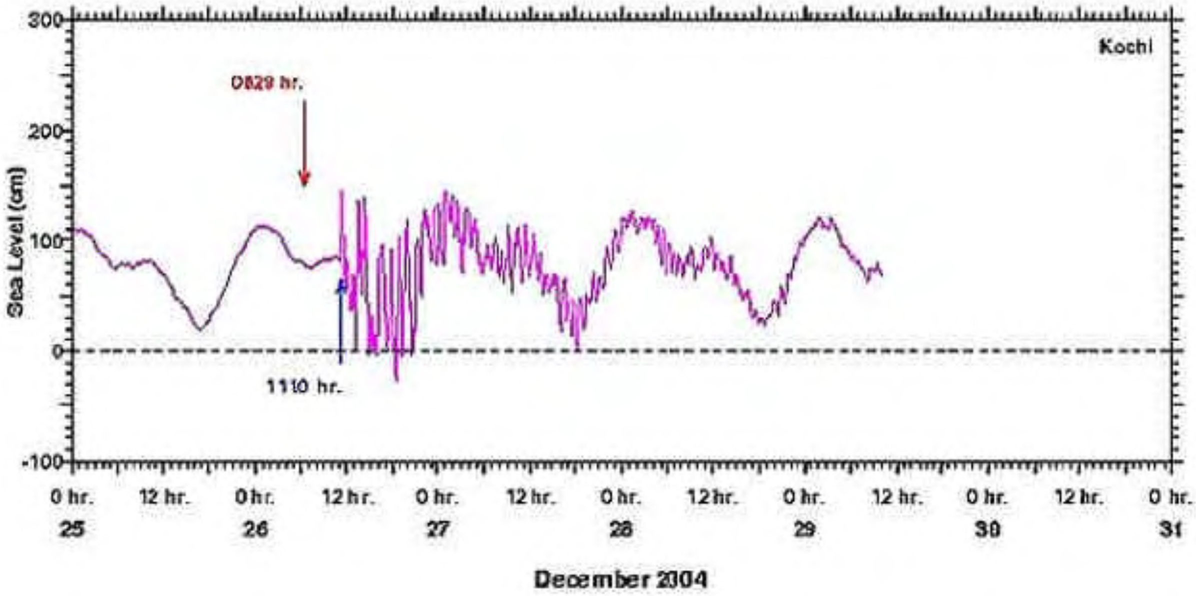


Figure 7. Tide-gauge record at Cochin (source: NIO website).

much less but for this coincidence. Probably the waves which continued in the evening could have also caused some inundation but for the low tide in the evening.

The time of arrival of the waves at different coastal locations was recorded during field visits by interviewing local people. Though the time of arrival of different waves (1st, 2nd, etc.) was also noted down following the ITIC format, no convergence in observation could be obtained except for the highest wave. Hence the time of arrival of the highest wave only is presented in Figure 1 for 25 locations spread over the entire coast. Along the Thiruvananthapuram coast where no damage occurred, the time of maximum inundation was reported to be during 13:00–14:00 h, which coincided with the high tide. However, along the Quilon coast, the time of maximum inundation was earlier by about one hour, which again indicates a link with the flood tide (the time of occurrence of the high tide advanced towards south along this coast, while the tsunami propagated to the north). Along the Alleppey and Cochin coasts, the time of maximum inundation was reported to be in the afternoon. However, towards north of Munambam and the whole of northern Kerala coast, the time of maximum inundation barring one or two locations was late in the evening or around midnight, coinciding with the second high tide of the day when two high waves were also recorded. It is quite possible that the highest waves in the afternoon, which progressed towards northern Kerala coast, were more unnoticeable due to the low tide. Thus, it is seen that maximum inundation was a cumulative effect of the tsunami and tidal level.

The run-up level distribution shows wide variations along the coast (Figure 2). In the Pozhiyur to Vizhinjam (southernmost) sector, the run-up level was only up to 1.5 m, whereas in the Vizhinjam–Varkala sector, it was 2–2.5 m. In the Thangasseri harbour area of the Quilon coast, the run-up was about 2.5 m, whereas in the segment to its north, it was up to 3 m. The run-up level increased further north, reaching about 3.5 m. In the Cheriyazhikkal area, run-up up to 4.5 m was reported. In Azhikkal and up to Kayamkulam inlet, severity of attack of the tsunami was further intensified, with the highest run-up of up to 5 m.

