Are we ready for a major tsunami in the Indian Ocean?

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The Indian Tsunami Early Warning System (ITEWS) was established at the Indian National Centre for Ocean Information Services, Hyderabad in October 2007 following the devastating tsunami on 26 December 2004. The Intergovernmental Oceanographic Commission of United Nations Educational, Scientific and Cultural Organization (IOC/UNESCO) coordinated with the National Tsunami Warning Centers in the Indian Ocean region and promoted the establishment of a well-knit tsunami early warning system called Indian Ocean Tsunami Warning and Mitigation System (IOTWMS) so that all countries on the Indian Ocean can get benefitted. The end-to-end capabilities of this warning system have been well-proven during the tsunamigenic earthquakes that occurred since September 2007. The capability of the system is examined, with special reference to Indian Tsunami Early Warning System (ITEWS), to ascertain the readiness of the Indian Ocean region to face a major tsunami.

Keywords: Advisories, capacity building, inundation, modelling, tsunami.

Introduction

TSUNAMIS are rare but can be the deadliest and costliest hazard when they occur. In 2004, the Indian Ocean Tsunami killed more than 228,000 people and caused damages over USD 10 billion. Tsunami, meaning a 'harbour wave' in Japanese is a series of waves in the sea caused by the displacement of large volume of water. Earthquakes, volcanic eruptions, landslides and other underwater explosions, including underwater detonations of nuclear devices, glacier calving, meteor impacts all have the potential to generate a tsunami. However, the earthquakes on the sea bed remains to be the cause for most of the recent tsunamis. Normally, the large magnitude earthquake, having potential to generate a tsunami, happens at the subduction zone where the oceanic plate pushes against the continental plate and subducts below the continental plate. The seas around India have two such subduction zones, one on the eastern side, the Andaman–Nicobar–Java–Sumatra coast and the other on the north-western side the Makran coast (Figure 1).

In 2004, when the destructive tsunami occurred in the Indian Ocean following a massive earthquake of magnitude M_w 9.2 northwest of Sumatra, Indonesia, no tsunami early warning system existed in the Indian Ocean. The large devastation, especially the unprecedented loss of life, could have been avoided, if there was an early warning system for tsunamis in the Indian Ocean region. To avoid such situations in future, the Government of India decided to establish a state-of-the-art Indian Tsunami Early Warning System (ITEWS) at the Indian National Centre for Ocean Information Services (INCOIS), Hyderabad.

The requirements of a tsunami early warning system are: (i) an efficient system to detect and warn the tsunami, (ii) a fail proof communication system to disseminate the warnings/advisories and (iii) a mitigation system at community level to prepare the community to act wisely. This article examines the current status of detection, generation and dissemination of early warnings of tsunamis and the preparedness of the region to face a tsunami. We shall mainly use the details of ITEWS to make this assessment.

Indian tsunami early warning system (ITEWS)

