"End-to-end tsunami early warning systems" in collaboration with IOC-UNESCO IOTWMS
(Dedicated to the memory of Professor Samantha Hettiarachchi)

Guest Editor: Priyan Dias
Guest editorial

Early warning systems to reduce tsunami impacts
Professor Samantha Hettiarachchi, PhD (Lond), DIC, was a Senior Professor in Civil Engineering at the University of Moratuwa, and a Fellow of the National Academy of Sciences, Sri Lanka (NASSL). He made exceptional national and international contributions in the areas of coastal engineering, coastal zone management and disaster risk reduction. He was the Vice-Chairman and Acting Chairman of the steering group that installed the Indian Ocean Tsunami Warning and Mitigation System (IOTWS), collaborating with 26 Indian Ocean rim states under the auspices of UNESCO/IOC. Under his leadership UNESCO/IOC produced a definitive guideline on Tsunami Risk Assessment, now in its second edition (UNESCO, 2015). In Sri Lanka, his expertise was used by Coast Conservation Department, the Lanka Hydraulic Institute (LHI), the Disaster Management Centre (DMC) and the National Science Foundation. He was consulted by the Governments of Indonesia and Oman, in addition to that of Sri Lanka.

Professor Hettiarachchi died at the relatively young age of 62 in April 2018, after a courageous battle against cancer. This special issue is meant to celebrate his life and work. It is appropriate that this *gedenkschrift* is carried in IJDRBE, because he collaborated very closely with its Chief Editors, being an editorial board member from its inception. He was also a keynote speaker at the 3rd International Conference on Building Resilience at Ahungalla in 2013, a conference series that is closely associated with this journal. The issue will be launched, fittingly in partnership with UNESCO too, at the 9th conference in the series to be held in Bali in January 2020. The actual call for papers was issued at a memorial lecture in Prof Hettiarachchi’s honour, delivered in Colombo by Professor Eduard Kissling, Professor of Geophysics at ETH Zurich, under the auspices of the NASSL.

There are nine contributions in this issue, titled Early Warning Systems for Reducing Tsunami Impact. Three of them are from Sri Lanka, which is to be expected given Prof Hettiarachchi’s rootedness in his home context. However, there are others from Japan, Canada, Indonesia and Sweden; and two from the United Kingdom. The UK is where Prof Hettiarachchi engaged in most of his initial academic collaborations. He obtained his doctorate from Imperial College London working under Prof Patrick Holmes, in the course of which he developed links with HR Wallingford; and subsequently worked for a year in the Maritime Engineering Group of Ove Arup and Partners, London. It is only after the Indian Ocean tsunami of 2004 that he broadened his travels and interactions, many of which are reflected by the author affiliations in this issue.

Japan is a country that extended significant technical assistance to Sri Lanka soon after the tsunami. The Canadian paper is from the University of Calgary (jointly with LHI), which launched the International Institute for Infrastructure Resilience and Reconstruction (IIIRR), largely spearheaded by some Sri Lankan academics there. Indonesia is a key country that was involved in the IOTWS. The Swedish Lund University link is thanks to the European Union funded seven-country ASCENT project, intended to strengthen research and innovation capacity for the development of societal resilience to disasters. This project was led by Professors Dilanthi Amaratunga and Richard Haigh of Huddersfield University, who are the joint chief editors of IJDRBE and authors in two of the papers herein. Many of the other authors are Professor Hettiarachchi’s students, two of them full professors – one at the...
University of Swansea and the other at the University of Peradeniya. The last paper in the issue is from a group at Moratuwa University that Professor Hettiarachchi was leading at the time of his demise.

The papers are arranged roughly in the sequence of a tsunami and its effects. The first one deals with tsunami propagation to the Bangladeshi coast; and the second with an assessment of the adequacy of the wave buoy and tide gauge system for sensing such propagations, with respect to generating warnings for Sri Lanka. Both these papers draw attention to lesser known tsunamigenic sources, namely, the Arakan segment of the Sunda trench, the Makran fault, Carlsberg Ridge and the Chagos Arcipelago. The third paper, although on storm surges, looks at the way that coastal phenomena could affect coastlines, and physical mitigation measures against the same. It also accounts for climate change, something that every coastal manager would need to consider. This paper also compares hard and soft intervention measures for mitigation. The latter has been recognized as being especially important for tackling low frequency (though high impact) tsunami hazards – which would be the case for the Indian subcontinent and the East African coast – since it may be difficult to justify high investments for hard solutions. The fourth paper is about tsunami impact on building structures, an area in which this writer himself has collaborated on with Professor Hettiarachchi (UNESCO, 2015; Hettiarachchi and Dias, 2013).

The fifth paper focuses on the interface between the upstream and downstream components of an early warning system. The second paper is a good example of upstream issues, which are mostly technological – e.g. the adequacy of buoys and gauges. The sixth and seventh papers are largely concerned with community (or downstream) aspects – the former with the identification and utilization of social networks for warning and the latter with cultural dimensions and community inclusiveness. But the fifth paper deals with matters such as decision making for issuing warnings and ordering evacuation, and holds a central position within the entire early warning process. It also happens to be in the middle of this collection, with four papers before it and four after. The last two papers are more generally on disaster management, the penultimate one still focusing on coastal and tsunami hazards, but the last on disasters in a generic way. In Sri Lanka at least, it was the 2004 Tsunami that highlighted the importance of disaster management, which also included the creation of the DMC.

The papers in this issue also incorporate a range of research methodologies. The first, third and fourth papers are genuinely quantitative in nature, involving numerical analysis. The fourth paper uses pushover finite element analysis; and the other two hydrodynamic modelling – while the third paper uses extreme events, the first attempts a probabilistic approach. The other six papers are qualitative. The second and seventh papers are reflective desk studies; while the other four use either questionnaires or structured interviews and/or focus group discussions, in some cases combined with document analysis. The fifth paper uses thematic analysis; the sixth one the graphical elements of social network analysis; and the last one correlation and regression analysis.

Hence this special issue is rich in methodological variety. This reflects the multidisciplinary nature of mitigating tsunami impacts. The papers at the start of the list, on tsunami propagation and impact, require quantitative approaches; while those at the end, dealing with community warning and response, are better tackled using qualitative ones. Professor Hettiarachchi’s evolving career also displayed this move from the quantitative to the qualitative. The first and third papers that use hydrodynamics are authored by his students in the nineteen eighties and nineties – they are Professors Janaka Wijetunge and
Harshinie Karunarathna referred to earlier. The last paper, based on a questionnaire survey, is authored by his students within the past two decades.

Priyan Dias

Department of Civil Engineering, University of Moratuwa, Moratuwa, Sri Lanka

References


A multi-scenario assessment of the seismogenic tsunami hazard for Bangladesh

Janaka J. Wijetunge
University of Peradeniya, Kandy, Sri Lanka

Abstract

Purpose – This paper aims to describe a multi-scenario assessment of the seismogenic tsunami hazard for Bangladesh from active subduction zones in the Indian Ocean region. Two segments of the Sunda arc, namely, Andaman and Arakan, appear to pose a tsunamigenic seismic threat to Bangladesh.

Design/methodology/approach – High-resolution numerical simulations of tsunami propagation toward the coast of Bangladesh have been carried out for eight plausible seismic scenarios in Andaman and Arakan subduction zones. The numerical results have been analyzed to obtain the spatial variation of the maximum tsunami amplitudes as well as tsunami arrival times for the entire coastline of Bangladesh.

Findings – The results suggest that the tsunami heights are amplified on either side of the axis of the submarine canyon which approaches the nearshore sea off Barisal in the seaboard off Sundarban–Barisal–Sandwip. Moreover, the computed tsunami amplitudes are comparatively higher north of the latitude 21.5o in the Teknaf–Chittagong coastline. The calculated arrival times indicate that the tsunami waves reach the western half of the Sundarban–Barisal–Sandwip coastline sooner, while shallow water off the eastern half results in a longer arrival time for that part of the coastline, in the event of an earthquake in the Andaman seismic zone. On the other hand, most parts of the Chittagong–Teknaf coastline would receive tsunami waves almost immediately after an earthquake in the northern segment of the Arakan seismic zone.

Originality/value – The present assessment includes probabilistic measures of the tsunami hazard by incorporating several probable seismic scenarios corresponding to recurrence intervals ranging from 25 years to over 1,000 years.

Keywords Numerical simulations, Coastal flooding, Disaster risk mitigation, Indian Ocean region, Shallow water equations, Tsunami amplitude

1. Introduction

The massive earthquake of moment magnitude $M_w = 9.1-9.3$ (Ammon et al., 2005) on December 26, 2004 in the Andaman-Sunda trench ruptured a 1,200 km long segment, starting near the northern part of the Sumatra Island and ending offshore of the Andaman Islands. The tsunami that was generated by this seismic event reached many parts of the Indian Ocean and beyond including Bangladesh (Wijetunge, 2005; Wijetunge et al., 2008; Choi et al., 2005a; Wijetunge, 2009a). Although the impact of the 2004 tsunami on Bangladesh was relatively less, the unprecedented scale of the devastation caused by the event in many countries (Wijetunge, 2009b; Choi et al., 2005b; Wijetunge, 2012; Wijetunge, 2014; Ranasinghe et al., 2013; Wijetunge, 2010a) necessitated an assessment of the tsunami threat to Bangladesh posed by Sumatra-Andaman seismic zone as well as other potential subduction zones in the Indian Ocean region (Wijetunge, 2010b). Accordingly, this paper describes a multi-scenario assessment of the seismogenic tsunami hazard to Bangladesh from potential active subduction zones in the Indian Ocean region. The analysis includes numerically simulated tsunami amplitudes off the coast of Bangladesh corresponding to eight plausible seismic scenarios covering a range of return periods from 25 years to over 1,000 years.
2. Tectonics and seismicity

2.1 Active subduction zones

There are two major subduction zones with tsunamigenic seismic potential in the Indian Ocean Basin, namely, a portion of the Sunda Arc stretching south from Bangladesh down to Java (Segment AE in Figure 1), and the Makran Subduction Zone (Segment FG) off the coastline of Pakistan and Iran in the Arabian Sea (Okal and Synolakis, 2008).

The western flank of the Sunda Arc may be further divided into four zones as shown in Figure 1:

1. Andaman–Myanmar (Arakan) (Segment AB);
2. Andaman–Northern Sumatra (Segment BC);
3. Southern Sumatra (Segment CD); and
4. Java (Segment DE).

However, tsunami events originating in that part of the Sunda Arc off southern Sumatra (Segment CD) and Java (Segment DE) are not considered in the present study since the location and orientation of these segments clearly suggest that the bulk of the tsunami energy from these fault planes will be directed away from Bangladesh [source directivity (Ben-Menahem and Rosenman, 1972),]. Moreover, source directivity as well as the presence of the landmass of India would prevent wave energy of any significance from reaching Bangladesh if a tsunamigenic earthquake were to occur in Makran Subduction Zone (Segment FG). Accordingly, only the tsunamigenic seismic scenarios originating from Arakan (segment AB) and Andaman-Northern Sumatra (Segment BC) of the Sunda Arc will be considered for the purpose of assessing the tsunami hazard to Bangladesh.

Figure 1. Subduction zones in the Indian Ocean Basin

Source: Modified after (Okal and Synolakis, 2008)
2.2 Past seismic activity

In the following, the tectonics and the seismic history of the Arakan and Andaman-Northern Sumatra subduction segments identified above are briefly reviewed.

The Northern Sumatra-Andaman zone encompasses offshore northern Sumatra and the Nicobar-Andaman Island chains. In this zone, the Indian plate is subducting obliquely beneath the Burma microplate with an estimated convergence rate of about 20 mm/yr to 40 mm/yr, with the higher rates to the south (Chlieh et al., 2007). Large earthquakes that have occurred in the Andaman-Northern Sumatra zone during the past 200 years include the events of $M_w = 7.9$ in 1881, $M_w = 7.7$ in 1941, $M_w = 9.1$ in 2004, and $M_w = 7.5$ in 2010. Moreover, about 25 earthquakes of magnitude greater than $M_w = 6.0$ have occurred during the past century, 11 of which during the past 50 years, yielding a rate of about one event every 4–5 years (Petersen et al., 2007). Further, preliminary paleoseismic data reported in (Rajendran and Gupta, 2009) and those in (Jankaew et al., 2008) indicate that at least one predecessor to the 2004 earthquake occurred about 700–1000 years ago.

The earthquake of $M_w = 9.1$ in 2004 in the Andaman-Northern Sumatra segment may also have increased the stress on adjacent segments of the subduction, raising the seismic hazard at both ends of the rupture, i.e. further south off southern Sumatra as well as further north in the northern Bay of Bengal along the coast of Myanmar (McCloskey et al., 2005).

Several recent studies suggest that the Arakan trench, where the Indian plate underthrusts the South-East Asian part of the Eurasian Plate, is still an active subduction zone (Socquet et al., 2006). GPS observations indicate a 23 mm/yr accumulation of backslip along the Arakan trench (Socquet et al., 2006). Nevertheless, some earlier works, for example (Ni et al., 1989; Guzman-Speziale and Ni, 2000), have suggested that subduction along Burmese Arc is not active at present.

Past seismic activity in the Arakan subduction zone includes historical reports of a large earthquake on April 2, 1762 along the coast of Bangladesh and Mynamar, from Chittagong in the north to Foul Island in the south, causing an uplift of 3-7 m (Le Dain et al., 1984). Recent paleo seismological work has also confirmed the presence of emerged coral structures (Satake et al., 2006), of an age compatible with the 1762 earthquake (Okal and Synolakis, 2008).

Socquet et al. (2006) noted that a significant portion of the Arakan trench is elastically locked and accumulating significant deformation, and therefore, there is a high probability of occurrence of subduction earthquakes in this area. Cummins (2007) also concluded that the Arakan trench is capable of generating a giant tsunamigenic earthquake with potential for causing great loss of lives and destruction. His assessment was based on an examination of the tectonic environment, stress and crustal strain observations as well as historical earthquake activity in the Arakan subduction zone. On the other hand, no large earthquakes are documented, even in the historical record, along the northern extension of the 2004 rupture, between Great Coco Island and the southwestern tip of Myanmar, forming the western end of the mouths of the Irrawady (Okal and Synolakis, 2008).

3. Tsunamigenic seismic scenarios

Two methods are generally available for delineation of seismic scenarios for tsunami simulations, namely, the deterministic method and the probabilistic method. A deterministic tsunami hazard analysis has already been carried out for Bangladesh at a coastal level spatial resolution of 600 m under Comprehensive Disaster Management Program (IWM, 2009). In view of this, the present study incorporates probabilistic measures of the tsunami hazard so far as feasible within the typical constrains of paucity of historical data pertaining to the subduction zones.
The present study utilizes recently published results of an extensive probabilistic tsunami hazard assessment for Indian Ocean Nations including Bangladesh, reported in (Burbidge et al., 2009), to delineate the earthquake magnitudes in Andaman-Northern Sumatra segment corresponding to the recurrence intervals (Tr) of 25, 50, 100, 200, 500 and 1,000 years covering a range of plausible short-, medium- and long-term scenarios. The magnitude and the source parameters of such earthquakes corresponding to different recurrence intervals are given in Table I. Note that probabilities have been assigned to each of the seismic events using the historical record and the available geophysical information (Burbidge et al., 2009). It must, however, be added that the relatively short length of the available historical record of seismic events may result in a higher margin of error for the seismic scenarios with longer return periods such as Tr = 500 years and 1,000 years.

Unfortunately, it is not possible to carry out such a probabilistic seismic hazard assessment for the Arakan segment at this time owing to the paucity of records of past seismic events in that part of the arc as well as due to the comparatively poor understanding of its seismo-tectonics. For example, although there is historical evidence that Arakan segment has experienced a major earthquake in 1762, there is no estimate of its magnitude. It is also not clear that it ruptured the megathrust fault specifically, nor that it generated anything more than a local tsunami (Burbidge et al., 2009). The potential for future occurrences of large tsunamigenic earthquakes in this segment is therefore unknown, particularly in a probabilistic sense.

However, Okal and Synolakis (2008) have delineated two worst-case seismic scenarios for the Arakan zone (Table I), one in its northern segment (Mw = 8.6, Scenario-6) and the other in the south (Mw = 8.8, Scenario-7). Scenario-6 is a fault model inspired by a repeat of the 1762 earthquake whilst Scenario-7 is categorized as a somewhat far-fetched nevertheless feasible event to occur immediately north of the termination of the 2004 rupture. A recurrence interval of Tr > 1000 years has been assigned to these presumably low probability, worst-case events given the uncertainty in regard to their frequency of occurrence.

<table>
<thead>
<tr>
<th>Seismic scenario</th>
<th>Return period (years)</th>
<th>Seismic zone</th>
<th>Mw</th>
<th>M0 (Nm)</th>
<th>Φ (deg)</th>
<th>δ (deg)</th>
<th>λ (deg)</th>
<th>L (km)</th>
<th>W (km)</th>
<th>H (km)</th>
<th>Δu (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>Andaman</td>
<td>7.4</td>
<td>1.2 × 10^20</td>
<td>10</td>
<td>12</td>
<td>90</td>
<td>50</td>
<td>40</td>
<td>25</td>
<td>2.1</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>Andaman</td>
<td>7.7</td>
<td>4.0 × 10^20</td>
<td>10</td>
<td>12</td>
<td>90</td>
<td>70</td>
<td>45</td>
<td>25</td>
<td>4.3</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>Andaman</td>
<td>8.1</td>
<td>1.5 × 10^21</td>
<td>10</td>
<td>12</td>
<td>90</td>
<td>150</td>
<td>65</td>
<td>25</td>
<td>5.5</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>Andaman</td>
<td>8.4</td>
<td>4.5 × 10^21</td>
<td>10</td>
<td>12</td>
<td>90</td>
<td>250</td>
<td>85</td>
<td>25</td>
<td>7.0</td>
</tr>
<tr>
<td>5</td>
<td>500</td>
<td>Andaman</td>
<td>8.7</td>
<td>1.5 × 10^22</td>
<td>10</td>
<td>12</td>
<td>90</td>
<td>500</td>
<td>95</td>
<td>25</td>
<td>10.5</td>
</tr>
<tr>
<td>6</td>
<td>&gt;1,000</td>
<td>Arakan</td>
<td>8.6</td>
<td>7.9 × 10^21</td>
<td>324</td>
<td>20</td>
<td>124</td>
<td>470</td>
<td>100</td>
<td>25</td>
<td>6.5</td>
</tr>
<tr>
<td>7</td>
<td>Arakan</td>
<td>8.8</td>
<td>1.6 × 10^22</td>
<td>20</td>
<td>15</td>
<td>90</td>
<td>470</td>
<td>175</td>
<td>25</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Andaman</td>
<td>9.1</td>
<td>4.5 × 10^22</td>
<td>Multi-segment source model of Ji (2005), reported in Ammon et al. (2005)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** Seismic zones - Arakan (AB) and Andaman (BC) in Figure 1.
4. Numerical simulation of tsunami propagation

4.1 Model set-up

Numerical simulations of tsunami propagation and inundation were carried out by using COMCOT (COrnell Multi-grid COupled Tsunami model) (Wijetunge et al., 2008) for all scenarios given in Table I. A dynamically coupled system of two nested grids was used to simulate the tsunami propagation from each of the seismic zones toward the shoreline of Bangladesh. The non-linear form of the depth-averaged shallow-water equations were used in the numerical simulation of tsunami inundation. COMCOT model has been validated by experimental data (Liu et al., 1995) and has been successfully used to investigate several historical tsunami events, including the 2004 Indian Ocean tsunami (Wijetunge et al., 2008; Wijetunge, 2009b). Further details of the model including governing equations and numerical formulation can be found in (Wijetunge et al., 2008).

Whilst the inner, second-level grid was the same for all simulations, three different versions of outer grids were used to accommodate the different locations of the subduction segments. The bathymetric data for the outer grids used in the simulations was obtained by interpolating GEBCO (Global Elevation and Bathymetric Charts of the Oceans) data with a resolution of 30 arc-seconds to a grid of 0.01 arc-degrees (about 1,000 m) spacing. Similarly, the computational domain of the inner grid, which is embedded in the outer grid for the simulation of tsunami propagation over the continental shelf off the coast of Bangladesh, was set-up at a finer resolution of 0.002 arc-degrees (about 200 m). The topographic data used in the study comprised the coastal digital elevation model at a horizontal resolution of 50 m, provided by the Institute of Water Modeling (IWM), supplemented with spot elevation data based on the Spot Elevation Map of Survey of Bangladesh at a scale of 1:20,000.

It must also be added that, at the outset, Okada’s (1985) dislocation model was used to obtain the initial sea surface elevation for the above co-seismic tsunami sources assuming that the sea surface follows the seabed deformation instantaneously.

4.2 Model validation

The tsunami propagation model set-up and formulation used in the present study was further validated by comparing the computed water surface levels due to the Indian Ocean tsunami in 2004 (scenario-8) with available records of measurements. Only a few field observations of maximum water levels due to the tsunami in 2004 are available off the coast of Bangladesh. These include the tide-gauge record at Hiron Point (Khan et al., 2010), which shows reasonably good agreement with the computed water level (Figure 2) with a difference of about 20 per cent between computed and measured water levels. As far as the impact of the 2004 tsunami on Bangladesh is concerned, two deaths have been reported in the sea off Barisal (Uddin, 2005). The notable peak in the computed maximum tsunami

---

**Figure 2.**
Comparison of computed maximum water levels along the coast of Bangladesh with the maximum tsunami height recorded by the tide gauge at Hiron Point.

- **Max. tsunami height measured at Hiron Point**
- **Barisal coastal region**
- **Computed**
- **Measured**
heights near the seaboard of Barisal coast in Figure 2 (around 90-90.3°E) is consistent with the reported casualties mentioned above.

Given the scarcity of observed tsunami heights off the coast of Bangladesh, such records for the neighboring coastline of northeastern India are also utilized for model validation in Figure 3. It can be seen in Figure 3 that the recorded maximum tsunami height extracted from the tide gauge record at Paradip in northeastern India (Nagarajan et al., 2006) shows good agreement with the computed peak water levels in the vicinity.

4.3 Computed tsunami amplitudes
The computed tsunami amplitudes corresponding to each of the seismic scenarios simulated were extracted off the shoreline of Bangladesh: along the coastlines of Sundarban-Barisal-Sandwip and Chittagong-Teknaf (Figure 4 shows the location of these coastal areas).

Let us first consider the computed tsunami amplitudes corresponding to seismic Scenarios 6, 7 and 8, with estimated recurrence intervals longer than 1,000 years (Figure 5),
representing worst-case scenarios for northern Arakan, southern Arakan and Andaman-Sumatra segments of the Sunda Arc, respectively. We see in Figure 5 that the maximum tsunami amplitudes near the coast of Bangladesh due to Scenario-8 in Andaman-Northern Sumatra seismic zone (i.e. an event similar to that generated the tsunami in 2004) are, in general, smaller than those due to Scenarios 6 and 7 in the Arakan seismic zone. Further, the computed tsunami amplitudes due to Scenario-7 are larger than those due to Scenario-6 along most parts of the coastline of Sundarban-Barisal-Sandwip, except in the vicinity of 89.7-90.0°E and 91.25-91.55°E.

However, along the coastline of Teknaf-Chittagong, scenario-6 results in larger tsunami amplitudes than scenario-7. This is primarily because of the proximity of the northern segment (Scenario-6) of the Arakan subduction zone to the coastline of Teknaf-Chittagong than the southern segment (Scenario-7). This means that, although Scenario-7 may be considered as the worst-case for most parts of the coastline of Sundarban-Barisal-Sandwip, the worst-case for the coastline of Teknaf-Chittagong is Scenario-6.

Accordingly, it is necessary to carry out detailed inundation modeling for coastal Bangladesh for both Scenarios-6 and 7 representing the worst-case (Tr > 1000 years), and then derive a composite of the computed inundation depths so as to yield the maximum of the two cases at each grid point.

Now, Figure 6 shows the variation of the computed maximum tsunami amplitudes corresponding to seismic Scenario-5 (Tr = 500 years), Scenario-4 (Tr = 200 years), Scenario-3 (Tr = 100 years) and Scenario-2 (Tr = 50 years) along the coastlines of (a) Sundarban-Barisal-Sandwip, and (b) Teknaf-Chittagong. The maximum tsunami amplitudes due to seismic scenario-1 (Tr = 25 years) are very small, and therefore, are not shown.

We see in Figure 6 that the tsunami amplitudes near the coast gradually decline with the decreasing magnitude of the respective earthquake scenarios as well as the recurrence interval. Two notable peaks in the tsunami amplitude variation along the coastline of
Sundarban-Barisal-Sandwip [Figure 6(a)] can be seen at around 89.3°E and at 90.2°E. These peaks are on either side of the axis of the submarine canyon which approaches the Nearshore Sea off Barisal at around 89.6°E. In Figure 6(b) for the Teknaf-Chittagong coastline, the tsunami amplitudes are comparatively higher north of the latitude 21.5°.

4.4 Tsunami arrival time
The information relating to the time it takes for the first wave of a tsunami to arrive at a given coastline is essential for emergency planning and in early warning. Accordingly, the arrival time contours corresponding to potential tsunamigenic earthquakes in the Andaman seismic zone, i.e. scenarios 1 to 5 and 8 identified in Table I, are shown in Figure 7. Note that the arrival times given are in minutes after the occurrence of the earthquake and are based on the first 1 cm rise of mean water level. It must also be noted that the tsunami propagation speed and thus the arrival time does not depend on the magnitude of the earthquake. The propagation speed depends on only on the water depth, and therefore, the arrival time contours shown in Figure 7 are applicable to tsunamigenic earthquake of any magnitude originating in the Andaman seismic zone.

The arrival time contours in Figure 7 indicate that the tsunami waves first reach the western half of the Sundarban-Barisal-Sandwip coastline (segment-A) in about 180 min after the earthquake. However, it takes 210-360 min for the tsunami to reach the eastern half of segment-A primarily owing to the shallow coastal water in that region. We also see that the tsunami waves propagate faster along the axis of the submarine canyon which approaches the Nearshore Sea off Barisal at around 89.6°E. Furthermore, the southern part of the Chittagong-Teknaf coastline (segment-B) receives tsunami waves in about 150-210 min after

Notes: (a) Sundarban-Barisal-Sandwip coastline; (b) Teknaf-Chittagong coastline. The amplitudes due to seismic scenario-1 are very small, and therefore, are not shown.
the earthquake. However, it could take 210-360 min for the waves to arrive at the northern part of the Chittagong-Teknaf coastline.

The arrival time contours corresponding to potential tsunamigenic earthquakes in the Arakan seismic zone, i.e. Scenarios 6 and 7 identified in Table I, are shown in Figure 8. The arrival time contours shown in Figure 8 are applicable to any tsunamigenic earthquake originating in the Arakan seismic zone since tsunami propagation speed does not depend on the magnitude of the earthquake.

The arrival time contours in Figure 8 indicate that the tsunami waves first reach the western half of the Sundarban-Barisal-Sandwip coastline (segment-A) in about 120-150 min after an earthquake in the Arakan seismic zone. However, it could take a longer time for the waves to propagate across shallow water off the eastern half of the Sundarban-Barisal-Sandwip coastline. On the other hand, given the proximity of the fault plane, most parts of the Chittagong-Teknaf coastline (segment-B) would receive tsunami waves almost immediately after an earthquake in the northern segment of the Arakan seismic zone.

5. Concluding remarks
A multi-scenario analysis of the seismogenic tsunami hazard has been carried out for Bangladesh. The assessment included probabilistic measures of the tsunami hazard by incorporating several probable seismic scenarios corresponding to recurrence intervals of 25, 50, 100, 200, 500 and over 1,000 years.

The computed tsunami amplitudes near the shoreline suggest that a seismic event of moment magnitude 8.8 in the southern segment of the Arakan subduction zone may be considered as the worst-case tsunami scenario for most parts of the coastline of Sundarban-Barisal-Sandwip. However, the worst-case for the coastline of Teknaf-Chittagong is likely to be a maximum-credible event of moment magnitude 8.6 in the

Figure 7.
Contours of arrival time in minutes after earthquake for tsunami generated in the Andaman seismic zone (Scenarios 1 to 5 and 8, in Table I).
Coastal Stretch A: Sundarban-Barisal-Sandwip, and Stretch B: Chittagong-Teknaf
northern segment of the Arakan zone. Both these events have been assigned a recurrence interval of over 1,000 years. The peak tsunami amplitudes corresponding to above events are 3 m in the coastline of Sundarban-Barisal-Sandwip and 3.5 m in Teknaf-Chittagong coastline.

Moreover, two notable peaks in the tsunami amplitude variation along the coastline of Sundarban-Barisal-Sandwip could be seen at around 89.3°E and at 90.2°E. These peaks are on either side of the axis of the submarine canyon which approaches the Nearshore Sea off Barisal at around 89.6°E. It was also noted that the tsunami amplitudes are comparatively higher north of the latitude 21.5° for the Teknaf-Chittagong coastline.

The computed tsunami arrival times indicate that the tsunami waves first reach the western half of the Sundarban-Barisal-Sandwip coastline in about 180 min after the earthquake; however, it takes 210-360 min for the tsunami to reach the eastern half of the coastline. Furthermore, the southern part of the Chittagong-Teknaf coastline receives tsunami waves in about 150-210 min after the earthquake; however, it could take 210-360 min for the waves to arrive at the northern part of the coastline.

Information such as those presented in this paper relating to the spatial distribution of the severity of tsunami hazard and the likely arrival times is essential in planning of evacuation of people during tsunami warnings as well as in formulating mitigation measures and in developing coastal land use plans and management strategies.

Finally, it must also be mentioned that there are several limitations typical in modeling tsunami propagation and inundation. Since the initial condition for the modeling is determined by the displacement of the ocean bottom along the fault line, the largest source of errors is the earthquake model. Another significant limitation is that the resolution of the modeling is no greater or more accurate than the bathymetric and topographic data used.
Although, relatively higher resolution topographic data were available for the present study, the resolution of the bathymetric data used is much less. It must also be added that shallow water models assume a uniform velocity profile across the flow depth and neglect vertical accelerations. Moreover, the shallow water formulation used in the present model does not explicitly account for all means of energy dissipation for a tsunami wave surging onshore. For instance, although energy dissipation due to bottom friction is included in the present model, dissipation due to turbulence is not explicitly formulated.

References


IWM (2009), “Use existing data on available digital elevation models to prepare useable tsunami and storm surge inundation risk maps for the entire coastal region”, Final Report, Volume-I: Tsunami and Storm Surge Inundation of the Coastal Area of Bangladesh, Institute of Water Modeling, Bangladesh and Bangladesh Institute of Social Research, Comprehensive Disaster Management Programme (CDMP), Ministry of Food and Disaster Management, The Government of Bangladesh.


**Corresponding author**

Janaka J. Wijetunge can be contacted at: jjw@eng.pdn.ac.lk
An update of proposed Sri Lanka warning system for east and west coast tsunamis

Sanjeewa Wickramaratne
Lanka Hydraulic Institute, Moratuwa, Sri Lanka

S. Chan Wirasinghe
Department of Civil Engineering, University of Calgary, Calgary, Canada, and

Janaka Ruwanpura
Office of Vice-Provost, University of Calgary, Calgary, Canada

Abstract
Purpose – Based on the existing provisions/operations of tsunami warning in the Indian Ocean, authors observed that detection as well as arrival time estimations of regional tsunami service providers (RTSPs) could be improved. In particular, the detection mechanisms have been eccentrically focussed on Sunda and Makran tsunamis, although tsunamis from Carlsberg ridge and Chagos archipelago could generate devastating tsunamis for which inadequate provisions exist for detection and arrival time/wave height estimation. RTSPs resort to assess estimated arrival time/wave heights from a scenario-based, pre-simulated database. These estimations in terms of Sri Lanka have been found inconsistent. In addition, current warning mechanism poorly manages non-seismic tsunamis. Thus, the purpose of this study is to investigate these drawbacks and attempt to carve out a series of suggestions to improve them.

Design/methodology/approach – The work initiated with data retrieved from global earthquake and tsunami databases, followed by an estimation of probabilities of tsunamis in the Indian Ocean with particular emphasis on Carlsberg and Chagos tsunamis. Second, probabilities of tsunami detection in each sub-region have been estimated with the use of available tide gauge and tsunami buoy data. Third, the difficulties in tsunami detection in the Indian Ocean are critically assessed with case studies, followed by recommendations to improve the detection and warning.

Findings – Probabilistic estimates show that given the occurrence of a significant earthquake, both Makran and Carlsberg/Chagos regions possess higher probabilities to harbour a tsunami than the Sunda subduction zone. Meanwhile, reliability figures of tsunami buoys have been declined from 79-92 to 68-91 per cent over the past eight years. In addition, a Chagos tsunami is left to be detected by only one tide gauge prior to it reaching Sri Lankan coasts.

Research limitations/implications – The study uses an averaged tsunami speed of 882 km/h based on 2004 Asian tsunami. However, using exact bathymetric data, Tsunamis could be simulated to derive speeds and arrival times more accurately. Yet, such refinements do not change the main derivations and conclusions of this study.

Practical implications – Tsunami detection and warning in the Indian Ocean region have shown room for improvement, based on the inadequate detection levels for Carlsberg and Chagos tsunamis, and inconsistent warnings of regional tsunami service providers. The authors attempted to remedy these drawbacks by proposing a series of suggestions, including a deployment of a new tsunami buoy south of Maldives, revival of offline buoys, real-time tsunami simulations and a strategy to deal with landslide tsunamis, etc.

Social implications – Indian Ocean is prone to mega tsunamis as witnessed in 2004. However, more than 50 per cent of people in the Indian Ocean rim countries dwell near the coast. This is verified with deaths of 227,898 people in 14 countries during the 2004 tsunami event. Thus, it is of paramount importance that sufficient detection levels are maintained throughout the Indian Ocean without being overly biased towards Sunda tsunamis. With respect to Sri Lanka, Makran, Carlesberg or Chagos tsunamis could directly hit the most populated west coast and bring about far worse repercussions than a Sunda tsunami.
Originality/value – This is the first instance where the threats from Carlesberg and Chagos tsunamis to Sri Lanka are discussed, probabilities of tsunamis are quantified and their detection levels assessed. In addition, reliability levels of tsunami buoys and tide gauges in the Indian Ocean are recomputed after eight years to discover that there is a drop in reliability of the buoy data. The work also proposes a unique approach to handle inconsistencies in the bulletins of regional tsunami service providers, and to uphold and improve dwindling interest on tsunami buoys.

Keywords Sri Lanka, Buoys, Indian Ocean, Tide gauges, Tsunami detection, Tsunami warning

Paper type Research paper

1. Tsunami warning and evacuation network

According to Bernard and Titov (2015), the evolution of warning systems has been influenced by severity of tsunamis and available technology. However, the warning process sequentially improved after certain “milestone” tsunamis, namely, Unimak 1946, Kamchatka 1952, Chile 1960, AK 1964, Japan 1993 and Indian Ocean 2004. It is undisputed that efficiency of Tsunami warning and evacuation (TWE) activities saves human lives. Thus, as much as the genesis of tsunamis is studied, so must their propagation and detection, warning dissemination, decision-making and evacuation be studied and simulated. The activities involved in each of the above elements can be made to form a network which then can be simulated to derive stochastic estimates of time taken to evacuate a particular location from the point of triggering the earthquake/tsunami. From the initial work of Fernando et al. (2008), there has been a progressive development of simulating the TWE network pertaining to the Indian Ocean region (Ruwanpura et al., 2009; Wickramaratne et al., 2009, 2011a, 2011b).

Deciphering the information flow is essential for developing a TWE network, but the estimation of time duration for each activity in the network must be equally precise. Wickramaratne (2010) resorted to obtaining opinions on the time estimations through field interviews with experienced professionals after an assessment of the interviewee’s credibility, via a parameter called Personal Ability Factor (PAB). Amongst the many challenges such simulation exercises experience, having to consistently update TWE networks is paramount. New developments in tsunami detection or warning; procedural changes in information processing and decision-making; and alterations to modes and plans of evacuation all result in time estimates of previously simulated networks being incorrect. Thus, one of the prime aims of this paper is to present an updated TWE network based on the one originally developed in 2011.

2. New developments in tsunami warning and evacuation process

The TWE process initiates with a tsunamigenic phenomenon which is an earthquake, the prime and most probable triggering event as observed since ancient times (NGDC, 2019). Nodes of the Global Seismographic Network (GSN) possess the ability to detect seismic signals from strong landslides, volcanic eruptions, nuclear explosions and even meteorite hits. In addition to the seismic signal, the oceanic signal (i.e. tsunami wave) is detected via deep ocean buoys, tide gauges and satellite-based techniques such as GPS. The Global Telecommunication System (GTS) is a digital communication platform that helps transmit real-time or near real-time wave data to warning centres and publishes the same data via the internet. International warning providers process such seismographic and oceanic signals and issue appropriate bulletins/warnings. In the context of the Indian Ocean, three regional tsunami service providers (RTSPs) [India (INCOIS), Australia (BOM) and Indonesia (BMKG)] have been in operation since October 2011 (IOTIC, 2016; Hettiarachchi, 2018). All
three service providers issue warnings to all Indian Ocean nations, thereby benefiting any given country with three channels of information. The Department of Meteorology (DoM) is the focal point of the Sri Lankan warning process as it receives RTSP information, local tide gauge readings through National Aquatic Resources Research and Development Agency (NARA) and local seismic probe readings through Geological Survey and Mines Bureau (GSMB). The decision-making process, with the cooperation of the Disaster Management Center (DMC), determines whether to issue a tsunami watch, alert or warning. When the TWE network was first modelled in 2009, the Pacific Tsunami Warning Center (PTWC) and Japan Meteorological Agency (JMA) were the sole warning authorities (Ruwanpura et al., 2009). However, Sri Lanka ceased to receive automated bulletins from them following the establishment of the three RTSPs in 2011. In addition, the appropriate alert to be issued is decided upon by estimated arrival times (ETA) as pre-computed by numerical models at RTSPs. Such refinements have led to an updated TWE network for Sri Lanka, which is shown in Figure 1.

3. Probabilities of tsunamis
To generate a tsunami, an earthquake must be of at least 6.5 magnitude, must rupture the Earth’s surface, causing a vertical movement of the sea floor, and its hypocenter must be located less than 70 km below the Earth’s surface (Yunarto and Sari, 2018; UWI, 2019). While submarine earthquakes account for approximately 80 per cent of all tsunamis worldwide (NGDC, 2019), non-earthquake events such as landslides, submarine volcanic eruptions or even a meteorite hit can trigger catastrophic tsunamis. In spite of their low probability of occurrence, these non-earthquake sources have caused some of the most
destructive tsunamis in history, namely, Santorini (seventh-century BC), Krakatau (1883) and Lituya Bay (1958). History repeated itself in 2011 when a landslide-triggered tsunami claimed the lives of 437 people in Indonesia (NGDC, 2019). Unlike mild landslides, a moderate volcanic eruption or meteorite hit would lodge a strong, ground-shaking signal which will be detected by GSN and bottom pressure sensors of tsunami buoys in the vicinity.

The Indian Ocean region could be affected by four main tsunamigenic sources: the Sunda subduction zone, Makran subduction zone, Carlsberg ridge and Chagos archipelago (Figure 2).

The Sunda subduction zone is a combined trench comprising the Sunda, Andaman and Arakan zones, but is often referred to as Sunda in general, and accounts for the highest number of earthquakes in the Indian Ocean region (Wijetunge, 2012). A search of world earthquake and tsunami databases reveals that amongst all earthquakes occurring in the Indian Ocean region between 1900 and 2018, 66 per cent generated from the Sunda trench. Of these Sunda quakes, 128 events met the criteria for being able to generate a tsunami (i.e. $>6.5$ of magnitude and hypocenter $<70$ km underground), and 30 of these quakes in fact realized tsunamis.

During the same time span, the Makran zone was responsible for 1.3 per cent of earthquakes in the Indian Ocean region (USGS, 2019). Amongst two earthquakes that could potentially trigger a tsunami, only one proceeded, which was the well-known 1945 Makran tsunami that claimed 4,000 lives and unaccounted property losses (Heck, 1947; Heidarzadeh et al., 2008a).

The US Geological Survey (USGS) states that the Carlsberg Ridge, including Chagos archipelago, is seismically active, with a major earthquake of 7.6 magnitude recorded on 15 July 2003. Altogether, there were three quakes in the region from 1900 to 2018 which were higher than 6.5 of magnitude. Amongst the three, the 7.3 magnitude quake which occurred on 30 November 1983 triggered a tsunami with a maximum water height of 1.5 m (NGDC, 2019). The Chagos archipelago and Carlsberg ridge are the two probable tsunamigenic sources that could affect the South and West coasts of Sri Lanka.

