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Tsunami Science in Sri Lanka

To commemorate the 20th Anniversary of the 2004 Indian Ocean Tsunami

Edited by: Professor Charitha Pattiaratchi
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Partners:

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University of Colombo, Sri Lanka

DMC Sri Lanka – Disaster Management Centre, Sri Lanka

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Collection of Peer Reviewed Plenary Papers presented at the "Tsunami Science In Sri Lanka" Symposium held on the 21st December 2024 at the BMICH, Colombo, Sri Lanka

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Tsunami Science in Sri Lanka

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Cover page photo credit - Prof. Charitha Pattiaratchi

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Introduction

Globally, coastal regions are becoming increasingly vulnerable to inundation through natural hazardous events that impact infrastructure and human populations. This region, at the land-ocean interface, is where the highest population densities are and where many depend for their livelihood. It is also highly dynamic and susceptible to coastal hazards such as coastal erosion, high swell wave events, storm surges and tsunamis which are exacerbated through mean sea level rise due to global climate change. Tsunamis, are rare events but one of the most catastrophic and destructive natural hazards impacting on coastal environments globally often with powerful and devastating forces resulting in complete devastation. It has the the potential to reshape landscapes, disrupt ecosystems, and cause large scale disruption to human populations and local economies. Tsunami (harbour-wave in Japanese as most tsunamis only generate oscillations in ports and harbours) is a series of waves caused by a large and sudden impulsive displacement of the ocean, usually the result of an earthquake below the ocean floor. This force creates waves that radiate outward in all directions away from their source crossing entire ocean basins. These extreme events are preserved in geological record spanning millennia and over more than 2000 years. On Sunday morning 26 December 2004 at 00:58:53 UTC, a massive earthquake measuring with moment magnitude 9.1 generated a large tsunami with maximum run-up > 30m in Banda Aceh, Indonesia. Tsunami waves were recorded in tide gauges around the world and Sri Lanka, on the direct path of the tsunami waves was severely affected with over 1000 km of the coastline – from Jaffna in the north to Negombo along the western coast experiencing coastal inundation resulting in massive loss of lives (> 35,000 people) and property damage. For a country that has never experienced such a devastating natural event, it was a massive disaster impacting its coastlines without any warning for which the country was grossly under-prepared. However, over the past 20 years there has been a considerable number of initiatives across many disciplines that has been completed and the country is tsunami 'ready' for the next event. These include the establishment of a tsunami warning and mitigation system that includes adequate warning prior to any possible tsunami impact, public educations, awareness and preparedness and evacuation. This also includes tsunami compatible coastal developments and effective development of national and local policies and capabilities. There has been appreciable progress in the up-stream, interface/mid-stream and down-stream aspects of tsunami during the past 20 years. Therefore, it becomes imperative to critically examine and review the progress and developments made in the said three segments in the past 20 years. It is equally essential to identify gaps and areas which merit priority consideration and intervention and lessons learned with a view to embarking upon a course of action so as to reduce risks and build resilience.

This volume, to commemorate the 20-year anniversary of the 2004 tsunami, is to showcase the development science associated tsunami impacts on Sri Lanka. The 12 papers were presented at a symposium held at the BMICH on 21 December 2024.

Prof. Charitha Pattiaratchi
Prof. Dilanthi Amaratunga
Prof. Ranjith Senaratne
Conference co-chairs and the co-editors of the book volume
December 2024

About the editors

PROFESSOR CHARITHA PATTIARATCHI

Charitha Pattiaratchi is a Professor in Coastal Oceanography at the University of Western Australia (UWA). He obtained his BSc, MSc and PhD in oceanography at University of Wales (Swansea). He has been at UWA since 1988 and currently is the leader of the Coastal Oceanography Group and The Integrated Marine Observing System (IMOS) ocean glider facility. His research encompass coastal ocean physical processes and their influence on climatic, biological, and geological processes in estuaries, the nearshore (beach) zone, and the continental shelf region. He uses field measurements, remote sensing, and computer modelling for his research. He has expertise in sea level processes including seismic and meteorological tsunamis and storm surges. He was the Chair of the Indian Ocean Tsunami Warning System Working Group 4: Modelling, forecasting and scenario development (2005–2011) and Physics of Estuaries and Coastal Seas Conference Steering Committee (2000 to date).

PROFESSOR DILANTHI AMARATUNGA

Dilanthi Amaratunga a leading international expert in disaster resilience with an extensive academic career. She has a PhD in Construction Management (UK), a BSc (Hons) with a First Class from Sri Lanka, a Fellow of the Royal Institution of Chartered Surveyors (RICS), a Fellow of The Royal Geographical Society, and a Fellow and a Chartered Manager of the Chartered Management Institute, UK. Dilanthi's research focuses on preparedness for disaster response, recovery and reconstruction, early warning and communication, disaster resilience cities, and built environment dimensions of climate change and sustainability. Dilanthi is recognised for her career-long impact up until 2023 and is placed among the global top 2% of influential scientists, according to the report of "Composite Citation Metrics" by Elsevier BV Netherlands and Stanford University, USA. In 2019, she won the prestigious Newton Prize which recognises the best research and innovation projects which create an impact socially and economically, between Indonesia and the UK from 2016 to 2019. Since 2024, she has project managed to successful completion 34 international research projects, over £ 20 million, having received funding from 20 funding agencies, and in partnership with 323 research partners in 67 countries, generating significant research outputs and outcomes. Her publications and external activities provide testament to the internationally recognised quality of her work. To date, she has produced over 500 publications and has made over 125 keynote speeches in around 40 countries. She provides expert advice on disaster resilience to national and local governments and international agencies including the United Nations Office for Disaster Risk Reduction (UNDRR). She is a member of the European Commission and UNDRR's European Science & Technology Advisory Group, one of two representatives from the UK, , Member of the UNDRR Expert Group on Principles for Resilient Infrastructure, Member of the UNDRR Making Cities Resilient 2030 (MCR2030) Regional Coordination Committee for Europe, a formally appointed Expert member of the ICG/IOTWMS WG-1 on Tsunami Risk, Community Awareness & Preparedness, and an expert member of the UN Women's , "Women's Resilience to Disasters programme". She is a keen PhD supervisor and has now supervised to completion 48 PhD students, and currently supervise 11 and co-supervise 8 PhD students.

EMERITUS PROFESSOR RANJITH SENARATNE

Prof. Ranjith Senaratne, Emeritus Professor of Crop Science, Faculty of Agriculture, University of Ruhuna, possesses over 40 years of experience in higher education, including teaching, research and administration and community development. He has held several senior administrative positions with distinction for a period of about 25 years, i.e. the posts of Dean, Faculty of Agriculture and Vice-Chancellor, University of Ruhuna, Chairman of the Ocean University, Vice Chairman, University Grants Commission, General President of the Sri Lanka Association for the Advancement of Science – 2023 and Chairman of the National Science Foundation, Sri Lanka.

As Vice Chancellor, University of Ruhuna, he has been strongly committed to promoting academic excellence, high impact research, creative enterprise, strategic partnership with industry, community development and international cooperation. In recognition of his outstanding contribution in education, science, community development and international cooperation, the University of Durham, UK conferred an honorary Doctorate (*honoris causa*) on him in 2007. Prof. Senaratne has provided strategic, inspirational and operational leadership to higher educational institutions, and he is a visionary leader and an institution builder.

Prof. Senaratne is a Fellow of the National Academy of Sciences, Sri Lanka and has over 100 research communications and papers to his credit. In addition, he has written and edited over 10 books related to agriculture, higher education, science & technology and national development.

Acknowledgements

With no previous history of tsunamis and the lack of prior knowledge of it in the populace of Sri Lanka, the country was thoroughly unprepared for the Asian Tsunami on 26th December 2004. Consequently, over 30,000 people perished, almost a million were displaced and around 150,000 people lost their livelihoods. Damage to infrastructure, particularly in the tourism and fisheries sectors, and to physical assets including residential houses was immense and estimated at around US $ 1 billion or 4.5% of the GDP of the country. To minimize damage to life and property in the event of such disasters in the future, the government enforced a ‘no-build’ coastal buffer zone of 200 m on the north and east coasts of the country and 100 m elsewhere. The resulting relocation of people whose houses were destroyed or badly damaged caused serious social and economic issues which to date largely remain unresolved.

In contrast, there has been appreciable progress in the upstream, midstream, and downstream aspects of tsunamis during the past 20 years. Therefore, it becomes imperative to critically examine and review the progress and developments made in the said three segments in the past 20 years. It is equally essential to identify gaps and areas which merit priority consideration and intervention and lessons learned with a view to embarking upon a course of action to reduce risks and build resilience in this regard.