The ITEWS comprises a real-time network of seismic stations, tsunami buoys equipped with bottom pressure recorders (BPRs), tide gauges and 24×7 operational tsunami warning centre to detect tsunami-genic earthquakes, to monitor tsunamis and provide timely advisories following unique standard operating procedure (SOP). The ITEWS uses data from national and international network of about 400 seismic stations all over the world. Based on seismic data received from these stations the earthquake is detected and the warning centre transmits the first bulletin indicating the location, magnitude, depth and other characteristics like 'a guess on the tsunamigenic potential' of the event. After the first bulletin is disseminated, the seismic data are further analysed for improved
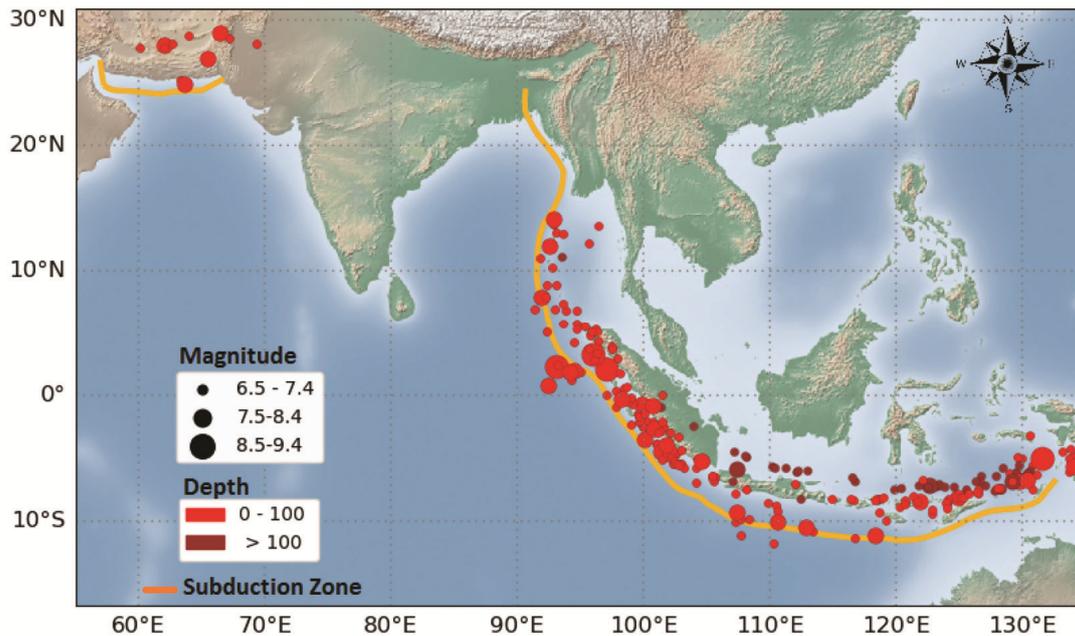
Figure 1. Subduction zones and historical earthquakes ($M \geq 6.5$) in the Indian Ocean.

accuracy of earthquake parameters (magnitude, depth, location and focal mechanism). Usually, the detection of the earthquake and the estimation of its magnitude (bulletin 1) happens within the first 5–10 min and the dissemination of the first bulletin reporting the earthquake characteristics and assessment of tsunamigenic potential happens in less than 10 min.

The ITEWS utilizes the tsunami buoys to monitor the tsunami waves in the open ocean. The tsunami buoy consists of a surface buoy and a Bottom Pressure Recorder (BPR) that can sense the sea level variations, accurate to 2 mm, and report data to ITEWS in real time. These accuracies are much higher than the normal height of tsunami waves, which are in the range of 5–10 cm, in the deep ocean. The current tsunami buoy network in the Indian Ocean consists of seven tsunami buoys maintained by INCOIS and National Institute of Ocean Technology (NIOT). The tsunami buoys and sea level gauges also help in validating the forecasted tsunami waves by the model.

The TUNAMI-N2 (Tohoku University's Numerical Analysis Model for Investigation of Near-field Tsunamis, version-2) model[1], customized for the Indian Ocean is used for estimating the tsunami travel times and run-up heights for different earthquakes. The model was extensively validated using 26 December 2004 tsunami field observations and surveyed inundation[2]. As the execution of the model is computer intensive and time consuming, the model was pre-run several times to generate tsunami travel time and run up heights at beach for different earthquake scenarios on 1000 segments covering Andaman–Sumatra–Java and Makran subduction zones in the

Indian Ocean. In the scenario database, each segment represents a 7.5 M_w earthquake with a rupture length of 100 km and 50 km width with slip of 1 m. Such unit is called 'a unit source'. In doing so, the model assumed the worst slip due to a possible earthquake and ignored the non-linearity in open ocean tsunami propagation. When a large earthquake occurs on the floor of the Indian Ocean, ITEWS quickly refers to this Open Ocean Propagation Scenario Database (OOPS-DB) and picks up the closest unit sources combination and interpolates to match the actual magnitude of tsunamigenic earthquake. The scenario database provides the information on expected arrival time and amplitude of tsunami wave at different segments of the coast pre-defined all along the 30 m bathymetry contour in the Indian Ocean (Figure 2). Each coastal segment, of approximate length of 50 km, is called coastal forecast zone (CFZ).