![Figure 2. Tectonic boundaries of Indian Ocean](source: Modified after Sting and Rémi (2006))
Thus, the probability of a tsunami, given an occurrence of a qualifying earthquake, P(T/E), is computed for the three regions based on the meagre data available for Sunda (S), Makran (M) and Carlsberg/Chagos (C) (Table I).

The number of qualifying earthquakes will increase with time and so will the chance that some of those events will lead to tsunamis. Thus, the above estimates are necessarily time-dependent.

4. Facilities for tsunami detection in the Indian Ocean

Deep ocean tsunami buoys and land-based tide gauges are the two main tools available for detection. Details of available deep ocean buoys are listed in Table II. Two Australian units have not been considered because of their remoteness to Sri Lanka.

Tide gauges provide all important water level information at land points on which they have been positioned. As of July 2019, the Indian Ocean harbours 43 GLOSS tide gauges with real-time or near real-time data transmission.

Buoys No. 1, 2 and 3 have been stationed to capture oceanic signals from the Makran subduction zone, although all three were offline as of July 2019. Amongst the seven buoys positioned in the eastern zone, five transmit real-time data [Figure 3(a)]. Although they provide cover for Arakan tsunamis, no tsunami buoys currently capture tsunamis from South to Northwest directions. Such tsunamis are left to be detected by tide gauges deployed onshore [Figure 3(b)]. The southwest quadrant is covered by two gauges in Maldives, three positioned near Chagos archipelago and one in Seychelles. Three gauges in Indonesia and one in Cocos Island serve the southeast quadrant.

### Table I.

<table>
<thead>
<tr>
<th>Region</th>
<th>Conditional probability of tsunami</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunda</td>
<td>P_{S}(T/E) = 0.23</td>
</tr>
<tr>
<td>Makran</td>
<td>P_{M}(T/E) = 0.50</td>
</tr>
<tr>
<td>Carlsberg/Chagos</td>
<td>P_{C}(T/E) = 0.33</td>
</tr>
</tbody>
</table>

### Table II.

<table>
<thead>
<tr>
<th>Buoy ID</th>
<th>WMO ID</th>
<th>Buoy owner</th>
<th>Country</th>
<th>Status as of July 2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23228</td>
<td>INCOIS</td>
<td>India</td>
<td>Offline</td>
</tr>
<tr>
<td>2</td>
<td>23226</td>
<td>NIOT</td>
<td>India</td>
<td>Offline</td>
</tr>
<tr>
<td>3</td>
<td>23225</td>
<td>NIOT</td>
<td>India</td>
<td>Offline</td>
</tr>
<tr>
<td>4</td>
<td>23223</td>
<td>NIOT</td>
<td>India</td>
<td>Online</td>
</tr>
<tr>
<td>5</td>
<td>23219</td>
<td>INCOIS</td>
<td>India</td>
<td>Offline</td>
</tr>
<tr>
<td>6</td>
<td>23218</td>
<td>NIOT</td>
<td>India</td>
<td>Online</td>
</tr>
<tr>
<td>7</td>
<td>23401</td>
<td>NDWC</td>
<td>Thailand</td>
<td>Online</td>
</tr>
<tr>
<td>8</td>
<td>23227</td>
<td>INCOIS</td>
<td>India</td>
<td>Online</td>
</tr>
<tr>
<td>9</td>
<td>23217</td>
<td>INCOIS</td>
<td>India</td>
<td>Offline</td>
</tr>
<tr>
<td>10</td>
<td>23461</td>
<td>NDWC</td>
<td>Thailand</td>
<td>Online</td>
</tr>
</tbody>
</table>

Notes: WMO – World Meteorological Organization; INCOIS – Indian National Center for Ocean Information Services, India; NIOT – National Institute for Ocean Technology, India; NDWC – Department of Disaster Prevention and Mitigation, Thailand

Source: Adopted from NDBC (2019)
5. Probabilities of tsunami detection

Mechanical systems, whether they be tide gauges or buoys, often experience failures where supply of critical sea level information is interrupted. Wickramaratne et al. (2011a, 2011b) assessed the reliability of tide gauges to be in the order of 80-99 per cent based on historic records of gauges in the Indian Ocean. Reliability is computed as the percentage of data availability in the given time period. A reassessed reliability eight years after the original study remains the same. With respect to tsunami buoys, Wickramaratne et al. (2011a, 2011b) presented a range of 79-92 per cent. With the increased number of buoys and heightened technology associated with DART (Deep-ocean Assessment and Reporting of Tsunamis) buoys, the reliability is reassessed based on available data from the US National Data Buoy Center (NDBC). Figure 4 indicates the reliability level of each buoy plotted against each year of NDBC operation from inception (2006) to 2018.

Thailand buoy (23401) offers the best reliability level and is also the longest serving unit to date. Indian buoy (23217) only functioned in the year 2016 and the south most buoy in the Makran region (23225) failed soon after deployment. Excluding those two problematic deployments, the newly derived reliability range is 68-91 per cent, which is a drop from the 79-92 per cent estimated in 2011 (Table III).

Figure 3.
Spatial distribution of tsunami detection setups in the Indian Ocean

Figure 4.
Reliability levels of Indian Ocean tsunami buoys

Notes: (a) Tsunami buoys; (b) tide gauges
Source: Modified after NDBC (2019) and PSMSL (2019)
These data also illustrate the vulnerabilities of deployed buoys as opposed to land-based tide gauges.

6. Overcoming detection issues in the Indian Ocean

6.1 Problem 1: less confidence in estimated arrival times estimated by regional tsunami service providers for Sri Lanka

Estimated travel time is based on a database of pre-simulated model outputs. Such models have been compiled for an array of model scenarios, including earthquake location and magnitude. With respect to RTSP-India, the array of simulations include approximately 50,000 scenarios aggregating from earthquakes at six different depths (10, 20, 40, 60, 80 and 100 km), of seven moment magnitudes (Mw) (6.5, 7.0, 7.5, 8.0, 8.5, 9.0 and 9.5) and pre-defined unit source scenarios in each of two major tsunamigenic locations in the Indian Ocean (INCOIS, 2019). In an event of initial confirmation of an earthquake, ETA is retrieved from the database for corresponding or worst-case model scenarios. There are two main drawbacks of this approach. First, there is a chance for an earthquake to occur for which parameters have not been modelled, such as ones at Carlsberg ridge or Chagos archipelago, let alone many other probable source points within these already designated tsunamigenic locations. Derivations based on worst-case scenario carry inaccuracies that could lead to lost faith in the system. Second, ETA and wave height estimations depend on nearshore bathymetric variations but individual models relegated to RTSP do not have adequate resolution of other countries’ data. This situation has resulted in accurate forecasts for RTSP countries but not for their dependent countries such as Sri Lanka.

6.1.1 Remedy 1. A suggested, remedy for the Indian Ocean is to launch a real-time forecasting platform within the existing framework of national disaster management. Such real-time modelling has already been discussed by Geist and Parsons (2006) and Davies et al. (2017), but is deemed cumbersome because of unavailability of accurate high-resolution bathymetric and topographic data and the necessity for time-intensive simulations. However, by breaking down real-time modelling into a few manageable tasks, we can begin to remove these barriers to implementation. Initial seismic data from RTSPs, global seismographic network and local seismographic information could trigger the model simulation locally. Thus, it is suggested Sri Lanka and other Indian Ocean rim countries to develop its own, high-resolution bathymetry data from their maritime boundary to shoreline. Because models shall be simulated by each country, no high-resolution global model is required but a high-resolution local model of the particular country is concerned. This move considerably shortens the computational time while further improvements could be made if simulations are carried out on a high-end computer platform. As for a fail-safe

<table>
<thead>
<tr>
<th>Buoy No. (WMO ID)</th>
<th>Available data range (dd/mm/yyyy)</th>
<th>Data reliability (%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>232418</td>
<td>23/06/2016-29/07/2019</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>23401</td>
<td>18/12/2006-29/07/2019</td>
<td>86</td>
<td></td>
</tr>
<tr>
<td>23227</td>
<td>25/10/2011-29/07/2019</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>23217</td>
<td>23/06/2016-12/05/2019</td>
<td>58</td>
<td>Available only in 2016</td>
</tr>
<tr>
<td>23461</td>
<td>20/01/2017-29/07/2019</td>
<td>91</td>
<td></td>
</tr>
<tr>
<td>23228</td>
<td>27/09/2011-26/12/2018</td>
<td>69</td>
<td></td>
</tr>
<tr>
<td>23219</td>
<td>07/03/2014-20/02/2019</td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>23226</td>
<td>07/03/2014-16/06/2019</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>23225</td>
<td>10/12/2002-29/07/2019</td>
<td>–</td>
<td>No data</td>
</tr>
<tr>
<td>23223</td>
<td>14/11/2014-29/07/2019</td>
<td>68</td>
<td></td>
</tr>
</tbody>
</table>

Table III. Overall reliability levels of Indian Ocean tsunami buoys
approach, national authorities are encouraged to share such models with RTSPs who will be able to execute the same country-specific models in tandem. As for model calibration and verification, it is suggested to use historic records of tsunami arrival times and wave heights. A schematic of the proposed changes is shown in Figure 5. Forecasts derived from this method will be much more accurate and authorities will enjoy greater flexibility in adopting/updating the models.

6.2 Problem 2: inconsistencies/lapses in regional tsunami service providers’ bulletins
A few inconsistencies/lapses in RTSP bulletins have been identified through three actual earthquake/tsunami events hereinafter referred to as Case study A, B and C (Figure 6).

6.2.1 Case study A: earthquake on 2 March 2016. An earthquake struck on 2 March 2016 at a depth of 24 km, 500 miles southwest off Padang, Indonesia at an initially estimated magnitude of 8.2 (USGS, 2019). The magnitude was later revised to 7.8 by USGS. The event triggered a minute tsunami and all three RTSPs issued arrival time and wave height forecasts which were different from each other. The confusing oncoming information was, nevertheless, well handled by Sri Lankan authorities who did not order an evacuation considering the fact that the epicenter was not on the major fault/subduction zone. None of the 22 Indonesian local buoys detected the weak tsunami signal (Kapoor and Suroyo, 2016). In addition, no detection by DART buoys was observed and, as a result, the bulletin issued by RTSP-India contained only tide gauge detections. Differences in the bulletins issued by RTSP-India and RTSP-Indonesia are shown in Table IV.

Had the tsunami been strong, the earliest beneficial detection from the perspective of Sri Lanka would have been at tide station Tanahbala (Indonesia) 1 h:09 min after the earthquake hit. Such late detections do not warrant a full evacuation in Sri Lanka, given the fact that the 2004 Asian tsunami hit eastern Sri Lanka 1 h:50 min after the quake.

6.2.2 Case study B: earthquake on 13 August 2017. On 13 August 2017, an earthquake of magnitude 6.4 occurred 71 km west of Bengkulu, Indonesia (USGS, 2019). Informed of the earthquake by the California Integrated Seismic Network (CISN), Sri Lanka issued an earthquake bulletin which several media outlets interpreted as a tsunami warning. A long uncertainty prevailed in Sri Lanka as none of the RTSPs provided any official information of the earthquake or arrival time forecast (DoM, 2019).

6.2.3 Case study C: volcanic eruption on 22 December 2018. The active volcano of Anak (Child) Krakatau in the heart of ruined Krakatau, which itself exploded in 1883, erupted on 22 December 2018, triggering a large chunk of the southern flank of the volcano to plunge...
into the deep waters off Lampung, Indonesia (BNPB, 2018). Being close to the land, a tsunami arrived in minutes and, according to the global tsunami event database, caused 437 fatalities and injured over 14,059 people (NGDC, 2019). Ironically, this scenario was modelled in 2012 by Giachetti et al. (2012). Since the existing tsunami warning system in Indonesia is earthquake-based, authorities did not issue a tsunami warning as the cause of the tsunami was not an earthquake. Sri Lanka too did not receive any official bulletin/alert or warning from Indian Ocean Tsunami Warning System because DART buoys did not register appreciable water level change (DoM, 2019). Yet, Paris (2018) states that a large uncertainty exists on the stability of the volcanic cone in this region where probability for future collapses and tsunamis is non-negligible.

Transoceanic tsunamis from volcanic eruptions are rare, although the original Krakatau eruption in 1883 reminds us that it is not an impossibility. Given that no seismic impulse is generated, the activation of the monitoring mode of tsunami buoys may not take place, leaving tide gauges to act as the sole detection tool.

6.2.4 Remedy 2. The above three case studies exemplify the fact that bulletins of the three RTSPs are still inconsistent, particularly, with the Indonesian system being

<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Wave arrival (UTC)</th>
<th>Wave amplitude (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tanahbala (Indonesia)</td>
<td>0.53S</td>
<td>98.5E</td>
<td>13:58</td>
<td>NA</td>
</tr>
<tr>
<td>Cocos island (Australia)</td>
<td>12.11S</td>
<td>96.69E</td>
<td>14:20</td>
<td>14:15</td>
</tr>
<tr>
<td>Christmas island (Australia)</td>
<td>10.40S</td>
<td>105.67E</td>
<td>15:02</td>
<td>NA</td>
</tr>
<tr>
<td>Padang (Indonesia)</td>
<td>0.95S</td>
<td>100.37E</td>
<td>NA</td>
<td>14:40</td>
</tr>
</tbody>
</table>
seismically based. Thus, a series of remedial measures have been suggested to address the identified drawbacks (Table V).

6.3 Problem 3: spatial and temporal unavailability of tsunami buoys

As of July 2019, the Indian Ocean possesses 12 tsunami buoys, of which 10 would be beneficial for Sri Lanka, India and Maldives. Positioning of tsunami buoys is largely influenced by the owner, and the spatial distribution of buoys in the Indian Ocean following the 2004 tsunami event clearly exemplifies this. In addition, the units need to be sufficiently proximate to the tsunami source for timely detection that results in adequate lead time in tsunami forecasts. However, a buoy system should also not be in the physical impact zone of an earthquake to allow it to issue a non-obliterated tsunami signal.

The existing buoy configuration still cannot detect all possible tsunamis in the Indian Ocean with sufficient time for warning and evacuation. Leaving aside mechanical and other operational issues which prevent detection, non-availability of buoys at the correct place could alone lead warning systems to be mere earthquake warning providers. Thus, this study next examines four probable tsunami events in the Indian Ocean and analyzes the discoverability of tsunami signals with available detection tools. Figure 7 illustrates the event locations alongside with spatial orientation of available gauges and buoys.

6.3.1 Event A: tsunami in the Sunda subduction zone. The majority of the earthquakes, and hence majority of buoys, have been positioned in the Sunda subduction zone. However, a sizable number of earthquake events have occurred further south along the fault line with their dip orientation being NE–SW. Thus, a representative hypothetical tsunami event from an earthquake of magnitude 9.0 occurring at 0.802N, 92.463E is selected for further review.

<table>
<thead>
<tr>
<th>Issue</th>
<th>Suggested improvements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case study A</td>
<td>Revival of current offline buoys: 23217 and 23219</td>
</tr>
<tr>
<td>Unavailability of tsunami buoys</td>
<td>To be improved after the revival of the two buoys</td>
</tr>
<tr>
<td>Late detection of tsunami</td>
<td>Although the complete inter-dependency of RTSPs is not</td>
</tr>
<tr>
<td>Inconsistent RTSP bulletins</td>
<td>encouraged, ETA forecasts require a certain degree of</td>
</tr>
<tr>
<td></td>
<td>mutual agreement. Research is needed to explore historic</td>
</tr>
<tr>
<td></td>
<td>ETAs and the level of agreement between service</td>
</tr>
<tr>
<td></td>
<td>providers. If the ETA from the Indonesian system</td>
</tr>
<tr>
<td></td>
<td>(which uses a seismic platform) differs from the</td>
</tr>
<tr>
<td></td>
<td>Australian or Indian systems, bulletin recipients should</td>
</tr>
<tr>
<td></td>
<td>be advised as to which information should receive</td>
</tr>
<tr>
<td></td>
<td>priority</td>
</tr>
<tr>
<td>Case study B</td>
<td>The quake was deemed minor and the RTSPs did not</td>
</tr>
<tr>
<td>No corroborating/succeeding information from</td>
<td>elect to issue a tsunami watch. It is up to national</td>
</tr>
<tr>
<td>RTSPs given an initial earthquake alert by</td>
<td>authorities to obtain further information from the RTSPs</td>
</tr>
<tr>
<td>CISN</td>
<td></td>
</tr>
<tr>
<td>Case study C</td>
<td>Landslides could occur in the Makran and Krakatau</td>
</tr>
<tr>
<td>Non-detection because of no seismic signal</td>
<td>regions. Landslide tsunamis are of insufficient strength</td>
</tr>
<tr>
<td>of landslide tsunamis</td>
<td>to grow into transoceanic tsunamis. However, RTSPs</td>
</tr>
<tr>
<td></td>
<td>may suggest a tide-reading-based framework for issuing</td>
</tr>
<tr>
<td></td>
<td>specialized warnings for the endangered regions. In</td>
</tr>
<tr>
<td></td>
<td>particular, gauges that lie on the propagation path can</td>
</tr>
<tr>
<td></td>
<td>alert rest of the areas to minimize casualties</td>
</tr>
</tbody>
</table>
This point triggered a minor tsunami from an earthquake event of magnitude 8.2 on 11 April 2012.

Table VI shows probable detection, based on distance from the source and distance to the closest Sri Lankan coastline. ETA of tsunami is a function of bathymetry and the distance to the source point, and thus ideally requires a numerical simulation for an accurate estimation of ETA. However, the 2004 tsunami provides a basic understanding of average travel speed (882 km/h) of a tsunami originating from the same region. Wickramaratne et al. (2009)

<table>
<thead>
<tr>
<th>Detection type</th>
<th>Identification</th>
<th>Status of detection tool</th>
<th>Distance from source (km)</th>
<th>Orientation from source (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buoy</td>
<td>23217</td>
<td>Offline</td>
<td>335</td>
<td>345</td>
</tr>
<tr>
<td>Tide gauge</td>
<td>Telukdalam</td>
<td>Offline</td>
<td>593</td>
<td>93</td>
</tr>
<tr>
<td>Tide gauge</td>
<td>Tanahbala</td>
<td>Offline</td>
<td>679</td>
<td>103</td>
</tr>
<tr>
<td>Tide gauge</td>
<td>Sibolga</td>
<td>Online</td>
<td>697</td>
<td>82</td>
</tr>
<tr>
<td>Buoy</td>
<td>23227</td>
<td>Online</td>
<td>725</td>
<td>326</td>
</tr>
<tr>
<td>Tide gauge</td>
<td>Padang</td>
<td>Online</td>
<td>906</td>
<td>283</td>
</tr>
<tr>
<td>Buoy</td>
<td>23401</td>
<td>Online</td>
<td>976</td>
<td>333</td>
</tr>
<tr>
<td>Buoy</td>
<td>23461</td>
<td>Online</td>
<td>1,005</td>
<td>200</td>
</tr>
<tr>
<td>Tide gauge</td>
<td>Langkawi</td>
<td>Online</td>
<td>1,015</td>
<td>52</td>
</tr>
<tr>
<td>SL coast</td>
<td>–</td>
<td>–</td>
<td>1,350</td>
<td>298</td>
</tr>
</tbody>
</table>

Note: The italic data represents either unavailable or unproductive data for Sri Lanka.
determined the stochastic time consumption in the Sri Lankan warning and evacuation process, for which an average of 30 min is adopted in this study. On this basis, detections by tide gauge Padang and all other succeeding ones do not yield sufficient time for full evacuation in Sri Lanka. The most beneficially located detection tools, buoy (23217) and gauges (Teluk dalam and Tanahbala), are offline as of July 2019. This leaves only one tide gauge (Sibolga) and one working buoy (23227) to provide beneficial detection.

6.3.2 Event B: tsunami in the Makran subduction zone. The Makran region generated a devastating tsunami on 27 November 1945, triggered by a submarine earthquake of magnitude 8.0 epicentered at 24.500N, 63.00E (NGDC, 2019). Contrary to the typical tsunami generation process, this tsunami was said to be initiated after submarine landslides following the earthquake (Heidarzadeh et al., 2008b). Given its geographic importance, coupled with an atypical generation mechanism, a representative hypothetical tsunami was considered from the same origin. The same method of investigation reveals that the quickest possible detection is from tide gauge Gwadar (Pakistan) followed by Ormara (Pakistan). At the time of this analysis, all three tsunami buoys positioned solely for Makran tsunamis are offline. However, the comparatively larger distance to Sri Lanka permits many detections on course (Table VII). A considerable threat exists for India, whose coastline starts just 512 km from the source and tide gauges such as Gwadar could even be destroyed because of the breadth of a tsunami.

Another setback for the buoys is the weak (or nonexistent) seismic signal of a landslide tsunami, which does not necessarily occur immediately after the main quake which triggered the landslide. Thus, tsunami buoys need to be kept in tsunami monitoring mode for a prolonged period of time. Fortunately for Sri Lanka, the presence of ample tide gauges compensates for the problematic issues with tsunami buoys.

6.3.3 Event C: tsunami in Carlsberg ridge. A representative earthquake occurring at 2.598S, 68.382E is selected. The location corresponds to a 7.6 magnitude earthquake which occurred on 15 July 2003. Table VIII indicates that none of the tsunami buoys would provide beneficial detection as both the east and west buoy systems are farther away from Sri Lanka.

6.3.4 Event D: tsunami in Chagos archipelago. Given the tsunami triggered by a magnitude 7.7 earthquake on 30 November 1983 in Chagos archipelago (6.852S, 72.110E), the potential of future tsunamis in this region cannot be ignored. In particular, the new fault line segment that wraps around Diego Garcia (Figure 2) requires further attention as both of

<table>
<thead>
<tr>
<th>Detection type</th>
<th>Identification</th>
<th>Status of detection tool</th>
<th>Distance from source (km)</th>
<th>Orientation from source (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tide gauge Gwadar</td>
<td>Online</td>
<td>93</td>
<td>133</td>
<td></td>
</tr>
<tr>
<td>Tide gauge Ormara</td>
<td>Online</td>
<td>180</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>Tide gauge Chabahar</td>
<td>Online</td>
<td>260</td>
<td>106</td>
<td></td>
</tr>
<tr>
<td>Tide gauge Karachi</td>
<td>Online</td>
<td>400</td>
<td>283</td>
<td></td>
</tr>
<tr>
<td>Tide gauge Muscat B</td>
<td>Online</td>
<td>463</td>
<td>333</td>
<td></td>
</tr>
<tr>
<td>Buoy 23228</td>
<td>Offline</td>
<td>489</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Tide gauge Masirah</td>
<td>Online</td>
<td>602</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Buoy 23226</td>
<td>Offline</td>
<td>652</td>
<td>138</td>
<td></td>
</tr>
<tr>
<td>Buoy 23225</td>
<td>Offline</td>
<td>794</td>
<td>146</td>
<td></td>
</tr>
<tr>
<td>SL coast</td>
<td>–</td>
<td>2,900</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>

Table VII.
Probable detection of Event B – Makran tsunami

Note: The italic data represents either unavailable or unproductive data for Sri Lanka.
its ends (one on the Carlsberg ridge and the other on the Sunda trench) have harboured four tsunami events as recorded by the global tsunami event database (NGDC, 2019). Thus, a representative event occurring at 6.852S, 72.110E is selected to assess its probable detection and arrival time to Sri Lanka (Table IX).

This tsunami is left to be detected by tide gauges because no tsunami buoy is located in a position that would allow it to detect the tsunami signal prior to it reaching Sri Lanka or even a larger part of India. The GLOSS tide gauge at Diego Garcia may not survive the impact as it is located close to the epicenter. In addition, detection at Male will not provide Sri Lanka with sufficient time for evacuation, leaving only one tide gauge (Gan II) to safeguard Sri Lanka.

6.3.5 Remedy 3. The above analyses show the varied nature of detection, given that Sunda tsunamis are increasingly detected by buoys whereas tsunamis from Chagos archipelago will not be detected by buoys before the wave strike Sri Lanka. The probabilistic assessment of tsunamis in each region indicates that although Chagos and Carlsberg earthquakes are rare, once they occur, they possess a higher probability to generate tsunamis than the conventional and anticipated Sunda tsunamis. Given the number of tide gauges (two) available for a Chagos event, coupled with the probability of detection associated with tide gauges (80-99 per cent), it is suggested that one additional tsunami buoy be deployed at 2.353286S, 72.730554E (Figure 8). The point is approximately 190 km south of Male, Maldives and will enhance detection of both Carlsberg and Chagos tsunamis.

The need for better planning for Carlsberg and Chagos tsunamis is also evident from the analyses. RTSP arrival time simulations have all been carried out only for Sunda and Makran tsunamis, leading RTSPs to resort to unplanned means of computing ETAs should a Carlsberg or Chagos tsunami occur. Thus, it is highly advisable to conduct these missing simulations and enrich the pre-simulated databases at RTSPs.

<table>
<thead>
<tr>
<th>Detection type</th>
<th>Identification</th>
<th>Status of detection tool</th>
<th>Distance from source (km)</th>
<th>Orientation from source (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tide gauge</td>
<td>GAN II</td>
<td>Online</td>
<td>562</td>
<td>68</td>
</tr>
<tr>
<td>Tide gauge</td>
<td>Diego Garcia-D</td>
<td>Online</td>
<td>684</td>
<td>319</td>
</tr>
<tr>
<td>Tide gauge</td>
<td>Male-B</td>
<td>Online</td>
<td>937</td>
<td>36.9</td>
</tr>
<tr>
<td>Tide gauge</td>
<td>Hanimadhoo</td>
<td>Online</td>
<td>1,150</td>
<td>26.9</td>
</tr>
<tr>
<td>Tide gauge</td>
<td>Point La Rue</td>
<td>Online</td>
<td>1,446</td>
<td>80.4</td>
</tr>
<tr>
<td>SL coast</td>
<td></td>
<td></td>
<td>1,629</td>
<td>52.8</td>
</tr>
</tbody>
</table>

**Note:** The italic data represents either unavailable or unproductive data for Sri Lanka

<table>
<thead>
<tr>
<th>Detection type</th>
<th>Identification</th>
<th>Status of detection tool</th>
<th>Distance from source (km)</th>
<th>Orientation from source (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tide gauge</td>
<td>Diego Garcia-D</td>
<td>Online</td>
<td>61</td>
<td>146.7</td>
</tr>
<tr>
<td>Tide gauge</td>
<td>GAN II</td>
<td>Online</td>
<td>679</td>
<td>9.4</td>
</tr>
<tr>
<td>Tide gauge</td>
<td>Male-B</td>
<td>Online</td>
<td>1,226</td>
<td>6.8</td>
</tr>
<tr>
<td>SL coast</td>
<td></td>
<td></td>
<td>1,679</td>
<td>32.2</td>
</tr>
</tbody>
</table>

**Table VIII.** Probable detection of Event C – Carlsberg tsunami

**Table IX.** Probable detection of Event D – Chagos tsunami

**Note:** The italic data represents either unavailable or unproductive data for Sri Lanka
6.4 Problem 4: dwindling interest in tsunami buoys

In spite of the proven and unmatched benefit tsunami buoys provide, their characteristic drawbacks have led buoy owners and warning authorities to reconsider future deployments. Tsunami buoy systems are necessarily expensive: nearly US$700,000 per unit (production and deployment) and have a short lifespan of 4-5 years (Wickramaratne et al., 2011a, 2011b). In addition, a considerable cost (~US$50,000 per trip) is incurred for any repair of the unit, which requires rental of chartered ships. Furthermore, as deployed units often encounter thefts or vandalism, the vicious cycle of redeployment or repair repeats itself. However, no alternative technology has emerged to date that could compliment the buoy system. High-tech systems, such as the seafloor cable observatories and GPS buoys system in Japan, are not feasible in the Indian Ocean of requirement that they be installed nearshore to facilitate GPS base stations.

6.4.1 Remedy 4

- Investment in alternative technologies is a must for a fail-safe warning system. For example, Chiang and Usama (2017) elaborated an alternative detection method called acoustic signal monitoring. Since the acoustic waves that radiate from an earthquake travels faster than the oceanic tsunami wave, special hydroponic instruments may be placed to capture such signals and incorporate them into the existing warning mechanism. Such technologies need further investigation to
determine their adaptability to the Indian Ocean and if viable, their feasibility and funding requirements for incorporation.

- Until a better technological platform for detection is established, existing buoy infrastructure should not be overlooked or considered as a system that is too cumbersome to maintain. RTSPs may take a lead role for sustaining the health of existing buoys although a collaborative funding mechanism needs to be established amongst participating nations in the Indian Ocean. Threats to buoys, such as vandalism, may be mitigated through better awareness programs for seafarers coupled with stringent law enforcement for wrongdoers. In addition, it is suggested to convert existing buoys to well networked, multi-purpose weather measurement stations. Hence, generating additional met-oceanic data such as salinity, temperature, waves and water currents could be commercially traded to support high maintenance costs of buoys.

7. Concluding remarks
This paper attempts to provide solutions for four key issues in the tsunami detection and warning process in the Indian Ocean. In particular, the topics include less confidence in ETA values provided by RTSPs for Sri Lanka; inconsistencies in RTSP bulletins; spatial and temporal unavailability of tsunami buoys; and dwindling interest in tsunami buoys in general. During the process, conditional probabilities of tsunamis, given an earthquake in each possible region in the Indian Ocean, are quantified and so as the probabilities of detection by tide gauges and tsunami buoys. In spite of being time-dependent, probabilistic estimates show that given the occurrence of a significant earthquake, both Makran and Carlsberg/Chagos regions possess higher probabilities to harbour a tsunami than the Sunda subduction zone. Meanwhile, previously estimated reliability figures of tsunami buoys have declined from 79-92 to 68-91 per cent over the past eight years. The study also unearthed the fact that a Chagos tsunami is left to be detected by only one tide gauge prior to it reaching Sri Lankan coasts. Thus, a new warning system is tabled below outlining suggested improvements in technology deployment and RTSP operations.

7.1 Deployment
- A new DART buoy is proposed at 2.353286S, 72.730554E which is approximately 190 km south of Male, Maldives. In an event of south or South-Southeast tsunami, this buoy would provide at least 1.5 h of lead time for Sri Lanka, 50 min for Maldives and a minimum of 1.5 h for India.
- The proposition also includes revival of at least two out of three of the offline buoys in the west Indian Ocean placed for detection of Makran tsunamis.
- No additional tide gauge or buoy system is required in the east Indian Ocean for Sunda tsunamis; however, preservation of existing units is of paramount importance.

7.2 Regional tsunami service providers’ operational changes
- A real-time forecasting platform within the existing RTSP warning framework, instead of a pre-simulated model approach, is launched. Umbrella countries are encouraged to adopt this basic model, and incorporate finer resolution, local
elevation data and use it to generate enhanced self-estimations of ETA. Such models may be updated over time and shared amongst RTSPs. The final aim is the concurrent execution of models by both the RTSPs and the source country, resulting in more robust and accurate estimates of ETA and wave heights.

- Research is suggested to explore historic ETAs of the three RTSPs and their level of agreement. If the ETA from the Indonesian system (which uses a seismic platform) differs from the Australian or Indian systems, bulletin recipients should be advised as to which information should receive priority.
- For non-seismic tsunamis, such as ones from landslides in the Makran and Krakatau regions, RTSPs may develop a tide-reading-based framework for issuing specialized warnings for the endangered regions.

In spite of the study being focussed on Sri Lanka, ramifications arising from it, including the suggestion for a new tsunami buoy and an upgrade of RTSP activities, will still be beneficial for all Indian Ocean countries.

References


Further reading


**Corresponding author**
Sanjeewa Wickramaratne can be contacted at: sanjeewa@lhi.lk
Coastal flood alleviation through management interventions under changing climate conditions

William George Bennett and Harshinie Karunarathna
College of Engineering, Bay Campus, Swansea University, Swansea, UK

Abstract

Purpose – Coastal flooding has disastrous consequences on people, infrastructure, properties and the environment. Increasing flood risk as a result of global climate change is a significant concern both within the UK and globally. To counter any potential increase in future flooding, a range of potential management options are being considered. This study aims to explore future coastal management practice for flood alleviation, incorporating the influence of climate change.

Design/methodology/approach – The Taf estuary in South West Wales, a macro-tidal estuary which has a history of coastal flooding, was chosen as the case study in this paper to investigate the impact of coastal management interventions such as construction of hard defences, managed realignment or altering land use of affiliated ecosystems such as salt marshes on the complex hydrodynamics and hence flooding of the surrounding areas of the estuary. The study was carried out using a numerical hydrodynamic model of the Taf estuary, developed using the process-based Delft3D modelling software.

Findings – The role of the selected management interventions on coastal flooding was investigated using an extreme storm condition, both with and without the impact of future sea level rise. The results highlight the scale of the effect of sea level rise, with the selected management interventions revealing that minimising the increase in flooding in future requires careful consideration of the available options.

Originality/value – This paper explores the highlighted role of coastal management practice in future with the influence of climate change to study how effective alternative methods can be for flood alleviation.

Keywords Risk reduction, Climate change, Disaster mitigation, Natural disasters, Flooding, Extreme weather events

Paper type Research paper

1. Introduction

Coastal communities are at increasing risk of flooding and erosion as a result of frequent occurrences of extreme storms and rising sea levels forced by global climate variabilities. The 2013/2014 winter storms, which threatened safety of people and damaged houses and millions of pounds worth coastal infrastructure in the UK and

This research formed part of the Valuing Nature Programme (valuing-nature.net) which is funded by the Natural Environment Research Council, the Economic and Social Research Council, the Biotechnology and Biological Sciences Research Council, the Arts and Humanities Research Council and the Department for Environment, Food and Rural Affairs. This research was supported by the UK Research Councils under Natural Environment Research Council award NE/N013573/1, Title CoastWEB: Valuing the contribution which COASTal habitats make to human health and WellBeing, with a focus on the alleviation of natural hazards. WB acknowledges the support of the Supercomputing Wales project, which is part-funded by the European Regional Development Fund (ERDF) via Welsh Government. CEFAS and the UK Met Office are acknowledged for providing wave and wind data. The paper contains public sector information, licensed under the Open Government Licence v3.0, from the Maritime and Coastguard Agency.
around Europe, highlighted the need for long-term coastal flood and erosion risk mitigation and management interventions. Current sustainable coastal management legislation stresses the need to develop coastal and flood defence solutions which do not negatively interfere with the natural environment. As a result, managed realignment is increasingly favoured, thus creating new intertidal areas that act as buffer zones against coastal flooding. Natural coastal ecosystems such as salt marshes, mangroves and coastal wetlands can also act as natural barriers against storm waves. They can help reduce the need for hard defences against flooding and erosion and lessen the effect of wave action on coastal infrastructure.

Combination of more natural and engineered approaches, which are known as “nature-based coastal defence approaches” have been identified as desirable solutions against coastal flooding and erosion as opposed to hard coastal defences alone. Salt marshes have been found to act as natural buffer zones, providing protection from storm waves and flooding (Temmerman et al., 2013). In addition, salt marshes can help reduce vulnerability of hard defences to bed scour and erosion (Dixon et al., 2008), and lessen the effects of wave action on the structure (Møller et al., 2001). Thus, a saltmarsh combined with a coastal defence may reduce the size and height of a seawall required to manage a coastline, with a near-linear relationship between saltmarsh width and seawall height for comparable levels of protection (King and Lester, 1995; Dixon et al., 1998; Bouma et al., 2014).

Catastrophic events such as Tsunami are not commonplace within the UK, although there is some debate that a Tsunami occurred in the Bristol Channel in January 1607 (Bryant and Haslett, 2007). Storms, however, are more frequent and have historically had severe impacts, which although not on the same scale as tsunami, are considerable. For example, the 1953 North Sea flood along the east coast of England forced 24,000 people out of their homes and led to the deaths of 307 people, alongside significant financial costs (Baxter, 2005). A storm surge occurred in December 2013 resulted in ten deaths and incurred EUR1.9bn worth of insured losses across the UK, The Netherlands and Denmark (Spencer et al., 2015).

In this paper, we compare the impact of three fundamentally different management intervention strategies for flood mitigation during extreme storm events in the small-microtidal Taf estuary, through a computational modelling study. Villages and towns along the Taf estuary regularly flood during storms, disturbing the lives and livelihoods of these coastal communities. Understanding the impact of management interventions on flood of alleviation under present and future climate conditions is fundamental for long-term sustainable coastal management. The paper is structured as follows: Sections 2 and 3 describe the case study area, and the methodology used to determine extreme storm conditions and the modelling approach, respectively. The results and discussion are given in Section 4, with conclusions drawn in Section 5.

2. Case study

The Taf is a small estuary (8.65 km$^2$) situated within Carmarthen Bay in South West Wales, UK (Figure 1). The estuary is macro-tidal with a mean spring tidal range of 7.5 m, a neap tidal range of 3.7 m (Ishak, 1997) and a tidal prism of $17.7 \times 10^8$ m$^3$ (Bristow and Pile, 2003). It is a funnel shaped sinuous estuary (Cousins et al., 2008) and at high water, it is tidal to an extent of 15 km upstream from Carmarthen Bay (Pye and Blott, 2009). Currents within the estuary are at a maximum as the sea enters the estuary and before it retreats, with peak tidal currents reaching 2.2 m/s (Ishak, 1997). The river Taf has an average daily freshwater discharge of 7.0 m$^3$/s with an extreme high of 60 m$^3$/s during winter months and extreme low of 0.6 m$^3$/s occurring during summer months (Halcrow, 2012). Within Carmarthen Bay,
swell waves are predominantly south westerly, with a fetch length of up to 6,000 km (Pye and Blott, 2009). Swell wave penetration into the estuary is limited by the orientation of the mouth of the estuary (Pye and Blott, 2009). However, locally generated wind waves within the estuary can be significant and have a wider array of directions. The Taf represents a typical Welsh estuary in terms of size, tidal characteristics and morphodynamic features. Within the estuary there exist several different environments such as sand flats, mud flats and saltmarshes (Figure 2) (Jago, 1974). There are four main areas of saltmarsh (Figure 2), Laugharne Castle, Laugharne South, Laugharne North and Black Scar, occupying a total area of 279 ha (Bristow and Pile, 2003). Ginst point and Wharley point are of importance (Figure 1), restricting the estuary mouth from the southwest and the northeast. The historic village Laugharne, located at the fringe of one of the largest marshes of the estuary, which regularly floods during winter storms, attracts the attention of policymakers and coastal managers as there is an urgent need to implement a sustainable flood prevention solution to protect the village. The current management policy in the Taf estuary is to allow the natural development of undefended shores, and to reduce the risk of flooding and erosion (Halcrow, 2012). This result in an array of policy decisions depending on the assets at risk, and the time frame considered. For the eastern bank of the estuary, and the western bank north of Laugharne, no active intervention is chosen. However, to protect the village of Laugharne and further south, a mixture of managed realignment and hold-the-line policies are used.

3. Methodology
3.1 Storm boundary conditions
To investigate the impact of different estuary management intervention scenarios on flood alleviation within the Taf estuary during extreme events through computational modelling,
it is necessary to derive storms that may have significant implications on the estuary and
the surroundings. Here, storm conditions are defined by extreme wave, wind and water
levels (tides and storm surge).

3.1.1 Waves. Wave hindcast data for Carmarthen Bay was provided by the Centre for
Environment Fisheries and Aquaculture Science of the UK wave hindcast data set. Data for
Carmarthen Bay was extracted from the nearest hindcast output (Figure 1), providing wave
characteristics for the period 1980-2017. The wave data set was filtered to identify storm
conditions following the approach described in Bennett et al. (2016). The method uses the
storm event definition of Dissanayake et al. (2015), taking a storm wave height threshold of
2.5 m, based on the UK Channel Coastal Observatory guidance (www.channelcoast.org/
reports/). The Generalised Pareto Distribution (GPD) was used to determine extreme wave
heights for a range of storm conditions. The GPD was fit to the peak storm wave heights,
with the GPD given in equation (1) (which is the combination of three statistical families),
and the method of Hawkes et al. (2002) was used. In equation (1), $\phi$ and $\xi$ are scale and
shape parameters, respectively, (Coles, 2001) and $u$ is the threshold that ensures model
convergence. The R statistical software package ismev (Coles, 2001) was used to fit the GPD
to the data (R Core Team, 2013):

$$
Pr\{X > x|X > u\} = \begin{cases} 1 + \xi \phi^{-1} (x - u)^{-1/\xi} e^{-u^{\xi}} & \xi \neq 0 \\ e^{-u^{\xi}} & \xi = 0 \end{cases}
$$


Figure 2.
Overview of the Taf estuary

Note: Numbers 1, 2, 3, and 4 denote Laugharne Castle, Laugharne South, Laugharne North, and Black Scar
marshes respectively.
The significant wave heights of storms corresponding to 1 in 1, 10, 50 and 100-year return periods were derived from the GPD (Figure 3). The average storm significant wave height was taken as the average value from the filtered storm conditions. The maximum storm wave period ($T_{\text{max}}$) as determined from the average of the ($T_{\text{max}}$) values for individual storms extracted from the hindcast data. The predominant direction across all the individual storm events was used as the storm incident direction ($W_{\text{d,avg}}$). These conditions are summarised in Table I.