To this end, Prof. Charitha Pattiaratchi, The University of Western Australia, Australia and Prof. Dilanthi Amaratunga, expert member of the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO), Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System (ICG/IOTWMS) based in the UK joined hands with Emeritus Prof. Ranjith Senaratne, University of Ruhuna and former Chairman, National Science Foundation, Sri Lanka in order to conduct a national conference on “Tsunami Science in Sri Lanka” on 21 December 2024 at the BMICH so as to commemorate the 20th anniversary of the tsunami in 2004.

In this connection, we called for thematic papers, and after review, thirteen papers dealing with various aspects of the up-, mid- and downstream segments of the tsunami were selected for presentation and inclusion in the proceedings. We wish to record our deep appreciation to the authors who prepared the papers included in this volume, made presentations at the conference, and contributed in no small measure to the success of the event. The event was attended by institutional leaders, scientists, professionals etc., from universities, public sector institutions, international agencies, and non-governmental organisations, among others. We acknowledge their active participation, which enriched and enhanced the deliberations during the conference.

The University of Western Australia provided financial support for the event. In 2023, Prof Dilanthi Amaratunga and Prof. Richard Haigh at the University of Huddersfield, UK initiated a project titled: 20 years after - then and now: An explorative study of the status of communities relocated in the aftermath of the 2004 Indian Ocean Tsunami in Sri Lanka, which was an explorative study of the status of communities (Original Tsunami settlers; Original settlers who moved back to the coast; New settlers; Host community) relocated in the aftermath of the 2004 Indian Ocean Tsunami in Sri Lanka, with SPAARC, University of Colombo, Sri Lanka, Federation of Sri Lankan Local Government Authorities (FSLGA) and with IOC UNESCO IOTWMS. The University of Huddersfield provided funding for this initiative whish was directly linked to this Tsunami science symposium. We are grateful to them for their generous patronage.

Mr. Chameera Randil, a freelancer, designed the cover page and typeset the volume and Miss Harshani Kanchana, Scientific Secretary attached to the office of the Chairman, of the National Science Foundation provided the requisite secretarial assistance from the inception till the end of the event, Harshani Kankanamge was instrumental in liaising with the venue for use of facilities and catering and we gratefully acknowledge their efforts and contribution.

Prof. Charitha Pattiaratchi
Prof. Dilanthi Amaratunga
Prof. Ranjith Senaratne
Conference co-chairs and the co-editors of the book volume
December 2024

Symposium organisation

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- International research collaboration: **"20 years after—then and now: An explorative study of the status of communities relocated in the aftermath of the 2004 Indian Ocean Tsunami in Sri Lanka,"** with the University of Huddersfield, UK, SPAARC, University of Colombo, Sri Lanka, Federation of Sri Lankan Local Government Authorities (FSLGA), and IOC UNESCO IOTWMS.
- University of Colombo, Sri Lanka
- Disaster Management Centre, Sri Lanka
- European Science & Technology Advisory Group (ESTAG) and Making Cities Resilient (MCR), United Nations Office for Disaster Risk Reduction (UNDRR)

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- Prof. Dilanthi Amaratunga, Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO), Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System (ICG/IOTWMS)

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Physics of Tsunamis Impacting Sri Lanka

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ABSTRACT

The Indian Ocean region experienced its most devastating natural disaster through the action of a Tsunami, resulting from of an Earthquake off the coast of Sumatra on 26th of December 2004. When the tsunami impacted Sri Lanka, it was not only one of the worst catastrophes but in terms of terminology, it was the first time, most Sri Lankans heard the word tsunami. The tsunami resulted in widespread damage both to property and human lives with over 250,000 deaths in the region and many millions homeless. In Sri Lanka, over 35,000 people lost their lives, and more than half a million people were rendered homeless. Sri Lanka was severely affected by the tsunami with over 1000 km of the coast – from Jaffna in the north to Negombo along the western coast experiencing coastal inundation resulting in loss of lives and property damage. The reflected waves from the Maldives Island chain had a significant impact along the west coast of Sri Lanka. In this paper the impacts of the tsunami along the west coast of Sri Lanka are presented through the personal experience of the author who was present at the beach in Payagala and Kalutara when the tsunami arrived. The author is one of the very few tsunami scientists to experience a tsunami. Physical processes associated with tsunami impacts in Sri Lanka are presented through imagery collected by the author during and subsequent to the tsunami impact and relating the imagery and the personal experience to physical processes. This achieved using sea level data and numerical model results and the subsequent development of the Indian Ocean tsunami warning system. Historical coastal flood events that have been misinterpreted as tsunamis are also explained.

Key words: Tsunami waves, Sea level observations, Numerical modelling, Tsunami warning

1. INTRODUCTION

The region from the continental shelf break to the limit of the tidal influence within estuaries may broadly be called the coastal margin and includes, in many cases the Exclusive Economic Zone (EEZ). Most of the global population lives adjacent to the coastal margin and in the case of Sri Lanka, 4.85 million or ~25% of the population lives within 1 km of the coastline. This region, the interaction between the land, where people live and the ocean where many depend for their livelihood is highly dynamic and susceptible to coastal hazards such as coastal erosion, high swell wave events, storm surges and tsunamis which are exacerbated through mean sea level rise due to global climate change. In addition, anthropogenic effluents enter the coastal waters through direct surface runoff, river inflows, groundwater discharge and wastewater outfalls. The coastal margin is also the habitat for a rich and diverse ecosystem and the nursery for extensive marine fisheries as well as forming a major recreational environment. Protection of this region through efficient and informed management of coastal hazards and utilization of renewable resources are essential for long-term sustainability.

The Indian Ocean region experienced its most devastating natural disaster through the action of a Tsunami, resulting from of an earthquake off the coast of Sumatra on 26th of December 2004. This resulted in widespread damage both to property and human lives with over 250,000 deaths in the region and many millions homeless. This event revealed the destructive effects of tsunamis, with a maximum run-up exceeding 30 m in Banda Aceh and 10 m at several sites in Sri Lanka (Liu

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et al. 2005; Inoue et al., 2007), In Sri Lanka, over 35,000 people lost their lives, and more than half a million people were rendered homeless. Sri Lanka has a very narrow continental shelf with the mean distance between the coast to the 200m depth contour being 20 km – at some locations (Figure 1). Along the southern coast, this distance is reduced to < 5km off Mirissa (Figure 1). The narrow continental shelf means that Sri Lanka is extremely vulnerable to the action of tsunamis as the shoaling effect occurs over a shorter distance and there is a negligible amount of energy dissipated over the continental shelf region resulting in higher waves impacting the shoreline leading to coastal inundation. Sri Lanka was severely affected by the December 2004 tsunami with over 1000 km of the coastline – from Jaffna in the north to Negombo along the western coast (Figure 1) experiencing coastal inundation resulting in loss of lives and property damage.

In this paper, the various aspects of the tsunami generation and propagation are discussed using the December 2004 tsunami. Personal experiences, tide gage measurements and numerical model are used as examples for planning for future losses through risk reduction and mitigation are discussed.

2. TSUNAMIS – GENERATION AND PROPAGATION

Tsunami is a Japanese word with the English translation, "harbor wave." Represented by two characters, the first character, 'tsu' means harbor, while the second character, 'nami' means 'wave' (Voit, 1987). The origin of this name is because Japanese fishermen observed oscillations or seiches in fishing boat harbours after an earthquake. Majority of tsunamis globally result in oscillations of enclosed bodies of water. A tsunami is a wave train consisting of a series of waves, of long wave length (> 100 km) and period (order of hours), generated in a body of water by an