In the sector immediately to the north of Kayamkulam inlet also, the tsunami onslaught was severe with run-up level up to 5.0 m. Further north, in the Arattupuzha region and up to Thottappally, the run-up level reduced to 3.5 m. From Thottapally onwards, there was further decrease till south of Anthakaranazhi inlet. In the zone around Anthakaranazhi inlet, there was an increase in the run-up level reaching up to 3.5 m. Further north, in the Chellanum–Puthuvype region around Cochin, run-up level decreased to 3 m. However, in the Edavanakkad region, the run-up level increased drastically and went upto 4.5 m. There was reduction in the run-up level further north, with a drastic reduction in the zone immediately north of the Munambam inlet. However, in the sector further north, the level increased showing up to 3 m around Vadanapally. There was again a drastic decrease in the sector south of the Ponnani inlet. An increase in the level was found north of Ponnani inlet and run-up level up to 2.5 m was found as we approach Beypore inlet, south of Calicut.

In the northern parts of Kerala coast comprising Calicut, Cannannore and Kasargod districts, the run-up levels were generally low up to 2.5 m. However, a short sector around Choottad was notable for a high run-up level of 3–3.5 m, which was not reported anywhere in the northern Kerala. A short sector north of Nandhi and the Kanjhagad–Manjeswaram sector showed run-up level of only up to 1.0 m.

In order to understand the impact of the tsunami on beach morphology, post-tsunami beach profiles were measured at five stations in the sector north on 14 January 2005 and four stations south of Kayamkulam inlet on 15 January 2005. For these stations pre-tsunami beach profiles (16 November 2004) were avaialble and the reference stones were intact without any damage due to the tsunami. The beach profiles are presented in Figure 8. Volume changes computed from the beach profiles are presented in Table 1.

It is seen that at N1 (just north of Kayamkulam inlet) nearly 53 m^3 of erosion had taken place, whereas at N2, further north of N1, an erosion of 16 m^3 had taken place. The highest quantum of erosion had taken place at N3, which is 2 km north of the inlet. At N4 and N5 (which are further north of the inlet) also erosion took place, though the quantum was much less. At S1, which is just on the southern side of the inlet adjacent to the breakwaters, a high quantum of deposition equal to 91 m^3 had been noticed. But at S2 which is about 200 m south of the inlet, an erosion equal to 38 m^3 had occurred. At S3, about 1 km south of the inlet, deposition of 65 m^3 was seen. At S4, which is further south of the inlet, a modest deposition of 13 m^3 was seen.

Thus, it is seen that erosion is in the northern side of the breakwaters, while deposition is noticed in the southern side except at one station. The erosion/deposition pattern obtained has to be seen in the backdrop of the coastal sedimentation processes prevalent in the area, in addition to the impact of the tsunami. The breakwaters at the inlet, jetting out into the sea act as a groyne, ever since the construction started a couple of years ago. Thus huge accretion takes place in the southern side of the inlet during this part of the year (called fair weather) due to the predominant northerly longshore currents. Due to the same reason, severe erosion takes place in the northern side of the inlet. In the present case, the pre-tsunami beach profiles were taken on 14 November, 42 days earlier. Thus the beach on the southern side of the inlet must have got considerably accreted with respect to the pre-tsunami profile and thereafter till the post-tsunami beach profiling on 15 January 2005. The field signatures on both the sides of the inlet showed scouring and erosion. However, the erosional effect of the tsunami was not sufficient enough to offset the depositional trend in the southern side, except at station S2. In a similar way, the erosion observed in the northern side may not be entirely due to the tsunami.

As a tsunami leaves the deep water of the open sea and propagates into the shallow waters, it undergoes transformation. Refraction, shoaling, diffraction and reflection are the transformation processes affecting the amplitude and propagation of the tsunami. Ocean bottom topography, coastal geomorphic set up and prevalent hydrodynamic conditions are significant factors that control the above transformation processes. How each of these factors has come into play in translating the effects of the December 2004 tsunami on various parts of the Kerala coast, is interesting and needs to be investigated. A superficial look at this is only possible right now due to limitations with regard to input bathymetry and coastal topography in simulations.

Results of simulations by Black[7] and Mahadevan *et al.*[8] suggest that the tsunami wavefront which originated from Sumatra got diffracted by the Sri Lankan island, diverting part of the wavefront to the southern part of the west coast of India. The combined refraction–diffraction process as the wavefront propagated in the shelf waters of the west coast, could have caused convergence and divergence zones leading to considerable along-the-coast variations in wave intensity. In addition to the refracted–diffracted wavefront, there could possibly have been strong reflected components from the Lakshadweep ridge. According to Murty and Rao[9], reflection plays a significant role in smaller oceans such as the Indian Ocean. Close to the shore, the types of coastal settings that are particularly prone to tsunami are exposed ocean beaches, cleared coastal land, river deltas and harbours[10].