To provide corresponding wind forcing required for the computational model, wind outputs from the nearby Pembrey weather station (Figure 1) were used, providing hourly wind records for the period 2002-2009. As with the wave data, the GPD was fitted to the wind data. The predominant wind direction was determined from the observed wind data during storm conditions. The return level plot for the storm wind velocity is shown in Figure 3, with wind speeds with different return periods summarised in Table I.

Time varying wind and wave conditions during a storm were created through the use of a representative storm profile. A three-point spline curve, which closely represents observed storm profiles, was used. In the storm profile developed in this manner, the storm begins when incident wave height exceeds the pre-selected threshold wave height and ceases when the wave height becomes smaller than the threshold. The storm peaks halfway between the beginning and the end of storm thus creating a symmetric storm wave height profile. The corresponding wind conditions for the chosen storm wave return period follow the same three-point spline shape.

**Notes:** Crosses indicate storm significant wave height and wind speed values, with the GPD fit and 95% confidence intervals indicated by the three curves. Dashed line indicates the threshold level.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average storm</th>
<th>1 in 1 year</th>
<th>1 in 10 year</th>
<th>1 in 50 year</th>
<th>1 in 100 year</th>
<th>$W_{d,\text{avg}}$ (degrees)</th>
<th>$T_{\text{max}}$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significant wave height (m)</td>
<td>3.37</td>
<td>5.13</td>
<td>6.94</td>
<td>8.15</td>
<td>8.66</td>
<td>225</td>
<td>6.82</td>
</tr>
<tr>
<td>Wind speed (m/s)</td>
<td>16.75</td>
<td>24.59</td>
<td>26.64</td>
<td>27.15</td>
<td>27.27</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** $T_{\text{max}}$ is the maximum storm wave period and $W_{d,\text{avg}}$ is the predominant storm wave direction.

**Table I.** Summary of statistically significant storm wave boundary conditions in Carmarthen Bay

**Figure 3.** GPD profiles for wave height (left) and wind speed (right)
3.1.2 Water levels. Statistically significant water levels during storms are obtained based on McMillan et al. (2011). Using data supplied by the National Tide and Sea Level Facility of the UK, they performed a statistical analysis to determine peak water levels and storm water level profiles using the Skew Surge Joint Probability Method for 40 of the UK national network (Class A) of tide gauge sites from around the coastlines of England, Scotland and Wales, together with equivalent data from 5 other primary sites. Their analysis provides sea levels with a range of return periods at 2 km spacing around the UK coastline. During extreme events, the total water level is a combination of the astronomical tide and the storm surge. Scaled surge shapes, such as the one for Mumbles tide gauge shown in Figure 4, have been derived following the method they used in their analysis. This allows derivation of appropriate total water level curves, thus incorporating the increase and decline of surge during the extreme event. The guidance provided by McMillan et al. (2011), suggests that the base astronomical curve should be halfway between the mean high water spring tide and highest astronomical tide, in this case 4.35 m ordnance datum. This was also used as the average storm water level for the analysis.

To create the final water level profiles for the desired range of storm conditions, the peak storm water level was combined with the time-varying surge profile for each return period to scale up the base astronomical curve (Figure 4). The peak storm water level conditions are summarised in Table II. In this analysis we assume that the storm peak coincides with high tide and the maximum surge occurs at the peak of the storm to represent the worst-case extreme event scenario.

To calculate future storm water levels, the impact of sea level rise was added to the storm water level curve calculated for present climate conditions. Regional relative sea level rise for Carmarthen Bay was extracted from the United Kingdom Climate Projections 18 marine data

![Figure 4.](image-url) An example of surge profile (McMillan et al., 2011), base astronomical tide and the storm tide at Carmarthen Bay

| Table II. Peak storm water levels in Carmarthen Bay, determined following McMillan et al. (2011) |
|---------------------------------------------------|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Average 1 in 1 year 1 in 10 year 1 in 50 year 1 in 100 year |
| Peak sea level 4.35 5 5.26 5.43 5.51 |
set (Palmer et al., 2018). Projected changes at 12 km intervals were extracted for the 50th percentile of the representative concentration pathway 4.5 scenario (Moss et al., 2010) from 2007 to 2100. As the base astronomical tide was calculated for 2017, the data set was utilised between 2017 and 2100 providing a relative sea level rise value of 0.444 m. The future 1 in 100 year peak storm water level was thus calculated as 5.954 m Ordnance Datum Newlyn.

3.2 Modelling approach
The area computational coastal modelling suite Delft3D (Lesser et al., 2004) was used to investigate changes in estuary hydrodynamics because of differing coastal saltmarsh management scenarios. Delft3D can simulate the interaction between water, sediment, ecology and water quality and has been extensively used within industry and research communities since its initial development to investigate coastal erosion and inundation problems. Examples of the range of use include efforts to model the effect of beach nourishment on the northern part of the Dutch coast (Grunnet et al., 2004), an investigation of the effects of offshore wind farms have on surface waves and circulation in Lake Ontario (McCombs et al., 2014), coastal erosion and flooding in Sefton, UK (Dissanayake et al., 2014, 2015; Bennett et al., 2019) and work to understand the effect vegetation and wetlands have on storm surge levels in south-eastern Louisiana (Hu et al., 2015). Delft3D allows for the implementation of various features, including vegetation characteristics, differing sediments and hard defences, which are key to accurately capturing the Taf estuary. The model will provide waves and hydrodynamics of the estuary and capture the impacts of river flow, salt marsh ecology and wave-current interactions on hydrodynamics. Taf hydrodynamic model encompasses the majority of the Taf estuary, extending out in to Carmarthen Bay to a depth of 22 m (Figure 5), to capture undisturbed water levels and waves.

The model bathymetry was created through combining data from the UK Hydrographic Office at 2 m resolution from 2013, Admiralty charts data from 1977 and from new high-resolution bathymetric surveys carried out within the estuary during this study.

Salt marsh vegetation is modelled with plant geometry simplified as rigid cylinders that are parameterised by plant height ($h_v$), stem diameter ($b_v$) and plant density ($n_v$) (Dalrymple et al., 1984). The drag coefficient ($C_D$) is the only parameter that cannot be measured in the field a priori. Therefore, the value $C_D = 1$ is selected based on experimental studies with stiff cylinders.
in unidirectional flow (Tanino and Nepf, 2008) and waves based on conditions in the Taf estuary. \( C_D = 1 \) was also successfully applied in recent modelling studies (Ashall et al., 2016; Hu et al., 2018). Finally, the river discharge is set to represent the most extreme conditions observed in the Taf, providing the worst-case storm scenario. Specifically, it has been set at a constant discharge of 60 m\(^3\)/s, which is the highest measured discharge (Ishak, 1997) (Table III).

Acoustic Doppler current profiler (ADCP) and current meter data from deployments in the Taf were used to validate the numerical model. The ADCP was deployed for ten tidal cycles between 10 and 16 June 2018 in the main channel of the estuary. The tidal model was run for the corresponding period. The coefficient of correlation, \( r^2 = 0.88 \), and Nash–Sutcliffe efficiency (NSE) coefficient, \( NSE = 0.78 \) (Nash and Sutcliffe, 1970), show good agreement between the model results and measured water depths in phase and amplitude. A single point current meter was deployed in the main channel upstream of Laugharne Castle marsh between 1 p.m. on 28 November 2017 and 2.45 p.m. on 30 November 2017. Despite issues with grounding of the meter on the tidal flats, comparison between flow velocities with modelled results show reasonable agreement. A coefficient of correlation \( r^2 = 0.68 \) and \( NSE = 0.48 \) indicate that the model predicts accurately flow velocities within the estuary.

### 3.3 Management intervention scenarios

Three different interventions: managed realignment, marsh grazing and construction of hard defences, were introduced to the saltmarsh areas of the estuary in the computational model including both “hard” and “soft” engineering options. The impacts under each intervention on hydrodynamics and flooding were discussed through a comparison of “current” hydrodynamic regime under “present” and “future” (end of century) climate.

Managed realignment involves altering breaching or complete removal of existing flood defences to increase flood accommodation space. Two potential areas for managed realignment have been identified within the Taf estuary (Figure 6) (Cousins et al., 2008). The two areas are currently privately-owned agricultural land. Mwche and Mylett farm sites provide 77.71 Ha of land for potential realignment through breaching of the existing defences (locations indicated in Figure 6). To implement managed realignment within the model, the existing flood defences were artificially breached, following the advice of Bristow and Pile (2003). The size of the breach is determined such that it does not lead to undesired morphological effects because of significant flow velocities through the breach. The method described in Leggett et al. (2004) was used to determine the breach width, based on the increase in tidal prism due to managed realignment at each location. The increase in tidal prism for Mylett and Mwche farm sites was estimated as 107,750 m\(^3\) and 46,350 m\(^3\),

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant width</td>
<td>( b_v )</td>
<td>2.58(^*)</td>
<td>mm</td>
<td>From field measurements</td>
</tr>
<tr>
<td>Plant height</td>
<td>( h_v )</td>
<td>34</td>
<td>mm</td>
<td>From field measurements</td>
</tr>
<tr>
<td>Plant density</td>
<td>( n_v )</td>
<td>2275</td>
<td>m(^{-2})</td>
<td>From field measurements</td>
</tr>
<tr>
<td>Drag coefficient</td>
<td>( C_D )</td>
<td>1.0</td>
<td>–</td>
<td>Tanino and Nepf (2008)</td>
</tr>
<tr>
<td>Bed roughness</td>
<td>( C_b )</td>
<td>65</td>
<td>m(^{1/2})/s</td>
<td>Marciano et al. (2005)</td>
</tr>
<tr>
<td>River discharge</td>
<td>( Q )</td>
<td>60</td>
<td>m(^3)/s</td>
<td>Ishak (1997)</td>
</tr>
<tr>
<td>Water density</td>
<td>( \rho_0 )</td>
<td>1025</td>
<td>kg/m(^3)</td>
<td>Well-mixed estuary</td>
</tr>
<tr>
<td>Horizontal eddy viscosity</td>
<td>( K )</td>
<td>1</td>
<td>m(^2)/s</td>
<td>Mariotti and Canestrelli (2017)</td>
</tr>
</tbody>
</table>

Table III. Vegetation model input parameters

Notes: \(^*\)On average. In fact, the plant width is a function of height. At the substrate the width is 3.3 mm and 1.86 mm at the tip.
respectively (Cousins et al., 2008). Using these values for the increase in tidal prism with the method of Leggett et al. (2004) provided breach widths of 46 m for the Mylett site and 41 m for the Mwche site. The breaches at both sites were placed at the end of existing creek networks, and near the locations of relic creeks from the reclaimed saltmarsh. These creek systems were then connected through lowering of the bathymetry either side of the breach.

The second scenario encompasses the impact of grazing of saltmarshes by local livestock, which is a common phenomenon in most Welsh estuaries. It will, however, reduce the vegetation height, and subsequently the resistance to wave and flow propagation on the marsh, diminishing their flood defence function (Davidson et al., 2017). To investigate the wider impacts of saltmarsh grazing in the Taf estuary, the extreme case in which all saltmarsh areas are grazed was investigated. Grazing was introduced into the model by artificially removing the vegetation cover from the marshes, which replicates the extreme scenario.

Finally, a surge barrier to protect the village of Laugharne from flooding is investigated. Although a barrier is likely to eliminate flooding, it has been the subject of debate, and has been rejected by the local communities because of the fears of the aesthetic impact of such a measure (Halcrow, 2012). To investigate the potential impacts that a surge barrier may have within the estuary a thin dam was implemented within the model at the boundary of Laugharne. This prevents any flow from entering the village because of waves or water level.

**Notes:** Numbers 1 and 2 indicated Mwche and Mylett farm sites respectively. White squares indicate breach locations.
4. Results and discussion

Each flood defence intervention scenario mentioned in Section 3 was modelled during both the “present” and “future” 1 in 100 year storm to investigate the differences of their impacts alongside the current estuary configuration with relative sea level rise.

Firstly, the peak storm water level in the Taf estuary and the water level differences because of the selected management intervention scenarios during “present” storm condition are shown in Figure 7. For the current state of Taf estuary, without any interventions, the tidal extent during the peak of the storm reaches the landward edges of the marshes, with water depths in the range 1-2 m. In the defended case, the hard defence at the boundary of the village of Laugharne causes little change in the overall estuarine peak storm water level. While the structure reduces the water depths on the landward side to zero, there are no noticeable changes beyond this. The effect of marsh grazing causes no significant change in water level. Because of the breaches in the managed realignment areas, there are large differences in water level between undisturbed and managed realigned sites. There are no significant wider differences seen outside of the marsh areas of the estuary.

The changes in wave height in the estuary for the chosen interventions for the “present” climate storm are shown in Figure 8. Without any interventions, for the current configuration in the Taf, the largest wave heights are seen in the areas around the mouth of the estuary (approximately 1.4 m). At the edges of the marshes, close to the tidal channel location, wave heights reach 0.6-0.7 m, while those on the marshes reduce to less than 0.2 m. It should be noted here that during westerly storms, local waves are generated within the estuary because of strong westerly winds and therefore, wave climate in the estuary is complex. The hard defence at the landward edge of Laugharne marsh causes very small

Figure 7.
Comparison of peak storm water depths at the Taf estuary under the selected intervention scenarios during the “present” 1:100 year storm

Notes: (a) Current condition; (b) difference between defended and current; (c) difference between grazed and current; (d) difference between managed realignment and current
changes in wave height coincident with the channel at the seaward boundary of the marsh, with a maximum difference of 0.06 m. With the reduction in wave attenuation because of the lack of vegetation because of grazing, the wave heights within the estuary are generally increased. Wave height change on marsh areas is noticeable with a maximum of 0.1 m increase; however, within the channel system reasonable increases are seen (approximately 0.02-0.05 m). Similar to the grazed case, managed realignment causes a general increase in wave height throughout the estuary. Other than the intervention with hard defences, the other two intervention scenarios increased the wave height on the marsh by around 0.1 m, which may be significant in terms of flooding and marsh erosion.

In Figures 9 and 10, the impact of sea level rise on the peak water depth and wave height for the current situation in the Taf estuary is highlighted. The change in water level in future is clear (Figure 9) with a fairly consistent increase across the estuary mouth of the estuary and into the bay, with a slight increase towards the mouth of the estuary. The funnelling
The effect of the estuary is such that while the increase in water level is approximately 0.42 m at the estuary mouth, it is over 0.01 m higher closer to Laugharne further up the estuary. While the wave height outside of the estuary increases significantly in future (Figure 9), the increases within the estuary are not as large. Within Carmarthen Bay and near the mouth of the Taf, the peak wave height difference between present and future is approximately 0.15 m. Within the estuary, and across the marshes, this is less but not insignificant, with increase between 0.05-0.1 m across marsh areas and less than 0.05 m offshore of the marshes. This may be because of the increase in water level reducing the role of attenuation from vegetation, as well as allowing waves to propagate and grow further onshore.

The differences because of the introduction of a hard defence with the influence of sea level rise are shown in Figures 11 and 12. The change in water level is again consistent with the impacts observed in Figure 8, a consistent increase across the estuary. While the hard defence prevents any increase in water level from impacting the village of Laugharne, it does not affect the overall pattern of water depth within the Taf. The change in wave height with the impact of sea level rise is similar to that shown under the current condition (Figure 10), highlighting the lack of impact of the hard defence on estuarine hydrodynamics.

Figure 10. Peak storm wave height under the “present” current condition alongside the difference because of the increase in sea level rise.

Figure 11. Peak storm water depth under the “present” defended condition alongside the difference because of the increase in sea level rise.

Figure 12. Peak storm wave height under the “present” defended condition alongside the difference because of the increase in sea level rise.
While it does not have any effect on the wider behaviour compared with the current condition, it does eliminate the flood risk to Laugharne (Figure 13).

Under the managed realignment intervention, the influence of sea level rise shows a similar pattern to Figures 9 and 11, although not wholly consistent. The increase in water towards the mouth of the estuary is very slightly reduced because of water being redirected at the two sites. Within the two areas as water is introduced, compared with the present condition the increase in water level is much less than that within the estuary and in the bay. The lower increase in the realignment areas may help in providing space for saltmarshes to rollback, which is important for management policy. However, it does not help with flood alleviation for Laugharne. Compared with the current configuration changes, the differences in wave height outside of both realignment sites is very similar (Figure 14). Within the two sites, there is a noticeable increase in wave height, linked with the increase in water depth. Because of the orientation of the two sites with respect to the predominant wind direction, it does not impact upon the wave energy within the main channels of the estuary.

In Figure 15, with extensive grazing, the increase in peak water depth across the Taf is noticeably different to the other three conditions. With the removal of vegetation, the

Coastal flood alleviation

Figure 13. Peak storm water depth under the “present” managed realignment condition alongside the difference because of the increase in sea level rise

Figure 14. Peak storm wave height under the “present” managed realignment condition alongside the difference because of the increase in sea level rise

Figure 15. Peak storm water depth under the “present” grazed condition alongside the difference because of the increase in sea level rise
increase because of sea level rise is greater than under the current (Figure 9) case, highlighting the drag effect of vegetation within Taf. Although this difference is noticeable, it is still a small magnitude change (approximately 0.01 m), and thus does not greatly influence coastal flooding within the estuary. Figure 16 shows that the impact of extensive grazing in future causes the wave height within the Taf to change less than that with vegetation (Figure 10). The difference between present and future is as with the other interventions, greatest outside of the estuary; however, within the estuary the differences are largely between approximately 0.04-0.08 m. When compared with the current configuration, the reduced attenuation effect of the vegetation is highlighted (Figure 10) because of the increased water level. While for the grazed case, the increase in water level only allows for a slight change in wave height.

5. Conclusions
Impact of coastal management interventions on future flooding of a small macro-tidal estuary is studied. The increase of extent, magnitude and frequency of flooding because of the effects of climate change are a threat to both the built and natural environment. A wide array of approaches are being considered and investigated to counter this threat, with salt marshes considered as natural buffers for flooding. It was found that, other than the impacts of future climate change (sea level rise), the interventions themselves may have significant impacts on the estuarine hydrodynamic characteristics and morphology. The study provides insights into the role of sea level rise on the function of different management interventions during extreme storms.

The results highlight that the village of Laugharne within the Taf estuary will become increasingly vulnerable in future because of the impact of relative sea level rise. Of the three intervention scenarios, the hard defence, which prevents onshore water and wave propagation, has the largest impact on future flooding of the village of Laugharne. Additionally, it has no influence on the wider hydrodynamic regime of the estuary compared to the current condition, although this option remains unpopular among local communities because of restricted access to the marsh and aesthetic issues. The implementation of the two managed realignment sites did not cause any large-scale change to the wider estuarine hydrodynamics, and also did not affect the water level at the boundary of the village of Laugharne. Therefore, the effect of managed realignment was limited to areas local to the two breach sites. The small increase in tidal prism of the estuary as a result of this scheme is an indicator for the lack of overall impact. The grazed case did cause widespread changes to the hydrodynamic behaviour of the Taf. However, it did not have a significant change on the water level and subsequent flooding, although it is important to consider the potential impact the change in hydrodynamics may have on estuary morphology. While the link between the changes in hydrodynamics and changes in morphology is complex and
nonlinear, the increase in wave heights across the marsh platforms prompts the potential to increase the vulnerability of the system to flooding.

The challenge of dealing with sea level rise remains a cause of increasing concern for future planning and management of coastal flooding. The results presented here highlight how sea level rise will impact on extreme storms, and subsequently coastal flooding for the small macrotidal Taf estuary. Identifying appropriate flood management solutions is complex and requires careful consideration of the short- and long-term effects.

References


Halcrow (2012), Lavernock Point to St Ann’s Head Shoreline Management Plan SMP2, Halcrow, London.


R Core Team (2013), *R: A Language and Environment for Statistical Computing*, R Core Team, Vienna.


**Corresponding author**

William George Bennett can be contacted at: w.g.bennett@swansea.ac.uk

---

For instructions on how to order reprints of this article, please visit our website: www.emeraldgrouppublishing.com/licensing/reprints.htm

Or contact us for further details: permissions@emeraldinsight.com
Vulnerability assessment of reinforced concrete buildings in Indonesia subjected to tsunami inundation forces

Dicky Hanggara and Anil Christopher Wijeyewickrema

Department of Civil Engineering, Tokyo Institute of Technology, Tokyo, Japan

Abstract

Purpose – This paper aims to evaluate the vulnerability of typical low-rise reinforced concrete (RC) buildings located in Indonesia subjected to tsunami loading.

Design/methodology/approach – The vulnerability of typical three-story RC buildings located in Indonesia subjected to tsunami loading is discussed using fragility curves. Buildings without openings in all stories and buildings with openings in the first story are considered. The fragility curves are obtained by performing tsunami pushover analysis for several load cases, using different tsunami load estimation standards and references. The generalized linear method is used as a curve fitting method to construct the fragility curves.

Findings – The fragility curves show that the three-story RC buildings without openings in all stories subjected to tsunami loading have a high probability of collapse. Openings in the first story will reduce the vulnerability of the buildings.

Originality/value – Fragility curves are obtained by carrying out tsunami pushover analysis to evaluate the vulnerability of typical three-story RC buildings located in Indonesia. The results of this study show the need to include tsunami loads in the design code for Indonesian buildings and the benefits of having openings in the first story of the building.

Keywords Vulnerability, Damage assessment, Fragility curves, Pushover analysis, Reinforced concrete buildings, Tsunami loading

Paper type Research paper

1. Introduction

Indonesia, which comprises 17,508 islands, is affected by the movement of several tectonic plates, namely, Eurasian plate, Australian plate, Philippine Sea plate and Pacific plate. A large number of structures have been damaged or destroyed in Indonesia because of recent earthquakes such as the 2004 Sumatra–Andaman Islands earthquake (moment magnitude $M_w = 9.1$), the 2010 Mentawai earthquake ($M_w = 7.8$) and the 2018 Central Sulawesi earthquake ($M_w = 7.5$) and the tsunamis generated by those earthquakes. The more recent 2018 Sunda Strait tsunami caused by the eruption and partial collapse of the Anak Krakatau volcano also resulted in many damaged or destroyed structures. These tsunami events have shown the need for research on vulnerability assessment and performance of structures located in Indonesia, subjected to tsunami loading.

The authors would like to thank Prof. Priyan Dias, Guest Editor for the invitation to contribute to the Special Issue in memory of the late Prof. Samantha Hettiarachi. Anil C. Wijeyewickrema was one year junior to Prof. Samantha and Prof. Priyan at University of Moratuwa (UOM) and is grateful for the friendly discussions with Prof. Samantha while at UOM.
Since the 2004 Indian Ocean tsunami event, several studies have been carried out and have resulted in the better understanding of tsunami forces on structures. In Japan, MLIT 2570 (MLIT, 2011) is used as a design guideline for buildings subjected to tsunami forces and in the USA, a specific chapter about tsunami loading has been added to ASCE 7-16 (ASCE, 2016). Indonesia, while having a high probability of tsunami event occurrence, does not have design guidelines for structures designed to resist tsunami loads, leaving Indonesian buildings vulnerable to tsunamis.

The vulnerability of buildings subjected to tsunami loading can be presented in the form of tsunami fragility curves that provide an estimate of expected damage or losses because of a prescribed tsunami intensity. Compared to seismic events, studies of fragility curves for buildings affected by tsunamis are still limited. Fragility curves were developed by Koshimura et al. (2009a, 2009b) for Banda Aceh, Indonesia and by Suppasri et al. (2011) for Thailand using post-tsunami data of the 2004 Indian Ocean tsunami and by Gokon et al. (2011) for American Samoa and Reese et al. (2011) for American Samoa and Samoa using post-tsunami data of the 2009 South Pacific tsunami. Suppasri et al. (2012) developed fragility curves for Sendai and Ishinomaki plains, while Suppasri et al. (2014) developed fragility curves for Ishinomaki city, using post-tsunami damage data of the 2011 Great East Japan earthquake and tsunami. These studies are based on post-tsunami damage data, with applicability limited to specific locations from where tsunami damage data was collected. Indonesia, despite the frequent tsunami events, has very limited post-tsunami damage data. Owing to this situation, the use of numerical analysis to evaluate the performance of structures is appropriate, to construct fragility curves for buildings in Indonesia subjected to tsunami loading.

Several researchers have developed tsunami fragility curves using different approaches. Park et al. (2012) developed fragility curves of earthquake and tsunami loads in sequence using the Sequential Seismic and Tsunami Analysis Program. Dias et al. (2009) and Nanayakkara and Dias (2016) developed a probabilistic model using Monte Carlo simulations to produce fragility curves. Nanayakkara and Dias (2016) developed a probabilistic model using Monte Carlo simulations to produce fragility curves. Attary et al. (2016) and Alam et al. (2017) developed tsunami fragility curves using tsunami pushover analysis considering randomly generated tsunami load parameters. Petrone et al. (2017) compared tsunami time history analysis and the pushover analysis method to develop fragility curves and concluded that the two methods give similar values but that the tsunami pushover method is preferred for its simplicity and ability to perform analysis iterations rapidly to construct fragility curves.

In the present study, fragility curves are obtained for typical three-story reinforced concrete (RC) buildings located in Indonesia subjected to tsunami loading. In general, 1-story and 2-story RC buildings found in less developed cities in Indonesia are non-engineered buildings (Paulik et al., 2019) but buildings with three or more stories will usually be designed following seismic codes. Here, the procedure proposed by Macabuag et al. (2014a) and Macabuag (2018) is used, where first, tsunami loads are calculated using estimation methods from different sources, namely, MLIT (2011), ASCE (2016) and Foster et al. (2017) (Section 2), and next a series of tsunami pushover analyses are carried out to evaluate the performance of the structure. The results of the analysis are then used to construct fragility curves. Furthermore, in the case of the 2004 Sumatra–Andaman Islands earthquake, it was observed that buildings with openings in the first story such as mosques, had survived the tsunami with minor damage (Saatcioglu et al., 2006). Hence,
the effect of openings in the first story on tsunami fragility curves and vulnerability will also be addressed in this study.

2. Tsunami load estimation methods
The forces on a building because of a tsunami can be categorized as hydrostatic forces (including buoyancy forces), hydrodynamic forces because of drag and bore impact forces and debris impact forces and debris damming forces. In addition, there could be forces acting on the foundation due to scour, sliding and overturning (FEMA, 2012; Yeh et al., 2014; Chock, 2016). The present study is limited to equivalent hydrostatic loads and hydrodynamic loads only.

Tsunami forces that can be obtained from design guidelines such as MLIT Technical Advice No. 2570 (MLIT, 2011), design codes such as ASCE 7-16 (ASCE, 2016) and research studies (Foster et al., 2017) are briefly reviewed here.

2.1 Tsunami design force recommendation in Japan – MLIT 2570 (MLIT, 2011)
The equivalent hydrostatic pressure \( p(y) \) is given by (Figure 1):

\[
p(y) = \rho g(a h - y),
\]

(1)

where \( \rho \) is density of water, \( g \) is acceleration due to gravity, \( h \) is the inundation depth at the building location and \( a \) is the inundation depth coefficient given in Table I.

2.2 Tsunami design force recommendation in USA – ASCE 7-16 (ASCE, 2016)
Tsunami loads on structures described in Chapter 6 “Tsunami loads and effects” of ASCE 7-16 (ASCE, 2016) are based on the work of Chock (2016). The drag force \( F_d \) and the initial impulsive (bore impact) force \( F_w \) are given by (Figure 2):

<table>
<thead>
<tr>
<th>Table I. Tsunami inundation depth coefficient ( a ) (MLIT, 2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No clear path between facility and tsunami</td>
</tr>
<tr>
<td>Distance from shoreline</td>
</tr>
<tr>
<td>( a )</td>
</tr>
</tbody>
</table>
$F_d = \frac{1}{2} \rho_s I_{tsu} C_d b (h u^2)$,  

(2)

$F_w = 1.5 F_d$,  

(3)

where $\rho_s$ is fluid mass density for design hydrodynamic loads, $I_{tsu}$ is tsunami importance factor which can be obtained from Table 6.8-1 of ASCE (2016), $C_d$ is the drag coefficient, $b$ is tributary width of tsunami affected area, $h$ is tsunami inundation depth and $u$ is flow velocity. As various studies have shown that the initial impulsive (bore impact) force $F_w$ can be greater than the drag force $F_d$ on a structure when there is standing water (Lloyd and Rossetto, 2012; Robertson et al., 2011), the bore impact force is taken as 1.5 times the drag force (Chock, 2016), an approach which originates from CCH (2000).

The momentum flux $h u^2$ can be determined using energy grade line analysis (EGLA) as recommended in ASCE 7-16 (ASCE, 2016) and Kriebel et al. (2017) (Figure 3).

The tsunami inundation depth $h_i$ at a particular inundation distance $x_i$, where the ground elevation is $z_i$, can be obtained from equation (4), where $Fr$ is the Froude number, $k = 1$ for the metric system and $n$ is the Manning coefficient (Kriebel et al., 2017):
The RHS of equation (4) is first computed at the run-up location \( x_i = x_R \), and equation (4) is used to step backward across the slope to the shoreline, where the Froude number \( Fr \) is calculated from:

\[
Fr = \alpha \left( 1 - \frac{x}{x_R} \right)^{1/2},
\]

with \( \alpha = 1 \) for the quasi-steady case and \( \alpha = 1.3 \) for tsunami bore conditions. The flow velocity \( u \) is calculated from:

\[
u = Fr \ (gh)^{1/2},
\]

The Manning coefficient \( n \) can be obtained from Table 6.6-1 of ASCE 7-16 (ASCE, 2016).

2.3 Tsunami design force recommendation by Foster et al. (2017)

Tsunami waves have long periods; hence, after the initial bore impact, the inundating flow can be considered as quasi-steady. Qi et al. (2014) examined quasi-steady forces on structures through flume experiments using a model building in steady-state open channel flow, and Foster et al. (2017) extended this study by considering unsteady flow.

Qi et al. (2014) and Foster et al. (2017) define hydrodynamic force \( F_D \) for steady and unsteady flow, respectively, considering sub-critical and choked flow for a building with width \( b \) in a channel with width \( w \) (Figure 4). The two different flow regimes are determined by far downstream Froude number \( Fr_2 \). The tsunami design force is calculated using the procedure of Foster et al. (2017) together with EGLA, as follows:

- Calculate upstream Froude number \( Fr_1 \) for inundation distance \( x_i \) using equation (5), with \( \alpha = 1.3 \), as the flow is unsteady.
- Calculate upstream inundation depth \( (h_1)_i \), using equation (4) and the upstream flow velocity \( (u_1)_i \), using equation (6) for inundation distance \( x_i \).
- Determine whether flow is subcritical or choked. When the flow is critical, the far downstream Froude number \( Fr_2 = 1 \), the Froude number downstream of the building \( Fr_d = Fr_{dc} \) and the upstream Froude number \( Fr_1 = Fr_{1c} \). The far downstream Froude number \( Fr_2 \) can be expressed in terms of \( Fr_d \) by:

![Figure 4. Schematic of a choked flow (Foster et al., 2017)](image-url)
The relationship between $Fr_1$ and $Fr_d$ in terms of $C_D$, $C_H$ and $(b/w)$ is given by:

\[
\left(1 - \frac{C_H}{w}\right) \frac{1}{2Fr_1^{4/3}} + \left(1 - \frac{C_D}{2w}\right)Fr_1^{2/3} = \left(1 - \frac{C_H}{w}\right) \frac{1}{2Fr_d^{4/3}} + Fr_d^{2/3},
\]

where $C_H$ is hydrostatic coefficient, $b/w$ is blocking fraction and drag coefficient $C_D$ is obtained from:

\[
C_D = C_D^0 \left(1 + \frac{C_D^0}{2} \frac{b}{w}\right)^2,
\]

where $C_D^0$ is hydrodynamic drag coefficient when blocking fraction $b/w = 0$. Determine $Fr_{dc}$ from equation (7) with $Fr_2 = 1$ and use this $Fr_{dc}$ in equation (8) to determine $Fr_{1c}$. Compare the $Fr_1$ calculated in step (a) with $Fr_{1c}$ to determine whether flow is subcritical or choked.

- Calculate the tsunami force from equation (23), Foster et al. (2017):

\[
F_D = \begin{cases} 
\frac{1}{2} C_D p b u_1^2 h_1, & Fr_2 < 1, \\
\lambda p b g^{1/3} u_1^{4/3} h_1^{1/3}, & Fr_2 \geq 1,
\end{cases}
\]

where $\lambda$ is given by equation (25), Foster et al. (2017):

\[
\lambda = 1.37 + 1.35(b/w) + 1.37(b/w)^2.
\]

3. Tsunami loads for generating fragility curves

The tsunami load cases shown in Table II are based on the tsunami load estimation methods discussed in Section 2. Similar load cases were also considered by Macabuag et al. (2018), but in the present study, the unsteady inundation flow regime of Foster et al. (2017) is considered, while Macabuag et al. (2018) considered the steady inundation flow regime. The load cases Foster1 ($b/w = 0.1$) and Foster2 ($b/w = 0.6$) correspond to a sparse building environment and a dense building environment, respectively.

The tsunami loads are calculated for a site with a uniform beach slope of 1:20 and a Manning coefficient $n = 0.04$, with a tsunami run-up $R = 15.0$ m. For load cases ASCE1 ($\alpha = 1$) and ASCE2 ($\alpha = 1.3$) the assumed drag coefficient is $C_d = 2.0$. For load cases Foster1 ($b/w = 0.1$) and Foster2 ($b/w = 0.6$), the hydrodynamic drag coefficient when there is no blocking (i.e. $b/w = 0$) $C_D^0 = 1.9$ and the hydrostatic coefficient $C_H = 0.58$ (Foster et al., 2017). These parameters were also used by Macabuag (2018). It is noted that the slope of terrain and the parameters $n, R, C_d, C_D^0,$ and $C_H$ will change with the location.

The calculated tsunami loads per unit width on the building are shown in Figure 5. The MLIT3 ($\alpha = 3$) load case yields the highest forces, while the ASCE1 ($\alpha = 1$) load case yields the lowest forces, for all inundation depths. The Foster1 ($b/w = 0.1$) load case corresponding
The tsunami inundation force transition from subcritical (low Froude number) to choked (high Froude number) flow. However, for the Foster2 \((b/w = 0.6)\) load case corresponding to a dense building environment, a similar transition occurs at a very small inundation depth \((h = 0.86 \text{ m})\) and is not seen in Figure 5.

The tsunami inundation force-inundation depth curves, have sufficient variability and can be considered adequate for the purpose of obtaining tsunami fragility curves.

### 4. Building description and design

In the present study, the fragility curves are developed for the typical three-story two-bay by three-bay RC buildings without openings in all stories and with openings in the first story (Figure 6). The buildings are located in Palu, Indonesia and designed following the guidelines SNI 1726 (SNI, 2012), the Indonesian design code for seismic loads for structures and SNI 2847 (SNI, 2013), the Indonesian national standard of RC building design. The soil is characterized as stiff soil (Site Class D). The spectral response acceleration parameters are \(S_s = 2.137 \text{ g} \) and

<table>
<thead>
<tr>
<th>Tsunami load case</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLIT1 ((\alpha = 1.5))</td>
<td>Equivalent hydrostatic load. No clear path between building and tsunami. Distance from shoreline &gt; 500 m</td>
</tr>
<tr>
<td>MLIT2 ((\alpha = 2))</td>
<td>Equivalent hydrostatic load. No clear path between building and tsunami. Distance from shoreline &lt; 500 m</td>
</tr>
<tr>
<td>MLIT3 ((\alpha = 3))</td>
<td>Equivalent hydrostatic load. Clear path between building and tsunami</td>
</tr>
<tr>
<td>ASCE1 ((\alpha = 1))</td>
<td>Hydrodynamic drag force</td>
</tr>
<tr>
<td>ASCE2 ((\alpha = 1.3))</td>
<td>Bore impact force</td>
</tr>
<tr>
<td>Foster1 ((b/w = 0.1))</td>
<td>Hydrodynamic drag force – unsteady flow regime. Sparse building environment</td>
</tr>
<tr>
<td>Foster2 ((b/w = 0.6))</td>
<td>Hydrodynamic drag force – unsteady flow regime. Dense building environment</td>
</tr>
</tbody>
</table>

**Notes:** MLIT1 \((\alpha = 1.5)\), MLIT2 \((\alpha = 2)\) and MLIT3 \((\alpha = 3)\): MLIT 2570 (MLIT, 2011); ASCE1 \((\alpha = 1)\) and ASCE2 \((\alpha = 1.3)\): ASCE 7-16 (ASCE, 2016). Foster1 \((b/w = 0.1)\) and Foster2 \((b/w = 0.6)\): Foster *et al.* (2017)
$S_1 = 0.701\, \text{g}$ at short periods and 1-s period, respectively. The buildings are intended to be used as residential buildings (Risk Category II). The plan dimension is $10.0 \times 15.0$ m, the story heights are 4.0 m in the first story and 3.0 m in other stories and the slab thickness is 180 mm. The dead load comprises member self weight, a 1.15 kN/m$^2$ load due to MEP (mechanical, electrical and plumbing) and floor finishing on slabs, and a 2.5 kN/m$^2$ load from partitions and infill walls. The floor live load is 2.5 kN/m$^2$ and the roof live load is 1.0 kN/m$^2$. As infill walls are considered as non-structural elements, the beam and column sizes for the three-story buildings without openings in all stories and with openings in the first story are identical. The section size of structural elements of the buildings is shown in Table III. The design compressive strength of concrete is 24 MPa, and the yield strength of longitudinal reinforcement bars and transverse reinforcement bars is taken as 400 and 240 MPa, respectively. The total seismic weight ($W$) of the buildings was 2,066 kN and the design base shear force was 0.117 $W$. The design process is carried out using ETABS (2016).

5. Structural model and tsunami pushover analysis
A two-dimensional finite element model of the central frame of the building is developed by considering both material and geometric nonlinearities using SeismoStruct (2018) (Figure 7). Beams and columns were modeled using the inelastic force-based frame element $infmFB$ with five integration points. For concrete, $con\_ma$, a uniaxial nonlinear confinement model based on Mander et al. (1988) is used. For steel, $stl\_mp$, a uniaxial steel model based on the constitutive model of Menegotto and Pinto (1973) is used. In SeismoStruct (2018), the P-$\Delta$ effects (geometric nonlinearity) are taken into account through the employment of a total co-rotational formulation developed and implemented by Correia and Virtuoso (2006).

<table>
<thead>
<tr>
<th>Story no.</th>
<th>Size (mm$^2$)</th>
<th>Longitudinal reinforcement</th>
<th>Transverse reinforcement*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam 1-3</td>
<td>250 × 450</td>
<td>4 No. 16</td>
<td>2 legs at 100 mm</td>
</tr>
<tr>
<td>Column 1</td>
<td>350 × 350</td>
<td>2 No. 20</td>
<td>2 legs at 100 mm</td>
</tr>
<tr>
<td>Column 2,3</td>
<td>300 × 300</td>
<td>2 No. 20</td>
<td>2 legs at 100 mm</td>
</tr>
</tbody>
</table>

Note: *No. 10 bar was used for transverse reinforcement
In the present study, tsunami pushover analysis is carried out using the tsunami load cases specified in Table II. Tsunami pushover is a quasi-static procedure where the structure is subjected to tsunami forces. Tsunami pushover analysis can be carried out by using the constant height pushover method (CHPO) – a displacement-controlled procedure or the variable height pushover method (VHPO) – a force-controlled procedure (Petrone et al., 2017).