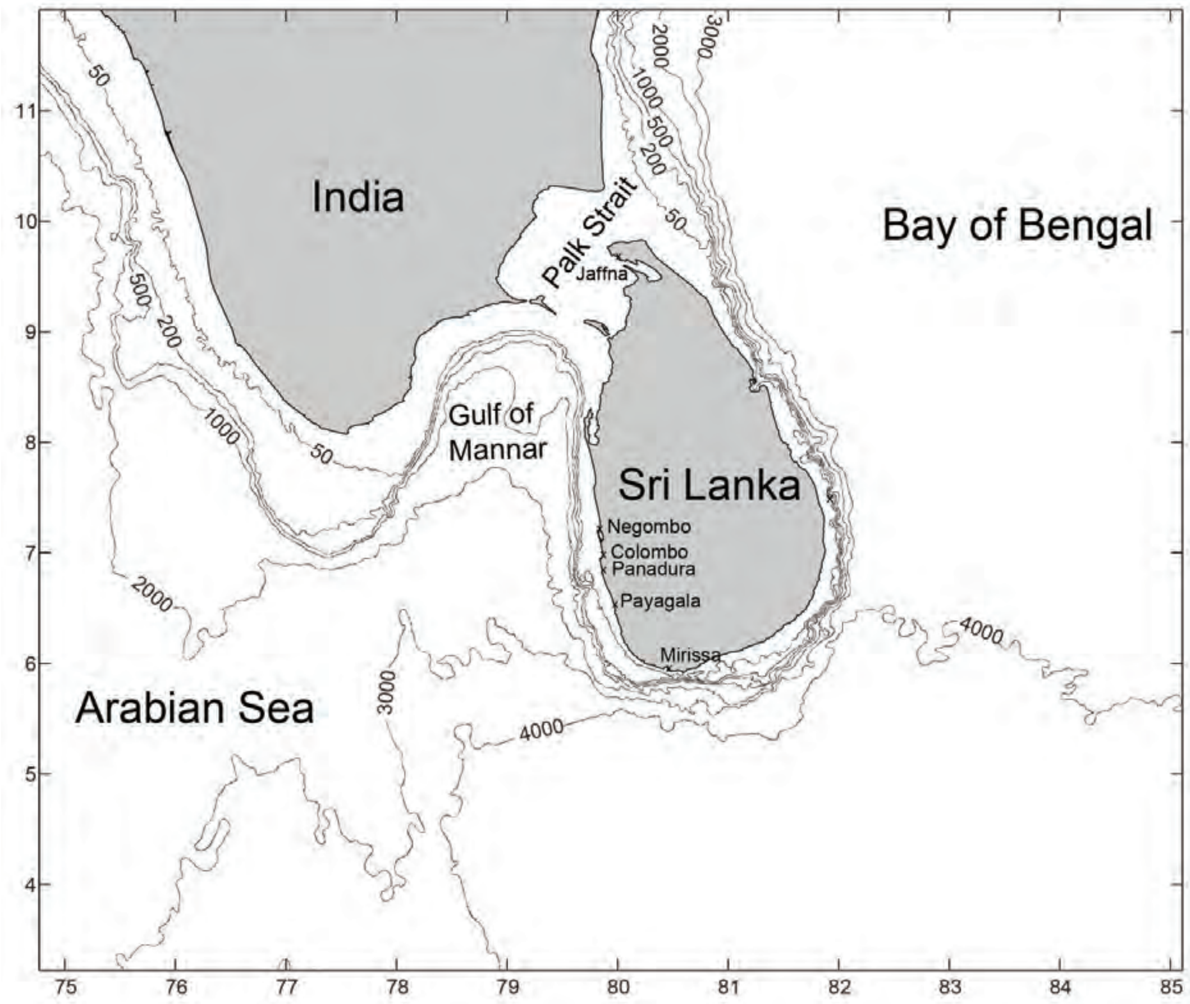

Figure 1. Map of Sri Lanka showing locations identified in the text and the location tide gages. Bathymetry contours are in meters.

impulsive disturbance that vertically displaces the water at the sea surface. Tsunamis are primarily associated with earthquakes in oceanic and coastal regions. There are also meteorological or meteo tsunamis that are generated by atmospheric effects (Pattiaratchi and Wijeratne 2014, 2015). Landslides, volcanic eruptions, nuclear explosions, and even impacts of objects from outer space (such as meteorites, asteroids, and comets) can also generate tsunamis (Wijeratne and Pattiaratchi, 2024). The most common type of tsunami is those associated with tectonic earthquakes, associated with the earth's crustal deformation. An earthquake which produces a tsunami is known as a tsunamigenic earthquake. When a tsunamigenic earthquake occurs beneath the sea, the water above the deformed area is displaced from its equilibrium position (Figure 2). Waves are formed as the displaced water mass, which acts under the influence of gravity and attempts to regain its equilibrium at the mean sea level. This displacement of the sea surface initiates a series of waves radiating outwards from the initial disturbance like that observed when a pebble is dropped onto a pond. When large areas of the sea floor elevate or subside, a tsunami can be created. The main factor that determines the initial size of a tsunami is the degree of vertical sea floor deformation, which is controlled by the earthquake's magnitude, focal depth (the depth below seabed at which the earthquake occurs), fault characteristics and coincident slumping of sediments or secondary faulting (Figure 2). Generally, for a basin scale tsunami (i.e. a tsunami that may impact a whole ocean basin) to be generated the earthquake should have a moment magnitude > 7.5 (same as Richter Scale) and the earthquake needs to be relatively shallow focal depth < 70 km (Figure 2; Okal, 1988). A shallower depth provides the strongest "impulse", but a deeper earthquake distributes the "impulse" over a larger area.

As the tsunami crosses the deep ocean, its wavelength from crest to crest may be several hundred kilometers or more, and its height from crest to trough will only be < 1m. They cannot be felt aboard ships, nor can they be seen from the air in the open ocean. The celerity (speed) of the tsunami is given by, $C = \sqrt{gH}$ where g is acceleration due to gravity and H is the total water depth. Thus, as the water depth decreases, the speed of the tsunami also diminishes. In the deeper ocean, the waves will reach speeds exceeding 10 ms^{-1} (> 900 km hr^{-1}). i.e. like that of a jet aircraft. The energy flux of the tsunami, which is dependent on its wave celerity and wave height, remains nearly constant. When they approach a coast, however, the wave heights of tsunamis increase owing to two transformations due to the decrease in depth: (1) energy that was distributed over a larger depth in the open ocean now has to be squeezed into a shallower depth; and, (2) leads to a decrease in the wave speed, and therefore in its wavelength. As a result, the energy must be accommodated in a smaller horizontal distance. This leads to an increase in wave height. In summary, as the speed of tsunami waves decreases, as it enters shallower water, the height of the wave grows. This is defined as wave the "shoaling" effect, and a tsunami that is imperceptible in deep water may grow to be several meters or more in height at the shoreline (Voit, 1987).

When a tsunami finally reaches the shore, it may appear as a rapidly rising or falling water level, a series of breaking waves, or even a bore.

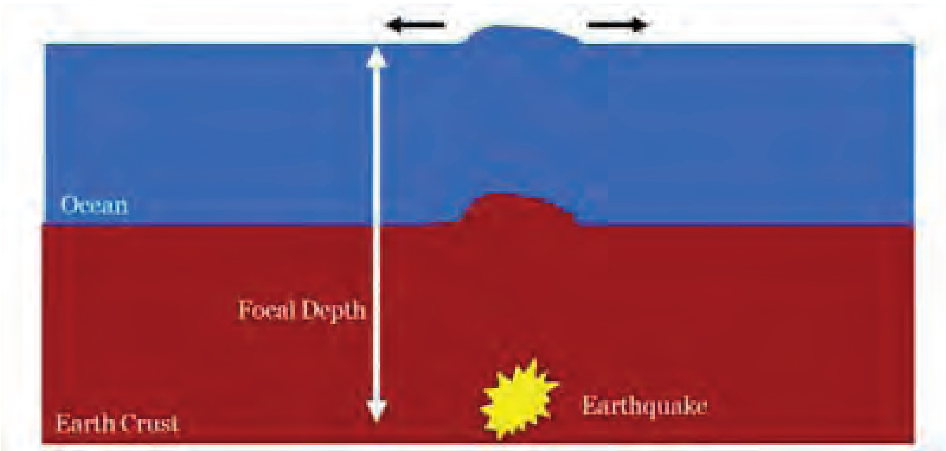

Figure 2. Schematic of generation of a seismic tsunami.

Generally, the highest water level is not reached during the first wave but rather the second or third wave (see section 4). Reefs, bays, river mouths, undersea features and the slope of the beach all help to modify the tsunami as it approach the shore. Tsunamis rarely become great, towering breaking waves. Sometimes the tsunami may break far offshore. Or it may form into a bore: a step-like wave with a steep breaking front. A bore can result if the tsunami moves from deep water into a shallow bay or river. As the effect of the tsunami on the shoreline is controlled by the local bathymetry, a coastal area may see no damaging wave activity while in another area, within several kilometers can experience destructive waves. The coastal flooding of a region can extend inland by several kilometers or more, covering large expanses of land with water and debris. Tsunamis may reach a maximum vertical height onshore above sea level, called a run up height, > 30 meters. A notable exception is the landslide generated tsunami in Lituya Bay, Alaska in 1958 which produced a 525 m run-up (Mader, 2004).

In the Indian Ocean, the Indo-Australian plate is sub-ducted beneath the Eurasian plate. This is the region known as Sunda Arc, located to the south of Indonesia (Figure 3). In total, ~ 6% of all tsunami activity in the Indo-Pacific region occurs in this region. Along Sumatra, destructive tsunamis, triggered by earthquakes have been reported in 1797 (affecting Padang), 1833 (affecting most of southern Sumatra), 1843 (affecting Nias Island) and 1861 (affecting southern Sumatra). There have been 19 earthquakes of magnitude 7 and higher that have occurred in this region since 1900 (Pattiaratchi and Woo, 2000). There were also 3 basin wide tsunamis subsequent to 2004 in 2005, 2006 and 2007 (Pattiaratchi and Wijeratne, 2009).

