The upstream-downstream interface of Sri Lanka's tsunami early warning system

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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.

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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 addtion 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

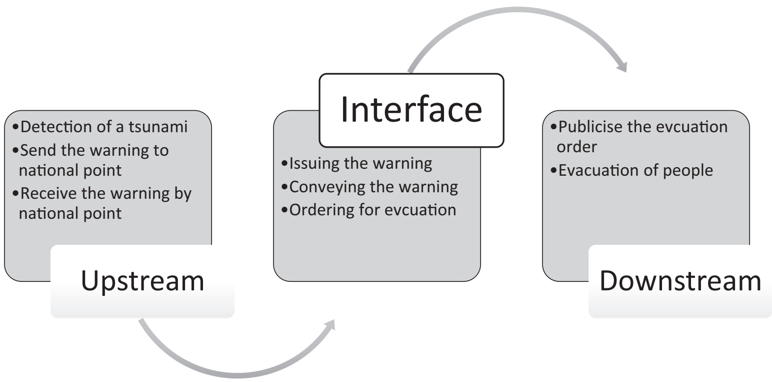


Figure 1. The position of interface within the end-to-end TEWMS

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 I. Key informants selected for interviews from stakeholder institutions in TEWMS in Sri Lanka

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

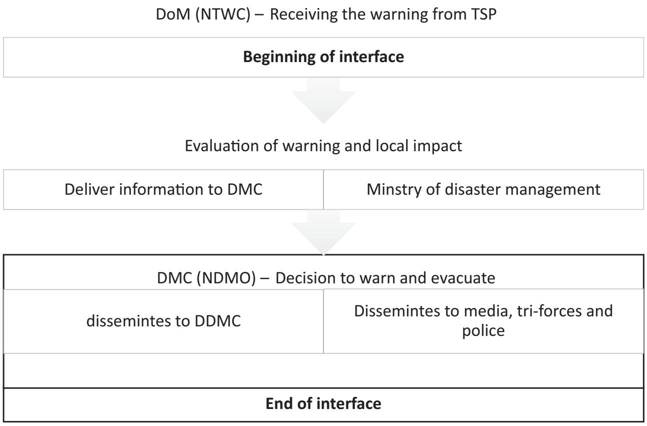
through multiple channels to a number of national and local stakeholders including the media and District Disaster Management Centres (DDMCs). The downstream process starts after the information is disseminated from DMC to local authorities and the media. Therefore, the interface in Sri Lanka is defined 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



Source: Authors' composition

Figure 2.
The interface of tsunami early warning in Sri Lanka

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 information throughout the interface process. A summary of the roles played by some of the key actors is provided in Table II.

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 Natios 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

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

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 $\times$ 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 the 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.

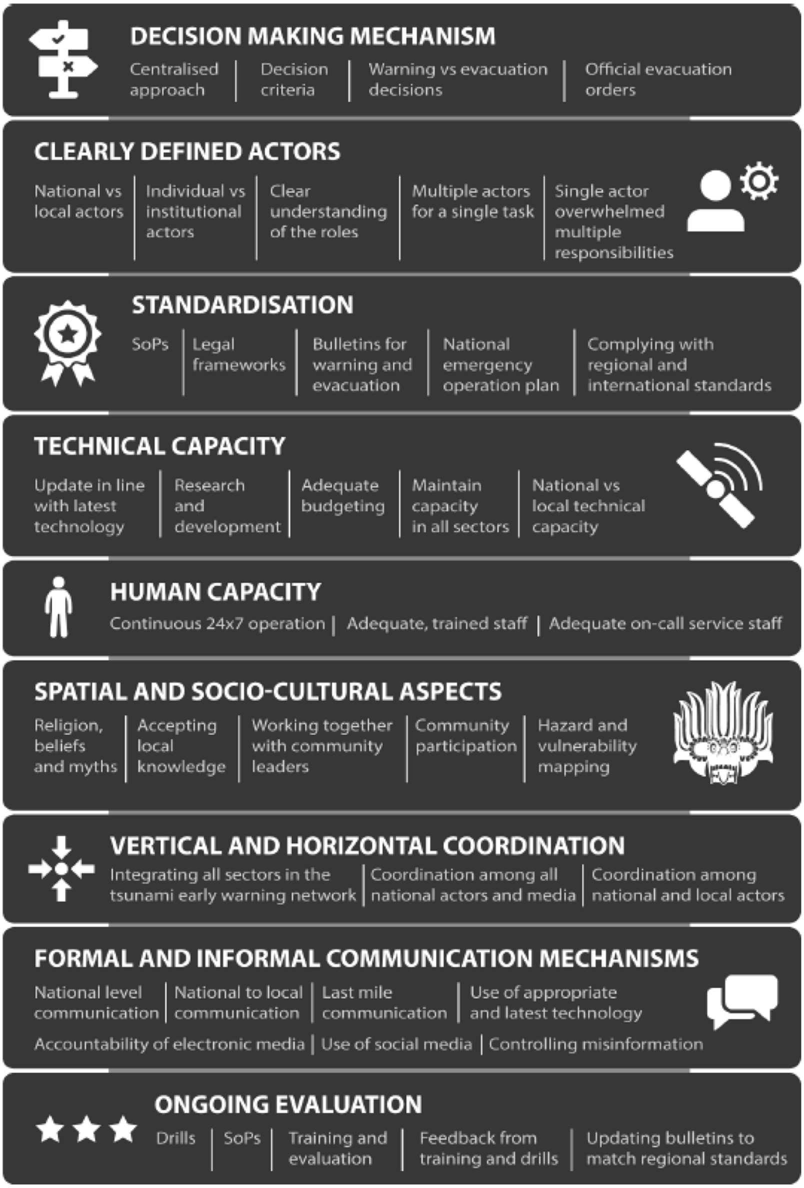


Figure 3. Analytical framework for tsunami early warning interface

- 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.

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