The run-up level shows a maximum at Kayamkulam inlet, recording up to 5 m, which incidentally is lower than the highest reported along the Tamil Nadu coast[11]. The high amplitude and total devastation at Kayamkulam inlet area could be the combined effect of refraction–diffraction and reflection from the Lakshadweep ridge coupled with a few other factors. A factor that could have contributed to the higher inundation at this location are the two breakwaters jetting out into the sea at the inlet blocking the northward propagation of the tsunami. The Thiruvananthapuram coast appears to be a divergence zone lying between two convergence (high amplitude) zones, Colachel in the south (in Tamil Nadu) and Kayamkulam in the north. North of Kayamkulam, the tsunami amplitude reduces in general with occasional high-amplitude zones typical of convergence zones. Edavanakkad, north of Cochin inlet, where run-up up to 4.5 m was observed, could be a major convergence zone. The northward decrease in amplitude could be expected, considering the fact that the diffracted–refracted wavefront loses its energy during propagation in the shallow waters. Another factor is that the reflected component from the Lakshadweep ridge system is absent for the northern Kerala coast.

Table 1. Volume changes at different stations adjoining Kayamkulam inlet

Station	Status	Volume change (m^3/m width of beach)
N1	Erosion	53.4
N2	Erosion	16.1
N3	Erosion	66.5
N4	Erosion	4.0
N5	Erosion	7.3
S1	Deposition	91.4
S2	Erosion	38.1
S3	Deposition	64.8
S4	Deposition	12.6