The only previous documented impact of an Indian Ocean wide tsunami was in 1883 due to the Krakatoa eruption (Wijeratne and Pattiaratchi, 2024). This caused a 35 m wave in Indonesia. The resulting tsunami has been reported in newspaper articles in Sri Lanka with impacts reported from Galle, Negombo and Arugam Bay where there was one casualty. The maximum wave height was reported to be 1 m and the tsunami impacted Sri Lanka 5-7 hours after the eruption.

3. THE 2004 DECEMBER EARTHQUAKE AND TSUNAMI

The earthquake which caused the tsunami was located off the west coast of northern Sumatra (16°N, 95.854°E) and occurred on Sunday, December 26, 2004 at 00:58:53 UTC (07:58:53 local time) with a focal depth of 30 km (Lay et al., 2005). The earthquake was the result of the interaction between the Indian, Burmese, Australian and Sunda tectonic plates. Here, the Indian plate subducted below the Burma plate along a fault line stretching from the Andaman Islands to Java. The main earthquake and subsequent aftershocks suggested this fault slipped 11 m of on a fault

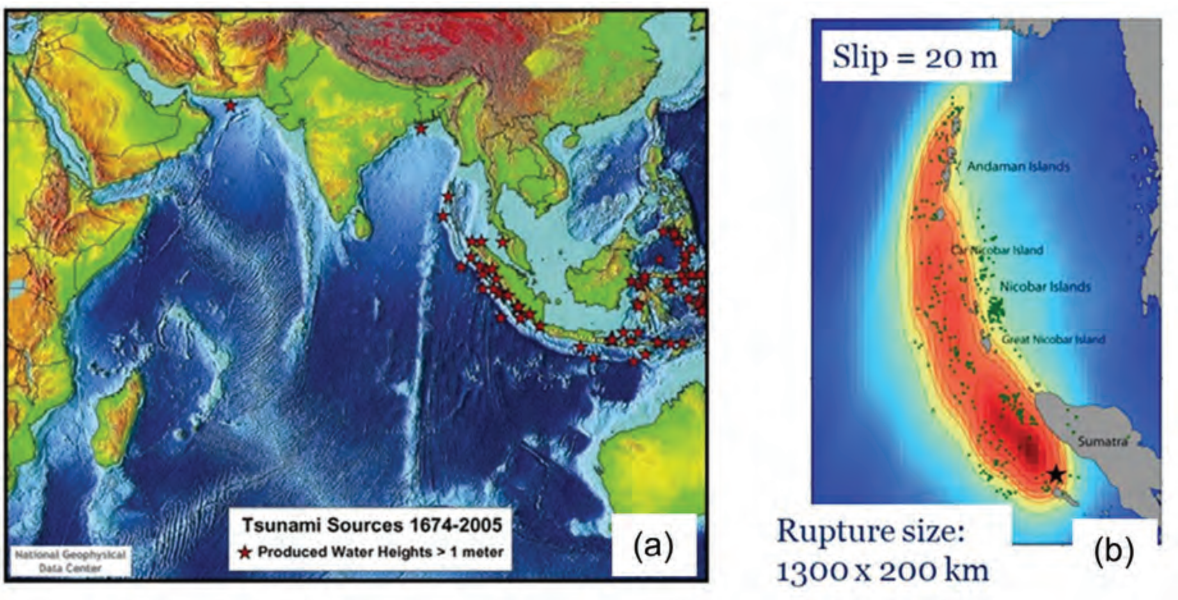

Figure 3. (a) Locations of earthquakes in the Indian Ocean resulting in wave heights > 1m. The highest number are along the Sunda arc; and, (b) fault characteristics of the 2004 Indian Ocean tsunami.

line 1,200 km long and 200 km wide (Figure 3b; Stein and Okal, 2005). In the month following the earthquake, there were over 350 aftershocks along the length of the ruptured fault. Of these, 85 had a magnitude greater than 5.5 and the largest was a 7.1 magnitude event.

The tsunami waves were recorded widely across the globe with tidal stations in countries bordering the Pacific and Atlantic oceans as well as those in the Indian Ocean and Antarctica recording water level changes induced by the tsunami (Figure 4; Titov et al., 2005). Maximum run-up heights recorded in the region range from 34.9 m in Banda Aceh to > 10 m in Sri Lanka and > 4 m in India (Table 1).

Table 1. Maximum run-up heights from the regions most affected by the tsunami

Location	Max. Run-up Height
India (Chennai Port)	4.1 m
Maldives (Fanadhoo)	4.65 m
Sri Lanka (Kahawa)	10.04 m
Sri Lanka (Hambantota)	10.61 m
Indonesia (Banda Aceh)	34.9 m

4. PERSONAL EXPERIENCE - PATTIARATCHI

Sunday 26th of December 2004 was a very beautiful day with clear skies and sunny. I was on holiday in Sri Lanka with my son, who had just finished his high school. On this day, Boxing Day, after the Christmas celebrations we had planned go to Bentota, where we had visited before to take part in water sports. We left Colombo around 7:30 am, with me driving a hired car, and stopped on the way to have some breakfast. As there wasn't much traffic on the road, we were making good progress. As I was crossing the Kalutara bridge, I could see some high wave activity on the beaches visible from the bridge, which I didn't really take much notice at the time. Only afterwards that it occurred to me that it was the initial waves from the tsunami. As we progressed past Kalutara, we encountered lots of people, very distressed, running onto the road and they looked very distressed. There were also a lot of monitor lizards crossing the road landward. This scene continued for several kilometers. People were trying to stop the cars on the road and as a safety measure, I locked the car doors from inside and continued the journey towards Bentota. There was a small traffic jam at a road junction, and I had to stop

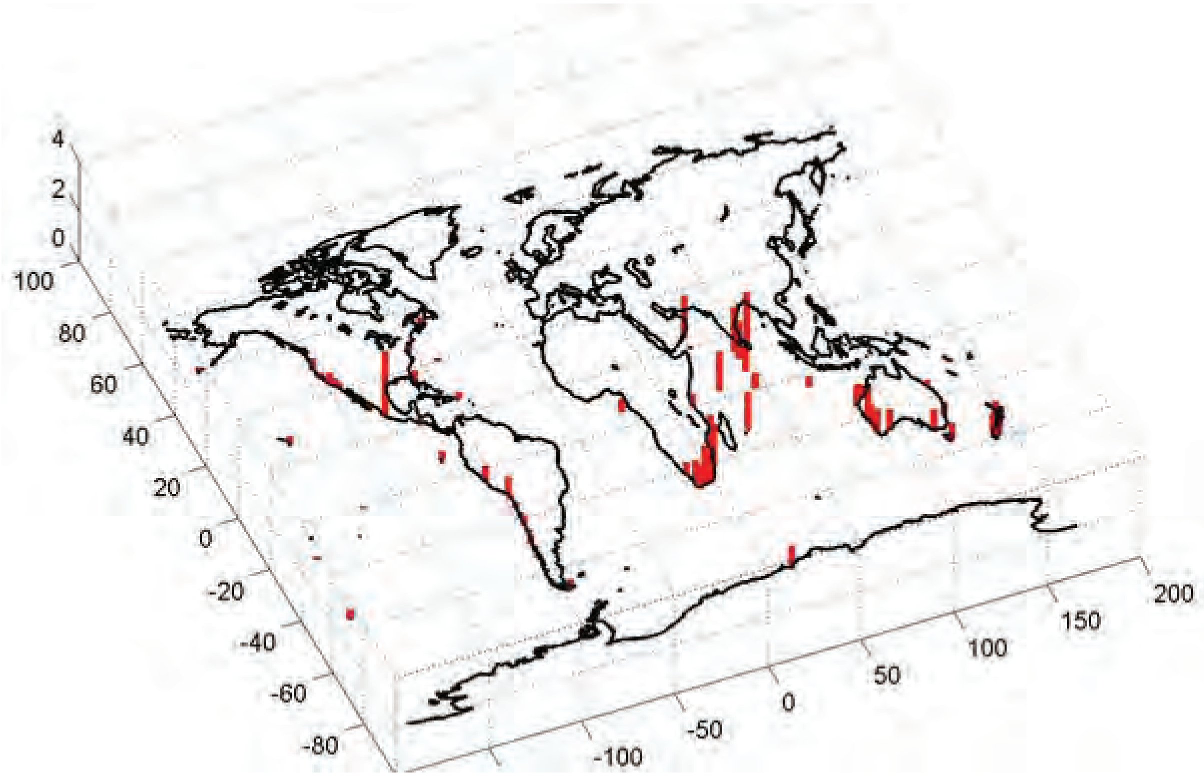

Figure 4. Global distribution of tsunami impact as recorded by coastal tide gages.