The tsunami threat level with expected wave arrival times and amplitudes at the beach is further mapped to CFZs using Greens law. The CFZs are mapped such a way that they coincide with the district boundaries that can be easily identified by the Disaster Management Officers (DMOs). Usually, a bulletin (the 2nd bulletin) carrying such information on 'potential threat' and expected tsunami wave arrival times at different coastal locations is generated and disseminated within 20 min of the occurrence of the earthquake.

By the time that bulletin is issued, one or other sea level gauge or the tsunami buoy, whichever is nearer to the earthquake location, observes the tsunami wave, if any generated, and reports the data to ITEWS. Such information on water level from sea level gauges or tsunami
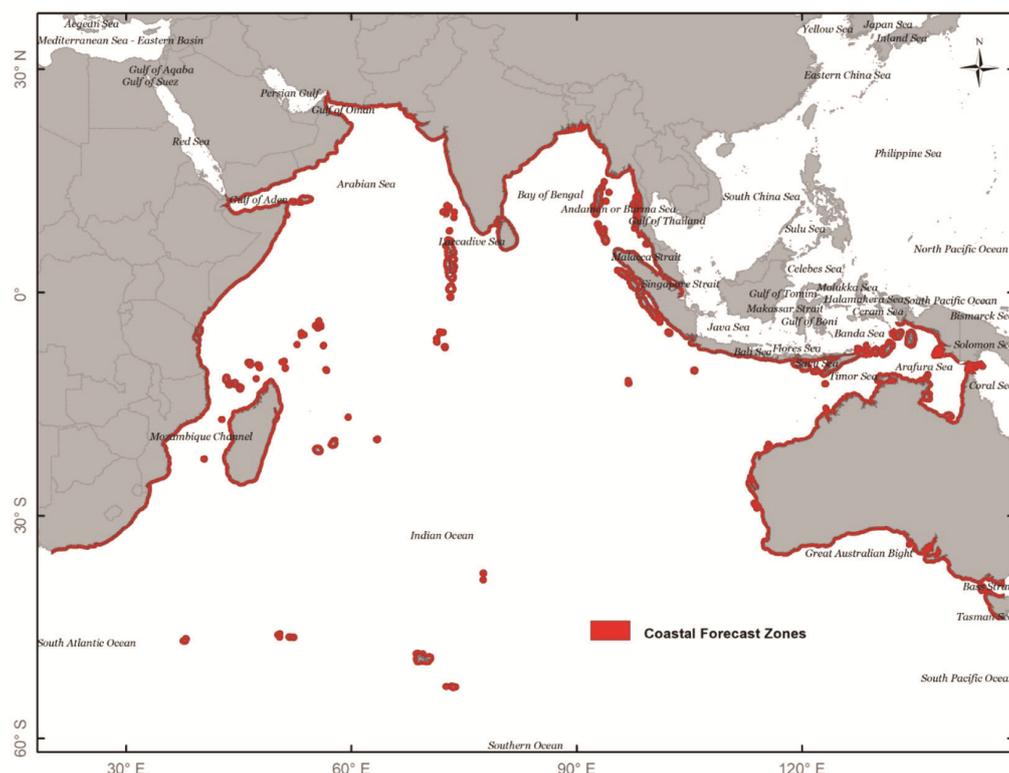
Figure 2. Coastal forecast zones in the Indian Ocean region.