The force-controlled VHPO method yields a pushover curve that does not capture post-peak behavior yet is considered adequate for the purpose of tsunami fragility analysis. Petrone et al. (2017) used the CHPO method, VHPO method and tsunami time-history analysis to obtain tsunami fragility curves and concluded that the VHPO method results were similar to the results obtained from tsunami time-history analysis. Hence, in the present study, the VHPO method is used.

In the case of the building without openings in all stories, the tsunami forces will act on the structural members and the infill walls, resulting in a 5 m wide tsunami affected area in every story of the building, up to the inundation height. For the building with openings in the first story, the width of the tsunami affected area is 0.35 m (width of column) in the first story and 5 m for the second and third stories, depending on the inundation height. As the tsunami water can flow through the building with openings in the first story, the tsunami forces are applied to all the columns of the first story [Figure 7(b)].

In SeismoStruct, the load combination used for gravity loads is 1.0DL + 0.25LL. The tsunami forces in VHPO analysis are applied as point loads applied at each floor level following the load discretization (B*) of Petrone et al. (2017), where an influence area approach is adopted to calculate the forces. The inundation depth is increased, and the resulting force magnitude and application point is used to obtain the pushover curves, as shown in Figure 8, for the load cases given in Table II. The last point of the pushover curves is related to convergence issues. As noted in Section 4, as infill walls are considered as non-structural elements, the buildings with and without openings in the first story have the same design requirements. Hence, the tsunami pushover curves will be similar for the buildings with and without openings in the first story.

6. Tsunami fragility analysis
6.1 Damage state classification and structural performance levels
Tsunami fragility curves are used to quantify the probability of exceedance at different performance levels as a function of tsunami intensity. In the present study, the inundation depth is considered as the tsunami intensity measure and the maximum inter-story drift ratio (IDR) is chosen as the engineering demand parameter (EDP) that closely

![Figure 7.](image-url)

**Notes:** (a) Building without openings in all stories; (b) building with openings in the first story
relates to the damage state of the building. Here, the methodology proposed by Macabuag et al. (2014b, 2014c) and Macabuag (2018) is adopted. The tsunami damage state classification, based on a physical damage description and related structural damage phenomena, is shown together with the associated damage criteria in Table IV. The tsunami damage state classification used in the present study is similar to the classification used by Macabuag et al. (2014a). It is noted that Macabuag et al. (2014a) refer to damage states DS1-DS6, but in the present study, only the relevant damage states given in Table IV are used in obtaining fragility curves.

In analogy with seismic fragility curves, three structural performance levels, namely, life safety-1 (LS-1), life safety-2 (LS-2) and collapse prevention (CP) corresponding to damage states DS1, DS2 and DS3 can be identified. For a particular structure performance level, the maximum IDR for each load case is obtained by using the damage criteria given in Table IV. The maximum IDR for different load cases corresponding to the structural performance levels LS-1, LS-2 and CP for buildings without openings in all stories and with openings in the first story are shown in Tables V and VI. For a particular damage state, the damage criterion will be reached for the building without openings at a lower inundation depth compared to the building with openings. Hence, for the building with openings when the damage criterion is reached, there should be more deformation of the RC frame and higher maximum IDRs are expected. The estimated threshold for the maximum IDR (i.e. limit state) is obtained from the mean value of maximum IDR for each load case.

<table>
<thead>
<tr>
<th>Damage state</th>
<th>Classification</th>
<th>Physical damage description</th>
<th>Structural damage phenomenon</th>
<th>Damage criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS1</td>
<td>Moderate damage</td>
<td>Damage to walls but no damage to columns</td>
<td>First yield of steel reinforcement</td>
<td>Steel reinforcement strain $\varepsilon_y &gt; 0.0013$</td>
</tr>
<tr>
<td>DS2</td>
<td>Significant damage</td>
<td>Heavy damage to several walls and some columns</td>
<td>First spalling of concrete cover</td>
<td>Concrete cover strain $\varepsilon_c &lt; -0.0018^*$</td>
</tr>
<tr>
<td>DS3</td>
<td>Collapse</td>
<td>Heavy damage to more than 50% of walls and several bent or destroyed columns</td>
<td>First crushing of core concrete</td>
<td>Core concrete strain $\varepsilon_c &lt; -0.0028^*$</td>
</tr>
</tbody>
</table>

Note: *Karthik and Mander (2010)
Pushover analysis that was used to plot the capacity curves shown in Figure 8 can also be used to generate the maximum IDR–inundation depth curves shown in Figure 9, where the structural performance levels LS-1, LS-2 and CP are also indicated. Note that the curves shown in Figure 9 are equivalent to the incremental dynamic analysis curves for peak IDR in seismic fragility analysis. In Figure 9(b), the kink in the curves corresponding to load cases MLIT1, ASCE1, ASCE2 and Foster1 occur when the tsunami water level has reached the bottom of the first story beam (i.e. the inundation depth is 3.55 m).

6.2 Fragility curves
Based on the maximum IDR–inundation depth curves (Figure 9), at each inundation depth, the tsunami load cases that result in reaching the selected structural performance level will yield the exceedance probability, which is then used to plot the fragility curves. The generalized linear model using a probit link function is used to plot the fragility curves.

**Table V.**
Maximum IDR (%) for different load cases and estimated threshold IDR for three-story RC building without openings in all stories

<table>
<thead>
<tr>
<th>Structural performance level</th>
<th>MLIT1 ((a = 1.5))</th>
<th>MLIT2 ((a = 2))</th>
<th>MLIT3 ((a = 3))</th>
<th>ASCE1 ((\alpha = 1))</th>
<th>ASCE2 ((\alpha = 1.3))</th>
<th>Foster1 ((b/w = 0.1))</th>
<th>Foster2 ((b/w = 0.6))</th>
<th>Estimated threshold IDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS-1</td>
<td>0.38</td>
<td>0.36</td>
<td>0.35</td>
<td>0.30</td>
<td>0.39</td>
<td>0.41</td>
<td>0.37</td>
<td>0.38</td>
</tr>
<tr>
<td>LS-2</td>
<td>0.71</td>
<td>0.68</td>
<td>0.68</td>
<td>0.72</td>
<td>0.71</td>
<td>0.72</td>
<td>0.68</td>
<td>0.70</td>
</tr>
<tr>
<td>CP</td>
<td>1.11</td>
<td>1.08</td>
<td>1.06</td>
<td>1.12</td>
<td>1.11</td>
<td>1.13</td>
<td>1.09</td>
<td>1.10</td>
</tr>
</tbody>
</table>

**Table VI.**
Maximum IDR (%) for different load cases and estimated threshold IDR for three-story RC building with openings in the first story

<table>
<thead>
<tr>
<th>Structural performance level</th>
<th>MLIT1 ((a = 1.5))</th>
<th>MLIT2 ((a = 2))</th>
<th>MLIT3 ((a = 3))</th>
<th>ASCE1 ((\alpha = 1))</th>
<th>ASCE2 ((\alpha = 1.3))</th>
<th>Foster1 ((b/w = 0.1))</th>
<th>Foster2 ((b/w = 0.6))</th>
<th>Estimated threshold IDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS-1</td>
<td>0.37</td>
<td>0.380</td>
<td>0.42</td>
<td>0.40</td>
<td>0.39</td>
<td>0.40</td>
<td>0.41</td>
<td>0.40</td>
</tr>
<tr>
<td>LS-2</td>
<td>0.76</td>
<td>0.71</td>
<td>0.81</td>
<td>0.78</td>
<td>0.75</td>
<td>0.77</td>
<td>0.80</td>
<td>0.77</td>
</tr>
<tr>
<td>CP</td>
<td>1.14</td>
<td>1.15</td>
<td>1.21</td>
<td>1.16</td>
<td>1.14</td>
<td>1.18</td>
<td>1.19</td>
<td>1.17</td>
</tr>
</tbody>
</table>

**Figure 9.**
Inundation depth vs maximum IDR for three-story RC building

(a) Without openings in all stories; (b) with openings in the first story

Notes: (a) Without openings in all stories; (b) with openings in the first story
The fragility curves of the typical three-story RC buildings for the three performance levels as a function of inundation depth are shown in Figure 10.

The buildings with openings in the first story as expected have a lower fragility for the same level of tsunami intensity (indicated here by inundation depth), when compared with the buildings without openings in all stories. This is attributed to the fact that the tsunami loads acting on the building are reduced because of the openings in the first story.

The fragility curves show that for the three-story RC building without openings in all stories; the probability of exceedance is almost 100 per cent when tsunami inundation depth has reached 4.5 m for LS-1, 5 m for LS-2 and 5.5 m for CP; while for buildings with openings in the first story, the probability of exceedance is nearly 100 per cent when tsunami inundation depth has reached 5.5 m for LS-1, 7 m for LS-2 and 7.75 m for CP. These results show that the considered buildings have a high probability of exceedance at any structural performance level, given that the recent 2018 Central Sulawesi tsunami had resulted in a 8 m inundation depth (Muhari et al., 2018).

7. Concluding remarks
In this study, the performance of three-story RC buildings located in Indonesia without openings in all stories and with openings in the first story, under tsunami forces is evaluated. The maximum IDR–inundation depth curves are used to generate fragility curves:

- The results show that three-story RC buildings with openings in the first story are less vulnerable to tsunami inundation forces than buildings without openings in all stories. It should be noted that there are other implications when the buildings have a first story with openings. Buoyancy forces are not considered in the present study but could lead to uplift and overturning of such buildings. On the other hand, debris depending on its size could pass through the building; hence, there will be no impact forces because of such debris. As the three-story building is designed following the seismic codes and is a low rise building, soft story effects are not relevant in this case.
- The fragility curves were obtained by considering tsunami inundation forces acting on buildings not affected by a prior seismic event. This scenario, although not

![Figure 10. Fragility curves of three-story RC buildings without openings in all stories and with openings in the first story for different performance levels](image)
realistic for buildings that sustain damage and have undergone inelastic deformations because of the preceding ground motion, is appropriate for locations where the peak ground acceleration (PGA) due to the seismic event is very low but the tsunami inundation forces are high. The buildings damaged in Sri Lanka, Thailand and India due to the 2004 Sumatra–Andaman Islands earthquake are an example of such a scenario (Inoue et al., 2007).

- The study should be extended to RC buildings with more than three stories, to investigate the difference in fragility for buildings without openings in all stories and with openings in the first story.
- In the present study, the tsunami inundation depth was selected as the intensity measure. The use of the tsunami peak force as the intensity measure, as suggested by Petrone et al. (2017), should be further investigated.
- The limit state IDR for the LS-1, LS-2 and CP performance levels were obtained from the mean values of maximum IDR for different load cases. It is preferable that such limit states are obtained for a range of buildings with different number of stories. In the case of seismic loading, Jeong et al. (2012) provide the limit state IDR for immediate occupancy (IO), life safety (LS) and collapse prevention (CP) for regular frame, irregular and wall-frame buildings.

The results of this study show the need to include tsunami loads in the design code for Indonesian buildings.

References


**Corresponding author**

Anil Christopher Wijeyewickrema can be contacted at: wijeyewickrema.a.aa@m.titech.ac.jp

For instructions on how to order reprints of this article, please visit our website: [www.emeraldgrouppublishing.com/licensing/reprints.htm](http://www.emeraldgrouppublishing.com/licensing/reprints.htm)
Or contact us for further details: permissions@emeraldinsight.com
The upstream-downstream interface of Sri Lanka’s tsunami early warning system

Richard Haigh, Maheshika Menike Sakalasuriya and Dilanthi Amaratunga

Global Disaster Resilience Center, School of Art, Design and Architecture, University of Huddersfield, Huddersfield, UK

Senaka Basnayake
Department of Climate Change and Climate Risk Management, Asian Disaster Preparedness Center, Bangkok, Thailand

Siri Hettige
Department of Sociology, University of Colombo, Colombo, Sri Lanka, and

Sarath Premalal and Ananda Jayasinghe Arachchi
Department of Meteorology, Colombo, Sri Lanka

Abstract

Purpose – The purpose of this paper is to deliver a detailed analysis of the functioning of upstream–downstream interface process of the tsunami early warning and mitigation system in Sri Lanka. It also gives an understanding of the social, administrative, political and cultural complexities attached to the operation of interface mechanism, and introduces an analytical framework highlighting the significant dynamics of the interface of tsunami early warning system in Sri Lanka.

Design/methodology/approach – Through the initial literature review, a conceptual framework was developed, highlighting the criteria against which the interface process can be assessed. This framework was used as the basis for developing data collection tools, namely, documentary analysis, semi-structured interviews and observations that focused on the key stakeholder institutions in Sri Lanka. Thematic analysis was used to analyze the data according to the conceptual framework, and an improved and detailed framework was developed deriving from the findings.

The views expressed in the paper are purely the views of the authors, and do not represent the views of any institutions or anyone attached to the institutions mentioned in the paper. The information is based on the data collected by the research team in Sri Lanka and the reports compiled after the data collection.

This research was co-funded by UK Global Challenges Research Fund (GCRF) and the Erasmus + Programme of the European Union Capacity Building in Asia for Resilience EducaTion (CABARET) 573816-EPP-1-2016-1-UKEPPKA2-CBHE-JP. The European Commission and UK GCRF support for the production of this publication does not constitute an endorsement of the contents which reflect the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.
Findings – The manner in which the interface mechanism operates in Sri Lanka’s tsunami early warning system is discussed, providing a detailed understanding of the decision-making structures; key actors; standardisation; technical and human capacities; socio-spatial dynamics; coordination among actors; communication and information dissemination; and the evaluation processes. Several gaps and shortcomings were identified with relation to some of these aspects, and the significance of addressing these gaps is highlighted in the paper.

Practical implications – A number of recommendations are provided to address the existing shortcomings and to improve the overall performance of tsunami warning system in Sri Lanka.

Originality/value – Based on the findings, a framework was developed into a more detailed analytical framework that depicts the interface operationalisation in Sri Lanka, and can also be potentially applied to similar cases across the world. The new analytical framework was validated through a focus group discussion held in Sri Lanka with the participation of experts and practitioners.

Keywords Early warning, Sri Lanka, Tsunami, Interface, Disaster risk reduction, Upstream–downstream

Paper type Case study

1. Introduction
The 2004 Indian Ocean Tsunami affected 14 countries and led to the deaths of more than 230,000 people (UNESCO, 2018). For Sri Lanka, this was the first tsunami on record and led to the deaths of more than 31,000 people, with over a million internally displaced and 150,000 who lost their livelihoods (Jayasuriya et al., 2006). At that time, there was no tsunami early warning system in the Indian Ocean. After the devastating 2004 tsunami, several countries came together to establish an effective tsunami warning system in the Indian Ocean region. An end-to-end tsunami early warning and mitigation system was established in 2008 and this became fully operational covering all the affected countries in 2013 (IOC/UNESCO, 2015a).

A tsunami early warning system should be end-to-end in nature, and should include several aspects of detection, warning, response and evaluation. It is typically understood to be as consisting of two main phases of upstream and downstream. The upper deals with the detection and forecasting (Bernard and Titov, 2015; IOC/UNESCO, 2015b), and the latter with warning dissemination and evacuation (de León et al., 2006; IOC/UNESCO, 2015b). Between these two, there occurs the interface where the decision to warning is taken and order for evacuation is given (Sakalasuriya et al., 2018). The interface mechanism is a complex and dynamic process involving a large number of stakeholders who operate at different levels. The decision-making involves technical knowledge as well as managerial and social skills to deal with the emergency situation and handle human subjects. At the national level, the interface mechanisms vary significantly depending on a wide array of geographic, demographic, social, political and cultural characteristics (Sakalasuriya et al., 2018). Although there are clear guidelines available at the national level, this complexity makes it difficult to operationalise the process and assess its effectiveness.

This paper describes the results from one part of a larger study to define and understand the interface mechanism in a tsunami early warning system; identify its strengths and weaknesses; and evaluate the socio-cultural and political complexities affecting the formation of the interface mechanism. In the first instance, a literature review was carried out to establish the current understanding of tsunami early warning system interface, and a conceptual framework was developed against which the interface process can be assessed (Sakalasuriya et al., 2018). The Indonesian and Sri Lankan tsunami early warning systems were selected as case studies for the analysis. The data collection tools were developed based on the conceptual framework, and primary data was collected regarding the operationalisation of the interface in these two countries.
In this paper, the findings from the study in Sri Lanka are presented, including recommendations to improve the interface of tsunami early warning system. The first section provides a brief literature review containing background information related to tsunami early warning systems, concepts underpinning the upstream–downstream interface and the conceptual framework used for the study. Section 2 details the research methodology. In Section 3, the findings are presented against the analytical framework. The concluding section sets out recommendations to improve the interface of the tsunami early warning system in Sri Lanka. The conceptual framework, developed from a literature review, was put to test during this study, and the framework was further improved to depict the interface of tsunami early warning system in Sri Lanka. The improved analytical framework is also presented in the concluding section, together with opportunities for future research.

2. Literature review

2.1 End-to-end tsunami early warning system and its components

Because of the scale of the threat posed by tsunami inundations on human lives, there has been considerable effort to establish early warning systems that can warn communities at risk. The end-to-end tsunami early warning and mitigation system is the single most effective way of predicting the impact of tsunami, and issuing warnings and evacuation orders to the public (Cecioni et al., 2014). With the prime objective of alerting the coastal communities about the potential tsunami impact, tsunami early warning systems engage a number of different institutions to deliver a variety of services, so that the system as a whole can deliver effective warning messages (IOC/UNESCO, 2015b; ISDR, 2004). The capacity to deliver timely predictions, accurate detection and warning messages, efficient alarms, reliable responses, strong communication, coherency and consistence are some of the essential requirements for the successful operation of a tsunami early warning system (Basher, 2006; Cecioni et al., 2014; Perry and Green, 1982). As with other hazard warning mechanisms, the tsunami early warning system includes four interactive elements: risk knowledge; monitoring and warning service; dissemination and communication; and response capability (de León et al., 2006; ISDR-PPEW, 2005). Failures in early warning systems mostly occur in preparedness in communication, and it is important to ensure monitoring and warning operates at its fullest accuracy to ensure the safety of the vulnerable communities (Basher, 2006).

The implementation and operation of an end-to-end tsunami early warning system involves technical knowledge, as well as the managerial knowledge of dealing with people and communities. Therefore, there are components of both natural and social sciences used in the system properties (Zschau and Küppers, 2002). An end-to-end tsunami early warning system starts with the detection of a potential tsunami, and extends to evacuation of people, and ends with their safe return to normal living conditions. It encompasses regional, national and local components, and involves regional, national and local stakeholders (de León et al., 2006; IOC/UNESCO, 2015b).

In general, early warning systems involve multiple components; are supported by a combination of different scientific bodies and experts; and engage a large variety of stakeholders. This complexity is also found in tsunami early warning systems, and sometimes more so, as they involve a regional dimension. A regional tsunami early warning system is typically divided into two phases: upstream and downstream. The upstream phase involves the detection of the earthquake and prediction of the tsunami by the tsunami service providers (TSPs), and delivering the warning to national warning centre for further analysis (IOC/UNESCO, 2015b). National-level warning organisations then evaluate the
country-specific impact of the tsunami, and if necessary, information is disseminated to the public and the order for evacuation is implemented. This is the downstream phase (Bernard and Titov, 2015). In addition to the technical aspects, the downstream process involves institutional, legal, social and cultural dimensions (Mukhtar, 2018). Between the upstream and downstream mechanisms, the decision to issue the warning and order for evacuation is taken in preparation for the tsunami impact, and this is known as the interface. According to Comes et al. (2015), the interface of an early warning system generally occurs between the two components of preparedness and response, and comprises of warning and evacuation decisions, deploying relief and organising the logistics for evacuation and sheltering. Interface is not merely the warning process, but the gap between the upstream and downstream mechanisms. However, in previous research as well as practical applications, the interface is rarely defined, and roles and functions within the interface vary significantly among and within countries. The operationalisation of interface remains largely unexplored in research and practice, and hence the large area of grey knowledge. It is difficult to understand its mechanisms as the key decisions can be taken nationally and/or locally, by political and/or administrative personnel, depending on geographic, political and cultural influences on the warning system.

The decision to issue the warning and the decision to evacuate the people take place in between these two mechanisms of upstream and downstream. This is where the interface of the warning system occurs. Those stakeholders involved in the interface mechanism vary significantly from country to country, as well as within a single country. Figure 1 illustrates the complexity of this process. For the purpose of the current study, interface is defined as starting from the reception of tsunami warning by the national tsunami warning centre (NTWC); goes through the process of national and local evaluation; and ends at where the order for evacuation is given and disseminated by the national and local disaster management organisations (Sakalasuriya et al., 2018). It encompasses three key actions of issuing the warning, conveying the warning and ordering for evacuation. The definition of interface and its position between upstream and downstream phases are further explained in Figure 1.

### 2.2 Conceptual framework

A detailed literature review was undertaken to understand the processes involved in a tsunami early warning system, from upstream monitoring and detection, to downstream

---

**Figure 1.** The position of interface within the end-to-end TEWMS

**Sources:** Authors’ composition; Sakalasuriya et al. (2018)
evacuation of the communities at risk. The review also considered the components and measures of an effective interface mechanism, between upstream and downstream. By doing so, the operationalisation of the interface of a tsunami warning system in a particular country can be assessed against key criteria. These measures were brought together into a single conceptual framework by the authors (Sakalasuriya et al., 2018). The conceptual analysis method was used to develop the framework (Jabareen, 2013). The below paragraph provides a summary of the issues discussed in the conceptual framework.

The ways in which decisions are taken within the interface are central to its operation. The authorities are responsible for taking speedy and accurate decisions, and in cases of potential or expected tsunami inundation, to warn and evacuate people (Ai et al., 2016). These decisions can be taken by the national- or/and the local-level actors, depending on the administrative structure pertaining to warning system and other local needs (InterWorks, 1998). For maximum effectiveness, it is important to integrate a wide range of stakeholders into the early warning system including those not typically recognised within the administrative structures, rather than just those organisations with formal mandates (Basher, 2006). The extent of decentralisation within a country is also a determinant of how a country’s tsunami warning system functions and especially its interface. While “warning decision” is generally recognised as a responsibility of the central authorities (Samarajiva, 2005), some argue that it is necessary to adopt a decentralised approach to disaster relief and evacuation processes (de León et al., 2006; Kapucu and Garayev, 2011). However, a decentralised tsunami warning system may fail to operate because of less sophisticated technology and inadequate human assets, which typically exist at the local level in developing countries (de León et al., 2006). The technical and human capacities of the stakeholders need to be adequate and up-to-date for the early warning system to function smoothly (Grabowski and Roberts, 2011; Kapucu and Garayev, 2011). At the same time, it is necessary to follow standard operating procedures (SOPs) regarding the warning and evacuation process (Nayak and Srinivasa Kumar, 2008), and develop and maintain the SOPs as specified by the intergovernmental oceanographic commission (IOC/UNESCO, 2016). The spatial and socio-cultural factors, such as hazard and vulnerability mappings (Bernard, 2005; Schlurmann et al., 2010), community education and participation (Collins and Kapucu, 2008; Dengler, 2005), indigenous and local knowledge (McAdoo et al., 2009) and religious and language difference (Perry, 2007), should also be taken into consideration when developing tsunami early warning systems. When a large number of institutions and individuals work together to provide safety to the people, it is essential that different institutions and sectors coordinate effectively, but also that each institution coordinates internally, including between administrative levels, for example, from the national to sub-national (Taubenböck et al., 2009; Waugh and Streib, 2006). On the other hand, all forms of formal and informal communication mechanisms should be accurate and timely to communicate among the stakeholders, as well as to disseminate the warning and evacuation information to the public (Aldunate et al., 2005; Samarajiva, 2005).

These issues formed the basis for a conceptual framework that comprises of nine components against which the interface mechanism can be assessed, and that can also be used as a guideline for its evaluation (Sakalasuriya et al., 2018):

- decision-making mechanism;
- clearly defined actors;
- centralised vs decentralised approach;
- standardisation of interface;
- technical capacity;
human capacity;
- spatial and socio-cultural aspects;
- vertical and horizontal coordination; and
- formal and informal communication mechanisms.

2.3 The tsunami early warning system in Sri Lanka

Sri Lanka’s coastal belt was severely affected by the Indian Ocean tsunami in 2004, recording the second highest death toll of 31,187 among the affected countries and with a further 4,280 people missing. A total of 23,189 persons were injured and the recorded number of displaced was 545,715 (Birkmann and Fernando, 2008; Hollifield et al., 2008). Prior to 2004, there was no recorded history of a tsunami event, and as a consequence, there was a lack of experience among the people, increasing their vulnerability. For the same reason, there was little in the way of formal preparedness for tsunami early warning in the country. After 2004, there was widespread recognition of a need to incorporate Sri Lanka in the regional disaster risk reduction mechanisms because of its vulnerability to future tsunami risks (Thomalla and Larsen, 2010). The Indian Ocean tsunami early warning and mitigation system (IOTWMS) was first established in 2008, and became fully operational within the region in 2013 (IOC/UNESCO, 2015a). Sri Lanka is a participating country of the IOTWMS, and the national disaster warning and management centres are operating under the training and guidance of the TSP (Hettiarachchi, 2018).

Since its inception, Sri Lanka has not experienced a tsunami, which has limited practical experience of the system. However, as a country exposed to tsunami risk, it is essential that Sri Lanka’s warning system and all its accompanying mechanisms function accurately in the face of an actual disaster (Birkmann and Fernando, 2008). Because of the infrequent nature of tsunami events, maintaining preparedness is a challenge, especially as memories of the 2004 event erode over time. The buffer zone which was initially operational in the coastal region soon after 2004 tsunami is not fully adhered to by the local people, and communities are extremely vulnerable to the immediate threat that can be caused by a tsunami inundation (Birkmann et al., 2010). On the other hand, given the economic and social conditions of the coastal communities, their resilience level is ranging from low to medium, requiring a greater amount of time and support to face an emergency situation (Sooriyaarachchi et al., 2018). In this context, it is important that the core warning system at the national level is functioning accurately and that all the mechanisms are in place to take swift decisions and actions in case of an actual tsunami event. This study set out to investigate and understand the operationalisation of the tsunami early warning system in Sri Lanka, especially decision-making and information dissemination process at the national level.

As an island exposed to sea from all sides and because of its complex political and administrative structures, Sri Lanka provides an interesting case to examine the issues arising at the national level. The study can be a strong foundation to adapt the analytical framework to similar island countries such as Madagascar, Maldives, Timor-Leste, Seychelles and Mauritius (UNESCO, 2018). The Disaster Management Act was officially launched in Sri Lanka in 2005, and legal and administrative systems needed to be adjusted to suit the preparedness mechanisms for tsunami (Thomalla and Larsen, 2010). Since its initiation, practitioners focused more on the technical aspects of the warning system rather than the administrative and social aspects (Birkmann et al., 2010). Therefore, in this study, the emphasis is on the complex issues around decision-making and warning dissemination,
which involves the human and social subjects. It will also clarify the ambiguities on roles and responsibilities of stakeholders involved in the warning system in Sri Lanka (Thomalla and Larsen, 2010).

The aim of this paper is to provide an analysis of the complex political, social and cultural dynamics affecting the interface of tsunami early warning in Sri Lanka. In doing so, the authors try to identify the shortcomings of its operation, and thereby provide recommendations to improve the early warning system as a whole. The conceptual framework identified through literature review is applied to the tsunami early warning interface in Sri Lanka to assess its effectiveness, and the additional complexities that occur at the operational level were also examined during the analysis. The case of Sri Lanka is used to test the conceptual framework and to improve it to a country-specific analytical framework.

3. Methodology
Based on the conceptual framework highlighted in the literature review, data collection tools were developed for the study. Several data collection techniques were used, including documentary analysis, interviews and observations. The existing documents, both at a national and international levels, were analyzed using the documentary analysis method. The organisational documents are not neutral sets of transparent decisions or guidelines; rather they represent the values and constructs of the organisation itself, as social facts. The documentary analysis is used here to understand these constructs from the perspective of the organisation. However, the researchers understand that these documents do not demonstrate the actual operation of the institutions and cannot be used as evidence (Atkinson and Coffey, 2004).

For primary data collection, the key informants were interviewed from the following institutions:
- Department of Meteorology (DoM)–NTWC;
- Disaster Management Centre (DMC)–National Disaster Management Organisation (NDMO);
- Department of Fisheries and Aquatic Resources (DoFAR);
- National Aquatic Resources, Research and Development Agency (NARA);
- Geological Survey and Mines Bureau (GSMB);
- Coast Conservation Department (CCD);
- Ministry of Health (MoH); and
- Ministry of Disaster Management (MDM).

There are several key stakeholder institutions involved in the tsunami early warning system in Sri Lanka, and they were reasoned to be appropriate for data collection by the research team because of each of their specialist involvement in the interface process (Table I). As pointed out by Eisenhardt and Graebner (2007), informants for primary evidence can be chosen based on their specific knowledge and distinctive role in a particular field. By choosing a sufficient number of informants from a diverse set of institutions, the data tends to be less biased and more dynamic in perspective. An interview guideline was developed and semi-structured interviews were conducted with key personnel from the above-mentioned departments, ministries and institutions, who are directly involved in early warning activities before, during and after a tsunami. The individuals selected for the interviews were among the top-ranking officers in the relevant institutions. They should
have knowledge about the SOPs, legislations and guidelines in tsunami warning system, as well as direct and long-term experience on the operationalisation of the interface mechanism in Sri Lanka. The positions of the key informants who participated in the interviews, alongside the relevant institutions, are listed in Table I.

In addition to interviews and documentary analysis, observation was also used as a method to gather useful data related to the interface process, such as operations within departments; position and operation of tsunami towers; and the drills and simulation exercises. The lessons learnt from previous tsunami exercises conducted under IOWave16, and table-top exercises, were also considered for this study to identify the shortcomings within the existing system.

Thematic analysis was used to analyze the collected data. Thematic analysis is a flexible approach used to analyze qualitative data by identifying, analyzing and reporting patterns within the data. While organising the data sets and describing them, it can also be used to interpret the various aspects of the subjects being researched in a detailed manner (Braun and Clarke, 2006). The themes are based on the original conceptual framework developed during the literature review phase, and the themes additionally identified through the data analysis. Using the data analysis, the original conceptual framework was updated to reflect the Sri Lankan situation in particular, and the practicalities of the interface mechanisms. The conceptual framework that was initially developed through literature review was further improved using the framework analysis method. At the same time, a draft of synergised SOPs for all national interface institutions of Sri Lanka was developed. A focus group discussion (FGD) was held in Sri Lanka to present the findings and the recommendations of the study, with the participation of key personnel at the managerial level of national interface institutions in Sri Lanka, and experts in tsunami early warning systems. The two main outcomes of the research, namely, the updated analytical framework and the synergised SOPs, were presented at the FGD, and framework was validated during the discussion.

4. Analytical framework
4.1 Defining the interface in Sri Lanka
In Sri Lanka, the tsunami bulletins from TSPs are received by the Department of Meteorology (DoM) which acts as the NTWC. This warning information is assessed and cross-checked with other sources, before being communicated to the DMC, the primary national disaster management organisation (NDMO) of Sri Lanka. The decision to disseminate the warning and order for evacuation takes place at the national level, and with the involvement of both DoM and DMC. The DMC issues the warning and evacuation orders

<table>
<thead>
<tr>
<th>Institution</th>
<th>Position of informant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ministry of Disaster Management</td>
<td>An additional secretary</td>
</tr>
<tr>
<td>Department of Meteorology</td>
<td>A director</td>
</tr>
<tr>
<td>Department of Meteorology</td>
<td>A deputy director</td>
</tr>
<tr>
<td>Disaster Management Centre</td>
<td>An assistant director</td>
</tr>
<tr>
<td>Department of Fisheries</td>
<td>An assistant director</td>
</tr>
<tr>
<td>Coast Conservation Department</td>
<td>A senior engineer</td>
</tr>
<tr>
<td>Geological Survey and Mines Bureau</td>
<td>Geologist</td>
</tr>
<tr>
<td>National Aquatic Resources, Research and Development Agency</td>
<td>A senior scientist</td>
</tr>
<tr>
<td>Ministry of Health</td>
<td>A medical doctor</td>
</tr>
<tr>
<td>Department of Meteorology</td>
<td>A meteorologist</td>
</tr>
</tbody>
</table>

Table I.
Key informants selected for interviews from stakeholder institutions in TEWMS in Sri Lanka
through multiple channels to a number of national and local stakeholders including the media and District Disaster Management Centres (DDMCs). The downstream process starts after the information is disseminated from DMC to local authorities and the media. Therefore, the interface in Sri Lanka is defined as starting from the reception of warning information at DoM and ending with the orders received by the national- and local-level stakeholders for dissemination (Figure 2).

4.2 Decision-making mechanisms

The DoM of Sri Lanka has the primary responsibility for issuing the tsunami warnings as the NTWC of the country. According to the respondent from DoM, immediately after an earthquake, NTWC at DoM receives earthquake information and messages from the California Integrated Seismic Network (CISN). DoM also confirms the earthquake message with the information provided through the United States Geological Survey (USGS) and earthquake messages from Indian Ocean TSPs. GSMB also receives earthquake information from its own regional centres, who analyze them further for location, depth and magnitude. DoM is required to use all of these possible information sources and analyze data within the shortest possible time, to make an accurate decision. The decision-making criteria for DoM are guided by the specifications given by UNESCO and the Indian Tsunami Early Warning Centre. Accordingly, DoM should be alert for tsunami generation if magnitude of the earthquake is greater than 6.5 and depth from the epicentre is less than 100 km, and that are nearshore or offshore of the Indonesian region or Makran zone (DMC, 2015).

After confirmation with all parties, the tsunami warning bulletins are issued by DoM to be used by DMC for dissemination. After understanding the severity of the tsunami threat using information received from TSPs, the DoM issues tsunami warnings and disseminates this to the Director General of DMC, the Secretary to the Ministry of Disaster Management, the Secretary to the President and other relevant departments.

Real-time sea levels should also be used as key observations by DoM to determine the existence of a major tsunami threat or to cancel the tsunami warning following an earthquake. The real-time sea level data is used together with numerical modelling output to provide accurate tsunami information (UNESCAP, 2009). To fulfil this requirement, National Aquatic
Resource Agency (NARA) continuously monitors changes of sea level and communicate the situation with DMC and DoM (Interview). NARA does not maintain a 24 × 7 roster because of inadequate capacity. However, they will remotely monitor, even during holidays and night, if there is a tsunami threat to Sri Lankan coast. The DoM also receives information regarding sea level changes from NARA, and the latter is responsible to keep the DoM updated about the latest developments when the tsunami reaches the Sri Lankan coast (sourced from interviews).

DMC acts as the National tsunami focal point in Sri Lanka. After receiving the warning information, DMC has the responsibility of managing the emergency situation and warning dissemination. On receipt of the early warning and recommendation for evacuation, the Secretary of the Ministry Disaster Management should issue the evacuation order at national and district levels (DMC, 2015). DMC is also accountable for circulating warning information to the media networks and other institutions at national level such as Department of Railway, Department of Fisheries, Department of Health, Sri Lanka Telecom, Sri Lanka Transport Board, Ceylon Electricity Board and Ports Authority. The local disaster management officers and district secretaries of the coastal areas exposed to tsunami are also relying on the DMC’s information to implement local preparedness plans. In addition, DMC should deliver the warning information to the “office of the chief” of the defence staff, Sri Lankan Police, Army, Navy and Air Force headquarters. While taking the central decisions of information dissemination and disaster management, the DMC is responsible for managing the information and decision-making flow through to the grassroots level (DMC, 2015).

It is essential that the formal order for evacuation is officially signed off by the secretary to the MDM (DMC, 2015). A state of disaster can be declared by the president or by the disaster management council upon the motion of the president (Sri Lanka Disaster Management Act, 2005). The primary role of issuing the order for evacuation lies with the secretary to MDM. However, the director general of DMC has the authority to issue the evacuation order in their absence or on behalf of the secretary to MDM. The Director of the Emergency Operation Centre (EOC) and Duty Officer at DMC are also authorised to issue evacuation orders on behalf of the secretary to MDM and the Director General of DMC.

The guidelines and criteria for decision-making related to warning decision and dissemination are specified in the documents analyzed in the study, including the National Emergency Operation Plan (NEOP), the Disaster Management Act and SOPs of the individual institutions. However, during interviews, it was revealed that some of the guidelines are not well documented and the specifications of individual institutions differ from each other. The decision-making responsibilities of DoM and DMC are also confusing, such as overlaps in responsibility. For example, the DoM has the capacity to analyze the risk and convey the warning to national-level stakeholders, yet DMC maintains direct links with the TSP during an emergency. However, the DMC does not take any actions until official bulletins are issued by DoM. While this type of redundancy can be beneficial if planned and managed, it can also lead to conflicting decisions and misunderstanding. Even some top-level stakeholders were not certain about the specific decision-making power of the relevant institution, and several respondents felt this created confusion within the interface mechanism (sourced from interviews).

4.3 Clearly defined actors
Through the interviews and documentary analysis, 18 different key actors were identified as having an important role in the tsunami interface process. While some stakeholders are key in decision-making, others play a significant role in receiving and disseminating warning
Identifying all the stakeholders and integrating them in the warning system is essential for delivering clear and timely warning information, especially those stakeholders who are not officially recognised in traditional processes (Basher, 2006). It was discovered that some organisations, such as the Tourist Board and local-level DMCs, are not properly integrated into the main flow of tsunami information dissemination. NARA, which previously operated at its fullest capacity to monitor the sea level, is no longer operating on a 24 × 7 basis because of a number of issues, including lack of resources. The Monitoring, Control and Surveillance (MCS) divisions at the local level in Jaffna and Mannar, operating under DoFAR, also do not operate 24 × 7. DoFAR faces multiple challenges of lack of resources and technology, which affects their capacity to deliver warning messages to one-day boats. This issue is further discussed in Section 4.6.

4.4 Centralised versus decentralised approach
It was also discovered through interviews and documentary analysis, that a centralised approach is used in tsunami early warning decision-making in Sri Lanka because of the geographical conditions and administrative structures. Rosenthal and Kouzmin (1997) highlight that the decision-making in disasters is affected by five dimensions: scale, administrative response, governance style, response strategy and timing. Accordingly, the colossal nature of tsunami disaster and its impact requires the decisions to be taken centrally for a country such as Sri Lanka, and the administrative structure also supports the centralised decision-making mechanism. As a small island and one that operates on a centralised governance system, the key decisions of issuing the tsunami warning and ordering for evacuation are taken at the national and ministerial levels, whereas the district and local institutions are vested with the responsibilities of delivering information and facilitating the timely evacuation of people. A notable gap during the course of the implementation of the tsunami recovery process is the almost total exclusion of local government from the decision-making processes.

4.5 Standardisation of interface and legal frameworks
SOPs are the guidelines to be followed in a tsunami situation. They are agreed upon by key stakeholders and help them decide on who, what, when, where and how for tsunami early warning and response should be enacted (United Nations ESCAP, 2018). In Sri Lanka, the tsunami warning process goes through the hierarchy from one institution to the other; from TSP to DoM, from DoM to DMC and from GSMB to DMC. SOPs are principally prepared by DMC and DoM, and these are prepared internally for the institutions to follow. Institutions such as MoH and MDM also have their own internal guidelines. Although separate sets of SOPs are available for certain organisations, SOPs of different institutions are not formally integrated. Because of a lack of understanding of each other’s roles and an absence of integration, disagreements and misperceptions can occur during an emergency. At the time of data collection, an integrated and synergised SOP was not available at the national-level interface institutions in Sri Lanka.