the car. I lowered my window and asked what had happened and the response was (in Sinhalese) 'the sea has come ashore'. I looked up at the clear sky and there was no wind and immediate realised that it had be a tsunami. I told my son – we don't experience tsunamis in Sri Lanka so we should go and take some photographs that I can use in my lectures. When we came to the railway crossing at Payagala, oruwa (fishing boat) on the road which obviously prevented me from going further. I got down from the car and asked people around how many waves have come, and they replied 4 or 5. My understanding of the tsunamis at that time was that it consisted of a packet of waves and I told myself that the tsunami has come and gone and we were. I was very wrong as I will describe later. So, I took some photographs, and then proceeded back along towards Colombo. I was feeling a little bit sad for my son as I had promised him that we could go for a swim. I know this other beach where we can go and have a look so let's see whether we can go for a swim on the beach because we came this far, the tsunami has come and gone, we are safe and we can have a little dip and go back to Colombo. The beach went to was next to Tangerine Beach hotel in Kalutara (Figure 5) and there were many people milling around there. The road was a dead end and as I was parking my son told me 'Dad, turn the car facing the land' which I did, and I got down and told the people, look, there is nothing to worry about. The waves have come and gone we are safe. I continued to take more photos (Figure 5c). Then this man comes to me and says, 'Sir, look' and pointed to the ocean. I could then see this big wave coming towards us, and I could see the water going towards the land on the road and I started to run towards where I had parked my car (I had water up to my knees by this time). The car was not there anymore. My son did not wait for me, he got into the car and drove away,

Figure 5. (a) Satellite images of Tangerine Beach Hotel; and, (b) photograph taken by Pattiaratchi on the beach

and I chased after him, and then finally caught him up and got into the car. We started coming back to Colombo fielding many phone calls from people in the Government. There was not much traffic till we got to the Panadura roundabout bypass road starts. There some very angry people with big heavy sticks trying to hit cars to try and prevent them using the road as was flooded. So, I had to go through to Moratuwa but the road was one big traffic jam. Then I started getting phone calls from various people and was instructed to go to the Moratuwa police station to get an escort to Galle Road to make my way to Temple trees, the Prime Ministers' office and residence.

One of the most puzzling things in this experience was when I had deemed myself safe when the initial waves had come there were many other waves that were impacting. The explanation for this will be provided in Section 4.

This was highlighted when I returned to Payagala two days after the tsunami impact to find that most of the building that I had seen intact when I was initially there was all destroyed (Figure 6). For example, the railway station was missing its roof (Figures 6a,b) with the water flowing over the roof which was at ~ 7m. The question is when the tsunami was only expected to be a packet of waves why was there damage many hours after the initial arrival of the tsunami waves ?

Figure 6. (a,b) Images of Payagala railway station after the impact of the tsunami. The height of the waves are estimates at ~7m that flowed over the roof of the station; and, (c) Qucikbird satellite image. Location of the railway station is circled, and the arrow shows the railway crossing where I was standing perhaps 10 minutes prior to this image being acquired.

5. THE IMPACT OF 2004 DECEMBER TSUNAMI ON SRI LANKA

Sri Lanka is located off the southern tip of India (Figure 1). The island has a length of 445 km; width of 225 km; a total area of 65610 km^2 and a coastline of 1760 km. It has a high density of population with ~5 million people live within 1 km of the coast. Sri Lanka has a very narrow continental shelf with the mean distance between the coast to the 200m depth contour being 20 km (Figure 1). Sri Lanka is located approximately 1550 km from the epicenter of the Earthquake. There are no sub-surface features between the earthquake region and Sri Lanka which results in the total energy of the tsunami being impacted on the coasts of Sri Lanka. In other regions, for example, along the west coast of Australia, the presence of subsurface topography results in the dissipation of tsunami wave energy (Pattiaratchi, 2020). Tsunami waves were recorded to first impact along the eastern coast at ~0855 local time and then propagated along the southern and the northern coasts reaching Colombo at ~1000 and Jaffna at ~1020 (Figure 1). It has been recorded that a total of 30983 people have lost their lives, another 4924 missing, 23248 injured and 596374 people rendered homeless.

Prior to 2004, Sri Lanka did not have a permanent tide gage recording sealevel in the Island. In 2003 through a collaboration between the authors, NARA and NOAA a tide gage was established at Mutwal harbour fishery harbour, Colombo in August 2004 and was recording sea level data, at two-minute intervals.

The data clearly showed the influence of the tsunami and indicated the tsunami arrived at 0952 local time as a leading elevation wave reaching a maximum height of 2.65 m over 10 minutes (Figure 9); that is, the highest water level for the initial wave was reached at 1002 local time. The tide gage at Mutwal fishery harbour is a stilling well which measures the height of a float inside a cylindrical well (Figure 8c). During the tsunami, the cable in the encoder (Figure 8b) was dislodged and no data were recorded for intermittent periods (Figure 9c). The cable was re-set manually by co-author, Wijeratne. Fortunately, an offshore tide gage (an InterOcean S4 wave and current recorder maintained by Lanka Hydraulic Institute Ltd), located in 16 m water depth also recorded the water levels at 10-minute intervals during this period (Figure 10). The S4 water level data were used to obtain the missing data at the Mutwal tide gage. The resulting time series (Figure 10) showed that in Colombo, the highest water level of 3.13 m occurred during the sixth wave, 3.5 hours after the first wave at 1330 local time (Pattiaratchi and Wijeratne, 2009). The maximum wave height (trough to crest) was 3.87 m. These indicated the

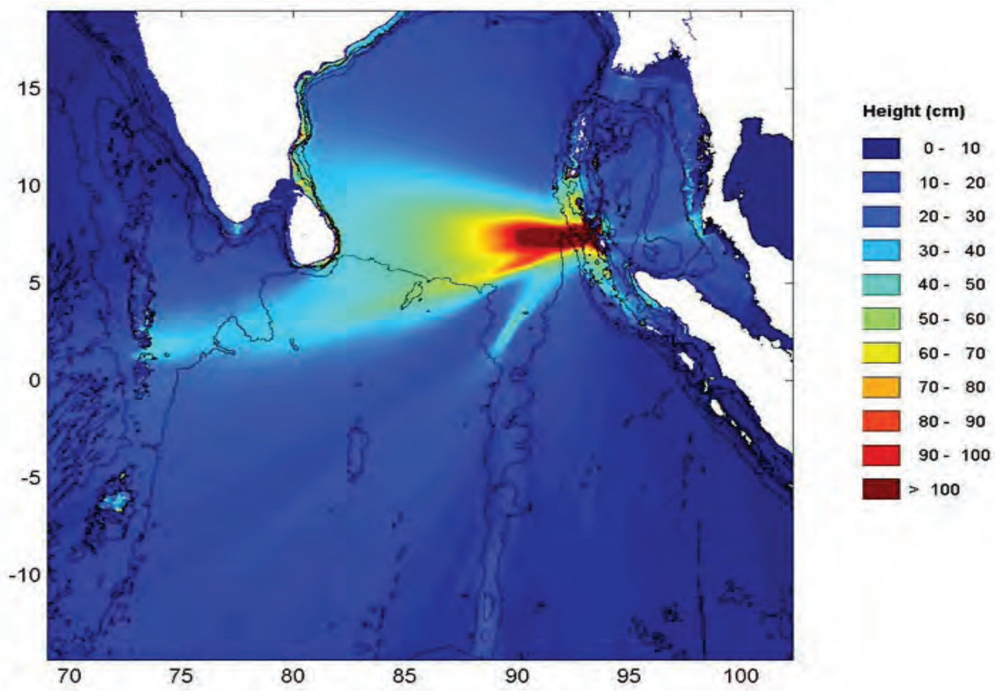

Figure 7. A numerical model simulation of deep water propagation of the tsunami originating to the east of Sri Lanka. Image shows maximum wave heights.