Table 1. TSP – key performance indicators set by IOTWMS of IOC/UNESCO

KPI no.	Key performance indicators	Target value
1	Elapsed time from earthquake to issuance of first earthquake bulletin	10 min
2	Probability of detection of Indian Ocean earthquakes with $M_w >= 6.8$ (USGS final value)	100%
3	Accuracy of earthquake magnitude	0.3*
4	Accuracy of earthquake hypocentre depth	30 km*
5	Accuracy of earthquake hypocentre location	30 km*
6	Elapsed time from earthquake to issuance of first threat assessment bulletin	20 min
7	Probability of detection of tsunami above threat threshold	100%
8	Accuracy of the tsunami forecast amplitude/height	Factor of 2

*In comparison with final USGS parameters for the earthquake.

buoys confirms the generation of a tsunami following the earthquake. The observed sea level is also used to compare with the model estimated tsunami travel time and amplitude and include as 'confirmed threat' in the subsequent bulletins (usually 3rd bulletin onwards).

This three-pronged approach, detection of earthquake (tsunamigensis), modelling of tsunami (potential threat) and real time observations to confirm (confirmed threat) and monitor the tsunami waves adopted by ITEWS makes it most pragmatic methodology that prevents the false warnings on tsunamis. Since its inception in October 2007, ITEWS maintained the discipline of not issuing any false warning while issuing accurate early warnings following large earthquakes within stipulated timelines[3,4]. The stipulated timelines to issue the early warnings start-

ing from issuing the earthquake bulletin (the 1st bulletin) and the expected accuracy levels of various parameters are given in Table 1. The timelines and accuracy levels followed at ITEWS are according to the guidelines of IOC/UNESCO. The entire process has been automated with minimum manual intervention; especially, the first bulletin containing the earthquake information gets generated and disseminated automatically with no manual intervention.

Communication and dissemination of early warnings and advisories

Different types of communication systems used at ITEWS include website, e-mails, satellite links, GTS,

mobile, telephone and fax. They are tested through communication tests every six months involving the disaster management authorities at state and district level in India and with the National Tsunami Warning Centers (NTWC) of the Indian Ocean rim countries. Twice a year communication tests named 'COMMs Tests' are conducted under the coordination of ICG/IOTWMS ensuring the participation of all countries on the Indian Ocean rim. Since March 2011, 18 COMMs Tests have been conducted involving 24 countries and the disaster management agencies in India. The feedbacks were obtained and analysed to identify the bottlenecks, if any, in the communication between warning centre and others. Email seems to be the most efficient way of communication followed with GTS and SMS. The e-mail reached the targeted agencies 90% of the time within 1–2 min. However, the multiple communication channels/systems ensure fail-safe transmission and reception of tsunami early warnings by the concerned.

Performance of Indian Ocean tsunami early warning and mitigation system

Since its inception, ITEWS detected and reported 616 earthquakes (up to January 2020) of magnitude ≥6.5 M globally and 99 in the Indian Ocean. A summary of the performance of ITEWS against the key performance indicators set up by IOC/UNESCO[5] for the above events is given in Table 1. Among them, six earthquakes were tsunamigenic in the Indian Ocean, necessitating more than one bulletin (i.e. earthquake information). For those earthquake events, the model results were analysed, real-time water levels were closely monitored and tsunami advisories/warnings were issued according to set procedures.

With these arrangements, the tsunami early warning system is able to detect every tsunami-genic earthquake occurring on the ocean floor, assess its potential to generate a tsunami and provide appropriate advisories/early warnings in 10–20 min after the occurrence of earthquake. For mainland India, there is a minimum of 1.5 h for disaster management officials to act and move the vulnerable community to safer locations. But for Andaman & Nicobar Islands, the tsunami wave arrival time could be <20 min. In such cases, it is a necessity that vulnerable communities move to safer locations when they feel the ground is shaking.

Improvements in tsunami early warning

Use of Global Positioning System in tsunami early warning

Large earthquakes (say $M_w > 8.5$) are generally underestimated when estimated using the first few minutes of seismic data. Normally, the warning centres cannot afford to wait longer to estimate the earthquake magnitudes. Thus, waiting for longer time period to gather seismic data becomes a limiting factor in tsunami warning. Studies suggest that displacement data from near-field GPS/Global Navigation Satellite System (GNSS) will help in overcoming this limitation[6–8]. The displacement data from near-field GPS/GNSS stations, if received and processed quickly, can be used for the estimation of moment magnitude much quicker than that can be achieved using the seismic waveform alone[9].