With the occurrence of the Indian Ocean tsunami in 2004, the need to have a NEOP was highlighted through the Disaster Management Act, No. 13 of 2005. The NEOP was prepared by DMC and all the SOPs pertaining to evacuation plans are described in this document. NEOP and the Disaster Management Act are the legal documents for disaster management in the country, covering the response mechanisms for meteorological, hydrological,
Table II.
Roles played by key actors

<table>
<thead>
<tr>
<th>Key actors</th>
<th>Roles within the interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>DoM</td>
<td>Receive tsunami information and updates from TSPs</td>
</tr>
<tr>
<td></td>
<td>Evaluate, monitor and issue tsunami warnings</td>
</tr>
<tr>
<td></td>
<td>Send tsunami warning information to DMC</td>
</tr>
<tr>
<td></td>
<td>Operating 24 × 7</td>
</tr>
<tr>
<td>DMC</td>
<td>Receive warning information from DoM</td>
</tr>
<tr>
<td></td>
<td>Issue the official tsunami warning to the public</td>
</tr>
<tr>
<td></td>
<td>Issue the evacuation order under MDM approval</td>
</tr>
<tr>
<td></td>
<td>Disseminate warning and evacuation order to all other actors</td>
</tr>
<tr>
<td>GSMB</td>
<td>Monitor earthquakes at three monitoring stations</td>
</tr>
<tr>
<td></td>
<td>Receive earthquake information from regional centres</td>
</tr>
<tr>
<td></td>
<td>Calculate the risk of earthquakes</td>
</tr>
<tr>
<td></td>
<td>Issuing information to DoM and DMC</td>
</tr>
<tr>
<td></td>
<td>Participate in evaluation and decision-making</td>
</tr>
<tr>
<td></td>
<td>Update risk information by monitoring new developments</td>
</tr>
<tr>
<td>DoF</td>
<td>Receive information from DMC and DoM</td>
</tr>
<tr>
<td></td>
<td>Monitoring Controlling Surveillance (MCS) division of DoF immediately</td>
</tr>
<tr>
<td></td>
<td>disseminates the warning via SSB to 20 radio rooms (local MCS centres)</td>
</tr>
<tr>
<td></td>
<td>Local MCS divisions mostly operating 24 × 7, send the warning message to multi-day boats</td>
</tr>
<tr>
<td></td>
<td>Send the warning message to fishing communities living in the coastal areas</td>
</tr>
<tr>
<td></td>
<td>Pass information to managers at Ceylon fishery harbours</td>
</tr>
<tr>
<td>CCD</td>
<td>Support authorities by providing operational resources</td>
</tr>
<tr>
<td></td>
<td>Support evacuation and rescue operations</td>
</tr>
<tr>
<td>NARA</td>
<td>Measure sea levels using three monitoring stations</td>
</tr>
<tr>
<td></td>
<td>Be alert about sea levels after receiving warnings from DOM</td>
</tr>
<tr>
<td></td>
<td>Send information on sea level changes to DoM and DMC</td>
</tr>
<tr>
<td></td>
<td>Estimating damages to aquatic and fishery after the tsunami</td>
</tr>
<tr>
<td>MoH</td>
<td>Safeguard health institutions to minimise damages</td>
</tr>
<tr>
<td></td>
<td>Be on alert for service in emergency situation</td>
</tr>
<tr>
<td></td>
<td>Providing safety for patients</td>
</tr>
<tr>
<td></td>
<td>Plan the continuation of critical services</td>
</tr>
<tr>
<td>Tri forces (army, navy, air force)</td>
<td>Lead evacuation and rescue operations</td>
</tr>
<tr>
<td></td>
<td>Providing relief and essential services</td>
</tr>
<tr>
<td></td>
<td>Safeguard private property</td>
</tr>
<tr>
<td>Sri Lanka Police</td>
<td>Disseminate warning messages</td>
</tr>
<tr>
<td></td>
<td>Activate sirens and PA systems</td>
</tr>
<tr>
<td></td>
<td>Maintain law and order, rescue operations</td>
</tr>
<tr>
<td>Media</td>
<td>Receiving information and updates from DoM</td>
</tr>
<tr>
<td></td>
<td>Disseminate the warning to the public</td>
</tr>
<tr>
<td>MDM</td>
<td>Approve warning and evacuation orders</td>
</tr>
<tr>
<td></td>
<td>Issue official warning and evacuation orders</td>
</tr>
<tr>
<td></td>
<td>Lead the risk assessment and coordination</td>
</tr>
</tbody>
</table>

Note: Interviews

biological, technological and man-made disasters in Sri Lanka. The existing legal framework of the country allows the DMC and other stakeholders to operate according to the emergency situations that arise from time to time.

During the FGD that was held for validation of data with national and international experts, it was discovered that the SOPs followed by the DoM with regard to issuing of tsunami bulletins were not updated in line with the regional requirements. The tsunami bulletins are specified for the region by TSPs to be issued and followed by the national- and
local-level DMCs in individual countries. The bulletins followed by the DMC and DoM in Sri Lanka were found to be obsolete and were not updated since 2012. This is a major shortcoming discovered within the SOPs in Sri Lanka, which has resulted in the country’s warning mechanism to be at variance from others in the region and not complying with international standards. The high-level officers in interface institutions in Sri Lanka were informed of this drawback during the FGD, which prompted them to act swiftly to make amendments. This issue is further discussed in Section 4.11.

4.6 Technical capacity
The improvement of technology used in tsunami early warning systems depends both on disaster risk and socio-economic factors (Bernard and Titov, 2015). Since the 2004 Indian Ocean tsunami, government and international agents work together to improve the national tsunami early warning system in Sri Lanka and keep it updated with technological advances, especially to facilitate the process of prediction and warning at the DoM. The DoM, NARA and GSMB are the main institutions that use high-end technology within the country to determine the magnitude of tsunami. All the other institutions require technical capacity to disseminate the warning information, and the DoFAR needs specialist equipment to manage radio communication with fishing boats. In addition, DMC is endowed with the responsibility of updating the technology and maintaining tsunami early warning towers located around the country. It was discovered during the data collection that most of the national-level institutions are well equipped to deal with tsunami emergency at the interface level. The only significant issue is in the DoFAR, where there is no proper mechanism to pass warning messages to one-day boats. These boats are not equipped with radio systems. Currently, the DoFAR is developing a system to overcome this issue. There are also issues of weak and breaking signals of single-sideband modulation (SSB) systems that deliver messages to multi-day boats, and a lack of radio communication facilities in a number of local MCS divisions operating around the country. These problems need to be addressed to provide the ability to warn fishermen at risk from tsunami. Previous research often highlighted that institutions in developing countries have a lack of technical resources to deal with natural disasters (de León et al., 2006). This was found to be partly the case in Sri Lanka, especially in DoFAR and at the local level. However, key national-level institutions such as DoM and DMC have acquired adequate technical capacity over the years to deal with a tsunami situation and update the technology according to international standards (interviews). Having such technical capacity at the national level is crucial, as TEWMS cannot afford to fail during an emergency because it carries a large responsibility to provide reliable information (Grabowski and Roberts, 2011).

4.7 Human capacity
The human factor brings an important dynamic to the issue of early warning, especially with regard to decision-making and response (Perry, 1979). The historical experiences of failures in a tsunami early warning mechanism have highlighted the need for adequate organisational capacity and preparedness for emergency response in the operationalisation of warning system (Kapucu and Garayev, 2011). In Sri Lanka, DoM, which acts as the NTWC, operates on a continuous basis and 24 × 7. Officers are on duty on a roster basis. While working on disaster-related information, the weather forecasters also have to provide day-to-day weather information to the public and media through the National Meteorological Centre (NMC). This is a heavy workload for the specialists in the DoM, and can also distract them from one duty to another. There is a need to expand human capacity at DoM and engage people in specialised tasks rather than in several. The EOC of the
national DMC in Sri Lanka also functions 24 × 7, and two officers are on duty at a time. However, the annual transfers and promotions to other divisions at both national DMC and district DMCs have caused problems. Once the trained officers are transferred or promoted, the institutions have to either rely on untrained staff, recruit new staff or train existing staff to suit the vacant position. Although GSMB functions on a 24 × 7 roster duty basis, very few staff members operate in the night and that number is not adequate for an actual tsunami situation. The MCS division of DoFAR also has inadequate capacity to carry out continuous services, and as a result, only seven local MS centres around the country operate on a 24 × 7 basis. NARA also struggles to provide 24 × 7 sea level measurements. As a result, sea levels are monitored mainly during day time. However, when the DMC announces the threat of a tsunami inundation, NARA arranges emergency facilities to monitor sea levels based on the warning information.

4.8 Spatial and socio-cultural factors

The cultural factors, including religion, local languages, myths and beliefs play a significant role in shaping the public response to disasters, and thus it is essential to consider the barriers and opportunities that arise in early warning systems because of the socio-cultural factors (McAdoo et al., 2009; Perry, 2007). The NTWC and DMC in Sri Lanka have been facing challenges because of the predictions given by astrologers which tend to misguide and confuse the general public. Given the complexity that some of these social and cultural factors bring into the picture, public opinions and responses cannot be taken for granted and an appropriate public education strategy needs to be developed in collaboration with media institutions. Community participation is important for the effective operation of an early warning system. About 75 per cent of the vulnerable population has undergone tsunami preparedness training (interviews from DMC). Tsunami preparedness is included in school curriculum at primary and secondary levels to raise awareness of school children. Furthermore, all of the coast around Sri Lanka has been hazard mapped at the scale of 1:50,000 by DMC. This information needs to be widely disseminated.

4.9 Vertical and horizontal coordination

When working towards the common objective of providing safety to the public, it is important that all stakeholders coordinate effectively to minimise confusion and inaccuracies (Taubenböck et al., 2009; Waugh and Streib, 2006). Yet, in the case of Sri Lanka, certain misunderstandings occur at the national level because of the lack of effective coordination and not having a synergised SOP. The DoM receives tsunami-related messages from TSPs, and after a thorough assessment, warning information is disseminated to DMC for further actions. Furthermore, DoM is responsible for continuously interacting with GSMB and NARA to receive information related to seismic and oceanic activities. As DoM receives tsunami information from TSPs on a regular basis, DoM does not recognise a need to liaise with GSMB in the event of a tsunami situation, as they could only provide earthquake information. NARA is mainly responsible for monitoring sea level and it could, at best, only provide information on sea level changes after a tsunami wave has already reached the Sri Lankan coastline, which would be too late for DoM to integrate into their decision-making process.

4.10 Formal and informal communication mechanisms

Once the decision to warn and evacuate is taken at the national level, the information regarding the disaster and warning is communicated to the public. Good communication and information dissemination is essential to operationalise an effective tsunami warning
system. It should be clear, accurate and timely, both between institutions and from institutions to the public (Aldunate et al., 2005; Samarajiva, 2005). In Sri Lanka, DMC has the primary responsibility of disseminating information to the media and to the local stakeholders who engage with providing safety to the public. DMC maintains a number of communication modes such as telephone, SMS, fax, HF/VHF systems, VPN system and early warning towers to disseminate messages. Other stakeholders at the village level use communication modes such as megaphones, loudspeakers and temple bells. The use of multiple communication channels ensures redundancy. Since the tsunami occurrence in 2004, the public are more alert than before, and usually pay attention to earthquakes in the Indian Ocean region. However, gaps in communication were identified in the fisheries and tourism sectors. In spite of the large number of tourists visiting Sri Lanka each year, including many to coastal regions and who may be unfamiliar with tsunami risk, there is a lack of targeted information, such as in multiple languages, or emergency information in hotels. Sign boards were set up soon after the 2004 tsunami, specifying safety routes and information, but these were not properly maintained. The communication flow can be improved further by addressing these issues and integrating fishery and tourism sectors into the main tsunami institutional network.

4.11 Ongoing evaluation

During the course of data collection and analysis, it was established that the continuous evaluation process, related to stakeholders and functions of early warning system, is an essential component of analyzing the tsunami interface process. Although this issue was not a part of the initial conceptual framework, a considerable number of previous researchers have emphasised the significance of ongoing evaluation in any form of early warning mechanism. It is important to keep the warning and response operation up to date by testing the system for accuracy (UNISDR, 2006). The errors and mistakes that can occur in case of an actual disaster can be minimised by detecting the weaknesses in advance through continuous evaluation (Titov et al., 2005). Public education of hazard awareness, research and development are important parts of the evaluation process (Paton et al., 2008). While carrying out the scheduled tsunami drills and system evaluation processes regularly, the evacuation routes and signs should be maintained at a satisfactory level. The evacuation plans and maps should also be updated continuously, taking into consideration changes of transport infrastructure and other development activities (Mas et al., 2012). Conversely, feedback from the drills and evacuation exercises should be taken into account when planning buildings and infrastructure (Mas et al., 2015).

As highlighted in Section 4.5, in spite of changes to the format of tsunami warning bulletins issued by TSPs at the regional level and followed by national institutions in Sri Lanka, the SOPs in Sri Lanka had not been updated since 2012, resulting in divergences between information and protocols at the regional and national levels. It is evident that proper mechanisms were not in place to maintain the SOPs and tsunami bulletins, and they were not operating in conformance with regional protocols. This was in spite of regular drills, simulations and participation in IOWave (Indian Ocean Wave) exercises. A potential reason identified through the interviews and FGDs was the failure to maintain SOPs according to international requirements. Although the officials from Sri Lanka have regularly participated in the regional and international training and workshop events, the recommendations and improvements suggested to them were not implemented at the national level. Interview respondents also revealed that a national debriefing did not take place in Sri Lanka after regional trainings.
In the NEOP, all the processes related to tsunami warnings and alerts are clearly specified, as well as the SOPs for the respective institutions. These specifications are required to be tested regularly using drills and simulation exercises. The IOWave exercises are normally carried out every two years at the regional level, and include participation by many of the Indian Ocean countries and their respective stakeholders, including Sri Lanka. DMC and other relevant stakeholders prepare reports to provide feedback to improve the system. DMC also conducts national simulation exercises to test the technical components of the TEWMS once every year, and provides training to address the weaknesses that are observed within the system.

5. Conclusions and recommendations
The analysis provided in Section 4 is based on the conceptual framework developed at an earlier stage of this research. The operationalisation of the interface in an end-to-end tsunami warning system was assessed against each criterion of the framework. The findings revealed that in Sri Lanka, the SOPs, decision support guidelines, legal framework, the roles and responsibilities of the stakeholders and the communication flow are clearly specified and easily available for reference. However, improvements are needed in several areas to ensure the proper functioning of the warning system. Several institutions face issues regarding technical and human capacity including DoM, DMC, GSMB, DoFAR and NARA. Issues exist in terms of clarity of SOPs and the roles of different stakeholders during decision-making processes. The gaps in communication and evaluation processes should also be addressed to better deliver the warnings to the public.

The analytical framework, initially identified through the literature review, was tested in the present study. These results have revealed several areas where the conceptual framework can be improved. For instance, ongoing evaluation of the tsunami interface mechanism was shown to be a significant and vital component, and this has been added as a main concept to the analytical framework.

The improved analytical framework for the interface of tsunami early warning system is presented in Figure 3, as nine major concepts with sub-components added under each concept.

In addition, the study revealed several important aspects that need to be addressed to strengthen the interface mechanism of the end-to-end tsunami warning system in Sri Lanka. The recommendations are as follows:

- SOPs should be prepared for all the institutions engaged with tsunami warning and evacuation at all levels, and they must be approved by a national-level disaster institution before implementation.

- A synergised national SOP should be developed as a general guideline for all the stakeholders in the tsunami warning system, to better understand the flow of command, coordination and communication.

- To integrate the role of GSMB and to use their fullest capacity, GSMB should establish better coronation and communication links with DMC and DoM.

- It is important to engage other relevant institutions such as Marine Environmental Protection Authority (MEPA) to participate in near- and offshore tsunami warning processes, and use the available resources. Links can be established between national disaster organisations and MEPA to improve the capacity and the information flow.

- It is essential to improve the technical capacity of the institutions related to DoFAR and MCS divisions. All one-day boats should be equipped with radio systems to receive the tsunami warnings issued by the DoFAR.
Human capacity should be improved and maintained at a satisfactory level in all institutions, and specialist trained officers should be allocated, particularly to DoM to analyze risks before issuing warnings. A mechanism should be in place to retain the trained staff in the same department and to train existing staff in case of transfer or retirement.
• Given the fact that continuous evaluation is a critical aspect of the early warning system, an independent committee could be identified to undertake periodic evaluation of the functioning of the system based on a clear check list as an added precaution to ensure the reliability of the early warning system, from national through regional to local levels.

6. Practical implications and future work
As mentioned in Sections 4.5 and 4.11, the tsunami bulletins issued by the national-level institutions were not updated since 2012. After the findings of the study were presented at the FGD, the national-level institutions were prompted to update the bulletins to match the regional standards. During the validation process, a draft of synergised SOPs was also presented to the stakeholder to be adopted by national interface institutions. A formal agreement is yet to be made among the stakeholders in terms of establishing a permanent guideline to be referred at the national level.

The revised analytical framework can be applied to other countries at risk from tsunami, but that may have very different political, geographic, socio-cultural and technical contexts. In addition, there is a need to further develop and test the framework for a multi-hazard environment, which has been prioritised in the Sendai Framework for Disaster Risk Reduction, and can afford potential synergies and efficiencies for early warning.

References


About the authors

Professor Richard Haigh is Chair of Disaster Resilience at the University of Huddersfield, UK. His main research interests include disaster risk governance and multi-hazard early warning. He has secured over 20 related research grants. Richard is a UK Advocate to the UN Making Cities Resilient campaign and an expert member of the Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System (ICG/IOTWMS) WG-1 on Risk, Community Awareness and Preparedness. He is Founding Editor-In-Chief of the International Journal of Disaster Resilience in the Built Environment. https://pure.hud.ac.uk/en/persons/richard-haigh

Maheshika Menike Sakalasuriya is a PhD student at the School of Art, Design and Architecture, of University of Huddersfield, UK. She is also attached to the Global Disaster Resilience Centre as a Research Assistant. Her main research interest is on post-conflict issues, and currently undertaking her PhD on the consequences of post-conflict infrastructure reconstruction interventions. She has also developed knowledge and interest in disaster prevention, conceptual analysis and theory building, and involved in research related to natural disasters and early warning systems. She has published several papers on both post-conflict reconstruction and early warning systems, especially focusing on the theoretical frameworks and conceptual analysis. Maheshika Menike Sakalasuriya is the corresponding author and can be contacted at: Maheshika.Sakalasuriya@hud.ac.uk

Dilanthi Amaratunga is a Professor of Disaster Risk Management at the University of Huddersfield, UK. She is the Editor-in-Chief of the International Journal of Disaster Resilience in the Built Environment, and has led the international peer review panel of the UN Global Assessment Report input papers in 2015. Dilanthi has also led and chaired a large number of international conferences, demonstrating her role as a leader and as a conduit to international collaboration and engagement. Dilanthi has published over 250 peer-reviewed articles and delivered over 60 invited presentations around the world. She is also a member and the formal advocate of UNISDR “Making Cities Resilient” Campaign and the Working Group leader of the Words into Action on Accountability and Governance. For further information, see www.dilanthiamaratunga.net

Dr Senaka Basnayake is the Director of Climate Resilience Department of Asian Disaster Preparedness Center (ADPC) in Thailand. He has more than 28 years of experiences in the field of meteorology and climatology and has vast experience in implementing projects and programmes on climate risk management and climate resilience in Asia. Before joining ADPC in 2010, he has served as a Scientist at SAARC Meteorological Research Centre in Dhaka, Bangladesh, from 2007. He has also worked as a Senior Meteorologist and Deputy Director of Department of Meteorology in Sri Lanka. He holds a B.Sc. (special) degree in Physics, a Postgraduate diploma and Ph.D. degree in Meteorology. For further information, see www.adpc.net

Siri Hettige is an Emeritus Professor of Sociology, Department of Sociology at the University of Colombo, Sri Lanka. He is also the Chairman, Social Science Research Committee, National Science Foundation, Sri Lanka, and the former Director of the Social Policy Analysis and Research Centre.
University of Colombo. He also served as the Dean, Faculty of Arts, University of Colombo (1999-2002), and the Head, Department of Sociology (1987-1988, 1995-1999). He is an Adjunct Professor at RMIT University, Melbourne and an Adjunct Research Associate at CEPUR, Monash University, Australia. His research interests include migration; poverty; education; youth and identity; politics; inequality; governance and development; and community studies. He has published widely in the areas of Youth, Peace and Sustainable Development and is widely recognised as one of the prominent academics leading research in areas of poverty, conflicts and youth studies.

Sarath Premalal holds a Bachelor’s degree in Physics Special (1980-1984) and Master’s degree in Physics from the University of Peradeniya, Sri Lanka. He joined the Meteorological Department as a Meteorologist in 1988. He did his second Master’s degree in Meteorology (1992-1993) in the University of Reading, United Kingdom. He was offered a Guest Professorship in 2018 in the South China Sea Institute of Oceanology, CAS, China. He worked as a Weather Forecaster and a Meteorologist in charge at national-level organisations in Sri Lanka. He was also working in the Centre for Climate Change Studies (CCCS) in the Department of Meteorology. He was a consultant expert for number of EIA reports and national and international research projects. Premalal joined the SAARC Meteorological Research Centre in 2012 and worked nearly 18 months as a Scientist at the synoptic division. He became the Director General of Meteorology in June 2017 and retired from the service in October 2018.

Ananda Jayasinghe Arachchi is the Deputy Director, Department of Meteorology. dananda52@hotmail.com

For instructions on how to order reprints of this article, please visit our website: www.emeraldgrouppublishing.com/licensing/reprints.htm Or contact us for further details: permissions@emeraldinsight.com
A study of people-centered early warning system in the face of near-field tsunami risk for Indonesian coastal cities

Harkunti Pertiwi Rahayu
School of Architecture, Planning and Policy Development, Bandung Institute of Technology, Bandung, Indonesia

Louise K. Comfort
GSPIA, University of Pittsburgh, Pittsburgh, Pennsylvania, USA

Richard Haigh
School of Art, Design and Architecture, University of Huddersfield, Huddersfield, UK

Dilanthi Amaratunga
University of Huddersfield, Huddersfield, UK, and

Devina Khoirunnisa
Bandung Institute of Technology, Bandung, Indonesia

Abstract

Purpose – This study aims to identify the gaps in current policy and propose a viable framework for policy improvement regarding people-centered tsunami early warning chain in Padang City. The objectives are to describe the gaps and flaws in the current policy regarding local tsunami early warning chain, to identify potential actors to be involved in the tsunami early warning chain and to assess the roles and capacity of actors, and their potential for involvement in early warning.

Design/methodology/approach – This study is an exploratory study using social network analysis (SNA) on regulations and other legal documents, and primary data sources from a focus group discussion and semi-structured interviews.

Findings – The study found that the existed regulation lacks extension nodes to relay warnings to the populations at risk, often referred to as “the last mile.” Moreover, receiving warning information from both formal and informal sources is important to mobilize people evacuation more effectively during an emergency. The study found that mosque communities and disaster preparedness leaders are the potential actors who should be involved in the local early warning chain.

© Harkunti Pertiwi Rahayu, Louise K. Comfort, Richard Haigh, Dilanthi Amaratunga and Devina Khoirunnisa. Published by Emerald Publishing Limited. This article is published under the Creative Commons Attribution (CC BY 4.0) licence. Anyone may reproduce, distribute, translate and create derivative works of this article (for both commercial and non-commercial purposes), subject to full attribution to the original publication and authors. The full terms of this licence may be seen at http://creativecommons.org/licenses/by/4.0/legalcode

This research was support by the National Academies of Sciences, Engineering, and Medicine (2000004899-FFATA).
Practical implications – The research findings were presented as a recommendation to Padang City Government and have been legalized as the new tsunami early warning chain procedure in the Padang City Mayor Regulation 19/2018.

Originality/value – This research investigated local tsunami early warning dissemination in Padang City using SNA. The study demonstrates a close collaboration between researchers, practitioners and the community.

Keywords Early warning, Tsunami, Social network analysis, Community level, End-to-end warning system, Warning dissemination, Tsunami early warning chain, Community level early warning dissemination

Paper type Research paper

Introduction

The 2004 Indian Ocean Tsunami was a major disaster not only for Indonesia but also for other Indian Ocean countries, and worldwide. The catastrophe caused more than US$7bn of economic losses, 229,866 deaths and 42,883 missing casualties. These devastating impacts led to the Indonesian Government developing the Indonesian tsunami early warning system (InaTEWS), as well supporting regional early warning efforts, which became known as the Indian Ocean tsunami early warning system. The InaTEWS was established and fully operational less than four years after the disaster.

Despite these efforts, recent events suggest there are still shortcomings in the implementation of end-to-end tsunami warning systems. For instance, in 2018 Indonesia suffered two deadly non-tectonic tsunami events, the first in Palu due to a coastal landslide induced by an earthquake (Kumar et al., 2019), and the second in the Sunda Strait due to the flank collapse of Gunung Anak Krakatau (Solihuddin et al., 2019). The InaTEWS was not able to warn the at risk populations in a timely manner, in part due to the InaTEWS having been developed to detect tsunami induced by tectonic activities. Investigations in the aftermath of the events suggested numerous contributory factors, including the types of tsunami source, the high level of tsunami hazard, lack of preparedness, high vulnerability because of population density in the coastal area and a “failing” tsunami early warning system.

Early warning systems are blamed for the loss of lives due to disasters more often than they are praised for the lives saved. This is likely due to the difficulty in accounting for the number of lives saved by a successful warning, in contrast to the ease by which the number of deaths can be calculated when warning system fails to adequately reach at risk communities. These failings are often attributed to the institutional dimension, rather than the technological dimension (Garcia and Fearnley, 2012). Warning products from the upstream part of the warning system often fail to reach the population at risk due to some missing links at the local level (Spahn et al., 2014). Moreover, different dissemination methods might deform the information content. Consequently, tsunami warning systems need to be supported by an end-to-end chain of information to deliver warnings in a timely manner.

A tsunami early warning system is a complex and dynamic system, involving not only the technology but also socio-technology, multi-level stakeholders and governance. The InaTEWS data and information flow, as shown in Figure 1, is composed of two main components, i.e. upstream and downstream. These are often referred to as the structure and culture components, respectively, and involve many multi-level government actors, as well as a wide range of regional, national and local stakeholders (BMKG, 2012).

The upstream is a system, which is very much relying on technological performance for monitoring, detecting, analyzing and disseminating tsunami warnings to the interface
agency and local government. The technology capability of several national government actors, led by Indonesian Agency for meteorology, climatology and geophysics (BMKG), the BMKG is very significant in the upstream component. The downstream component is a socio-technological system for conveying tsunami warning, and includes decision-making, as well as issuing and disseminating the evacuation order and tsunami warning information to all people at risk. This downstream component depends on many factors such as local government policy/regulation on tsunami warning, supporting infrastructure for evacuation and behavior of the people in responding the warning. A previous study in Padang City exposed the wide range of responses by people when they received warning information during tsunamigenic earthquake on September 30, 2009, ranging from immediate evacuation to postponing evacuation, to refusing to evacuate because of a variety of reasons and logical frameworks of thinking (Rahayu and Nasu, 2011). A more detailed analysis from 400 responses indicated that after both receiving formal warning from government and natural warning, such as strong shaking, some followed designated evacuation routes, while others acted spontaneously, even trespassing on neighbors’ land (Rahayu, 2012). Rahayu concluded that more effective tsunami early warning can be achieved by understanding and accommodating these behaviors of the people, and using this information to plan and/or improve downstream warning chain (Rahayu, 2012).

Since 2011 and along with Australia and India, the InaTEWS has been a designated Tsunami service provider for 24 countries in the Indian Ocean region. The system has also been tested by several real events, as it was established in 2008, with a high rate of success and able to issue tsunami warning less than 4 min after the earthquake (Triyono, 2012). However, studies have also revealed some flaws and limitations in the regulations...
governing the system, as well as its implementation. For example, in terms of reaching the population at risk, besides national mass media and remotely controlled tsunami sirens, InaTEWS has only the authority to relay the warning messages to the emergency operations centers (EOCs) at the city and regency level (BMKG, 2012). The task of extending the chain of warning to the population at risk is mandated to the local governments, as also regulated in Indonesian Law no. 24/2007 regarding disaster management.

This makes it necessary for cities and regencies with areas exposed to tsunami hazard to be ready with the local level procedure regarding how to disseminate the warnings at times of tsunami emergency. However, the agencies in charge often lack the capacity to develop an end-to-end warning system, as it requires efforts in terms of funding, time and successful multi-stakeholder partnerships (Thomalla et al., 2009).

For example, although Padang City is recognized as one of the leading Indonesian cities for disaster risk management, as of 2017, there were still found to be some missing links in their tsunami warning chain. Their regulation regarding the tsunami early warning chain (Padang Mayor Regulation no.14/2008) had not been updated since 2010, and thus, has not considered the InaTEWS service guidelines that were established in 2012. Also, the regulation only focused on the city level decision-making procedure and had not specified the other “interface actors,” besides the Padang City EOC, and city television (TV) and radio channels. Interface actors are the persons or organizations that are responsible for disseminating the warning message to the public at the community level. These actors are essential in an end-to-end early warning system, especially in the case of near-field tsunami events.

Other studies have concluded that a people-centered approach is the best approach for an effective early warning system (Garcia and Fearnley, 2012). This requires the “last mile” population to “own” the system. This sense of ownership should be not only achieved through the involvement of the civil society in the whole process (i.e. community-based) but also by acknowledging their roles in the policies and help to build their capacity through economic aids and trainings (Spahn et al., 2014).

The topic of social capital is often associated with a community-based or people-centered early warning system. Indeed, the community-based approach in all disaster phases puts an emphasis on local partnership, leadership and voluntary involvement. Therefore, to initiate people-centered early warning systems, it is necessary to identify the potential actors in the community with the capacity as these interface actors. Identifying potential interface actors in the community does not guarantee effective end-to-end warning dissemination, but cognition of their involvement is vital at times of emergency (Comfort, 2007). This suggests a people-centered approach needs to be incorporated into tsunami early warning policies.

**Objectives**

To address this gap, this study aims to identify gaps in the current policy and propose a viable framework for policy improvement regarding people-centered tsunami early warning chain. It will achieve this through a detailed study of tsunami early warning in Padang City and address several objectives:

- to describe the gaps and flaws in the current policy regarding local tsunami early warning chain;
- to identify potential actors in the community to be involved in the tsunami early warning chain; and
- to assess the roles and capacity of these actors and their potential for involvement in the tsunami early warning chain.
Literature review
Sumatera, Java and Bali are Indonesian major islands, which lie very close to the active subduction zone parallel to the west coast of Sumatera from Aceh to Lampung, and south from Java, Bali and Nusa Tenggara coasts. As a consequence, the regions located along these shorelines are highly exposed to the threat of near-field tsunamis. According to the tsunami hazard assessment by the Indonesian national earthquake center (PUSGEN) in 2017, there is a potential of M 8.7 to M 9 tsunamigenic earthquake along this subduction zone. In addition to that, the major cities in these regions have a high population concentration in the coastal area, leading to a high social-economical vulnerability against the tsunami hazards. The Indian Ocean tsunami in 2004, Pangandaran tsunami in 2007 and Mentawai tsunami in 2011 were some of the devastating tsunamis generated from the fault.

In the wake of the 2004 Indian Ocean tsunami, InaTEWS was developed through the collaboration of 17 national level institutions in Indonesia (BMKG, 2012). In the early warning model proposed by UN-ISDR, a people-centered early warning system should consist of four elements as follows: risk knowledge, monitoring and warning service, dissemination and communication and response capability (Basher, 2006). The risk knowledge and response capability elements should be implemented in the communities at risk. In the InaTEWS, the warning service is focusing on two of these four elements: the monitoring and warning service, otherwise called the upstream part, and the dissemination and communication element or the downstream part.

The upstream part of InaTEWS is mainly technological, relying on hardware detection devices and decision support systems, whose operation is handled by the BMKG. Meanwhile, the downstream part is the responsibility of the national disaster management agency, interface agencies and local government. As a result, the responsibility for passing on the warning information to the “last-mile” population is mandated to the local government at the city or regency level. This part, in particular, requires a partnership of multi-institutional stakeholders to disseminate warning information in a timely manner, including when there is a very limited lead time. To achieve this, the warning chain needs to be exercised frequently and established in some form of regulations. It is also necessary to evaluate the system to ensure successful warning dissemination and response when a tsunami does occur.

Attention also needs to be paid to the response capability element, such as evacuation. Studies on evacuation behavior have been published for over 50 years. Earlier studies tended to focus on evacuation behavior as individual actions. More recently, as early warnings have been implemented for many hazard types, evacuation has been viewed as collective actions, as evacuees are motivated by actions taken by others, and external information such as warnings (Mawson, 2005).

There are many variables concerning the decision-making to protect oneself from an impending hazard. Mileti and Peek (2000) defined the processes that evacuees go through after receiving a warning as a sequence of hear, perceive and response. In their study, they also note that the content, style and channel of warnings, as well as characteristics of the receiver, are the important factors that determine the response outcomes. Depending on the people’s characteristics, evacuees might have varying responses to different sources of the warnings they received. Several factors such as risk awareness, personal trust to the government and mass media, involvement in the community and social networks can influence their preferred warning information source. These preferences can have a great influence on the evacuation decisions, and thus, people-centered early warning systems should consider disseminating the warning messages through various channels (Lindell and Perry, 2012).
A study by Taubenböck et al. (2009) found that about 30 per cent of their samples who received tsunami warnings during the 2007 Padang earthquake were informed through informal sources. The study highlighted the need to involve empowered neighborhood leaders for informal warning dissemination to cope with the critical time of the tsunami lead time in the case of near-field tsunamis. Besides, the involvement of local stakeholders can be very beneficial, as it was found to increase local resilience and aid for faster social recovery (Kapucu, 2015).

Sorensen stated that the key issue in establishing an effective early warning system is to join the detection sub-system with the dissemination and response sub-system (Sorensen, 2000). In the case of the downstream tsunami early warning system in a local community, challenges can be found in reaching the neighborhood leaders and mobilizing evacuations in a timely manner. Moreover, an additional challenge may also be found in integrating the bottom-up approach of local community involvement with the top-down nature of the upstream part of the early warning system, such as the InaTEWS (Thomalla et al., 2009).

In her seminal paper, Comfort asserts that a common operating picture among actors in an emergency response is a salient component for successful crisis management (Comfort, 2007). Thus, in the case of downstream tsunami early warning system, an integrated scheme for the warning chain should be established as a formal plan and simulated through training. Meanwhile, according to Krackhardt, influence is achieved when formal power is in line with informal power, such as when cognitive accuracy is implemented (Krackhardt, 1990). Consequently, in developing a community-based tsunami early warning system, neighborhood leaders, who have the means and capacity as interface actors in the early warning chain, should be recognized in the formal plans. Moreover, having a recognized operating plan will be crucial to ensure smooth coordination between emergent voluntary actors in the community and formal agencies (Whittaker et al., 2015).

On the other hand, an end-to-end warning chain should be the goal of a people-centered early warning system. An end-to-end early warning system emphasizes the connectedness of actors to make sure the warning messages reach the last-mile population in a timely manner (Spahn et al., 2014). This requires a sufficient communication capability and a clear operating procedure regarding the warning chain to be implemented by all the actors involved. Hence, it is important to visualize the network as a whole in the process of planning the downstream early warning system.

**Methodology**

This study is an exploratory study, which uses semi-quantitative methods. The study involves several data collection and analysis methods. To understand the subject in an in-depth manner, primary and secondary data were collected in several layers (in the provincial, city and district scale) as illustrated in Figure 2.

**Data collection**

This study uses mainly three different methods to collect data. Firstly, secondary data was collected through document reviews on existing regulations and legal plans regarding the tsunami early warning system in Padang City. The documents include:

- Padang Mayor Regulation 14/2010 regarding Padang City tsunami early warning chain;
- Padang City tsunami contingency plan; and
- National tsunami early warning system standard operating procedure (SOP).
The primary data was collected in two methods. A focus group discussion (FGD) about the downstream tsunami early warning system in Padang City was conducted on February 22, 2016. In parallel, a field survey through semi-structured interview was conducted in the Koto Tangah District in Padang City as the cross-validation for the FGD data.

The Padang tsunami contingency plan mentions a number of organizations in regard to tsunami emergency. However, according to the contingency plan, the majority of these organizations are responsible only in the emergency services of their respective sectors, while only a few are involved in the early warning chain. In practice, it was found that multiple organizations have taken some roles in the early warning system although they were not stated in the regulation. For the exploratory purpose of the research, the organizations identified from this regulation were invited to attend the FGD, which was conducted on February 22, 2016. The aim of this FGD was to develop the social networks of tsunami early warning chain and identify actors within the community who could potentially be incorporated for policy improvement. Delegates from 20 different organizations attended the FGD.

In parallel with the FGD, a survey was conducted to cross-validate the findings regarding local interface actors. The survey was conducted on February 20-27, 2016 in Koto Tangah District, Padang City. In total, 71 community respondents were surveyed using semi-structured interviews. These were used to understand their expectations and past experiences of receiving tsunami early warning messages. The objective of this survey was to create a complete view of the tsunami early warning chain from the community perspective. Table I presents a summary of the respondents’ characteristics.

Among the respondents are 36 community leaders. This group was identified as potential interface actors during the FGD. Despite the limited number of respondents, purposive and simple clustered sampling was used to increase the reliability of the data. The distribution of different community roles they represent and the sub-district of the respondents are shown in Table II.

**Analysis methods**

Social network analysis (SNA) has often been used in studies examining communication and cooperation between people and organizations during emergency responses, humanitarian aid interventions, and recovery after disaster events (Kapucu and Demiroz, 2017; Bisri et al., 2016; Kim and Hastak, 2018). This study offers a different usage of SNA by focusing on the downstream early warning chain, which presents a different set of interests to be emphasized in the study.

SNA can be used in different ways during quantitative, qualitative or mixed methods studies. A quantitative SNA may help researchers understand the form of networks through various metrics such as network size, density, etc., or of certain actors through their degree of centrality and betweenness. A qualitative SNA approach may help better understand the

![Figure 2. Input data and network types flowchart](image)
<table>
<thead>
<tr>
<th>Variables</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age</strong></td>
<td></td>
</tr>
<tr>
<td>&gt; 18</td>
<td>2</td>
</tr>
<tr>
<td>19-30</td>
<td>21</td>
</tr>
<tr>
<td>31-40</td>
<td>13</td>
</tr>
<tr>
<td>41-50</td>
<td>14</td>
</tr>
<tr>
<td>51-60</td>
<td>12</td>
</tr>
<tr>
<td>&gt; 60</td>
<td>6</td>
</tr>
<tr>
<td>Missing</td>
<td>5</td>
</tr>
<tr>
<td><strong>Gender</strong></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>33</td>
</tr>
<tr>
<td>Female</td>
<td>37</td>
</tr>
<tr>
<td>Missing</td>
<td>3</td>
</tr>
<tr>
<td><strong>Monthly income (in thousands IDR)</strong></td>
<td></td>
</tr>
<tr>
<td>&gt; 500</td>
<td>30</td>
</tr>
<tr>
<td>500-2,000</td>
<td>6</td>
</tr>
<tr>
<td>2,000-5,000</td>
<td>17</td>
</tr>
<tr>
<td>&gt; 5,000</td>
<td>11</td>
</tr>
<tr>
<td>Missing</td>
<td>9</td>
</tr>
<tr>
<td><strong>Occupation</strong></td>
<td></td>
</tr>
<tr>
<td>Student</td>
<td>14</td>
</tr>
<tr>
<td>Civil worker</td>
<td>13</td>
</tr>
<tr>
<td>Teacher</td>
<td>6</td>
</tr>
<tr>
<td>Private employee</td>
<td>4</td>
</tr>
<tr>
<td>Self-employed</td>
<td>9</td>
</tr>
<tr>
<td>Common labor</td>
<td>4</td>
</tr>
<tr>
<td>Housewife</td>
<td>9</td>
</tr>
<tr>
<td>Retired</td>
<td>3</td>
</tr>
<tr>
<td>Not working</td>
<td>3</td>
</tr>
<tr>
<td>Missing</td>
<td>8</td>
</tr>
<tr>
<td><strong>Education level</strong></td>
<td></td>
</tr>
<tr>
<td>Elementary school</td>
<td>5</td>
</tr>
<tr>
<td>Junior high school</td>
<td>1</td>
</tr>
<tr>
<td>Senior high school</td>
<td>33</td>
</tr>
<tr>
<td>Diploma</td>
<td>7</td>
</tr>
<tr>
<td>Bachelor</td>
<td>15</td>
</tr>
<tr>
<td>Masters/doctoral</td>
<td>4</td>
</tr>
<tr>
<td>Missing</td>
<td>8</td>
</tr>
</tbody>
</table>

**Table I.**

Respondents’ characteristics

<table>
<thead>
<tr>
<th>Sub-district</th>
<th>Freq</th>
<th>(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parupuk Tabing</td>
<td>15</td>
<td>21</td>
</tr>
<tr>
<td>Lubuk Buaya</td>
<td>21</td>
<td>30</td>
</tr>
<tr>
<td>Batang Kabung Ganting</td>
<td>11</td>
<td>15</td>
</tr>
<tr>
<td>Pasie Nan Tigo</td>
<td>9</td>
<td>13</td>
</tr>
<tr>
<td>Padang Sarai</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>Bungo Pasang</td>
<td>7</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Community roles</th>
<th>Freq</th>
<th>(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disaster group</td>
<td>14</td>
<td>20</td>
</tr>
<tr>
<td>School</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Mosque community</td>
<td>13</td>
<td>18</td>
</tr>
<tr>
<td>Sub-district office</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Community member</td>
<td>35</td>
<td>50</td>
</tr>
</tbody>
</table>

**Table II.**

Sub-district and community roles of respondents
context of relationships and can also yield better overviews for smaller networks. To answer our research objectives, SNA will be used qualitatively in this study. There are three points of interest to be emphasized:

1. Gaps and flaws of the existing early warning chain according to the comparison of networks;
2. Identified mid-actors based on different networks; and
3. Evaluation of how these mid-actors can better strengthen and fasten the information flow in a tsunami early warning chain.