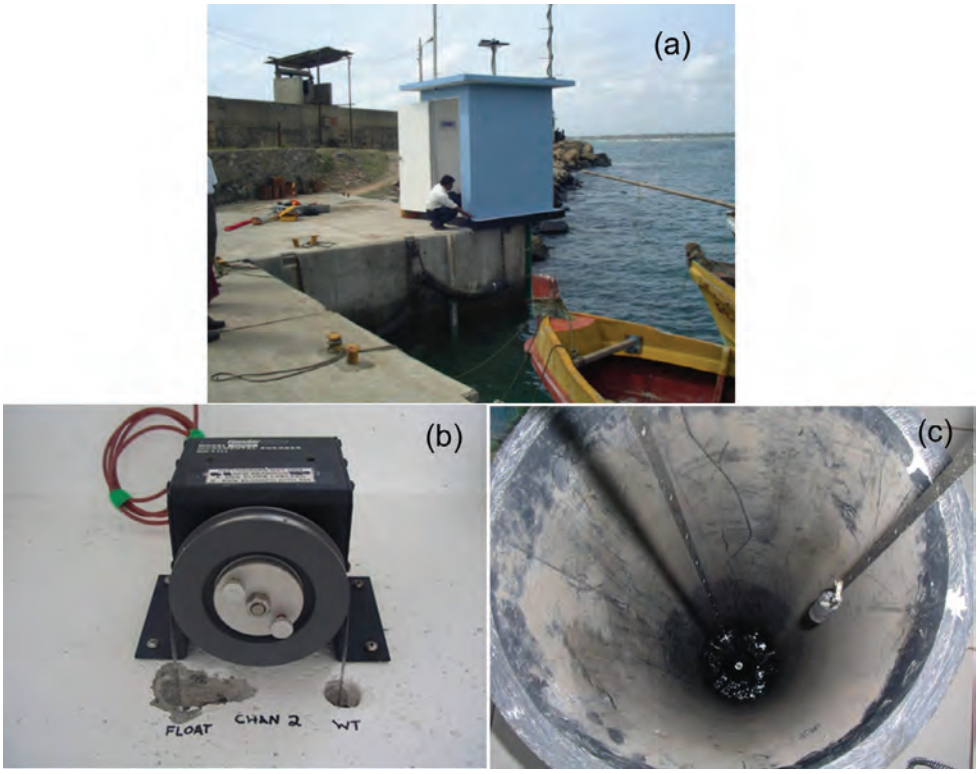

Figure 8. Images of the Mutwal (Colombo) tide gage that recorded the 2004 tsunami. (a) hut containing the tide gage; (b) pulley system for the encorder; and, (c) the stilling well.

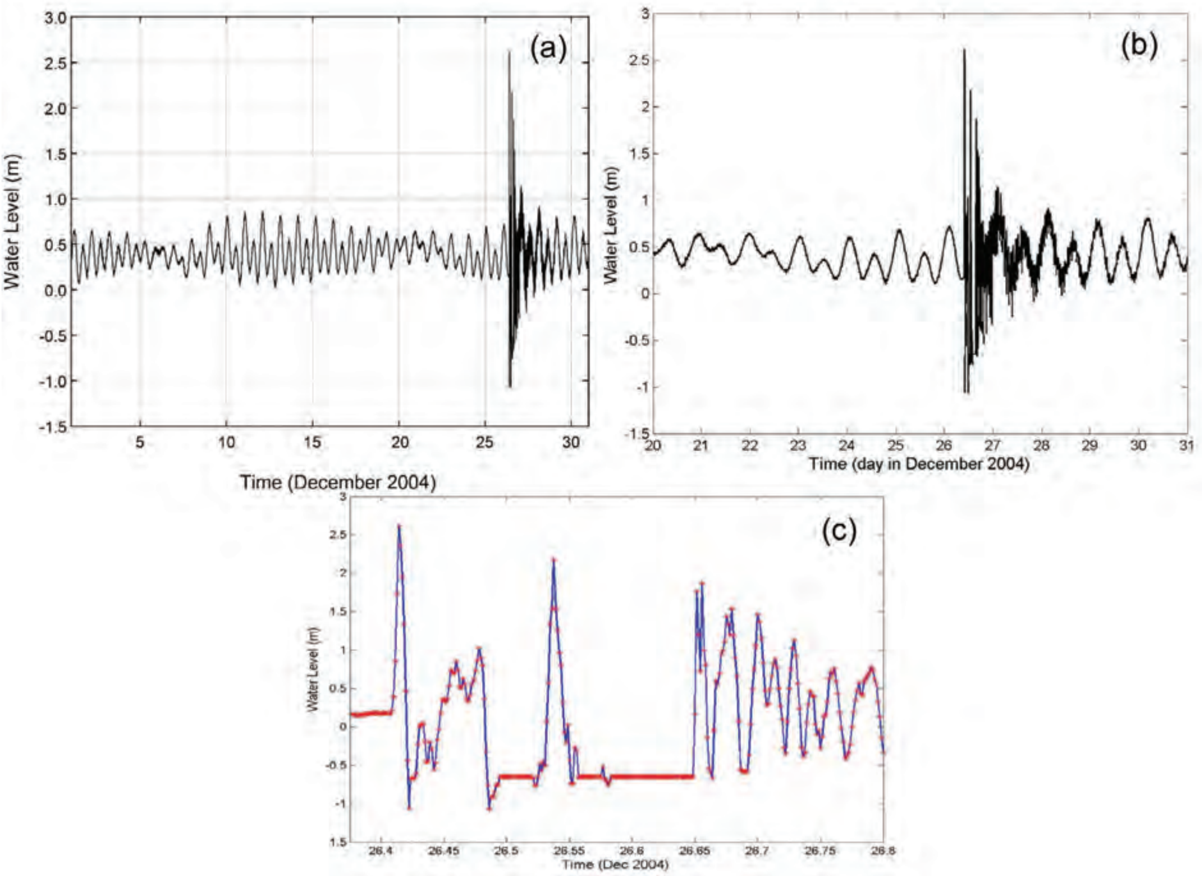

Figure 9. Time Series of sea level recorded at Mutwal tide gauge sea levels during December 2004: (a) 1-31 December; (b) 20-31 December; and, (c) 26 December.

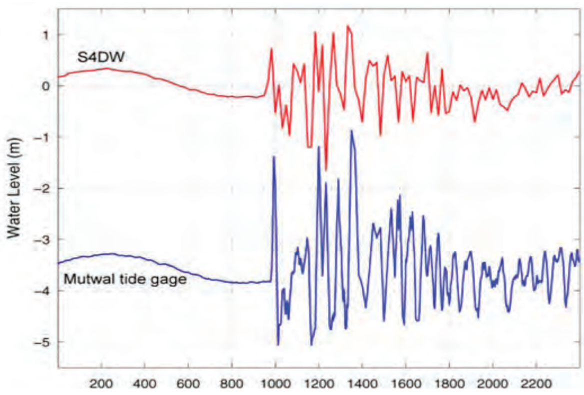

Figure 10. Time Series of offshore S4 tide gage ad Mutwal tide gauge sea levels on 26 Dec 2004. Note that the Mutwal data has been offset by -4 m.

wave incident along the west coast of Sri Lanka has many sources. These records also indicate the discrepancies that were observed during the personal experience of Pattiaratchi (Section 4).

The tsunami occurred on a clear sunny day with no clouds. This allowed for a series of cloud free images to be collected by Quickbird satellite along the west coast of Sri Lanka (Section 2). The satellite images illustrate the onshore-offshore movement of the tsunami waves (Figure 11). When the wave propagate onshore the coastal water level increases resulting in inundation (Figures 11b,d,g) whilst during the wave troughs the water level recedes resulting in the exposure of the sub-aerial beach (Figures 11c,f). It should noted be that the apparent relationship between wave profile and images are only indicative as the satellite acquired these images within a few minutes whilst the time between the arrival of the first wave and maximum wave was 3.5 hours.

To investigate why there was a such a long delay (3.5 hours) between the initial and largest waves, we undertook a numerical simulation using the ComMIT software (Titov et al., 2011). A tsunamigenic earthquake like that for the 2004 tsunami was prescribed as the initial condition and the simulation continued for the time that the tsunami waves impacted both Sri Lanka and the Maldives Island chain (Figure 12). Time Series of tsunami wave propagation maps indicated the tsunami waves approaching the east coast of Sri Lanka and impacting the east coast (Figures 12a,b). A reflected wave from Sri Lanka is seen to propagate to the east (Figures 12c,d), The waves wrap around the southern and western coasts (Figures 12c,d) and the main tsunami impacts the Maldives (Figures 12e,f). A reflected wave is seen to travel east and impacting the west coast (Figures 12f,g). The elapsed time for the tsunami's deep-water propagation from Sri Lanka to the Maldives island chain and return was ~two hours. Thus, the second largest wave in the record, which occurred at 1200 (Figure 10), could be attributed to the reflection from the Maldives island chain (Pattiaratchi and Wijeratne, 2009).

Results from the numerical simulations (Figure 12) indicated that there were different processes that contributed to higher wave heights and resulting run-up (defined as the highest water level on land). Along the west and southern coasts, the direct impact of the tsunami wave propagating from the earthquake source was the primary source (Figure 12b). Here, the shoaling effects of the narrow continental shelf (Figure 1) amplified the tsunami waves. In contrast, along the west coast the reflected waves from the Maldives was the primary source with the highest waves arriving 2-3 hours after the first wave (Figures 10 and 12g). These results are also reflected in the measurements of wave run-up recorded along the coastline. The highest run-up (~10 m) were along the south-east coast whist higher wave run-up was also measured along the west coast (Figure 13). The maximum run-up of > 10 m were recorded at Hambantota and Kahawa (location of the train disaster) and 11 m at Kalmunai (Wijetunge, 2012). Other selected locations where measurements were available (http://www.drs.dpri.kyoto-u.ac.jp) include (Figure 13): Nilaveli (5.1 m), Kirinda (9.1m), Tangalle (3.7m), Dickwella (4.9 m), Matara (5.8 m), Koggala (9.3 m), Galle (4.9 m), Payagala (6 m), Panadura (5.6 m) and Colombo (2.7 m).