The Indian Seismic and GNSS Network (ISGN) and the GPS-Strong Motion Accelerometer network recently established on the Andaman & Nicobar Islands are expected to be integrated with the existing tsunami early warning system soon to help in the quicker estimation of earthquake magnitudes, especially for the large earthquakes near Andaman & Nicobar Islands.

Inversion of tsunami waveform recorded by the tsunami buoys or coastal sea level gauges is another method for accurate characterization of seismic ground motion, rupture direction and its extent. It is the inversion of tide-gauge data from Paradip, the northernmost of the Indian east-coast stations available for the 2004 event, led Neetu et al.[10] to conclude that the source length was greater by roughly 30% than the initial estimate of Lay et al.[11]. The technique of tsunami waveform inversion using the sea level data is also being developed and integrated within the early warning process. Once, the alternate estimation of earthquakes magnitude and characterisation based on GPS and tsunami waveform inversions are integrated with the operational system, the tsunami early warnings will get another boost for their precision in providing early warnings.

Real time modelling and prediction of inundation

Greater precision of tsunami early warnings can be achieved by adopting the execution of tsunami models in real time considering the actual characteristics of the event and extending the model further landwards for the estimation of level and extent of inundation due to the incursion of tsunami wave. Numerous numerical models have been developed to simulate the tsunami wave propagation, and the associated coastal inundation. For example, MOST[12], TUNAMI-N2[13], etc. However, a finite element based Advanced CIRCulation (ADCIRC) model, mostly used to estimate the surge height and inundation during the landfall of cyclone/hurricane has been adopted as a tsunami model and also to estimate the inundation during a tsunami.

The ADCIRC model has been set up for the Indian Ocean domain (64°S to 29°N and 10°E to 160°E) with 30 arc-sec GEBCO data (https://www.gebco.net/data_and_products/gridded_bathymetry_data/documents/gebco_2014.pdf) for the bathymetry. The inland topography was
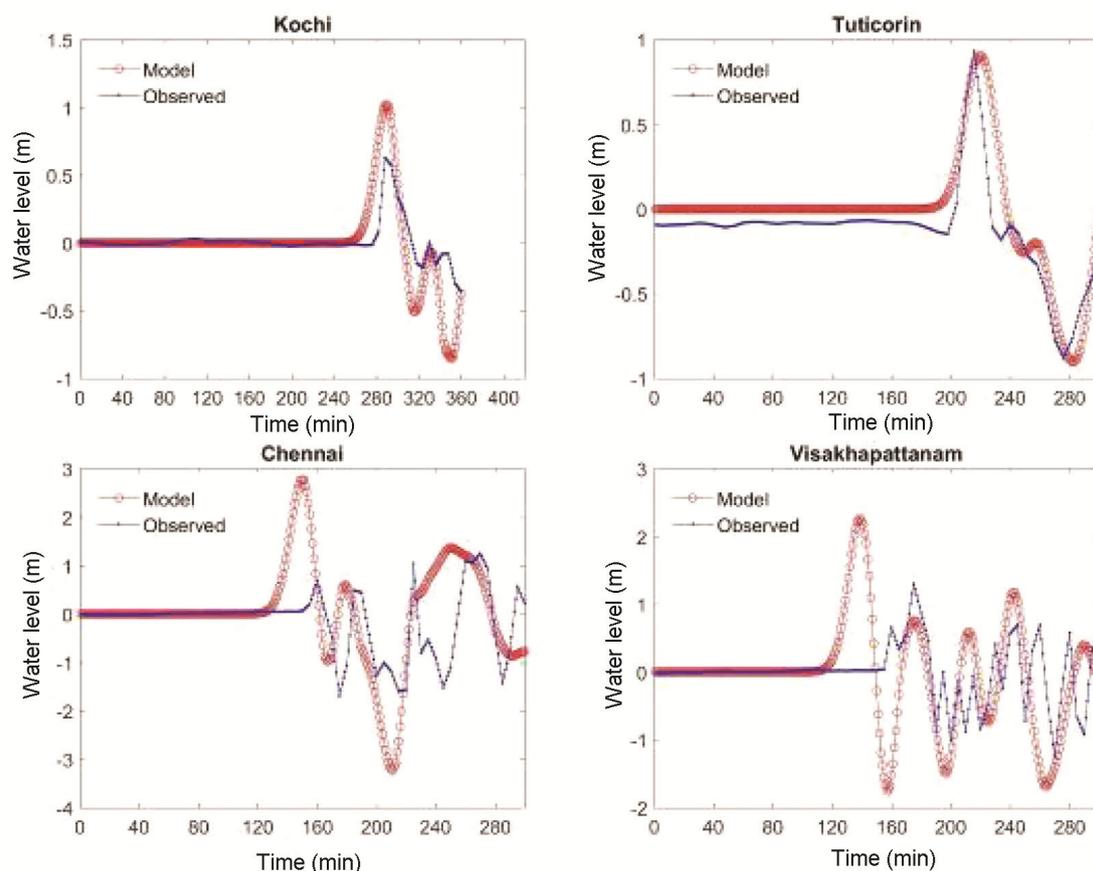
Figure 3. Validation of ADCIRC model wave heights with the observations from tide gauges.