A social network graph can be created by analyzing the pattern of communication between nodes (could be an actor or organization) in an intended system. This study puts emphasis on understanding the gaps and differences between tsunami early warning networks based on three types of collected data, as shown in Table III.

This study is a semi-quantitative study mainly using SNA as a network visualization tool and descriptive network interpretation analysis. To conduct the SNA, the software UCINET 6 was used. The results were then interpreted and analyzed descriptively using additional information from the literature, document review, FGD and survey.

**Results**

*Network 1 (original network): documented in plans and regulations*

Network 1 (original network) is based on the Padang City Mayor Regulation 14/2010 regarding the implementation of the Tsunami early warning system. In the document, seven

<table>
<thead>
<tr>
<th>Network type</th>
<th>Data input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network 1: original network based on legal documents</td>
<td>Document review on existing plans regarding tsunami early warning system: National TEWS SOP, Mayor regulation, Tsunami contingency plan</td>
<td>Network matrix, Identified list of actors to be invited for the FGD</td>
</tr>
<tr>
<td>Network 2: government model developed based on FGD</td>
<td>The FGD among key stakeholder at city level conducted in February 2016 involved representative from 20 identified organizations (governmental, NGO and private) from the provincial and city level</td>
<td>All stakeholders approved a network regarding the city level TEWS, Identified local-level stakeholders who are potentially able to be involved in the people-centered tsunami early warning chain in Padang City</td>
</tr>
<tr>
<td>Network 3: community model developed based on the result of field study</td>
<td>Semi-structured interview with 73 respondents from the community. The respondents were selected based on their sub-district and roles in the community</td>
<td>Current state of the downstream tsunami early warning system practice in the community level, Identification of roles and capacity of the actors identified in the previous FGD, Proposed framework for people-centered tsunami early warning system</td>
</tr>
<tr>
<td>Network 4: the complete network developed based on the integration of government model and community model</td>
<td>Integration of Network 2 (government model) and Network 3 (community model)</td>
<td>Proposed framework for people-centered tsunami early warning system</td>
</tr>
</tbody>
</table>

**Table III.**

Different types of network
organizations were identified to be included in the tsunami early warning chain for Padang City. Figure 3 presents a list of organization and their responsibilities. A network matrix was then created based on the regulation to produce a social network graph, as shown in Network 1 (original network) in Figure 4.

In Figure 4, as in all the other networks, the BMKG serves as the tsunami warning information provider. Meanwhile, in this Network 1 type, the Padang City EOC (EOC – Pusdalops Kota) is the only organization that receives the information in Padang City. Then, under city jurisdiction, the EOC must report to the City Mayor regarding the information received. The Mayor will make decision for an evacuation order, based upon the level of

<table>
<thead>
<tr>
<th>Actor/Organization</th>
<th>Role and Responsibility</th>
<th>Node symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG Pusat)</td>
<td>Provide tsunami warning information to Padang City Emergency Operations Centre (EOC)</td>
<td>●</td>
</tr>
</tbody>
</table>
| Padang City Emergency Operations Centre/EOC (Pusdalops Kota Padang) and Disaster Management Agency (BPBD/PK Kota Padang) | - Receive warning information from Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG Pusat)  
- Propose suggestion for further actions to Padang City Mayor  
- Relay warning information to the population at risk directly or through interface actors | ●           |
| Padang City Mayor (Walikota Padang) | Make decision regarding actions to be taken following the tsunami warning | ☑           |
| Padang City Communication and Information Agency (Diskominfo - Kota Padang) | Relay information from Padang City EOC to local television and radio channels | ●           |
| Local Television and Radio Channels (TVRI and Classy FM) | Relay information from Padang City EOC (Pusdalops Kota) and Communication and Information Agency (Diskominfo) to the population at risk through live broadcast | ●           |
| Indonesian Amateur Radio Union (RAPI) | Relay information from Padang City EOC (Pusdalops Kota) and Communication and Information Agency (Diskominfo) to the population at risk through live broadcast | ●           |
| Citizen Band Radio (RAPI) | Relay information from Padang City EOC (Pusdalops Kota) and Communication and Information Agency (Diskominfo) to the population at risk through live broadcast | ●           |
| Disaster Preparedness Community Group (Kelompok Siaga Bencana - ESB) | Relay information from Padang City EOC to last-mile population in their respective communities | ●           |
| Padang City Vice-Mayor (Walik Walikota Padang) | Lead the preparation for emergency response based on tsunami early warning from Padang City EOC | ●           |
| Padang City Secretary (Sekretaris Daerah) | Assist the preparation for emergency response based on tsunami early warning from Padang City EOC | ●           |

**Figure 3.** Roles and responsibilities of actors as regulated in Padang City Mayor Regulation 14/2010

**Figure 4.** Network 1 (original network) based on City Mayor Regulation 14/2010
tsunami warning information. This identifies the very critical role of Padang City EOC as a disruption in the communication line between national agency for meteorology, climatology and geophysics (BMKG) as the national service provider (NSP) and the Padang City EOC, which might result in a delay or even failure in the evacuation order and emergency response.

In the local regulation, i.e. City Mayor Regulation 14/2010, it was specified that the role of Mayor of Padang City includes making a decision regarding further actions, i.e. evacuation order and incident command system, to be taken after receiving the warning. This means that Padang City EOC will not carry out dissemination of the tsunami warning and evacuation order before receiving the instruction from the Padang City Mayor. This tie, presented as red lines on Figure 4, clearly depicts the redundant line of decision-making and communication between the Padang EOC and the Padang Mayor after receipt of the warning from the NSP, and before it is disseminated to the community. This procedure may not be feasible and practical, as the tsunami might happen at any time, and would require the Padang City Mayor to be available at any time. For example, there are many situations when the Mayor has duties out of the city or abroad, which could undermine or delay the tsunami warning dissemination process under this regulation.

Network 2 (government model): as identified by actors in focus group discussion

The first FGD was conducted on February 26, 2016. It was attended by 20 organizations from Padang City and West Sumatra Province. During the FGD, the main discussion topic was how the tsunami early warning dissemination should be conducted in the city and at the community level. The discussion resulted in a consensus emerging on the ideal tsunami early warning dissemination chain for Padang City, and involving related organizations from the city and at the community level. Based on the agreed chain, a social network graph, namely, Network 2 (government model) as presented in Figure 5, was created.

The communication of tsunami early warning in the network, as identified during the FGD, has two main purposes. The first, which is in line with this paper’s main focus, is to inform the last-mile community about the coming tsunami and order an evacuation. On the other hand, some of the organizations identified in the network indicated the main purpose is as an incident command system during post-disaster emergency response. Similarly, this function was actually found in Network 1 (original network) as the responsibility of Padang City Vice-Mayor and Secretary. These organizations are community health centers (Puskesmas and Pustu), Police (Kapolda), public works agency (Dinas PU), development planning agency (Bappeda), social agency (Dinas Sosial) and several others.

The second FGD meeting was conducted three months later at the district level, i.e. Padang Barat District. This second FGD focused on identifying other potential stakeholders from mid-actors as an interface from the city level to the community. The roles of new mid-actors, i.e. three NGOs actors and two civil society organizations (CSOs) or community leaders, were identified and played an important role in the public dissemination of warning messages. These are Red Cross (PMI), tsunami preparedness community (Komunitas Siaga Tsunami/Kogami), mercy corps, disaster preparedness school (Sekolah Siaga Bencana/SSB) and mosque community (Komunitas Masjid). The existence of these new mid-actors will be further explored and discussed in Network 3 (community model).

Based on these two FGD meetings, both at the city and district level, Network 2 (government model) was developed. In comparison to the previous Network 1 (original network), Network 2 (government model) has more redundancy in the warning dissemination and involves more agencies at the city level. Moreover, critical ties such as between Padang City EOC, BMKG and the Mayor of Padang, has been replaced by more
robust backup communication ties. For example, in Network 2 (government model), the Regional Office of the BMKG (for West Sumatera), who is responsible for West Sumatera region, has established several communication lines, such as with the Padang City Mayor, several other agencies in Padang City (for emergency response function) and several NGOs and community leaders (for tsunami early warning dissemination).

Network 3 (community model): toward a people-centered early warning system
According to the finding of Network 2 (government model), four mid-actors (community leaders) were the consideration of the sampling method in the community survey. For the development of the later network, i.e. Network 3 (community model), an emphasis was put to investigate the potential roles of four types of these mid-actors (community leaders) as local interface actors, i.e. sub-district office (Kelurahan), schools (Sekolah Siaga Bencana), mosque communities and disaster preparedness groups (KSB).

The network matrix was created based on a network census through an in-depth survey using semi-structured interview in Koto Tangah District, Padang City. Respondents were asked how they received or will receive evacuation orders in the case of tsunami. Additionally, local interface actors were asked if they would communicate with other actors or relay the information to the community members. The network census resulted in Network 3 (community model) as shown in Figure 6.

According to the survey in Koto Tangah District, it was found that various communication devices are involved in the dissemination of tsunami warnings to the last-

Figure 5.
Network 2 (government model) developed based on FGD
mile community, i.e. a community that does not have access to the tsunami warning information or an evacuation order because of its location or physical ability. There are four main warning channels of tsunami warnings identified for the last-mile community. These are tsunami sirens activated by Padang City EOC (32 per cent), access to mainstream media such as TV and radio channels (45 per cent), through other telecommunication devices with their links or acquaintances in the civil institutions (17 per cent). Thus, this leaves the rest to rely on warnings from local mid-actors or community leaders (29 per cent).

Discussion
Padang City is a coastal city with the highest risk of near-field tsunami in Indonesia. A tsunami hazard model shows a high probability of the occurrence of Mentawai Megathrust Tsunami to hit Padang City (Griffin et al., 2017). Since the 2004 Indian Ocean tsunami, disaster risk reduction interventions have been in place in Padang. It is also one of the pioneer cities for disaster risk reduction in Indonesia. Thus, the awareness and preparedness of the city toward tsunami might be expected as better than other coastal cities and regencies in Indonesia. Despite this expectation, the study indicates there are several aspects that require improvement in the downstream warning chain of tsunami early warning in Padang City.
Under the Indonesian disaster management law, i.e. UURI no 24/2007, and the compliance with the autonomous of government system in Indonesia to local government level, the responsibility to protect the people from disaster is at the local government level. This means that the City Mayor (or regent for regencies) has the highest responsibility to evacuate all the people at risk and leave no one behind. Upon receiving a warning from national agency for meteorological, climatology and geophysics (BMKG), and as described in the grand scenario of InaTEWS, issuing an evacuation order is the responsibility of the mayor (BMKG, 2012).

As discussed at the analysis of Network 1 (original network), there were too many critical ties in the Padang City tsunami early warning chain. These include the full reliance on the Padang City EOC to receive early warning information from the NSP and the decision-making role of Padang City Mayor. Although, further in the study, it was found that there is backup support from the Regional Office of BMKG West Sumatra region for the Padang City EOC. This reflects the need to revise and update the regulation with the advanced real-field condition. Moreover, the existing regulation regarding tsunami early warning chain in Padang was established in 2010, which was two years before the new guidelines of InaTEWS. This regulation was in the form of a mayor decree and has not yet been institutionalized in the local law. These indicate a need for Padang City to renew or improve its regulation regarding the downstream tsunami early warning system.

Padang City’s communication and information agency (Diskominfo) is the only institution whose involvement in the tsunami early warning chain has been specified in the regulation but was found to have no significant role in the practice. In the regulation, the agency has the responsibility to relay information to mainstream media such as TV and radio channels. Instead, in practice, these channels are already established through informal ties with Padang City EOC, while the role of Padang City communication and information agency is only to make sure that the channels broadcast the information.

As a coastal city with the highest risk of a near-field tsunami, losses of minutes or seconds during the lead time for evacuation in Padang City could mean risking the loss of lives due to failed evacuation. These risks should be anticipated by simplifying the bureaucracy related to procedure in tsunami warning dissemination, as well as by increasing redundancy in communication lines to strengthen the tsunami warning chain. As shown in Network 1 (original network), the decision-making responsibility of Mayor of Padang might slow down or undermine the tsunami early warning and evacuation order dissemination.

These results suggest the early warning chain at the city level should be simplified. This could be done by mandating the pre-defined decision-making role to disseminate the warning and evacuation orders to the Padang City EOC so the dissemination process could be carried on almost as soon as they receive the warning information if found necessary. In practice, the decision-making role of the Padang City Mayor has also been bypassed in most cases. It is, therefore, feasible to mandate the decision-making role to the EOC. Supporting this need, the guidelines of InaTEWS have provided pre-defined action to be taken by the Indonesian city EOC related to the level of potential tsunami, i.e. major warning, warning and advisory, as shown in Figure 7.

The Mayor of Padang has a very critical and important role of issuing an evacuation order for mobilizing evacuation during a tsunami emergency by exercising his or her authority. According to several respondents, they had been convinced to evacuate from a potential tsunami during the 2007 and 2009 Sumatera earthquake after receiving a tsunami evacuation order conveyed by the incumbent Padang City Mayor through the radio of the Republic of Indonesia, the local radio channel (Personal Communications, 2016).
Although Padang City EOC is the first and only gateway organization stated in the regulation as receiving warning information at the city level, in practice, the Regional Office of BMKG located in Padang Panjang could take for heads-up for a potential tsunami or have a backup role as the focal point in case the Padang City EOC faces some communication difficulties. According to our findings from the FGD meetings, the Regional Office of BMKG has established several communication ties with the Padang EOC, the Mayor of Padang and sectoral agencies (SKPDs) in Padang city through a WhatsApp messenger group. Furthermore, several other NGOs and local community leaders were also identified to disseminate warnings to the public, covering some of the last-mile population.

Finally, a survey was conducted in the Koto Tangah District in Padang City to improve the tsunami warning system for Padang City by cross-validating the findings from the FGD, i.e. Network 2 (government model), and findings from the results of the study, i.e. Network 3 (community model). Completed questionnaires were collected from 71 respondents, from which 36 are mid-actors and 35 are community members. The geo-location of those 71 respondents can be seen in Figure 8.

Among the 36 mid-actors, there were community leaders (mid-actors) grouped into four categories as follows: sub-district office (Kelurahan), disaster resilience schools (Sekolah Siaga Bencana), community mosques (Masjid) and disaster preparedness community groups (KSB). Meanwhile, from the 35 community respondents, it was found in Network 2 (government model) that about 10 respondents (29 per cent of sample populations) could not receive tsunami warnings from any existing communication devices, including sirens. This means that Network 3 (community model) as also shown in Figure 9(a) has a capacity on disseminating the tsunami warning system of 71 per cent, i.e. only 71 per cent of the samples receive tsunami warning messages. Meanwhile, the remaining 29 per cent of the people are categorized as the last mile, i.e. people who do not have access to tsunami information through existing device communication in Padang City, i.e. siren, which is operated by Padang City EOC.
The community leaders (mid-actors) identified above have their own capacity and network of communication. The community mosques (Masjid) have a mosque network and can use the mosque speaker for alerting the surrounding community. Meanwhile, the disaster preparedness community groups have used a wide variety of communication networks,
such as radio communication (HT), WhatsApp messenger group, SMS and even through
direct communications. These people are the people in the community who have the first
access to warning information from the City EOC. The disaster resilient schools use SMS
and telephone to disseminate the tsunami warning information to the parents and students.
Finally, the sub-district office uses HT, WhatsApp messenger group, SMS and the internet.
Based on Network 2 (government model) and Network 3 (community model), a combined
model was created as shown in Figure 10.

Based on our findings from the survey, the potential actors to be involved in the early
warning chain as interface actors have different characteristics. There is a varying level of
willingness to participate in the tsunami early warning chain, as well as their capacity to
reach tsunami early warning information and understand the warning information. This
should be a consideration for further studies and planning for community-based early
warning systems.

Several of the community leaders interviewed in the Koto Tangah Districts were
already taking voluntary roles as the interface actors in the tsunami early warning chain.

Figure 10. Network 4 (complete network)

LEGEND

<table>
<thead>
<tr>
<th>NODE COLORS</th>
<th>NODE SHAPES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warning provider and focal point</td>
<td>Send tsunami warning recommendation</td>
</tr>
<tr>
<td>NGO and CSO</td>
<td>Receive and forward</td>
</tr>
<tr>
<td>Mass media</td>
<td>Receive warning and respond</td>
</tr>
<tr>
<td>Governmental agency</td>
<td></td>
</tr>
</tbody>
</table>

Note: Based on the Integration of Government Model and Community Model
For example, they have sacrificed some funding from their own income to buy handy-talking devices to receive warning messages directly from the Padang City EOC (semi-structured interview in Koto Tangah District, 2016). Moreover, some of the disaster preparedness group (KSB) members had been voluntarily attending in city-level discussions and trainings regarding tsunami early warning system and represent the last-mile population.

According to the field survey findings, there are several flaws with the sirens installed in the city. One of the major problems is that only a minority of people understand the meaning of each sound pattern made by the sirens. As such, information such as Warning-1 (first warning message), Warning-2 (updated warning information), Warning-3 (tsunami has made a landing) and Warning-4 (warning cancellation) might not be fully conveyed to the last-mile community. Moreover, several community members conveyed their lack of trust in these sirens as these devices tend to be “unmanned” and “technologically-dependent” (Personal Communication, 2016). In contrast, people might put more trust in their community mosques, including during a tsunami emergency. As described by Mulyasari and Shaw (2012), Masjid is one form of CSOs with relatively strong leadership by influential people from the community.

Furthermore, the SNA method has also been useful in identifying communication ties among these community members. Our study found that community members have also established communication ties among themselves. Specifically, communication ties are identified between the disaster preparedness group (KSB) members with the sub-district officers and community mosques. In other words, the community leaders do not only take the role of relaying information received from city level institutions, such as Padang City EOC but also share the information among themselves. This finding indicates that there are some partnerships already established among these leaders, which could be institutionalized.

To present recommendations to assist Padang City Government in the improvement of the existing tsunami early warning chain SOP, this study proposes a simplified framework representing the common practice of people-centered tsunami early warning chain. This is presented in Figure 11. In the proposed framework, the actors in the downstream tsunami early warning chain are structured into four layers. The first consists of information...
provider institutions at the national, provincial and city levels. Then, information is disseminated by the Padang City EOC to the community members, both directly through sirens or indirectly through other organizations in the city and community level. In the framework, mid-actors, consisting of four groups of community leaders, have important roles in connecting the communication chain between city level institutions with the local community members, including the last-mile population.

The results presented in this paper have been communicated to the Padang City Mayor and senior officials in several related institutions in Padang City (Rahayu et al., 2018) via a series of public engagement meetings. These include a workshop on improving the downstream tsunami early warning SOP in Padang City on September 1, 2016, and a tabletop exercise for improved SOP in Padang City conducted September 2, 2016. These events were in conjunction with the 2016 Indian Ocean wave exercise (IOWave16) conducted on September 7 and 8, 2016 throughout 24 Indian Ocean member countries.

To get a better understanding and better engagement, as the first FGD conducted in Padang City on February 22, 2016, the research team have been working closely with several actors from the Padang City Government and community leaders in developing the people-centered early warning procedure by empowering the critical nodes as identified in this study. Finally, the procedure has been successfully tested and exercised, i.e. end-to-end tsunami exercise, during the IOWave16. This end-to-end tsunami exercise was not only able to test the performance of all stakeholders identified in Network 4 (complete network) of people-centered early warning system but also to involve about 1,300 community movement to evacuate to shelter as acknowledged and reported by ICG/IOTWMS IOWAVE16 task team in the IOWAVE16 exercise report (Intergovernmental Oceanographic Commission, 2017).

Finally, after a series of public engagement events and testing during IOWAVE16, the improved SOP referred to as the people-centered tsunami early warning system for Padang City has been institutionalized as an academic paper in improving the Padang City Mayor Regulation 19/2018 regarding tsunami early warning system.

**Conclusion**

This study was able to work on the possible improvements of the tsunami early warning system (downstream) for Padang City, using an in-depth and holistic network model. Exhaustive data assessed through a series of FGD meetings with actors from city level and district level, then combined with data obtained from semi-structured interviews in the field were used to improve the downstream tsunami early warning chain (original network). The result of this study was a three-tier of network model, i.e. proposed network, enhanced network and complete network (people-centered early warning system).

Four interface actors (mid-actors) in the community, namely, sub-district offices (*Kelurahan*), schools (*Sekolah Siaga Bencana*), community mosques (*Masjid*) and disaster preparedness community groups (*KSB*) were identified, which have different potential roles for their involvement in the downstream tsunami early warning chain, as well as different level of willingness of participation and capacity to receive and disseminate the tsunami warnings to the public. To synchronize these differences, capacity building is necessary for these actors through training and provision of better communication devices to participate in the tsunami early warning chain.

The involvement and empowerment of community leaders have several advantages beyond the warning dissemination process. From the field semi-structured interviews with the community leaders and community members, the values, which are important in people-centered early warning systems are identified among them, such as volunteerism, leadership
and trust. These values are highly advantageous and may strengthen the people-centered early warning system among the communities.

Moreover, the capacity of local police and the army (who are legally appointed as interface agencies in the InaTEWS), which might be hampered or overwhelmed by the amount of work during an emergency state, could make use of the assisting hands from local community leaders. This further justifies the need to involve community leaders and focus on community-based tsunami early warning and preparedness. Furthermore, with a solid partnership with the local government and the empowerment of these community leaders, these links of cooperation could also be used not only for tsunami early warning chain in a near-field tsunami but also adapted for other types of sudden onset hazards.

To conclude, this study was able to contribute to improving the downstream early warning systems by developing recommendations in improving the people-centered tsunami early warning chain model for Indonesia. Moreover, several findings, which are the strong points of this study are:

- removal of a single gateway agency or zero-redundancy in downstream warning chain;
- a critical shift in the role of mayor in the near-field tsunami warning system;
- identification of a backup function of Regional Office of BMKG to provide early information for heads up in the downstream warning chain; and
- finally, the identification of key interface actors (called mid-actors) in the community who have capacities to receive and relay warnings to the last mile community.

This study offers an insight into the current gaps and challenges in the downstream tsunami warning system in Padang City. The results presented will contribute not only to improve the tsunami early warning chain of Padang City but also as guidelines for other coastal cities and regencies. The findings can also be adopted as part of the existing tsunami early warning system, completing its end-to-end channel, by investigating its reliability and its compliance with the state of the art of InaTEWS. The process development of the three-tier network model can be replicated to other coastal cities and regencies in Indonesia, as well as to other regions, which is exposed to near-field tsunami and having similar government systems, i.e. autonomous at local government level.

References


BMKG (2012), “Tsunami early warning service guidebook for InaTEWS”.


Rahayu, H.P. (2012), Integrated Logic Model of Effective Tsunami Early Warning System Kochi University of Technology, Kochi.


Corresponding author
Harkunti Pertiwi Rahayu can be contacted at: harkunti@pl.itb.ac.id

For instructions on how to order reprints of this article, please visit our website: www.emeraldgrouppublishing.com/licensing/reprints.htm
Or contact us for further details: permissions@emeraldinsight.com
The human dimension of early warning – a viewpoint

Mo Hamza and Peter Månsson

Department of Building and Environmental Technology, Faculty of Engineering,
Lund University, Lund, Sweden

Abstract

Purpose – The 2004 Boxing Day tsunami prompted global efforts to develop end-to-end multi-hazard warning systems. Taking this event as a starting point, and drawing on experiences from the following advancement of the Indonesian tsunami early warning system, this paper aims to highlight the importance of paying attention to human factors and the perceptions and behaviors of end recipients when trying to design efficient early warning systems.

Design/methodology/approach – The study is a viewpoint where theoretical frameworks for the design of efficient early warning systems are used as backdrop to an extensive review and analysis of secondary data, including scientific papers and newspaper articles.

Findings – The paper presents what an end-to-end warning system means, explores process problems related to perception and communication and concludes with views and recommendations toward more inclusive early warnings.

Originality/value – Research and practice related to early warning systems have traditionally had a strong focus on technological elements whilst the target groups of early warnings (i.e. communities) have received far less attention and resources. This paper focuses on the human dimension of warning systems and uses a real case to exemplify how efficient warning systems not only require a sound scientific and technological basis, but also depend on the awareness, trust and will of the people they aim to protect.

Keywords Early warning, Risk analysis, Vulnerability, Risk perception, Tsunami, Risk reduction

Paper type Viewpoint

Introduction

Natural and technological hazards result in a major loss of life, social disruption and environmental degradation. The ability of a nation to manage emergencies, rather than react to crises is critically dependent on the availability and flow of real-time information that is linked through a variety of information networks. Warning the public of an impending disaster is the last line of defense in a nation's effort to mitigate losses that both natural and technological hazards impose on communities.

Hazard warning systems are social and organizational processes, which use technological and other means to reduce risk and loss. However, there is a lot more to early warning systems than issuing the warning itself. In other words, what happens after the warning is as important as the process of prediction and forecasting. The community end of early warning has received less attention, and certainly less resources, than the technology end. There have been leaps and major breakthroughs in technology development, which this paper will demonstrate. However, these have not been matched with an equal focus or understanding of those who are supposed to receive the warning and are expected to act on it.

The extensive studies on tsunami risk reduction by Chang Seng (2010) and Løvholt et al. (2014) show that a lot of progress has been made since the 2004 Indian Ocean Tsunami with regard to institutional arrangements in support of warning systems; understanding and mapping tsunami hazard; understanding and assessing physical and societal vulnerability
(spatial exposure, demographic factors or factors related to warning and evacuation); and progress in using hazard and vulnerability information. However, among the studies’ main conclusions is that there is still some way to go where societal factors are concerned or what we term here the human dimension of early warning.

No matter how sophisticated or advanced the technology or how accurate the forecasting and warnings are, if the information does not reach the people in danger in a timely and understandable manner, that can be acted upon or if they act in ways counter to what is expected as a consequence of a warning, then the warning system fails. Equally, any warning system can only be as strong as its weakest link. In most cases, the end recipients of the warning message (i.e. the community) are the weakest link, especially if the system’s value and function is not well understood. There is an urgent need for more attention to be given to the design and implementation of the links in a warning system rather than assuming that a high-end technology solution will by default trickle down and function in a societal system that has not gone through enough sensitization and awareness processes to work as an integral part of the overall chain of warning.

Methodology
This paper aims to highlight the human dimension and factors in early warning. The paper is primarily a desk-based review that demonstrates the process of early warning in a general sense with a focus on the often neglected, yet most crucial, aspect of early warning – the very people that the system is meant to protect. To contextualize the issue and avoid abstraction, the paper draws heavily on the Indian Ocean Early Warning System experience especially in Indonesia, throughout its several iterations of development since the main event in 2004.

The 2004 Indian Ocean tsunami, which killed nearly a quarter of a million people, prompted a concerted international effort to develop more and better warning systems in the region. Hardest hit was Indonesia, where at least 168,000 people perished (Rivers, 2016). Indonesia was also soon to receive international assistance, notably from Germany, which helped set up a new warning system. This case study forms the basis upon which conceptual issues are demonstrated and further reflected upon. The paper then concludes with a set of suggestions and recommendations for more effective and inclusive early warnings that fully integrate the end-user.

Process and technology
Effective early warnings bring scientific and technical abilities of hazard identification and forecasting together with effective communication, the commitment of public policy and crucially, the understanding and active participation of local communities. There are several views and classifications of what the components or stages of early warning are. For example, the UNISDR early warning platform (UNISDR, 2006) and Villagrán de León (2014) list four interrelated components, where failure in any component results in the whole system becoming defunct. These are: risk knowledge; monitoring and warning; dissemination and communication; and response capabilities.

Alternatively, an earlier classification by Smith (1996) presents what we think is more applicable and appropriate early warning systems components to the purpose of this paper. There is a big discrepancy between the attention and resources that the following three stages of early warning get from governments and funding agencies. These are:

- **Forecasting and risk evaluation**: This is the scientific and technical dimension of the system that primarily employs observation and prediction, based on scientific expertise and advanced technologies (e.g. mathematical modeling, remote sensing,
etc.). A great deal of effort and resources have gone into this stage resulting in significant advances in early warning to various types of hazards especially hydrometeorological hazards and to a great extent geophysical/tsunami-related events.

- **Warning and dissemination:** This covers the institutional and political dimension where forecasts are turned into messages and transmitted by appropriate agencies as recommendations for action. There has also been considerable investment in this stage, but as the paper will show in the following sections the effect and results have not been consistent depending largely on the governance system and national priorities as well as political will.

- **Response and action:** This is the human factor that includes risk perception and decision-making where warnings are expected to translate into actions. Institutional and political aspects of early warning systems broaden out and acquire a social dimension that includes the ultimate end of warning (i.e. people) and where risk evaluation by the end-user plays a crucial role in whether the warning is acted upon or, indeed, how people interact with the entire system as a whole. This component has not received as much attention or investment as the first two stages.

A typical organizational warning chain could be split into three broad categories (Davis *et al.*, 1998) with three sets of actors in a warning dissemination chain: originators – the scientific generators of warnings (meteorologists, hydrologists and volcanologists, etc.); intermediaries – government decision-makers and the media; and disseminators and recipients of warning messages – multiple target audiences (emergency services, military, power companies, airports, port authorities and vulnerable communities). However, in this paper, and with the review of the Indian Ocean early warning case, we will separate disseminators from recipients rather than lump them in the same category. In the case we review, officials at governmental agencies or those in charge of the dissemination infrastructure at met-offices, national disaster management agencies, airports, harbors, etc., are one type of actors actively contributing to the issuing of the alarm message and its dissemination, whereas the general population are passive recipients of the alarm message but an active part of the early warning systems as responders.

In all but the most unexpected sudden-onset natural events, warnings are usually staged so that the warning level is stepped up as the event evolves – as it comes closer, as conditions worsen and as a severe event becomes more likely. A series of warnings will, therefore, be issued, and warning dissemination should ideally become an interactive and iterative process through flow of information and advice. However, as illustrated by the tsunami warning system in Indonesia, this might not always be the case if the system breaks down at the part where the warning is issued.

The German Indonesian Tsunami early warning system (GITEWS) comprised 22 buoys connected to seafloor sensors, which were to quickly detect earthquakes, discern whether they would produce a tsunami, monitor how ocean waves were propagating, and predict where they might go. This data were then to be sent to round-the-clock staffed warning centers, which would perform analysis and determine whether conditions are met for issuing a tsunami warning alert. If so, the alert would be disseminated on local radio and television and people at risk would also be informed to evacuate through sirens or phone notifications (GITEWS, 2019). The system was developed between 2005 and 2008 and formally handed over to the national Indonesian Meteorological, Climatological and Geophysical Agency (BMKG) in 2011 (Helmholtz-Gemeinschaft, 2019).
Due to various reasons, which is further discussed in the sections on ‘risk perception’ and ‘communication’ below, the German system has had its fair share of failures and malfunctions. Several calls have also been made to upgrade or replace it. With technical and financial backing ($3m) from the US National Science Foundation, the development of a new high-tech system of sea floor sensors, data-laden sound waves and fiber optic cables was also initiated. Allegedly, it would both be faster in detecting and relaying alerts and less prone to tampering or vandalism. However, since January 2017 the project has been stalled due to inter-agency wrangling about who should provide the 1 billion rupiah ($69,000) to complete the project (Wright, 2018). As of today, the backbone of Indonesia’s tsunami warning system is a network of 134 tidal gauge stations augmented by 170 land-based seismographs and a system to disseminate warnings through sirens, TV, radio and cell phones. However, the BMKG claims that the system is very limited as they can only afford to maintain 70 of the 170 seismographs and only have sirens in about 56 locations of an estimated need for a 1,000 (Thomas, 2019; Wargadiredja, 2018).

As a consequence, and not surprisingly, the weaknesses of Indonesia’s tsunami warning system were revealed again in 2018. On the 28th of September, a 7 m high wave crashed into Sulawesi and led to the loss of 2,200 lives at a beach party in Palu. Due to its deep bay and surrounding mountains, Palu was seen as a protected city, and hence, not equipped with sirens. Unexpectedly, the long stretched and narrow bay amplified the tsunami. The earthquake that preceded the tsunami-damaged the cell phone towers that were supposed to relay the alert to people in the area (Mead, 2018). In the absence of functioning ocean buoys, this non-disseminated alert was based on seismographic sensors and tidal gauges. Yet, the closest gauge to Palu was 125 miles away and as it only recorded a 2-3 inches rise in water levels, it anticipated the wave at beaches would be below 0.5 m high. Tsunami waves slow down and grow in height as they approach shores, but there were no tidal gauges close enough to measure changes in the immediate area. Besides, tsunamis in Sulawesi tend to happen soon after the earthquakes, leaving little time for tidal gauges set at 15 min intervals to register them before they come ashore (Singhvi et al., 2018). Only three months later, on December 22, an eruption of Anak Krakatao caused undersea landslides and a tsunami that killed about 400 people on the islands of Sumatra and Java. The head of BKMG announced that they were not able to issue an alert as Indonesia’s detection system was designed for earthquake activity and not for tsunamis caused by underwater landslides and volcanic eruptions (Griffiths, 2018).

**Risk perception and awareness**

The crucial and determining issue of an early warning system’s success is not only whether the message reaches its final destination. In a lot of cases, the message filters out and down to the community level – individuals and households. However, why do people not heed the warning or act on the warning message? Reasons could be related to the nature of the message itself, i.e. language used and how technical information is translated into recommended action (Hamza and Morinière, 2010). Acting on the warning or not, even if the message is understood, has more to do with people’s perception of risk and their own vulnerability. This is known as *social amplification of risk* (Twigg, 2003) when events relating to hazards interact with a variety of social, psychological, institutional and cultural processes in ways that can heighten or attenuate perceptions of risk and thereby shape risk behavior.

On the institutional side, Buchanan-Smith and Davies’ study (1995) reveals that institutional response to early warning forecasts is influenced by a variety of external factors – political, attitudinal, legal, financial, logistical, ideological and institutional – that
are unrelated to the scientific data. If such factors influence institutional responses, it is equally likely that they should also influence communities’ and households’ responses to early warning, yet our knowledge and understanding of this area remains limited especially in developing countries.

A community’s view of its own risk is very different from that of an outsider. Outsiders will find it very difficult to understand how communities perceive and react to hazards and risks. There are several reasons for this. First, early warning specialists and communities look at a potential disaster from a completely different starting point. Early warning systems start centrally, at international or national levels, as is the case in the Indonesia Tsunami Warning System, and then move outwards and downwards (individual villages or neighborhoods are on the periphery of the system). For the individual at risk, their home and immediate locality, are at the center of the picture. Factors or priorities that are of primary importance to the villager or household at risk are likely to be invisible to the system managers, who work on a much larger scale (Twigg, 2003).

Second, the two groups measure and describe risk in very different ways. Technical specialists draw upon scientific and engineering methods of analysis to quantify risk, principally in mathematical terms of probability. It is not easy to translate such mathematical calculations into everyday language (e.g. high, medium or low risk). People exposed to hazards and potential disasters tend to perceive and describe risk in qualitative rather than quantitative terms (FAO/WHO, 2009).

Third, the common assumption among disaster professionals is that they alone understand and assess risk objectively (i.e. scientifically), whereas the disaster victims’ understanding and assessment is merely subjective, even irrational (Salter, 1995/1996; Slovic, 2001).

Therefore, what seems logical and rational to scientists and institutions higher up in the early warning chain may not seem so for an individual or a household. A clear example is that a household may perceive the risk of evacuation, in terms of losing control of its assets and resources - property rights, livestock left behind, etc., - as more devastating than the risk of the hazard (GPC, 2019). Where there is concerns of, for example, disputed property rights, risk of land grab, criminality or possible looting, people could potentially see that as a higher risk than the risk of staying put and not evacuating in the face of an impending hazard. A lot of these decisions follow both simple and/or complex risk evaluations, which, as humans, we do instinctively in both conscious/cognitive and sub-conscious ways. This could form part of the answer as to why some of those who live in coastal areas and receive an adequate warning still do not evacuate or abide with resettlement programs to move out of risk-prone areas in the aftermath of disasters (Løvholt et al., 2014). The point this article tries to advance is that with the best intentions and a well-functioning early warning system in terms of issuing, disseminating and delivering the warning message to those it is intended for, there are still societal and governance determining factors that are unrelated to the warning side of the system. These are what Løvholt et al. (2014) term “cognitive factors” in evacuation behavior. A human-centered early warning system needs to take account of such factors, as well as address what hinders evacuation and relocation within a broader risk management/reduction governance system. Equally, the prospect of evacuation to a shelter or camp could induce perception of more vulnerability in a shelter than if they stayed in their own property (Eisenman et al., 2007). Especially vulnerable groups like female-headed households, the elderly and the disabled are probably more prone to this kind of perception or take longer to evacuate when it comes to access to safe places and available infrastructure for evacuation (Løvholt et al., 2014). There might also be strong cultural factors such as Purdah in Pakistan, which prohibits women to venture far from their homes unaccompanied.
by husbands or adult male members of the family. Women form a disproportionate percentage of fatalities and injuries in disasters because of their inability to evacuate when their husbands are away, or because of having to care for children or elder family members (Ferris, 2010). When critical issues of this nature are not considered, the warning system could be abandoned by the very people it was meant to protect.

Another critical issue that shapes people’s perception to risk is public trust in the warning system itself. Villagrán de León (2014) cites the Cuban textbook success case with hurricane early warning and evacuation as largely due to the trust that Cuban people have in a highly decentralized and neighborhood-based system (i.e. a people-centered early warning), while contrasting that with other cases including Hurricane Katrina in 2005 where the warning came late and in an ambiguous form (Fussell, 2006 cited in Villagrán de León, 2014). Frequent false alarms are a major factor in denting that trust or could cause confusion when the alarm is issued (Chang Seng, 2010; Donovan et al., 2018). Reportedly, six of the 18 tsunami warnings that BMKG has issued since 2008 have been false alarms (Emmett, 2018).

As well as false alarms, the failure of the alarm to reach those at risk could also lead to a break of trust with the system. In 2012, an 8.6 magnitude earthquake hit off the coast of Aceh and two of the six evacuation sirens in Banda Aceh failed (Pasotti, 2014). Moreover, contrary to expectations of how people should behave when an alarm is issued, people did not run to the government shelters but tried to drive away which created traffic jams. Luckily, the strong earthquake only produced a minor tsunami that time (Casey, 2014). In March 2016, a magnitude 7.8 earthquake resulted in tsunami warnings for parts of Indonesia, but no tsunami materialized. However, the warning caused widespread panic in the coastal city of Padang, where thousands of persons fled to higher grounds before the alarm was called off two hours later. Apparently, the BMKG had received conflicting reports where a major problem was the complete lack of data from the 22 tsunami-detection buoys deployed during the GITEWS project (Emmett, 2018). According to Indonesia’s National Disaster Mitigation Agency (BNPB), the buoys – which cost more than US$300,000 USD per unit – had been disabled due to theft, vandalism or just stopped working due to lack of funds for maintenance (Rivers, 2016).

Communication and dissemination

Typical early warning systems are little more than a sequence of strong institutions, such as a meteorological service, a broadcasting corporation or a government disaster response agency linked by a chain of communication tools and methods. Davis et al. (1998) contend that part of the problem with inadequate early warning systems is when communication linkages are regarded as secondary to the institutions being linked, possibly because these powerful bodies have not wished to be responsible to or come under any overarching coordinating body. Often the links appear to have been made out of necessity, without detailed creative thought going into determining the precise nature of the connections in the warning chain (Davis et al., 1998). The Indonesia Tsunami Warning system shows some evidence of absence of any person or key entity with the responsibility to coordinate or manage the entire process of getting the warning from the originators to the intermediaries and from the disseminators to the recipients.