The name *tsunami*, meaning *harbour wave* derives its name from a *Seiche*, a free oscillation in an enclosed or semi-enclosed body of water, similar to the oscillation of a pendulum where the oscillation continues after the initial force has ceased (Miles, 1974). Several factors cause the initial displacement of water from a level surface, and the restoring force is gravity, which tends to maintain a level surface. Once formed, the oscillations are characteristic only of the system's geometry (length and depth) and may persist for many cycles before decaying under the influence of friction. This processes also occurs on the continental shelf and is illustrated in the data collected at Mutwal where oscillations in the water level after the high wave continues for more than 3 days until 29 December (Figure

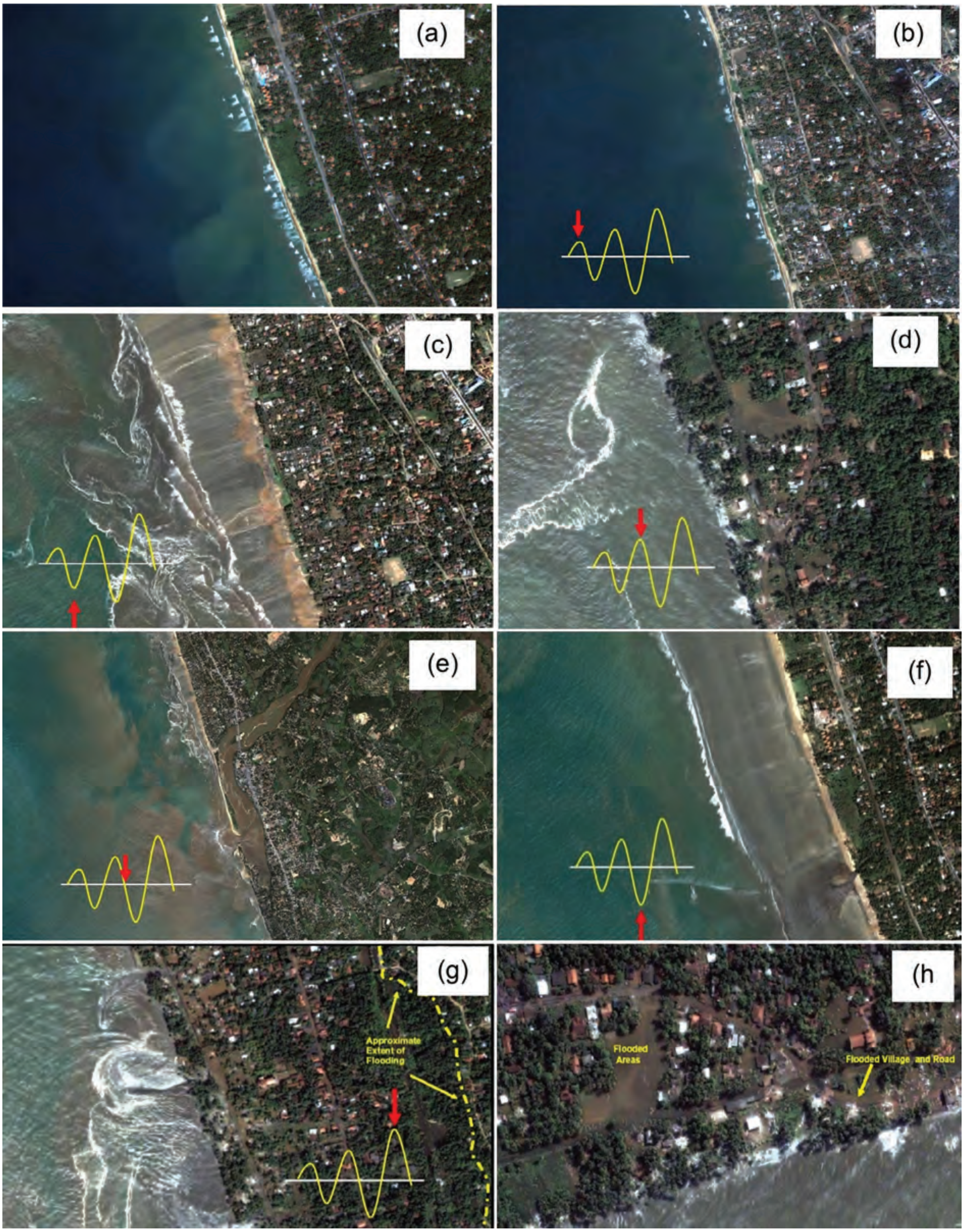

Figure 11. Time Series of Quickbird satellite images from the west coast of Sri Lanka. (a) prior to tsunami wave arrival; (b) arrival of the first wave crest; (c) receding of the water level during the trough of the wave; (d) as (b); (e) mean water level at the Kalu Ganga entrance, Kalutara; (f) as (c); (g) increase in water level during the wave crest – the maximum wave height and extent of the inundation; and, (h) flooded regions. Note that the relationship between wave profile and images are indicative as the satellite acquired these images within a few minutes whilst the time between the arrival of the first wave and maximum wave was 3.5 hours.

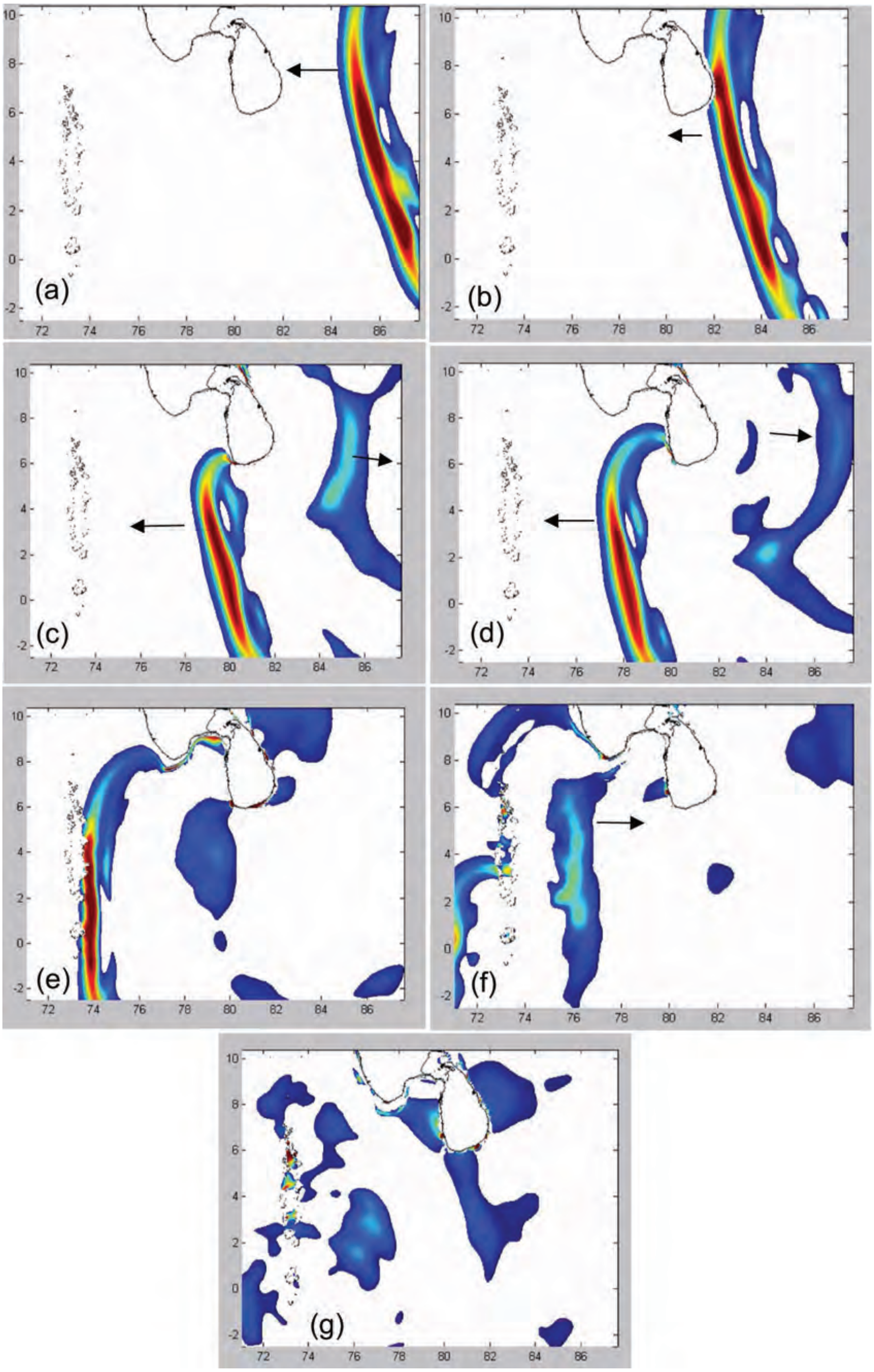

Figure 12. Time Series of tsunami wave propagation simulated using ComMIT software for the region around Sri Lanka and the Maldives. Arrows indicate wave propagation direction. (a) Tsunami approaching the east coast of Sri Lanka; (b) impact of the first wave crest on the east coast; (c) propagation along the south coast and reflected wave propagating to the east; (d) as (c); (e) wave impacting Maldives; (f) reflected wave from Maldives propagating to the east; (g) higher water levels along the west coast of Sri Lanka due to reflected wave from Maldives.