replaced by CARTOSAT + Airborne Laser Terrain Mapping (ALTM) data. An unstructured triangular gridded mesh was developed in such a way that the grids are finer (~150 m) in the shallow water and coarser in the deeper water (~20 km). The model was tested using 2004 tsunami event and the results were validated using observed sea levels recorded by the tide gauges at Kochi, Tuticorin, Chennai, Visakhapatnam, Paradip, Cocos Island, Columbo, Diego Garcia, Hanimadhoo, Male, Phuket and Tapah-Noi (time of arrival and height of tsunami wave at the location). Figure 3 shows the validation of wave heights at tide gauges located along the Indian coast. The slight mismatch mostly in phase is due to the limitation of coarse resolution GEBCO bathymetry used for the model simulations. However, tsunami wave arrival time in model matched well with the observations[10]. The model derived inundation level and the extent of landward tsunami wave ingress was tested by comparing them with the observations reported in Maheshwari *et al.*[14] for Nagapattinam–Cuddalore region; a region badly affected by the 2004 tsunami. Figure 4 shows the computed inundation extent along Cuddalore and Nagapattinam regions. The computed and observed inundation extents at Cuddalore and Nagapattinam locations are 2 and 3 km, and 1 and 3 km respectively.

Capacity building through community awareness and preparedness

ITEWS coordinates community awareness and preparedness activities in India in collaboration with state/district disaster management officials and through Ministry of Home Affairs (MHA) and National Disaster Management Authority (NDMA) at national level. Since 2009, ITEWS coordinated five Indian Ocean wide tsunami mock exercises called IOWAVE (IOWAVE-2009, IOWAVE-2011, IOWAVE-2014, IOWAVE-2016 and IOWAVE-2018) in coordination with ICG/IOTWMS and national and state disaster management agencies in India, and four mock exercise for the Indian coastal states in collaboration with NDMA and MHA.