At a cost of US$62m to develop, the GITEWS was recognized as one of the most advanced tsunami warning systems in the world (Bojanowski, 2010). Despite this, it failed to alert when a 7.7 magnitude earthquake struck the ocean floor outside the Mentawai islands and generated a tsunami that killed over 400 people in October 2010. It appears that two buoys off the islands had been vandalized (Zielinski, 2010) and the head of the BMKG said the system had failed because of inexperienced operators, who did not have the expertise to
monitor whether the buoys functioned as intended (DailyMail, 2010). German designers, however, refuted the criticism and said the system was working, but that the earthquake had been too close to the shores to allow time for warnings to be communicated and that sirens remained silent even after the warning center had issued the alert, none of which was the fault of the German engineers. Moreover, the German response pointed to the fact that the local relay of alerts (the so-called “last mile”) is the responsibility of the Indonesian authorities and they had failed to meet German standards by letting cables to sirens be strung from palm trees rather than being buried in the ground (Bojanowski, 2010).

Problems of communication are not limited to links and channels between institutions. It is extremely important to understand the needs and the difficulties of communicating warnings to dispersed and heterogeneous populations, many of whom are at basic levels of subsistence economies. Some segments of a population may require special warnings simply by virtue of their unique character. These population segments include those in special facilities such as schools, prisons, old-age homes, hospitals and other institutions. The warnings required by such institutions are probably not different from the sort provided to the general public. However, it is likely that such facilities would require more time for warning response (Gross, 2003).

Where people at risk understand that they might not get warned by authorities and that the earthquakes themselves should be regarded as the warnings (Casey, 2014), relying on collective community memory or indigenous folktale have shown to have made a difference (Villagrán de León, 2014). There is anecdotal evidence that this notion might partly explain the remarkable difference in terms of lives lost in the Aceh province and on Simeulue Island from the Boxing Day tsunami in 2004. Despite being located only 150 km from each other, 170,000 people perished in Aceh, whilst only 7 out of 70,000 residents died on Simeulue. Unlike in Aceh, locals on Simeulue had kept alive memories of a 1907 tsunami they called “Smong”. Through poems and lullabies, they had told stories of an earthquake that swallowed the water followed by a giant and destructive wave. When people felt the earthquake and saw the water subsiding, they instinctively knew what was going to happen, shouted “Smong” to alert each other and started to run for higher grounds (Pasotti, 2014; Syafwina, 2014).

This correct reading of the actual and critical natural phenomena that leads to a disaster highlights another issue in early warning and that of the difference between weather forecasting and issuing of warnings. In Sri Lanka, the Meteorology Department issues weather bulletins under the headings of “Bad weather warning/Cyclone warning”. These bulletins provide technical information such as wind speed, position of a cyclone, its movement and characteristics. However, no information is provided in forecasts about what action should be taken in response to weather information. There is no responsive warning system based on preparedness, which would include public education programs, preparedness plans, etc. (Patabendi, 2003). In all, to reduce the risk of hazard impact, forecasting and warnings cannot and should not be separated from the manner in which the generated information is presented, delivered, communicated and used. Such ways should be informed by people’s perceptions of risk and vulnerability as highlighted in the previous section.

Put together, effective communication for effective warnings, therefore, relate to a number of elements important for developing national capacities – namely, public information and education, professional training (e.g. engineering, communications, teaching, public administration), emergency services, hydrology, meteorology and most of all, community awareness.
Toward a more effective and inclusive system

During the past two decades, tsunamis in Indonesia have highlighted weaknesses of the existing warning system in terms of technical limitations and failures. The degree to which public awareness about how to respond to warnings has been achieved cannot be generalized. Some places have achieved a high degree of awareness as a consequence of experiencing tsunamis or from having being part of early warning initiatives such as the GITEWS project (e.g. Banda Aceh and Padang), while others did not. Calls to improve the system have also been made in the wake of each new disaster. Interestingly, both the causes of and remedies to the problems are connected to human factors. Stolen buoys or stripped of expensive electronic parts (Emmett, 2018) or damaged by fishermen who accidentally hit the buoys with their boats or anchoring off them (Wargadiredja, 2018) were among the reasons cited for the damage that led to the malfunctioning of the system, which the paper addressed. Globally, the National Oceanic and Atmospheric Administration (NOOA), reports cases where fishermen have detached buoys from the sea bed and dragged them after the boat to attract fish or destroyed their moorings to prevent others from using them (Ogburn, 2013).

Both theft and fishermen practices reflect opportunism where one person’s gain is another person’s loss. However, in this case, the loss of buoy data does not only affect one but also potentially hundreds of thousands of people. Efforts to educate fishing communities about the importance of the buoys have proved ineffective. Instead, the NOAA has started to use a combination of surveillance and deterrence techniques, including ship tracking and the use of live cameras and loudspeakers that will record and speak to persons who may contemplate vandalizing buoys (Ogburn, 2013). However, monitoring the functionality of buoys requires human resources and expertise, and systems like these incur extra cost on top of the initial expensive cost of the actual system. The BKMG has repeatedly stressed lack of funds as being a major constraint for maintaining the Indonesian tsunami early warning system. Naturally, allocation of resources is a question of political will and the Indonesian government never allocated the US$2.3m needed to cater for the yearly maintenance of the GITEWS (Wargadiredja, 2018). Having the political will is one thing. Having the means to match it is another. One must acknowledge that highly sophisticated warning systems are expensive and that there are a lot of competing priorities, such as education, health care, infrastructure, which all need to be resourced as well in countries with resource scarcity and priorities of national development where warning systems compete for funding (Lovholt et al., 2014).

Even if the Indonesian government was able and willing to allocate the required resources to maintain a state-of-the-art system like the GITEWS and its planned successor, some Indonesian islands may be located too close to potential sources of tsunamis for such systems to have any effect (i.e. to allow the time for registering earthquakes, assessing their potential for generating tsunamis, disseminating alerts and giving residents enough time to escape).

The Indonesia case demonstrates what we already know that technical systems are not immune from failure. Some experts argue that Indonesia might be better off spending less on sensors and putting more efforts into educating coastal residents about what to do if they experience earthquakes that are likely to trigger tsunamis (i.e. quakes that make it difficult to stand up and endure beyond 20s) in tandem with ensuring the availability of response infrastructure, such as evacuation routes and high-rise shelters (Mead, 2018; Singhvi et al., 2018).

To make early warning systems more effective, a better understanding is needed of the contextual factors and constraints that generate diverse perceptions of risk, and hence, diverse responses to all kinds of warnings. If we are going to acquire a better understanding
of such matters, we will have to modify our approach toward communicating with communities at risk and putting as much emphasis on the community end of early warning as on technology aspects. In other words, ownership of the system needs to acquire as much importance and centrality in the design as technology. This paper addressed the constraining human/social factors of responding to an alert. Early warning systems’ design needs to not only pay lip service in a token way to human factors but also fully integrate such factors that might contribute to the system breaking down (i.e. poverty, prioritizing self-gain out of necessity, lack of understanding of the collective value of the system to society at large or the tragedy of the commons). The common perception of “it does not or will not happen to me,” lack of ownership surrounding the design or, indeed, a combination of these factors, as seen from the case discussed above have major and devastating implications not only in terms of waste of valuable financial resources but also ultimately in loss of lives.

In summary, the paper highlighted several key elements in the success of an early warning system. Forecasts must be accurate in predicting the location, time and severity of a hazard event. Warnings must be disseminated in time for populations at risk to make themselves safe. Information needs to be understood by those who are expected to act upon it. Appropriate response to warning needs to be institutionalized and instilled in daily practice as if it was a second nature through information and awareness campaigns, trainings, drills and regular exercises.

As far as the actual message or the content of warning is concerned, it is critical that messages are credible and received by their intended audience in a timely, reliable and accurate manner. That warnings contain clear factual and behavioral advice and are received from more than one source or channel is also critical (Villagrán de León, 2014). The more sources, the more likely the warnings will have credibility. And finally, the effectiveness of warnings is improved by detailed knowledge of those at risk, and by customizing warnings and targeting them in a specific manner. The importance of people’s involvement in the design, development and operation of their warning system cannot be emphasized enough. An understanding of the value of the system among fishermen, for example, could lead to them guarding rather than vandalizing the buoys. The principle of “poacher turned into ranger” applies here.

Warning dissemination is likely to be more efficient and effective the more direct it reaches the target group than through complicated or confusing channels and in as a short period of time as possible to allow a reasonable window for people to act and respond in an organized way and minimize potential panic. Hazard warning systems often have ‘fanned’ and/or ‘cascaded’ dissemination processes. Any bottlenecks in the system where information is delayed or withheld for any reason, intentionally or through malfunction also needs to be addressed and dealt with.

Most early warning systems take a supply-side approach to communication, seeing it as a process whereby experts at the top or center issue information outwards and downwards to target population. This leads to more focus on technology and most of the resources are spent on the latest, state of the art and shiniest gadgets, ignoring the fact that an early warning system is as good as how it understands people’s behavior and perception. Twigg (2003) argues that we need to move toward a more demand-led approach. By drawing on people’s understanding of their own situation, priorities and perception of risk, it produces data that could inform a better design or a more adequate chain of communication. In addition, the process serves the community by structuring its understanding of problems and priorities and enabling it to identify possible solutions (Hall, 1998). Ideally, this should be a dynamic iterative process stimulating regular rethinking and improvements, not just
one-off assessment. There is no shortage of appropriate participatory techniques available that could be adapted to this context. The anecdote of the Simeulue Island is instructive of how indigenous knowledge may supplement technological systems and even substitute them in areas where high-end systems are too expensive to enact or deemed as ineffective due to their close proximity to anticipated earthquake epicenters. Although focused on the human dimension of early warning systems, this paper has not attempted to devalue how scientific and technological achievements have advanced our possibilities of detecting threats and warning people at risk. It merely points to the fact that the efficiency of warning systems may be compromised by human decisions as well as technological limitations. Warning systems ought to be based on information from both scientists, as well as the people they seek to serve. Whilst technical systems have their role (depending on where an earthquake strikes), they must be combined with efforts to prepare people to understand natural cues, what they might mean, and take actions, which are going to make the difference to them surviving or not. With the likelihood of technological equipment failing and the short time available, the only protection may be what one knows beforehand. By combining local knowledge on coping strategies and new technology for disaster monitoring and response, we may ensure the capacity needed for removing ourselves from harm’s way in times to come.

References
DailyMail (2010, 281010), “Indonesia’s tsunami warning system failed because it was broken, say officials as death toll climbs to 340”, Mail Online, available at: www.dailymail.co.uk/news/article-1324471/Indonesias-tsunami-warning-failed-broken.html


Hall, N. (1998), Improved Vulnerability and Capacity Analysis for Community-Based Disaster Mitigation, Mimeo.


Corresponding author
Mo Hamza can be contacted at: mo.hamza@risk.lth.se

For instructions on how to order reprints of this article, please visit our website: www.emergalgrouppublishing.com/licensing/reprints.htm
Or contact us for further details: permissions@emeraldinsight.com
Abstract
Purpose – This study aims to evaluate the coastal disaster resilience and the disaster management framework of Sri Lanka, by conducting a case study in a few coastal areas in the district of Matara which were majorly affected in 2004 by the Indian Ocean Tsunami. Although it has been 15 years since the disaster struck the country, Sri Lanka is still struggling in building back better. This reveals the need to strengthen the action plan toward coastal disaster management by identifying the barriers and challenges that still exist in policies and frameworks, the use of technology in evacuation planning, implementation of evacuation plans and capacity building of the community.
Design/methodology/approach – This study was conducted through structured and in-depth interviews among the general public and government officials targeting the eventual outcome as to ascertain barriers incorporated with the disaster management framework and then possible improvements to the framework were identified and suggested.
Findings – The findings showed that the practice of an administrative-oriented disaster management framework was a key element in creating a welfare-oriented community that is still building back better in Matara, which was one of the worst affected cities in the country during the 2004 Tsunami.
Originality/value – This paper facilitates resilience development by identifying the overall development of the system after 2004. The required modifications needed to strengthen the system have thereby been identified through the developed output which was produced by analyzing the barriers and challenges.
Keywords Resilience, Barriers, Enablers, Tsunami, Disaster management framework, Coastal disaster resilience
Paper type Research paper

This study was conducted with the financial aid from CABARET (Capacity Building in Asia for Resilience Education), a project of the European Union’s Erasmus + Programme - Key Action 2 - Capacity Building in the field of higher education.

The European Commission’s support for the production of this publication does not constitute an endorsement of the contents, which reflects the views only of the authors, and the Commission cannot be held responsible for any use, which may be made of the information contained therein.
1. Introduction

The 2004 Indian Ocean Tsunami (IOT) was one of the deadliest coastal disasters in recent history, resulting in over 230,000 deaths across more than 15 countries ranging across Asia to Africa (Suppasri et al., 2015). The earthquake which generated the tsunami had a magnitude of $M_w$ 9.3, making it the first “extreme” earthquake since the 1964 earthquake (Stein and Okal, 2007, 2005). Sri Lanka was among the countries that were majorly affected, as the tsunami hit at least four-fifths of the country’s coastal belt. It caused 29,729 human deaths, displaced 889,175 number of people and over 79,100 houses were destructed (Department of Census and Statistics, 2017; Disaster Management Center, 2018).

Prior to the 2004 IOT, the disasters induced by natural hazards which largely affected the country were floods and landslides, with floods being the major disaster affecting Sri Lankan citizens. As Sri Lanka had not experienced tsunamis in the recent past prior to 2004, the country was woefully unprepared to face such a disaster (Jayasuriya et al., 2006). This was one of the reasons for the high number of losses, as Sri Lanka did not possess any standard tsunami early warning (EW) mechanisms at the time (Siriwardana et al., 2017).

The studies conducted by Burbidge et al. (2008), Latief et al. (2008) and Jankaew et al. (2008) have shown that the return period of a tsunami with a magnitude similar to that of the 2004 IOT will be between 520 to 1,000 years. Yet after the 2004 IOT, several other earthquake-generated tsunamis have occurred in the Indian Ocean, in the years of 2005, 2007, 2010 and 2012. Each of the earthquakes had magnitudes equal to or greater than $M_w$ 8.0 (Suppasri et al., 2015). Since 2004, Sri Lanka was not affected by these tsunamis; hence, the preparation and risk reduction focus on Tsunami risk has decreased compared to the other countries in the region (Rathnayake et al., 2019). However, the knowledge and the awareness of the citizens regarding tsunamis and preparation to face them must be continuously maintained.

The main aim of this research study was to identify barriers and challenges in the disaster management mechanism and to evaluate the context of the affected communities at 15 years after the disaster. Another major focus was given to evaluate the capacity of the whole system to face another disaster of the same kind. The context of the study here is the coastal community that experienced the 2004 Tsunami in the Matara area, which is situated in the Southern Province of Sri Lanka. The term system is used to include the multiple stakeholders in the community, which includes community residents, administrative officers, government processes and non-governmental organizations (NGOs). The affected community, volunteers, divisional secretariat office and other relevant governing organizations are some of the elements of the defined system. The organizations, communities and individuals who do not function during the undisturbed state of the system were recognized as the external elements. Identifying the overall development of the system after 2004 and required modifications to produce an output that facilitates further resilience development in the country was the community contribution of this research study.

2. Methodology

This paper is part of a broader study in analyzing the disaster risk reduction (DRR) process considering tsunamis. It discusses the field observations of the case studies carried out in the Dikwella District Secretariat (DS) Division, which is situated in the Matara District which was heavily damaged by the 2004 IOT. Residents and administrative officials in two Grama Niladari (GN) Divisions, Dodampaha East and Wattegama South, were interviewed. A GN Division is the smallest governing level in Sri Lankan state governance. The interviews were conducted using a structured questionnaire regarding the following four
aspects which were developed to cover and identify the most relevant barriers in the disaster
management mechanism; policies and frameworks in DRR, the use of technology in DRR,
implementation of evacuation planning and capacity building of the community. The 39
interviewees comprised self-employed personnel, professionals (such as doctors and
teachers), farmers and fishermen. Furthermore, administrative officers who have had
experience in past disaster events were also interviewed.

3. Policies and frameworks for disaster management in Sri Lanka
Prior to the 2004 IOT, the Reconstruction and Rehabilitation Act No 58 of 1993 existed to
provide relief to affected persons, reconstruct property and rehabilitation of victims in the
aftermath of a disaster. After the 2004 IOT, a number of legal frameworks were developed,
to define and facilitate disaster management in Sri Lanka. In 2005, the Disaster Management
Act No 13 was formed. It provided for the formation of the National Council for Disaster
Management (NCDM) and the Disaster Management Centre (DMC) (Jayasiri et al., 2018). It is
used to govern the disaster management structure in the country. The NCDM was
established as the supreme body in disaster management in Sri Lanka (Siriwardana et al.,
2018). Figure 1 illustrates the structure of the NCDM (MDM, 2005).

Sri Lanka has also defined other policies and guidelines for disaster management such as
the National Policy on Disaster Management, which looks at increasing the country’s
resilience against disaster risks, the Comprehensive Disaster Management Programme,
which provides a comprehensive investment plan to minimize the impact on the citizens’
livelihood and the country’s economy in the face of a disaster, the National Disaster
Management Plan, which looks into reducing the impact of a disaster on various aspects of
the country such as communities, infrastructure, economy and development activities and
the National Emergency Operation Plan, which provides the Standard Operating
Procedures to be used by all associated agencies in time of a disaster (Jayasiri et al., 2018).

In the context of disaster management, the Ministry of Disaster Management (MDM)
(MDM, 2019) of Sri Lanka works with a number of inline ministries and organizations in
activities of DRR, and it also coordinates with the NCDM. Figure 2 shows the structure of
the various departments under the MDM (MDM, 2019). With these overall upstream
organizational structures, the DMC acts as the focal point in coordinating lower-level
agencies, as illustrated in Figure 3 (Hettiarachchi, 2008). The line departments mentioned
here are the Ministry of Health, Department of Irrigation, Forestry Department, Ministry of
Defence, Coast Conservation and Coastal Resources Management Department, Ministry of
Industries, etc.

When observing the defined administrative processes in Sri Lanka, it is evident that the
involvement of external bodies, such as non-governmental and voluntary communities were
excluded from the disaster management frameworks. However, their influence and
intervention are crucial in disaster management. One such focus area is humanitarian
assistance (Rathnayake et al., 2018), as was seen during the aftermath of the 2004 IOT,
where over 500 international aid organizations were involved in recovery and rehabilitation
work (Silva, 2009). In the course of the study, it was identified that the participation of
external bodies such as the armed and police forces had played a vital role during the post-
disaster period. Therefore, such external bodies can be identified as major stakeholders in
the DRR process. As such, there is currently a discernible gap in linking them to and
governing their impact on the DRR process.

During interviews with the administrative officials from the two GN divisions, the
officials expressed their discontent at the way their role in disaster management becomes
ineffective because of the involvement of external bodies such as the armed forces and
political influences. This directly showcases the negative impacts because of the gap in the inclusion of helpful external bodies.

Another point of interest is the support gained from private organizations in evacuation planning in terms of technology and monetary aspects. There has been clear disorganization
in the distribution of funds and relief items, possibly because of the lack of inclusion of such funding and relief agencies in the defined DRR process. The administrative process can be strengthened by facilitating increased coordination between such private organizations and the relevant governmental agencies.

Land use planning and resettlement and relocation policies in the administrative process are also major problematics areas (Dissanayake et al., 2018). Many NGOs that participated in building permanent resettlement or restoration of damaged residences for victims displayed a lack of knowledge regarding property rights in the country, resulting in situations such as change of property ownership between spouses (Ruwanpura, 2009). Also, most of these NGOs had put a timeframe of two years for resettlement activities. However, in some parts of the country, victims of the 2004 IOT were residing in temporary shelters for up to 4 years (Mulligan and Nadarajah, 2012).

4. Effective use of technology in disaster risk reduction
The technological advancement over the world has resulted in the development of existing mechanisms to deliver EW alerts toward the vulnerable community level. Different Web-based and mobile-based applications have evolved to make the existing platforms more efficient and convenient for usage by the layperson. These advancements can be incorporated in each stage of the DRR cycle to perform efficient functioning.

During the pre-disaster stage, geographical information systems can be used to generate hazard maps and risk maps to effectively identify and illustrate vulnerable areas during disasters. With these technological advancements around the world, the need of updating the multi-hazard maps in Sri Lanka was identified as a key parameter to enhance the resilience level of the country (Jayasiri et al., 2018). But, the accuracy of the development of multi-hazard maps varies with the return period of each hazard category which is to be integrated with reference to the existing base maps. This can be identified as another research area that can be explored and undertaken under the concept of Multi-Hazard Early Warning (MHEW).

Numerical simulation studies were carried out by researchers to identify the tsunami mitigation measures with respect to structures (Samarasekara et al., 2017). This is already in operation in Sri Lanka under the DMC and multiple line agencies. Global survey technologies combined with computer-aided simulations, big data analysis and database analysis of past disaster incidents can be used to analyze and predict possible disasters and communicate to the government and citizens through MHEW mechanisms. During the disaster and post-disaster phases, technology such as automated drones can be of use in identifying and rescuing trapped disaster victims with minimal danger to rescuers.

Under this research study, a major focus was directed toward the identification of community exposure toward different modes of receiving tsunami EWs and the awareness of modern approaches. The structured interviews with the GN officials and the community revealed that the majority of the community still relies on more traditional modes of receiving EW alerts than on novel digitally enhanced applications. This can be interpreted more in Figure 4.

From the analyzed interview responses, the most preferred mode of receiving tsunami EWs can be extracted as the notification disseminated through the EW towers. This was preferred as the best option by 39 per cent of the responses received.

The DMC has established EW towers in each major town in the coastal zone at prominent places. The EW tower in the Dikwella DS Division has been established in the Dikwella Police Station, as denoted by (1) in Figure 5. During the interviews, the administrative officials revealed that the siren had been audible up to a maximum distance...
of 1,000 m during the drills that had been conducted. The audible area is marked from the black circle in Figure 5. The EW tower is 2.83 km away from Dodampahala East GN Division (3) and 432 m away from the Wattegama South GN Division (2). Mobile EW alarm systems (vehicles with sirens attached) are available for other areas.

Next to the warnings given by the EW towers, the majority of the community has shown a preference for the traditional modes of EW. Amongst them, bells or sirens, loudspeakers and TV/radio ranked the highest preferred, exceeding the preference for the modern digital platforms. The low mobile phone and smartphone usage in the community, lack of awareness regarding modern digital platforms and credibility issues of the information received from the other modes can be considered as main reasons behind the interview responses.

Social media platforms such as Facebook and Twitter have ranked as the most efficient modes of delivering EWs in other countries over the world (Collins et al., 2016).
However, when comparing this fact with the obtained data set, the preference for social media when receiving the tsunami EW was almost null. This has revealed that the exposure and the willingness of the community to adapt to new changes are considerably low. The lack of knowledge and the awareness of modern digital communication platforms associated with tsunami EWs can be considered as probable reasons for these community responses.

Short messages service (SMS) is used frequently and has become a trustworthy mode of EW communication in many countries that are highly affected by coastal hazards. Considering the community response of the study location, the receipt of tsunami EWs through SMS has been listed as the most preferred method by 12 per cent of the responders.

Another identified platform, which is highly used among the community in other countries is social media apps which enable communication with a larger number of people, especially during and after a disaster. Presently, there are also mobile applications that are being developed for the sole purpose of EW communication and other knowledge dissemination during a disaster. In Sri Lanka, such a mobile application exists, named the Disaster and Emergency Warning Network (DEWN) which was developed by a leading telecommunication company in Sri Lanka and operated by the DMC (Jayasiri et al., 2018). For such services to be fully utilized, the providers need to fully incorporate and integrate the available facilities and technology.

During the study, it was observed that there is a lag in the usage of digitally enhanced communication platforms in the community area of the study. This highlights a lack of exposure and awareness regarding services such as DRR relevant mobile applications. The use of technology at the grass-root level is low, and a significant difference was observed in the technology usage between the younger and older age groups. The elderly population in the community do not show a significant usage of common technology available, whereas millennials do. This tends to be a major drawback in implementing such technologies. One of the initial research findings indicated that 60 per cent of the interview respondents were reluctant to respond to EW messages and 75 per cent of them have no faith in the EWs received.

5. Implementation of evacuation plans
5.1 Disaster evacuation
Implementation of evacuation planning is a key segment that is considered under Coastal Disaster Resilience and Management to minimize the effects of such disasters. In the absence of thorough planning and training, there is the chance of damage and loss occurring that could have otherwise been prevented. For example, during the 2005 Nias Earthquake and Tsunami, about 10 people died due to panic when the evacuation was being conducted from the Sri Lankan coast (Suppasri et al., 2015). Another point to be remembered in DRR planning is that the majority of the victims during disasters such as the 2004 IOT were women and children (Jayasuriya et al., 2006). Therefore, the safety of women and children during evacuation planning should be a priority.

After the 2004 IOT, several training drills had been organized for the general public in each GN division by the government. The DMC frequently organizes EW drills to educate people who live in high hazard potential areas. The main aim of these drills is to make citizens aware of tsunamis and for them to practice skills needed for safe evacuation during a coastal hazard such as a tsunami. From the study, it was gathered that during initial training programs, members of each GN division were divided into groups, with each group being assigned a specific duty during a disaster. These duties included door-to-door disaster
warning and rescue of differently abled and elderly persons. From the results of the interviews, a lack of participation of the general public in EW drills and awareness camps was detected. This means that current public knowledge about coastal disasters and practices used for evacuation planning has slowly reduced.

As part of evacuation planning, the DMC has instructed citizens to prepare and maintain an evacuation pack, which should include their national identity cards, valuable governmental certificates and other valuables and store it in a prominent place. This is so that in case of a disaster or emergency, people can quickly evacuate. However, the interview results indicate that only 18 per cent of the interviewees currently follow this practice.

The study in the two GN divisions revealed that 40 per cent of the residents are reluctant to evacuate from their property during a disaster. One reason for this is because of fear of thievery, as during the 2004 IOT many robberies occurred and the same was repeated during a few past drills. The second reason is the lack of faith in EW systems. This could be partly due to the fact that in the past, a few false alarms had been given. There had also been several instances where training drills had been conducted without informing the public, allowing them to think that an actual disaster would occur. The third reason is the lack of necessary facilities in safer locations.

5.2 Evacuation shelters

The presence of planned evacuation shelters, in addition to providing safe refuge during the disaster, reduces the urgency of rehabilitation and reconstruction, so that those activities can be done in a well-planned and durable manner. When such shelters are poorly planned and insufficient for the evacuated population, the lives of the shelters’ residents become difficult, especially those of women’s and children’s lives. Mulligan and Nadarajah (2012).

In the study area, evacuation shelters are based on a community building in high land. It was observed from the interviews that people tend to take shelters from the nearby temple in Dodampahala East GN Division. The temple has been denoted as the evacuation shelter of the division. There the facilities are the next important factor. Depending upon the time of stay the capacities are determined.

When the community is located more inland, residents deemed it safe to stay in their houses given the assumption that the houses are at a higher elevation. A major example is the Wattegama South GN Division, marked by (2) in Figure 5, which is situated about 500 m away from the coastal line and is at a relatively high altitude. The area does, however, have an evacuation point named by the GN division, which is near a natural rock and the rock has been called the Tsunami Rock.

A major gap identified is that the structural stability and the strength of the structures which are found in evacuation routes such as bridges as well as the buildings used as evacuation shelters for vulnerable communities. These evacuation shelters lack sufficient capacity and basic facilities such as water and sanitary facilities to satisfy all the vulnerable members in the area. Also, another gap identified was that the new constructions of schools and other public buildings are in lowland areas, making them unsuitable to be used as evacuation shelters during coastal disasters.

6. Capacity building of the community

The damage and loss of property, the inward flow of seawater into agricultural land and the destruction of marine life in the ocean made the return-to-career life after the tsunami extremely hard, especially for people involved in trade, agriculture and the fishing industry. Restoration of businesses took 2 months, restoration of agriculture took 6 months and restoration of fisheries took even longer as even after one year, only 40 per cent had been
restored (Suppasri et al., 2015). Out of the interviewees, 32 per cent reported that during the time of the disaster, they had no idea how it would affect their methods of income. From the people who were involved in a career at the time of the Tsunami, 31.5 per cent reported that they did not return to the same career or started in a different path of work afterward. The people who did resume in the same path reported that they took time periods ranging from a few days to 5 or 6 years to return to work. However, 77 per cent of those people returned to their work by three months after the tsunami.

In terms of immediate post-disaster management after the 2004 IOT, many organizations were involved in search and rescue operations to find those displaced during the disaster. These organizations include the army, navy, air forces and police, staff from local administrative divisions such as the GN and DS divisions, media organizations and NGOs such as the Red Cross organization. The immediate aftermath of the disaster also required the provision of supplies like dry rations, potable water and other supplies. Out of the interviewees, 92 per cent responded that provisions were supplied by NGO’s. The government was also involved in providing supplies through the relevant administrative levels.

The IOT caused many damages in the infrastructure systems in the area. The electricity lines were damaged and cut off, the inward flux of seawater caused the water sources to be contaminated and unusable, the transportation systems were blocked off and the public transportation systems were put on hold. From the interview results, the median level of time taken to restore electricity lines was ten and a half days. The time taken to access drinking water without provisions had a median level of nine days. By September 2005, pipeline water provision was restored to all citizens who were served prior to 2004 IOT (Illangasekare et al., 2006). The time taken to restart using the transportation systems after the disaster had a median level of six days for the people in the studied communities.

The damage and losses caused by the tsunami were extensive and costly to the people. The complete replacement of damaged assets was estimated to cost nearly US$2bn (Jayasuriya et al., 2006). The government became involved in various ways to help the affected citizens. The damages and losses were assessed, and compensation and reparations were made to the people in terms of monetary support and equipment supply. Figure 6 shows the satisfaction of the people regarding government involvement during the aftermath of the 2004 tsunami aftermath as a score out of ten.

The government mechanism for re-establishment and restoration of damages and losses for the tsunami affected was as follows. First, the affected person had to file a police
statement stating the list of damages and losses. Then the government assessed damages and reparations were given in terms of monetary support to build back the losses or a new house or land to resettle elsewhere. Out of the interviewees, 74 per cent reported that at least some physical damage was repaired.

Administrative officers regretfully stated that most of the affected community in Matara, Sri Lanka has evolved into a welfare-oriented culture, where the citizens completely depend on external help to recover from the 2004 IOT disaster. A major observation from the study in Dikwella was that as a whole, the community currently stands at a lower level when compared to its status prior to the tsunami. The citizens have not reached a full recovery state, in terms of the yearly income and household states.

After the Tsunami, a 3-km long retaining wall has been constructed along the coastal line in the Dodampahala area. The coastal line in the study area has been marked as a protected area. However, there have been a series of constructions in that area, mostly hotels and restaurants. While many industries in the coastal zone experienced a downward growth rate following the tsunami, the growth rate of the construction sector increased from 5.5 per cent to 8-10 per cent in the following 3 years after the 2004 IOT (Naik et al., 2007).

7. Concluding discussion
The results of the study conducted in the Dikwella DS Division revealed several significant barriers that prevent the division from attaining satisfactory resilience in terms of livelihood restoration, emergency response and infrastructure capacity after the 2004 IOT. The lack of exposure and awareness of modern technology is a major gap. The administration process has also disregarded indigenous knowledge regarding EW mechanisms such as monitoring of animal behavior patterns prior to the occurrence of disasters.

There is a major drawback in evacuation planning and the interest and participation of citizens in disaster drills and training programs are low. Specific planning for more vulnerable community members such as those with special needs is missing. The residents in the area revealed a lack of knowledge regarding the impact of coastal disasters on aspects such as income methods and critical infrastructure. The available evacuation centers have insufficient capacity and facilities. Also, the construction of potential evacuation centers such as schools and governmental organizations being done in low-land areas reduces the safety of such buildings in the case of a disaster. As mentioned in the section showing the study results obtained regarding the effective use of technology in DRR, lack of faith, knowledge and understanding in EW systems exist in the community. The available EW towers also showcase a capacity inadequacy in reaching all citizens in the area.

The identified barriers have interdependencies and stakeholders (NCDM, local government, community, media, Department of Meteorology [MET], DMC) who have direct and indirect influence and responsibilities over addressing them. Figure 7 has been developed to illustrate this phenomenon in a systematic way.

A major focus was revealed from a recent research study that specially focused on people with special needs (Jayasooriya et al., 2019). This has denoted the lack of preparedness and lack of special mechanisms toward the evacuation of this sector of the population in a coastal community. Further, the barriers in the existing DRR mechanisms linked to EW in Sri Lanka were identified through previous studies (Hippola et al., 2019). These factors should also be addressed to facilitate a better mechanism.

Several barriers in the administrative process of DRR have been identified through this research study as well. There is a lack of policy and a defined process in linking
Figure 7. Barrier network
external organizations to the DRR process. This has led to disorganized provision support from various organizations such as coordination of the media-driven support with the local government processes. The documentation process in the aftermath of the previous disaster had taken a long time, making life even more difficult for the disaster victims. The processes and policies do not facilitate community empowerment, and as such, the community has failed to fulfill the disaster recovery stage. There is a questionable level of authority in the defined administrative process. This has been made evident by the constructions along the coastline in the disaster aftermath, which has been done disregarding the non-construction zoning policies implemented by the government in those areas.

When constructively observing these barriers, four major attributes can be identified:

1. Not all existing barriers are tangible.
2. There is a repetition of the same gap in various context.
3. The main responsible authority or stakeholder of barriers can vary or remains the same.
4. Some barriers are a result of cascading of another gap.

Figure 7 shows the process barrier network developed. Community, media, NCDM, local government, DMC and MET were the identified elements/institutions that have major links with the barriers identified from the study. It illustrates the cascading nature of every gap and how each of the intuitions is linked with the barriers. It can be used to identify the stakeholders to address the barriers. The use of this process will be valuable in all levels of decision-making. A gap prioritizing and clustering or ranking can be done using this network diagram methodology.

Often, a disaster caused by natural hazards has the propensity to escalate to disaster level because of existing political and economic conditions in the area (Pelling, 2001). Therefore, to minimize future damage and increase resilience, it is imperative that both the administration and community work together to establish a prepared and knowledgeable community.

References


**Author affiliations**

Danidu Kusal Rathnayake, University of Peradeniya, Kandy, Sri Lanka

Devmini Kularatne, University of Moratuwa, Moratuwa, Sri Lanka

Soni Abeysinghe, University of Peradeniya, Kandy, Sri Lanka

Ishani Shehara, University of Moratuwa, Moratuwa, Sri Lanka

Thilanga Fonseka, University of Moratuwa, Moratuwa, Sri Lanka

Sameera Darshana Jayasooriya Edirisinghe Mudiyanseelage, Department of Civil Engineering, University of Peradeniya Faculty of Engineering, Peradeniya, Sri Lanka

Wathuwala Gedara Chaminda Thushara Kamlrathne, Department of Sociology, University of Peradeniya Faculty of Arts, Peradeniya, Sri Lanka

Chandana Siriwardana, Department of Civil Engineering, University of Moratuwa, Moratuwa, Sri Lanka

Chaminda Senarathna Bandara Alagiyawanna Mohotti Appuhamilage, Department of Civil Engineering, University of Peradeniya Faculty of Engineering, Peradeniya, Sri Lanka, and Ranjith Dissanayake, Department of Civil Engineering, University of Peradeniya, Kandy, Sri Lanka

**Corresponding author**

Danidu Kusal Rathnayake can be contacted at: kusaldanidu@gmail.com

For instructions on how to order reprints of this article, please visit our website: [www.emeraldgrouppublishing.com/licensing/reprints.htm](http://www.emeraldgrouppublishing.com/licensing/reprints.htm)

Or contact us for further details: permissions@emeraldinsight.com
Framework to analyze Sri Lanka disaster management mechanism
Chameera Randil, Chandana Siriwardana and Kalana Hewawasam
Department of Civil Engineering, University of Moratuwa, Moratuwa, Sri Lanka

Abstract
Purpose – The purpose of this study is to develop a framework to assess the disaster management mechanism in Sri Lanka by means of the established indicators and newly derived indicators. This could be used to identify the parameters, which should be paid much attention to improving the resilience of the built environment.

Design/methodology/approach – This paper initially examines the effectiveness of the existing mechanism using data from a field study, by identifying the parameters needed to be considered based on the existing literature. Then the study continues on identifying new parameters of evaluation, covering a broad multidisciplinary scope inclusive of geographic, demographic, environmental, technological, social, economic and political perspectives. The identification process is based on regression relationships; hence, a framework will be developed to assess the resilience of the built environment.

Findings – The findings showed that the existing disaster management mechanism should be improved in terms of authoritative assistance while the humanitarian assistance is fulfilled to a satisfactory level as the resilience of the built environment is often community-based in Sri Lanka. Furthermore, resilience of a certain region could be effectively assumed with the indicators within the developed framework.

Originality/value – The existing evaluation criteria of the resilience framework in Sri Lanka is rather qualitative than quantitative. Therefore, this paper focuses on developing a framework where quantitative parameters are used to evaluate the existing mechanism from a number of responses from field surveys. In addition, recommendations for the key areas to be focused on developing the existing mechanism are stated.

Keywords Risk reduction, Evaluation, Resilience, Disaster management framework

Paper type Research paper

Introduction
Sri Lanka is an island situated in the Indian Ocean near the equator. Hence, the climate conditions present in the country can be specified as tropical. (Department of Meteorology, 2016). When the topography of the country is considered, the central part of the southern portion of the country is having a hilly terrain, while the other parts of the country is consisted with main flatlands with some isolated mountains located randomly. Because of the tropical climate conditions, Sri Lanka is essentially prone to hydro-meteorological hazards, inclusive of floods being the most destructive type of disaster (Ministry of Disaster Management, 2017a). Most of the time, many hazards occur due to an event of excessive rainfall, which triggers the hazards for flood, landslides and storms.

The country receives the rainfall in four main seasons a year, which can be classified as North-East monsoonal period that takes place from December to February, South-West monsoonal period that takes place from May to September and the two inter monsoonal periods, which take places in between the above mentioned main monsoonal periods. With the main monsoonal periods giving a mean annual rainfall of more than 3,000 mm, and the inter-monsoonal periods giving a mean annual rainfall of more than 1,000 mm, many
flood-related disaster situations can occur in the country as shown in Figure 1 (Department of Meteorology, 2016). Then, having Sri Lanka located very close to the Bay of Bengal, a weather change in the vicinity can drastically change the condition in Sri Lanka, causing massive disasters and destructions to the existing built environment.

The recent floods in 2016 May and 2017 May have caused many damages to the infrastructure and to the lives of people. As a study, this paper is focused on the 2017 May floods. Heavy rains of more than 400 mm in 12 h (Disaster Management Center, 2017) have received by the South-West region of the country, and the most severely affected areas are in the Kalu, Gin and Nilwala river basins, comprehending into the districts of Kalutara, Rathnapura, Galle and Matara. In fact, the Department of Meteorology had anticipated that the rainfall would not exceed 600 mm, however, it had exceeded 600 mm (Hettiarachchi et al., 2018). The loss of human lives and property can be shown as in Table I.

![Figure 1. Main 4 seasons of Rainfall](image)

<table>
<thead>
<tr>
<th>No.</th>
<th>Galle</th>
<th>Matara</th>
<th>Kalutara</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deaths</td>
<td>15</td>
<td>31</td>
<td>152</td>
</tr>
<tr>
<td>People affected</td>
<td>102,747</td>
<td>176,975</td>
<td>394,379</td>
</tr>
<tr>
<td>Families affected</td>
<td>25,692</td>
<td>43,382</td>
<td>103,987</td>
</tr>
<tr>
<td>Houses damaged</td>
<td>550</td>
<td>4,946</td>
<td>5,932</td>
</tr>
<tr>
<td>Houses destroyed</td>
<td>180</td>
<td>947</td>
<td>1,037</td>
</tr>
</tbody>
</table>

**Notes:** Top left: first inter-monsoonal period (March-April), top right: south-west monsoonal period (May-September), bottom left: second inter-monsoonal period (October-November), bottom right: north-east monsoonal period (December-February): all figures are in millimeters

**Source:** Department of Meteorology (2016)

**Table I.** Damage to the human lives and properties by floods, 2017 May

**Source:** UNISDR (2017)
When considering the numbers, it can be seen that the number of mortalities is at a higher level, in comparison to the numbers in floods, 2016 May. Since Sri Lanka had a similar flood in May 2016, it is expected to have built some mechanism on catering a disaster situation in floods, but for a certain degree, it could be seen that the disaster management process was not totally successful in some areas. Therefore, the degree of implementation of the national disaster risk reduction (DRR) and national disaster risk management frameworks is in question.