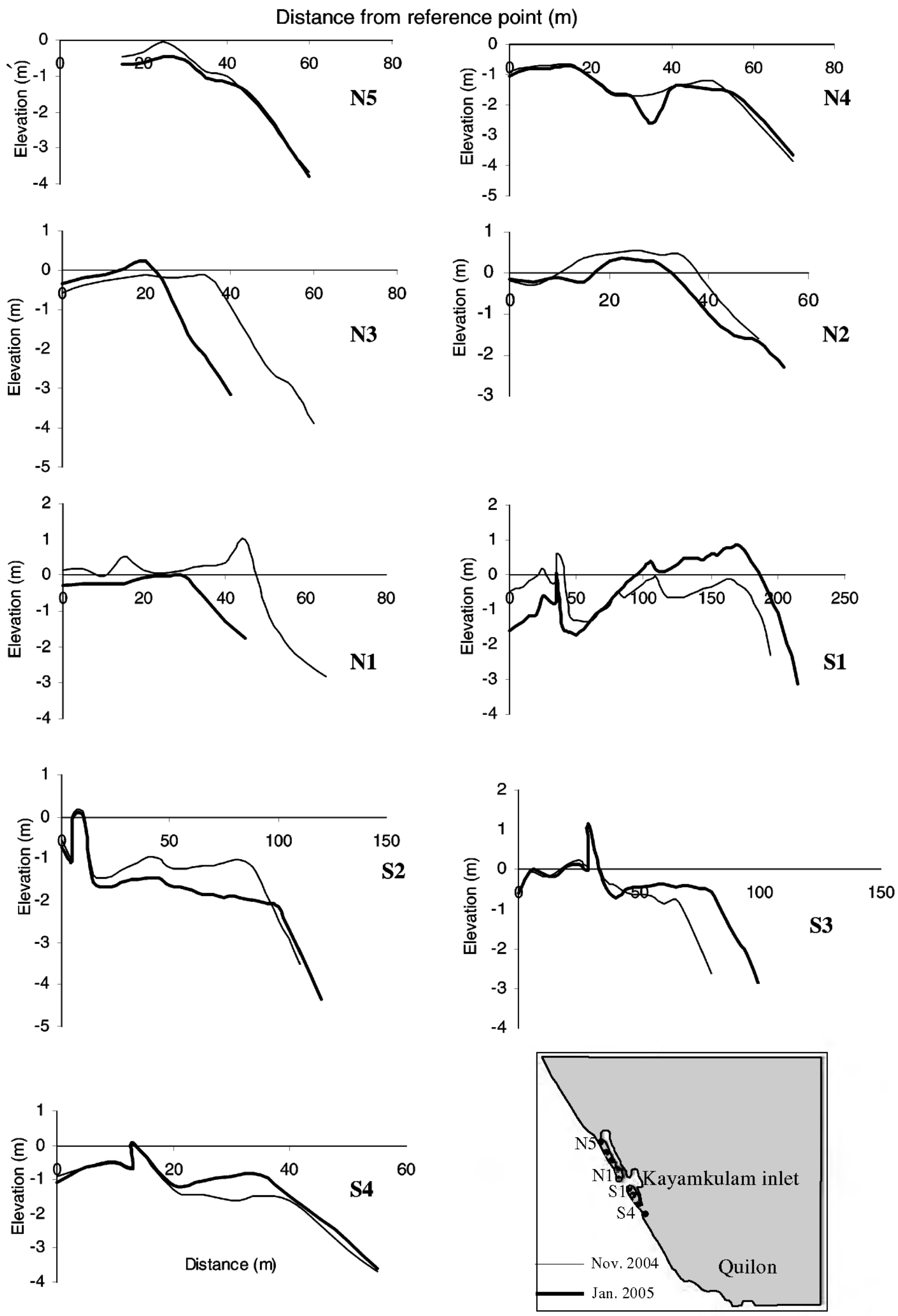


Figure 8. Pre- and post-tsunami beach profiles north and south of Kayamkulam inlet. N1–N5 are stations on the northern side of the inlet and S1–S4 on the southern side.

The interactions of the tsunami with tides, currents and waves could be crucial. Growth of waves by drawing energy from these hydrodynamic forces through Reynolds' eddy stresses is possible[9]. Arrival of the waves at high tide is a factor that compounded the inundation, leading to higher intensity of damage around Kayamkulam. In the same way, low tide minimized the effect, as observed in the northern tracts of the coast, where the tsunami arrived in the afternoon. The highest waves along northern Kerala coast occurred at midnight, coinciding with the next high tide and the occurrence of two major waves at that time. The observed run-up level distribution could only be understood by setting up inundation models, which rely on finer data on the innershelf bathymetry, hydrodynamic characteristics and coastal topography.

As seen in the Kayamkulam inlet region, the waves might have caused erosion in the beach and innershelf all along the coast depending on the wave intensity and inundation. We believe that the impact of this erosion on the overall sediment budget of the region depends on the hinterland slope and geomorphic set up. In locations such as Kayamkulam, the hinterland regions have a downslope towards the backwaters. Thus it is quite possible that in many locations, the eroded sediments from the innershelf and the beach might have been carried forward and got deposited in the hinterland and backwater system, resulting in a localized temporary loss of sediment from the beach-innershelf region.

One aspect that has to be taken note of is the role of shore protection and other coastal engineering structures in tsunami inundation. The Kerala coast is notable for the presence of sea walls along a major part of it. Though well-built and well-maintained, sea walls were able to contain inundations in some locations, e.g. Thangassery, Neendakara, it failed in several other locations. Edavanakkad is a classical example where the sea wall, in spite of being well-built, was completely damaged with huge constituent boulders thrown far away inland. Thus, construction of sea walls as a protection against tsunami does not seem to have any apparent merit, considering also the exorbitant cost involved as well as the aesthetic and environmental considerations. On the other hand, coastal engineering structures seem to increase the vulnerability at least in some instances, as was seen near the Kayamkulam inlet. It could be argued that the inundation at Kayamkulam would have been much lower, but for the presence of the breakwaters jetting out into the sea and obstructing the northward propagation of the waves. Thus, there is no single way of reducing the effect of the tsunami and other coastal hazards; the varied morphology of our coastal regions and their socio-economic setting might call for adoption of region-specific strategies. Strict implementation of CRZ rules, adoption of soft coastal protection methods like beach nourishment, bio-shield, sand dune and development according to Integrated Coastal Zone Management Plan are strategies that could be followed for tsunami hazard mitigation[12].

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Flood mapping and analysis using air-borne synthetic aperture radar: A case study of July 2004 flood in Baghmati river basin, Bihar

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This study pertains to analysis of Airborne Synthetic Aperture Radar (ASAR) images in mapping the flood inundation and causative factors of flood in the lower reaches of Baghmati river basin for the period July–October 2004. Integration of the flood inundation layer and land cover layer derived from LISS III data indicate that 62% of the agricultural area was inundated. Floodwater drained faster in the left bank, whereas it was slow in the right bank. The Digital Elevation Model of the area shows that the flood-prone right bank of the Baghmati river is a topographic low sandwiched between Kosi and Burhi Gandak highs (megafans). The Baghmati river flows at high elevation than the right bank area. Low width-to-depth, high Sa/Se ratios indicate vulnerability for flooding due to low carrying capacity and avulsion. Over-bank flow is observed to initiate from the reactivation of underfit channels and tributaries. The low topography, low carrying capacity and avulsive behaviour of the river are attributed herein to frequent and prolonged flooding of the right

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