Indian Ocean Tsunami Ready Programme (IOTR)[15] is a voluntary community based programme that facilitates tsunami preparedness as an active collaboration of the public, community leaders, local and national emergency management agencies. A National Board has been constituted to implement the IOTR programme in India by providing advocacy to the tsunami hazard affecting the communities and build capacity in the community. It will also help to increase the awareness in communities and among authorities through communication, exercises,
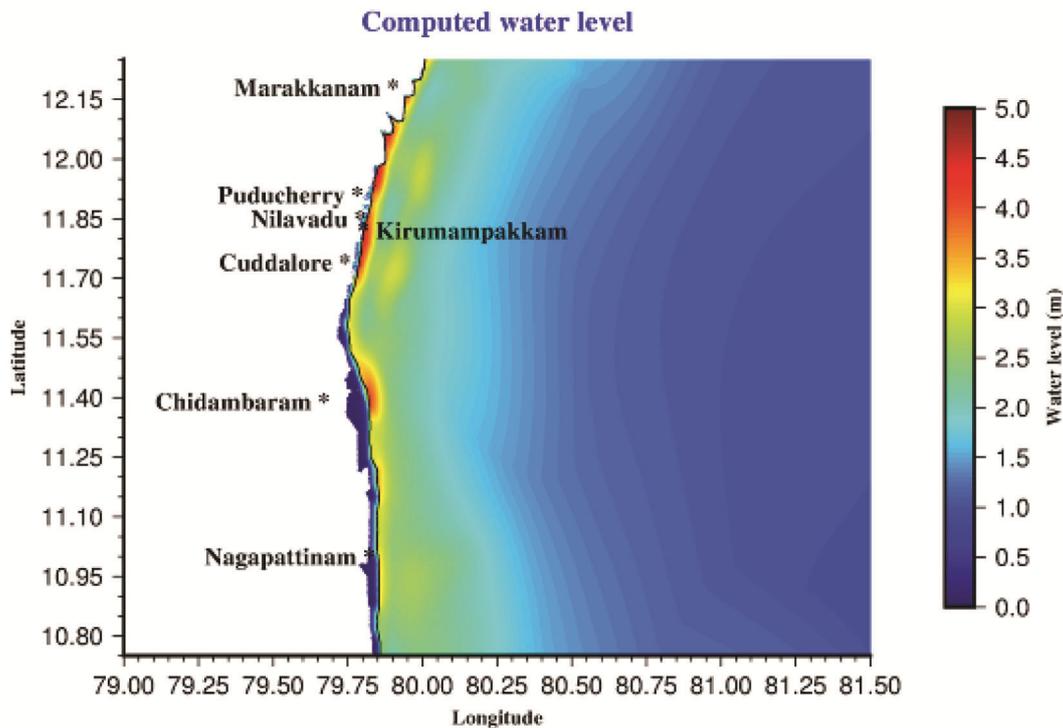
Figure 4. Computed inland extent of inundation along Cuddalore and Nagapattinam coasts.

training, information, preparedness and recognition programmes. The board will verify and evaluate the tsunami recognition request on fulfilment of guidelines and recognize the communities as 'Indian Ocean Tsunami Ready', and recommend for regional recognition. Towards this, ITEWC hosted a training programme on tsunami inundation modelling, inundation mapping, evacuation route mapping and preparation of SOP in collaboration with ICG/IOTWMS.

Conclusions

The ITEWC established in the aftermath of 2004 tsunami in the Indian Ocean is well equipped to receive data from hundreds of broadband seismometers and detect earthquake in less than 10 min. In addition, the modelling tools employed at ITEWC help in assessing the potential of earthquake in generating a tsunami and in determining the arrival times of tsunami and the expected wave height at each location along the coast of the Indian Ocean. That helped to generate and issue accurate location-specific tsunami advisories. The sea level data received in real time from tsunami buoys and sea level gauges (tide gauges) helped to monitor as well as validate the accuracy of tsunami model. The communication channels between the early warning centres or Tsunami Service Providers (TSP) and the NTWCs are tested every six months to ensure their working. Considering the consistent performance of ITEWC, IOC/UNESCO designated ITEWC as

TSP for the Indian Ocean region in October 2012. Together with time to time tsunami mock exercises, awareness workshops, training programmes, etc., the coastal communities as well as the disaster management authorities have been prepared to be tsunami ready. However, efforts are underway to issue advisories on near site tsunamis (local tsunamis) generated by landslides or volcanic eruptions. Further research on the detection of such events in real time and hydrodynamic modelling is necessary to deal with such 'typical' events.

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