Initially, this paper tries to assess and evaluate the degree of implementation of the current disaster management mechanism in Sri Lanka, at the community level. To start with, it is essential to explore the context of the disaster management mechanism of the country, by looking in to the different frameworks that have formed the current mechanism, and it is also important to compare them with the globally accepted and well-practiced mechanisms, to identify any possible improvements for the existing frameworks in the country. Therefore, this paper will initially summarize the Sri Lankan context of disaster management, and later it will move on to compare the Sri Lankan case with the global scenarios.

**Disaster management in Sri Lanka – current mechanism**

*National policy on disaster management*

The National Policy on Disaster Management which was published by the Ministry of Disaster Management in February 2013 comprises seven chapters. The first chapter is the preamble for the policy while the second chapter briefs on the vision — “Towards a safer Sri Lanka”, mission — Effective disaster management for safety and resilience of lives and properties “and following objectives. They are to achieve sustainable and resilient disaster management through:

- appropriate institutional, legal and implementation mechanisms;
- informed, scientific, multi-hazard risk reduction approaches mainstreamed in development and reconstruction based on national priorities; and
- participatory, multi-agency, multi-stakeholder engagement in line with national and international standards for effective disaster relief and response.

The third chapter briefs on the regulatory framework in disaster management in the perspectives of establishment of the National Council for Disaster Management (NCDM) and Disaster Management Center (DMC). Furthermore, it briefs on the roles of NCDM and DMC, national disaster management policies, national level coordination and the sub-national level coordination.

The next three chapters in the policy are about the functionality of the DMC. Fourth Chapter briefs on the guiding principles in managing a disaster in the perspectives of relief, equity and equality, transparency and accountability, participation and right to access information, quality service delivery, legitimacy of service delivery agencies and collective responsibility.

The fifth Chapter is on the national disaster management policy statements, which are detailed under main two topics on the aspects of governance on disaster management and DRR to be mainstreamed into overall planning and development. And the next chapter of national strategies for disaster management has six main strategies, which are governance, mitigation, preparedness, emergency operations and response, relief and early recovery, resettlement and rehabilitation. The Seventh and final chapter stresses the need for revising and updating the policy every five years, to suit the emerging needs (Ministry of Disaster Management, 2013).
When analyzing the policy, it can be seen that the policy is shaped by the Hyogo Framework for Action and it was defined in 2013s. Now it is in the process of aligning with the Sendai Framework for DRR, which is being published as the Sri Lanka Disaster Risk Management Plan 2018-2030 (Disaster Management Centre, 2018). As mentioned previously, even though the framework is in action, the measurements of the level of implementations are yet to be established, to evaluate the success of implementation, at national and regional levels.

Community resilience framework of Sri Lanka
Community Resilience Framework, 2015 issued by the Ministry of Disaster Management consists of seven sections. The first four sections explain on the background, goals and objectives of the framework (Target audiences), community-based risk management in Sri Lanka (Historical review of risk management, community-based approaches in risk reduction and limitations and challenges in community-based disaster risk management) and key lessons learned.

Section 5 of the framework describes the framework itself, starting from the definition of a resilient community. A resilient community is defined as:

 [...] ability of a community to “bounce back” and recover using its own resources’ and also the ability of groups or communities to cope with external shocks and stresses as a result of social, environmental and political change (Disaster Management Center, 2015).

Furthermore, it describes the behavior of a community after a disturbance by the extent of dealing with adversity by the means of exposure, sensitivity and adaptive capacity. Then the reactions ranging from downfall, recovered, build back and build back better can be observed, which are caused upon the availability of national resource management, risk-sensitive planning and social cohesion.

The sixth section of the framework focuses on the system-based approach in achieving resilience in building community resilience. The whole community is divided into five main sub-systems, namely, human, environmental, social, physical and economic, and each of the subsystems should share the risk knowledge, and the risk coping capacities of each system should be known by the system itself. Indicators can be assigned to measure the existing knowledge and condition on salient features specified for each subsystem. In addition to that two cross cutting features are identified in sharing the risk knowledge, as the involvement of government organization and the risk knowledge itself. Principles in building resilience are presented afterward.

Section seven briefs on the strategies to implement the framework in Sri Lanka. There, the divisional secretariat-based implementation is preferred as it is the closest governing body for a community. The implementation success will be measured by assigning key indicators for each aspect in the framework, which are well-being before and after a disaster vulnerability, resilience capacities, shocks losses and stress, reaction and program results, and the possible key indicators are mentioned in the eighth section in the categories of physical, human, economic, environmental and social aspects. (Disaster Management Center, 2015). It can be seen that this framework is also aligned with the Hyogo framework for action followed by the Sendai framework for DRR.

Regarding the evaluation of the implementation of the community resilience framework, it has briefly specified “potential indicators” on physical, human, economic, environmental and social categories to assess the success of the implementation of disaster management. However, further information is seldom available in this source, as it does not clearly establish the methodologies that can be adapted to quantify the implementation success of
the framework. The potential indicators specified in this report are used in this study to find the indicators on success of the implementation of the disaster management mechanism, as shown in the latter parts of the paper.

Since the aforementioned frameworks are the mainly used and accepted frameworks to assess the Sri Lankan context of disaster management, next the most significant global practices of disaster management is explored.

**Sendai framework for disaster risk reduction**

Being the globally accepted framework for DRR, Sendai framework for DRR has influenced in building many DRR frameworks, including the community resilience framework and the National policy on disaster management, as aforementioned. The framework consists of seven targets, four priorities for action and 13 guiding principles for DRR. Most of the content and the contextualization of this framework is quite similar to the case in Sri Lanka, as the Sri Lankan guide has been highly influenced by Sendai and Hyogo frameworks.

More importantly, the Sendai framework specifies a set of measures that should be considered in evaluating a framework, and also it recommends a set of assessing methodologies such as questionnaire surveys, roundtable discussions and field interviews. To assess and compare human perceptions toward the disaster management mechanism (UNISDR, 2015a). However, it was identified that there is much room in improving the spatial and the mathematical applications, to establish the impact on the people.

**Federal Emergency Management Agency guidelines**

Moving more on to the global literature, USA’s Federal Emergency Management Agency (FEMA) guidelines are globally accepted as established guidelines in implementing the disaster management work, and this has been implemented and tested many times, as a lot of disasters of different kinds has taken place in the USA, which also has shaped and optimized their guidelines to implement more successfully in a disastrous situation (US Department of Homeland Security, 2016). It has specified 14 Emergency Support Functions (ESFs) (such as transportation and communications) to be followed after a disaster. Affiliated to the ESFs, there are core capabilities (such as critical transportation and operational communications) aligned with each other, and also there are essential elements of information linked to ESFs. These core capabilities often define the specific actions to be taken while implementing the ESFs, and the essential information contextualizes the types of data required to make informed decisions. In addition, there are institutional responsibilities attached to the ESFs, which get the stakeholders involved.

More importantly, these ESFs are prioritized according to the core capabilities, and the activities of disaster management are carried upon according to the priority of the ESFs. In addition, they have formulated certain mathematical measures for certain activities such as door knocking times and scheduling of door knocking, and they use these in information dissemination, as well as in the evaluation of the emergency assistance given at a time of the disaster. However, there are records of the emergency assistance being late than expected at the hurricane Katrina, where local communities and business chains got together and managed to run the basic functions that should be carried in time of a disaster, without any assistance of the FEMA as well.

**Australian Institute for Disaster Resilience guidelines**

Australian Institute for Disaster Resilience also has a very comprehensive and transparent framework, which is published as a set of manuals and guidelines (Australian Institute for Disaster Resilience, 2018). Since Australia is subjected to heavy floods majorly, these
guidelines have been revised frequently, and the efficiency would be high. Similar to the FEMA guidelines, AIDR guidelines produce a priority event sequence in managing the disaster (Priority 1: Medical and health; lifeline facilities, Priority 2: Welfare; housing and damage; civil eng. and major building damage; agriculture, Priority 3: Insurance; business recovery; local and state government recovery, Priority 4: Research, assessments and analyzes by different stakeholders).

For the evaluation purposes, AIDR has a quantifiable approach, as it has defined some components of recovery which could be measured. These components are the return of evacuees, establishment of recovery centers to deal with residents seeking assistance, cleaning and storing the houses and business buildings, restoration of infrastructure, maintenance of public health and mental health support. In addition, as similar to the FEMA guidelines, AIDR guideline also provides some important calculations such as the door knocking time, where they actually use those end results for scheduling and optimizing the number of resources they have. Also using the same components of recovery, the evaluation of the disaster framework could be carried out.

Organizational structure of the disaster management center, in operations
As a lot of content was gone through the frameworks for disaster management, now it could be looked into the implementation strategy and the coordination/information dissemination methods used in the National Disaster Management Center.

National Disaster Management Center (DMC) is the main body in operations in an event of a disaster, and it acts as the coordinating body for the information received and transferring them to the relevant authority. DMC has a 24/7 operating National Emergency Operations Center for this purpose. DMC works in collaboration with many governmental organizations such as National Disaster Relief Services center as the main body of collaboration, Department of Meteorology, Department of Irrigation, military tri-forces, police and with Non-governmental organizations such as Red Cross, Sarvodaya, UNISDR and homegrown community based organization such as Sarvodaya to cater to the needs of a disaster.

When the operations are considered, the DMC is located in Colombo, while for each district, a district emergency operations center operates under the supervision of disaster management coordinator for the district. The organizational structure of the DMC is shown in Figure 2.

Problem statement
Even though there are mechanisms in responding to a disaster situation, the degree of fulfillment of the basic aspects that need to be addressed during a disaster is questionable, according to public opinion. In addition to that, there is no method of assessment for the effectiveness of the disaster management process and the effectiveness of the frameworks in Sri Lanka (Siriwardana et al., 2018). Post-disaster management assessment tools should be developed to assess the existing conditions, to identify the lagging behind areas of assistance and to improve on the lagging behind areas.

Methodology
The literature review of the study initially identifies the loopholes in assessing the disaster management mechanisms, then it reveals methodologies to evaluate the effectiveness of the same. The derived methodology using the literature is shown in Figure 3. The preferred type of data collection is by questionnaire (UNISDR, 2015b). The questionnaire was subjected to the victims of May 2017 floods to collect responses, for this case study.
Discussion: evaluation mechanism

Identifying the key factors of disaster management process with the disaster phase

A disaster is typically progressed in three major phases: normal/DRR stage, emergency response stage and recovery stage (Piper, 2017). In these three phases, different aspects of DM should be addressed and assessed, and referring to existing literature, 13 factors were selected to measure the extent of the effectiveness of DM practices and the DM framework in Sri Lanka. (Baas et al., 2008; Disaster Management Center, 2017, 2015; Ministry of Disaster Management, 2013; Ministry of Ecology, Sustainable Development and Energy, 2015; UNISDR, 2015b, 2015a) The 13 facts and their time of occurrence at a disaster time are shown in Table III below.

In a disaster, the sequence of the aforementioned fact indices appears in the following order, with respect to the time as shown in Figure 4.

Questionnaire

Below shown in Table II is the summarized questionnaire, which represents the previous factors and which was presented to the affected people. Questions in this questionnaire are based on the potential indicators that were found in the literature review, to assess the impact on people.
Selection of sample sizes and sample areas

To comply with the random sampling technique, it was determined that 140 was the sample size. Then, when selecting the areas from the flood-affected areas to collect samples, a whole spectrum covering the aspects in social definitions (urban, rural, estate) (Department of Census and Statistics, 2018), poverty index, population, land-use and technological characteristics were considered. The geographical areas were selected to represent all the aforementioned criteria (Section 11 for full criterion), as a regression analysis on developing an index for disaster management effectiveness could be performed, in later stages. The selected areas are Baddegama, Nagoda in the Galle district and Kotapola, Pitabedda and Matara (Four Gravets) in the Matara district as shown in Figure 5. The selected areas were inundated by the floods from Gin and Nilwala rivers (Table III).

It can be seen that most of these facts are not tangible. Therefore, it was essential to making a questionnaire in the next step such that these facts are covered, in a simple and tangible manner, therefore, an average person can understand.

After the numbers of respondents were finalized, field visits were done to the shown areas and data was collected, and 144 responses were collected to conform to the above-mentioned sample size. The summary of the collected data is shown in Table IV and Figure 6.

<table>
<thead>
<tr>
<th>Question indices</th>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Were you asked to move to another area prior to the disaster?</td>
</tr>
<tr>
<td>b</td>
<td>Were you educated about a possible disaster previously?</td>
</tr>
<tr>
<td>c</td>
<td>Did any type of early warning take place, from the responsible authorities?</td>
</tr>
<tr>
<td>d</td>
<td>Were you able to evacuate before the disaster?</td>
</tr>
<tr>
<td>e</td>
<td>Are you satisfied with the provision of humanitarian assistance?</td>
</tr>
<tr>
<td>f</td>
<td>Were you given a temporary camp or any other shelter?</td>
</tr>
<tr>
<td>g</td>
<td>Were you paid from any early recovery assistance program?</td>
</tr>
<tr>
<td>h</td>
<td>Was your house rehabilitated or rebuilt? Or in the process of rebuilding?</td>
</tr>
</tbody>
</table>

Figure 5.
Selected areas for data collection

A - Baddegama  
B - Nagoda  
C - Kotapola  
D - Pitabedda  
E - Matara
<table>
<thead>
<tr>
<th>Disaster stage (pre-disaster)</th>
<th>Fact indices</th>
<th>Fact</th>
<th>Relevance to DM process</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRR stage</td>
<td>1</td>
<td>Early warning</td>
<td>Includes accurate forecasting of weather and multi-hazard early warning systems</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Information availability</td>
<td>Includes lessons learnt from previous disasters, researches and availability of efficient technology in forecasting</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>DRR initiatives</td>
<td>Some of the DRR initiatives can be identified as: Inform people to abandon the areas which are vulnerable for hazards and to resettle in another area, which is less vulnerable for hazards Prohibiting construction in disaster prone areas carrying out special constructions to enhance the structural capacity to resist the risks of disasters having pre-identified safe locations and evacuation paths</td>
</tr>
<tr>
<td>Emergency response stage (disaster)</td>
<td>4</td>
<td>Evacuation</td>
<td>Removal of people to a safer location before they are exposed to the disaster within the lag time (Δ). The safe locations are identified as schools, temples and hospitals in most cases</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Search and rescue</td>
<td>At the time of the disaster, searching and rescuing people is mainly done by the military forces and the local fire brigades</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Leadership and coordination</td>
<td>Leadership traits such as local level decision-making and bearing responsibilities such as directing the affected to a secure location, providing facilities and shelter for them and unbiased distribution of relief aids are measured</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Provision of humanitarian assistance</td>
<td>Immediate provision of food, shelter and clothes for the affected. The items may include cooked food and dry food, drinking water, clothes, sanitary facilities, medicine and other requirements such as mattresses</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Initial damage and needs assessment</td>
<td>Damage and needs assessment is the first action taken by the government prior to the rehabilitation and rebuilding. This involves expertise in that area to investigate the damage percentages and the required resources in overcoming the hardships</td>
</tr>
<tr>
<td>Recovery stage (post-disaster)</td>
<td>9</td>
<td>Provision of early recovery assistance</td>
<td>This involves the provision of monetary assistance in terms of compensation in Sri Lanka. The government has the sole responsibility of this activity while some of the NGOs offer early recovery assistance by means of monetary as well as repair kits</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Temporary accommodation and repair</td>
<td>Providing a temporary shelter to live for the affected until the houses are restored. Most of the time they are temporary camps situated in religious places and schools</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>Rebuilding houses and buildings</td>
<td>Rebuilding is associated with major disasters where the disaster wipes out whole neighborhoods with the houses and the buildings. In such cases government with the help of other local and international authorities take the responsibility of rebuilding those houses and reinstating the people in those</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(continued)</td>
</tr>
</tbody>
</table>
The restoration of critical services such as electricity, water supply, telephone and telecommunication are considered here. The quickness of restoration is a good measure of the effectiveness of the task.

This involves uplifting the economical background of the affected. Provision of subsidies and provision of dry rations for them until sometime are a few of actions followed in this measure.

Table IV. Summary of number of responses for the questionnaire

<table>
<thead>
<tr>
<th>Question indices</th>
<th>Baddegama</th>
<th>Nagoda</th>
<th>Kotapola</th>
<th>Pitabeddara</th>
<th>Matara</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>b</td>
<td>15</td>
<td>10</td>
<td>4</td>
<td>4</td>
<td>27</td>
<td>60</td>
</tr>
<tr>
<td>c</td>
<td>10</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>40</td>
<td>54</td>
</tr>
<tr>
<td>d</td>
<td>13</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>33</td>
<td>51</td>
</tr>
<tr>
<td>e</td>
<td>21</td>
<td>20</td>
<td>19</td>
<td>5</td>
<td>51</td>
<td>116</td>
</tr>
<tr>
<td>f</td>
<td>8</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>27</td>
<td>42</td>
</tr>
<tr>
<td>g</td>
<td>19</td>
<td>19</td>
<td>14</td>
<td>20</td>
<td>43</td>
<td>115</td>
</tr>
<tr>
<td>h</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Total number of respondents</td>
<td>27</td>
<td>20</td>
<td>24</td>
<td>20</td>
<td>53</td>
<td>144</td>
</tr>
</tbody>
</table>

Figure 6. Summary of responses for the questionnaire

Analysis of data

Rate of responding

From the results in Table IV and Figure 6, the rate of responding can be obtained by dividing the divisional scores for each question by the number of respondents in that division. The results are shown in Table V. The extent of fulfillment of disaster needs can be
assessed by the summation along the rows, while summation along the columns reflects the spatial variation of the DM mechanism.

From Table V and Figure 7, it can be seen that the Matara and Baddegama being urban areas are well served in terms of DM, while other areas are not that much treated. Considering the horizontal totals, it can be seen that the humanitarian assistance (question index (e)-humanitarian assistance) and the early recovery assistance (question index (g)-compensation) responses are much higher than the other responses.

**Analysis of the national disaster management framework**

As identified in Table II, the facts of assessing the national disaster management mechanism should be linked to the results from the questionnaire survey. Here, the national level responses are considered, so despite the location, the total response for each question is taken into account. The 8 questions are related to the 13 facts by a weighting matrix, and the weights are determined by the average of 20 different combinations, considered in evaluating the weights for the questions. A weight value represents the portion of question that represents the fact, as a score out of 10, as shown in Table VI. The total score for each question is shown within brackets, near the question number.

To obtain a score for a fact, the non-zero weights should be multiplied with the score for the relevant fact, and the summation should be taken. As the number of weights put to evaluate the factors are different from fact to fact, to generalize the scores, the summation mentioned above is divided from the total weight. Furthermore, to make the scores comparable, the maximum (possible) score is calculated using the same conversion matrix,
by setting all the scores for the questions as 144 (as 144 responses were collected, and in an ideal situation, all scores should be 144). Then, the actually obtained score for a fact is divided by the maximum score to obtain a percentage. This could be identified as the data normalization procedure.

Obtained scores for the facts measuring the effectiveness of the DM mechanism are represented in Table VII and Figure 8.

From the results, it can be seen that some facts such as rebuilding houses (10) and restoration of facilities (11) are having very low scores, and for those aspects, more attention should be given in future DM operations. Then, the facts of early warning (one) and DRR (three) need attention and improvement too. A general focus should be given to the other factors, as far as the current situation is considered.

**Correlation of 13 facts among themselves**

A correlation analysis was performed for the 13 facts with the obtained scores, and the correlation coefficients are presented in Table VIII.

### Table VI.

<table>
<thead>
<tr>
<th>Questions asked from the affected</th>
<th>a (8)</th>
<th>b (60)</th>
<th>c (54)</th>
<th>d (51)</th>
<th>e (116)</th>
<th>f (42)</th>
<th>g (115)</th>
<th>h (3) Total weight</th>
<th>Possible maximum score</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Facts measuring the effectiveness of national DM framework</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>4.20</td>
<td>3.55</td>
<td>10.00</td>
<td>4.00</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>–</td>
<td>5.20</td>
<td>8.00</td>
<td>5.40</td>
<td>8.00</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>8.00</td>
<td>6.00</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>–</td>
<td>4.30</td>
<td>3.65</td>
<td>10.00</td>
<td>5.35</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>40</td>
</tr>
<tr>
<td>5</td>
<td>–</td>
<td>–</td>
<td>10.00</td>
<td>8.00</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>10.00</td>
<td>4.00</td>
<td>4.00</td>
<td>–</td>
<td>2.79</td>
<td>40</td>
</tr>
<tr>
<td>7</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>5.00</td>
<td>10.00</td>
<td>2.95</td>
<td>–</td>
<td>–</td>
<td>30</td>
</tr>
<tr>
<td>8</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>3.15</td>
<td>5.00</td>
<td>10.00</td>
<td>3.16</td>
<td>40</td>
</tr>
<tr>
<td>9</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.30</td>
<td>3.20</td>
<td>10.00</td>
<td>–</td>
<td>30</td>
</tr>
<tr>
<td>10</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>2.95</td>
<td>10.00</td>
<td>2.50</td>
<td>–</td>
<td>30</td>
</tr>
<tr>
<td>11</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>10.00</td>
<td>10</td>
<td>100.80</td>
</tr>
<tr>
<td>12</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>10.00</td>
<td>100.80</td>
</tr>
<tr>
<td>13</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>7.00</td>
<td>100.80</td>
</tr>
</tbody>
</table>

### Table VII.

<table>
<thead>
<tr>
<th>Fact no.</th>
<th>Generalized scores for facts after dividing by total weight</th>
<th>Percentage of fulfillment of the facts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24.77</td>
<td>31.63</td>
</tr>
<tr>
<td>2</td>
<td>48.69</td>
<td>50.84</td>
</tr>
<tr>
<td>3</td>
<td>21.20</td>
<td>21.03</td>
</tr>
<tr>
<td>4</td>
<td>39.64</td>
<td>47.26</td>
</tr>
<tr>
<td>5</td>
<td>71.90</td>
<td>55.48</td>
</tr>
<tr>
<td>6</td>
<td>39.14</td>
<td>47.26</td>
</tr>
<tr>
<td>7</td>
<td>52.48</td>
<td>55.48</td>
</tr>
<tr>
<td>8</td>
<td>44.07</td>
<td>47.26</td>
</tr>
<tr>
<td>9</td>
<td>47.84</td>
<td>68.74</td>
</tr>
<tr>
<td>10</td>
<td>35.05</td>
<td>47.26</td>
</tr>
<tr>
<td>11</td>
<td>3.00</td>
<td>2.08</td>
</tr>
<tr>
<td>12</td>
<td>3.00</td>
<td>2.08</td>
</tr>
<tr>
<td>13</td>
<td>80.50</td>
<td>79.86</td>
</tr>
</tbody>
</table>

Table VIII.

<table>
<thead>
<tr>
<th>Conversion matrix from questions to facts</th>
<th>10.00</th>
<th>7.00</th>
<th>8.00</th>
<th>5.00</th>
<th>10.00</th>
<th>2.50</th>
<th>–</th>
<th>30</th>
<th>74.15</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>10.00</td>
<td>10</td>
<td>144.00</td>
</tr>
<tr>
<td>12</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>10.00</td>
<td>10</td>
<td>144.00</td>
</tr>
<tr>
<td>13</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>7.00</td>
<td>10</td>
<td>100.80</td>
</tr>
</tbody>
</table>
According to the results, it can be clearly seen that in the disaster response stage, all three major activities have been well correlated [search and rescue (five), leadership and coordination (six) and provision of humanitarian assistance (seven)], which are mainly carried by tri forces in collaboration with community and volunteers under the guidance of DMC. Some other correlations can be seen as well, which means trying to address one fact will tend to address the other correlated factors, under the existing framework.

Spatial distribution of the effectiveness of the disaster management mechanism

The existing number of responses can be used to measure the extent of fulfillment of fact considered, by converting the regional responses using the conversion matrix shown in Table VI. The generalized results (percentages) showing the fulfillment are shown in Table IX and in Figure 9.

When considering Figure 9, it can be seen that the plot for Matara region encloses the highest height while the plot for Pitabeddara encloses the lowest height. Reasons for this spatial variation of results should be explored more, to make the DM framework more efficient.

Table VIII. Coefficients of correlations among 13 facts

<table>
<thead>
<tr>
<th>Question indices</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.26</td>
<td>0.16</td>
<td>0.21</td>
<td>-0.16</td>
<td>-0.28</td>
<td>-0.26</td>
<td>-0.40</td>
<td>-0.33</td>
<td>-0.53</td>
<td>-0.26</td>
<td>-0.26</td>
<td>-0.26</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.03</td>
<td>0.87</td>
<td>0.81</td>
<td>0.84</td>
<td>0.09</td>
<td>-0.23</td>
<td>0.15</td>
<td>-0.30</td>
<td>-0.30</td>
<td>-0.30</td>
<td>-0.30</td>
<td>-0.30</td>
<td>-0.30</td>
</tr>
<tr>
<td>3</td>
<td>0.04</td>
<td>-0.25</td>
<td>-0.23</td>
<td>-0.23</td>
<td>-0.26</td>
<td>-0.22</td>
<td>-0.34</td>
<td>-0.17</td>
<td>-0.17</td>
<td>-0.17</td>
<td>-0.17</td>
<td>-0.17</td>
<td>-0.17</td>
</tr>
<tr>
<td>4</td>
<td>0.90</td>
<td>0.74</td>
<td>0.78</td>
<td>-0.17</td>
<td>-0.27</td>
<td>0.01</td>
<td>-0.32</td>
<td>-0.32</td>
<td>-0.32</td>
<td>-0.32</td>
<td>-0.32</td>
<td>-0.32</td>
<td>-0.32</td>
</tr>
<tr>
<td>5</td>
<td>0.92</td>
<td>0.94</td>
<td>0.03</td>
<td>-12</td>
<td>0.28</td>
<td>-0.21</td>
<td>-0.21</td>
<td>-0.21</td>
<td>-0.21</td>
<td>-0.21</td>
<td>-0.21</td>
<td>-0.21</td>
<td>-0.21</td>
</tr>
<tr>
<td>6</td>
<td>1.00</td>
<td>0.11</td>
<td>-0.07</td>
<td>0.51</td>
<td>-0.19</td>
<td>-0.19</td>
<td>-0.19</td>
<td>-0.19</td>
<td>-0.19</td>
<td>-0.19</td>
<td>-0.19</td>
<td>-0.19</td>
<td>-0.19</td>
</tr>
<tr>
<td>7</td>
<td>0.10</td>
<td>-0.08</td>
<td>0.48</td>
<td>-0.19</td>
<td>-0.19</td>
<td>-0.19</td>
<td>-0.19</td>
<td>-0.19</td>
<td>-0.19</td>
<td>-0.19</td>
<td>-0.19</td>
<td>-0.19</td>
<td>-0.19</td>
</tr>
<tr>
<td>8</td>
<td>0.98</td>
<td>0.61</td>
<td>0.21</td>
<td>-0.21</td>
<td>0.94</td>
<td>0.56</td>
<td>-0.19</td>
<td>-0.19</td>
<td>-0.19</td>
<td>-0.19</td>
<td>-0.19</td>
<td>-0.19</td>
<td>-0.19</td>
</tr>
<tr>
<td>9</td>
<td>0.49</td>
<td>-0.18</td>
<td>-0.18</td>
<td>0.99</td>
<td>0.49</td>
<td>0.99</td>
<td>0.49</td>
<td>0.99</td>
<td>0.49</td>
<td>0.99</td>
<td>0.49</td>
<td>0.99</td>
<td>0.49</td>
</tr>
<tr>
<td>10</td>
<td>-0.29</td>
<td>-0.29</td>
<td>0.34</td>
<td>0.34</td>
<td>0.34</td>
<td>0.34</td>
<td>0.34</td>
<td>0.34</td>
<td>0.34</td>
<td>0.34</td>
<td>0.34</td>
<td>0.34</td>
<td>0.34</td>
</tr>
<tr>
<td>11</td>
<td>1.00</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
</tr>
<tr>
<td>12</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
</tr>
<tr>
<td>13</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
<td>-0.14</td>
</tr>
</tbody>
</table>

Note: Those italicized data are higher than 0.9, which shows very high correlations
So far, it has been clear that there are some factors in terms of DM that need more attention in DM practices, as from the results it was clear that some geographical areas were not successfully served with DM and disaster relief. Therefore, as an extension of the study, a set of indicators were identified and checked against the success of DM mechanism. The selected indicators from the study could be used for the development of a framework to evaluate the disaster preparedness, resilience of communities and DM mechanisms.

Regression analysis on region-specific indicators affecting the effectiveness of disaster management mechanism

For this purpose, some indicators are chosen and they are assumed to be driving factors (UNISDR, 2015b) on the effectiveness of national DM mechanism and on that hypothesis, the indicators should be checked against the overall scores of each region. In this study, these region-specific indicators were chosen according to literature and other indigenous factors representing the infrastructural and structural, geographic, demographic, environmental, social, economic and political aspects. Then, a regression analysis was performed between the data for indicators and total regional scores (Vertical summations of Table IV) to find the
correlating indicators. In performing the regression analysis, only 1st order, 2nd order polynomials and exponential functions were used to assume the correlations.

To perform the analysis, data was collected on the basis of divisions, as it is the smallest governance unit where the data is available. Regional data was collected from Google maps, Department of Census and Statistics (2018, 2017); Japan International Cooperation Agency (2009) and UNISDR, (2017). The results of the analysis are shown in Table X, with the correlation coefficient, $R^2$ value.

Furthermore, the table indicates the sign of the gradients and the order of the polynomials for the indicators. N/A stands for not applicable.

With these well-formed relationships and considering the correlation values, which are higher than 0.7, it can be seen that some factors as the distance to the coastal region (Indicators 1 and 2) may have added a great impact on the DM performance. Another phenomenon can be seen is that higher the population (Indicator 11), higher the success of the DM framework. At the same time, it could be seen that the Indicators 13 and 14 have high correlations despite the Indicator 12. Then, it can be seen that the indicators representing the built environment (15, 16 and 18) are having high correlations with the successfulness of the DM mechanism. As another aspect, influence of the politics (Indicator 22) can be well seen in this study. The number of politicians in the council is a measure of how resourceful and how facilitated the council is, and the more resourceful councils have managed disasters more efficiently.

Furthermore, into the details, when the environmental facts are considered, where the infrastructure is much developed and the density of houses is high, the DM procedure has succeeded in great terms. But this may not be the case when the concern is about flood risk assessment. Alternatively, higher tree coverage is suggestive of poor DM in action.

When considering the Indicator 10 representing the flow of the river, it is moderately correlated to the overall successfulness. And the Indicators 3-7 and 17 are poorly correlated. The other indicators are categorized as non-applicable, as the correlations shown by those indicators are not suggesting a convincing trend, even tough the correlation values are high on some occasions.

As an overall statement, it can be seen that the distribution of resources is more biased toward the urban areas, while the poor, rural and estate communities have suffered more comparing to the urban communities.

Conclusions and recommendations

When analyzing and observing the results, in most cases it could be seen that the elements of humanitarian assistance and the early recovery assistance have met considerable levels, with the existing framework for DM. Furthermore, it was clear that DRR initiatives and the early warning issuing are lagging behind, even compared to the existing condition in other facts. Therefore, special care should be taken and maintained toward initiating DRR activities and provision of early warnings.

Another aspect, which became clear was the correlation of the tangibles in a DM framework. This means, under the current framework, most of the tangible outcomes are fulfilled. The questions lie on the point whether the extent of fulfillment of the need is achieved actually. The implementation strategy of DM should be more thorough.

It could be seen that there is some eccentricity in the mechanism of DM when it comes to the spatial distribution of the effectiveness of the DM. It was clear that Pitabeddara area is reluctant to get assisted by DM mechanisms, most of the time because of the difficulties in approaching such areas.

Another interesting factor was the influence of poverty. The DM procedure has gone down where poverty has increased. This is a strong message given to the DM framework.
<table>
<thead>
<tr>
<th>No.</th>
<th>Aspect</th>
<th>Assumed indicator</th>
<th>Source</th>
<th>Coefficient of correlation $R^2$</th>
<th>Sign of the gradient</th>
<th>Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Infrastructural and structural</td>
<td>Distance from the coastal belt (km)</td>
<td>Ganesan et al. (2005), Rodrigue (2017)</td>
<td>0.9894</td>
<td>--</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Distance from the nearest capital (Which has a municipal council or an urban council) (km)</td>
<td>Ganesan et al. (2005), Rodrigue (2017)</td>
<td>0.9894</td>
<td>--</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>Distance from nearest A type road (km)</td>
<td>Adikariwattage and Bandara (2013), Disaster Management Center (2015); Hettige (2006), Rodrigue (2017)</td>
<td>0.0434</td>
<td>--</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Distance from nearest B type road (m)</td>
<td>Adikariwattage and Bandara (2013), Disaster Management Center (2015); Hettige (2006), Rodrigue (2017)</td>
<td>0.0210</td>
<td>--</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>No. of hospitals in the divisional secretarial division</td>
<td>Disaster Management Center (2015), Pourhosseini et al. (2015)</td>
<td>0.2172</td>
<td>+</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>Distance to hospitals (rural hospitals avoided) (km)</td>
<td>Disaster Management Center (2015), Pourhosseini et al. (2015)</td>
<td>0.0324</td>
<td>+</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>Construction material of the walls (Kabook and Mud)</td>
<td>Malalgoda et al. (2014), Technical Advisory Committee of Disaster Management Centre (2012)</td>
<td>0.0264</td>
<td>+</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>Geographic</td>
<td>Distance to the nearest source of disaster (landslides)</td>
<td>Cruz (2010)</td>
<td>0.8593</td>
<td>N/A</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>Distance to the nearest source of disaster (overflowing river) (m)</td>
<td>Disaster Management Center (2017), Japan International Cooperation Agency (2009)</td>
<td>0.4401</td>
<td>N/A</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>Flow of the river (m$^3$/s)</td>
<td>Disaster Management Center (2017), Japan International Cooperation Agency (2009)</td>
<td>0.3418</td>
<td>+</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>Demographic</td>
<td>Total Population</td>
<td>Malone (2009)</td>
<td>0.9669</td>
<td>+</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>Workforce population (15-60 years)</td>
<td>Malone (2009)</td>
<td>0.9570</td>
<td>+</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>Aged and child population</td>
<td>Malone (2009)</td>
<td>0.9669</td>
<td>+</td>
<td>1</td>
</tr>
</tbody>
</table>

(continued)
<table>
<thead>
<tr>
<th>No.</th>
<th>Aspect</th>
<th>Assumed indicator</th>
<th>Source</th>
<th>Coefficient of correlation $R^2$</th>
<th>Sign of the gradient</th>
<th>Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Environmental</td>
<td>Land-use pattern (Number of houses/Area)</td>
<td>Disaster Management Center (2015), Dissanayake et al. (2018)</td>
<td>0.9595</td>
<td>+</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>Tree coverage (Tree Area/Total area of the study area)</td>
<td>Disaster Management Center (2015)</td>
<td>0.9453</td>
<td>−</td>
<td>2</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td>Paddy fields and bare lands (Bare Land Area/Total area of the study area)</td>
<td>Disaster Management Center (2015), Dissanayake et al. (2018)</td>
<td>0.1145</td>
<td>+</td>
<td>1</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>Area for infrastructure</td>
<td>Disaster Management Center (2015), Dissanayake et al. (2018), Malalgoda et al. (2014)</td>
<td>0.9734</td>
<td>+</td>
<td>2</td>
</tr>
<tr>
<td>19</td>
<td>Technological</td>
<td>Availability of telephones, radio, television and other sources of technological equipment</td>
<td>UNISDR (2015a, 2008)</td>
<td>0.9776</td>
<td>+</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>Social and</td>
<td>Estimated headcount index (poverty)</td>
<td>Disaster Management Center (2015) Malone, 2009)</td>
<td>0.9692</td>
<td>−</td>
<td>1</td>
</tr>
<tr>
<td>21</td>
<td>economical</td>
<td>No of poor people</td>
<td>Disaster Management Center (2015), Malone (2009)</td>
<td>0.7379</td>
<td>N/A</td>
<td>2</td>
</tr>
<tr>
<td>22</td>
<td>Political</td>
<td>No. of members in the Pradeshiya Sabha</td>
<td>Trim (2004), Waugh and Streib (2006)</td>
<td>0.9960</td>
<td>+</td>
<td>exp.</td>
</tr>
</tbody>
</table>
implementers that they should be looking more into the high poverty having regions, proposing methods to overcome poverty with time, at least in a disaster situation.

In conclusion, it can be said that the existing DM framework of Sri Lanka is effective enough to serve to a certain extent. However, it should be more elaborate, transparent and strong enough to reach the communities, especially among the people who are in rural and estate areas. The existing framework could be made more advanced by considering the correlated indicators in Table X.

As an extension of the study, the correlated indices on Table X can be represented in a regression model to form a prediction index in DM effectiveness under the same DM framework. Multivariate regression analysis can be performed with more spatial data, to identify the contribution from each index to the successful implementation of existing DM framework. This index could be made available for each spatial region, therefore, the policymakers and implementers can have a better idea on which places and on which aspects they should be paying more attention to make the DM mechanism more fruitful.

References
Adikariwattage, V.V. and Bandara, J. (2013), “Transportation network analysis and applications in disaster management”.
Cruz, D. (2010), Increasing Resilience to Landslides in Quito Metropolitan District (MSc), Utrecht University, Quito.
Disaster Management Center (2017), “2017 Flood rapid impact assessment”.


Ministry of Disaster Management (2013), “National policy on disaster management”.


Technical Advisory Committee of Disaster Management Centre (2012), “How to make your house safe from natural disasters”.


**Corresponding author**

Chameera Randil can be contacted at: chameerarandil@gmail.com

For instructions on how to order reprints of this article, please visit our website: www.emeraldgrouppublishing.com/licensing/reprints.htm

Or contact us for further details: permissions@emeraldinsight.com
Emerald Open Research

*Easy, rapid & transparent publishing*

Emerald Open Research is a new open access platform that supports rapid publication and allows authors to achieve transparency through an open peer review process and open data policy.

Research will be freely available to read, download and reuse, reaching a truly global audience.

*Set your research free at*

[www.emeraldopenresearch.com](http://www.emeraldopenresearch.com)

Connect with us through social media
International Journal of
Disaster Resilience in the Built Environment

Number 2
“End-to-end tsunami early warning systems” in collaboration with IOC-UNESCO IOTWMS (Dedicated to the memory of Professor Samantha Hettiarachchi)
Guest Editor: Priyan Dias

153 Guest editorial
156 A multi-scenario assessment of the seismogenic tsunami hazard for Bangladesh
Janaka J. Wijetunge
169 An update of proposed Sri Lanka warning system for east and west coast tsunamis
Sanjeewa Wickramaratne, S. Chan Wirasinghe and Janaka Ruwanpura
187 Coastal flood alleviation through management interventions under changing climate conditions
William George Bennett and Harshinnie Karunaratna
204 Vulnerability assessment of reinforced concrete buildings in Indonesia subjected to tsunami inundation forces
Dicky Hanggara and Anil Christopher Wijeyewickrema
219 The upstream-downstream interface of Sri Lanka’s tsunami early warning system
Richard Haigh, Maheshika Menike Sakalasuriya, Dilanthi Amaratunga, Senaka Basnayake, Siri Hettige, Sarath Premalal and Ananda Jayasinghe Arachchi
241 A study of people-centered early warning system in the face of near-field tsunami risk for Indonesian coastal cities
Harkunti Pertiwi Rahayu, Louise K. Comfort, Richard Haigh, Dilanthi Amaratunga and Devina Khoirunnisa
263 The human dimension of early warning – a viewpoint
Mo Hamza and Peter Månsson
275 Barriers and enablers of coastal disaster resilience – lessons learned from tsunami in Sri Lanka
Danidu Kusal Rathnayake, Devmini Kularatne, Sonali Abeyesinghe, Ishani Shehara, Thilanga Fonseka, Sameera Darshana Jayasooriya Edirisinghe Mudiyanselage, Wathuwala Gedara Chaminda Thushara Kamalathne, Chandana Siriwardana, Chaminda Senarathna Bandara Alagiyawanna Mohotti Appuhamilage and Ranjith Dissanayake
289 Framework to analyze Sri Lanka disaster management mechanism
Chameera Randil, Chandana Siriwardana and Kalana Hewawasam

ISBN 978-1-83982-348-0
www.emeraldinsight.com/loi/ijdrbe