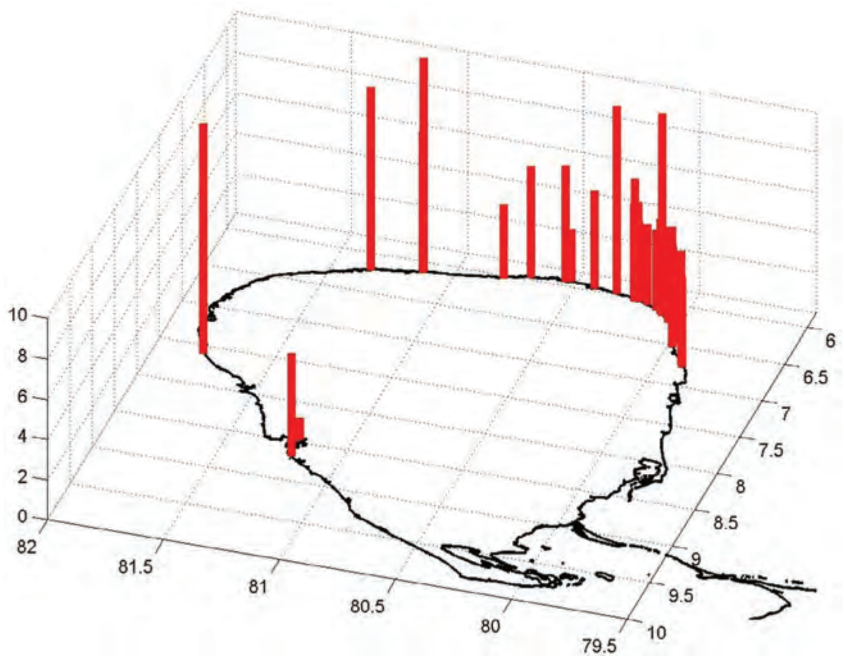

Figure 13. Run-up heights reported from locations around Sri Lanka. Data were collated from different sources (including those obtained from internet resources: http://www.drs.dpri.kyoto-u.ac.jp)

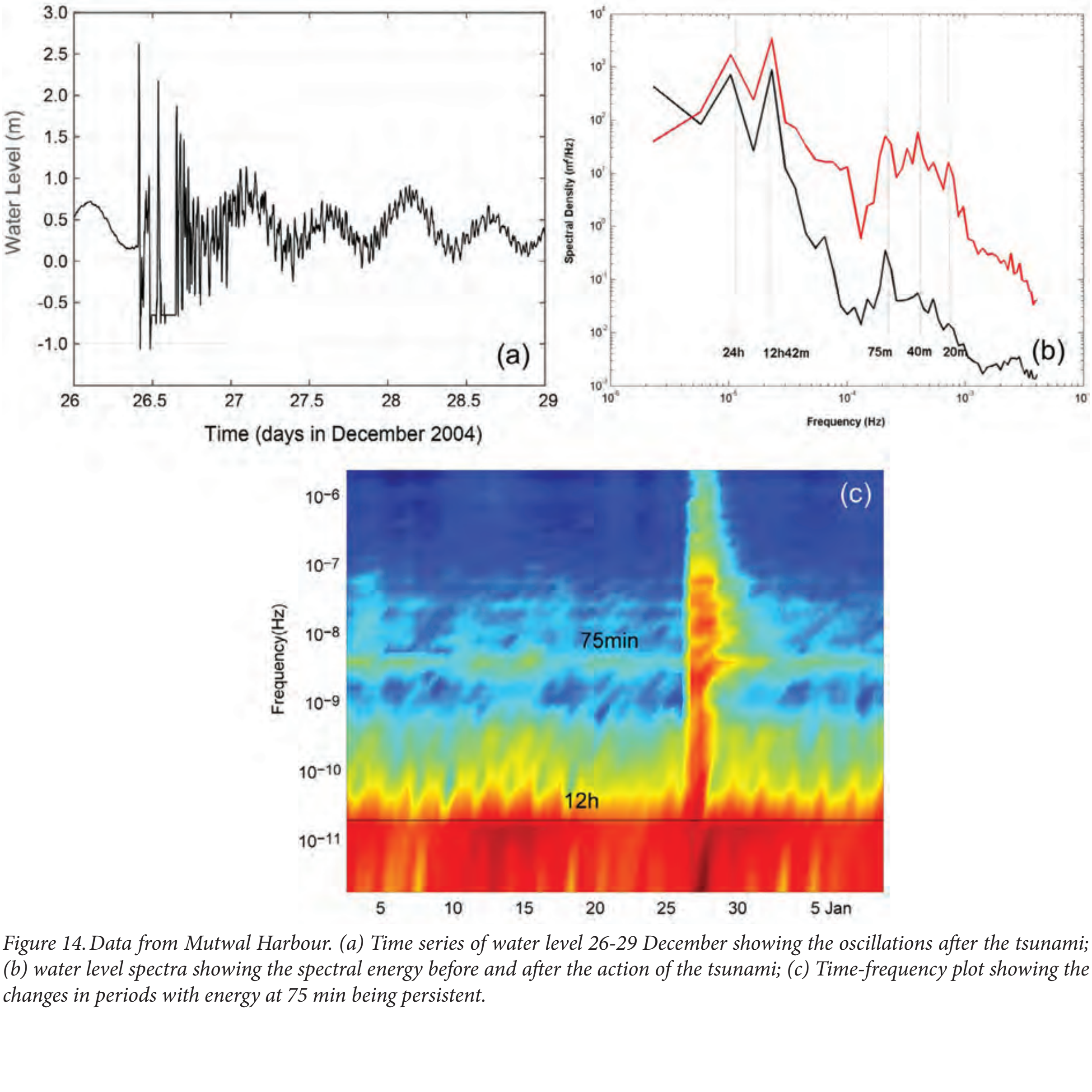

Figure 14. Data from Mutwal Harbour. (a) Time series of water level 26-29 December showing the oscillations after the tsunami; (b) water level spectra showing the spectral energy before and after the action of the tsunami; (c) Time-frequency plot showing the changes in periods with energy at 75 min being persistent.

14a). Note that before the tsunami impact the water level record does not contain any noticeable oscillations. At Mutwal, spectral analysis of 5 days of data obtained before and immediately after the tsunami indicated that the high frequency energy (e.g. at 75 mins) was enhanced after the action of the tsunami (Figures 14b,c). Although the tide gage was located within a harbour, the 75min oscillation relates to the first mode of the oscillation of the entire continental shelf of the study region: here, the continental shelf has a mean depth of 50m and a width (to the 200m contour) of 8 km. Hence, in this case, the tsunami enhanced the existing natural oscillation of the entire continental shelf.

6. HISTORICAL CONTEXT

In many circles (http://dhaneshw.blogspot.com/2020/11/tsunami-history-part1-20050208.html) it has been claimed that the first recorded impact of a tsunami in Sri Lanka was during the reign of King Kelanitissa who ruled the Kelani Kingdom (*Maya Rata*) over 2,200 years ago. However, the experience and data collected during of the 2004 tsunami indicates that the flood event described in historical texts such as the *Mahavamsa* was not due to a tsunami.

King Kelanitissa suspected that his brother, Uttiya had an interest in his wife and banished him out of the Kingdom. But Uttiya was sending letters to the Queen through a Buddhist priest. When the King discovered a letter, he believed that the priest was writing the love letters to Queen and instantly convicted him to death by boiling in a cauldron of oil. Immediately after the death of the priest there was a large flood event and the public believed that the flood was because the sea gods were infuriated in the death of the priest. The description in *Mahawamsa* says 'Wrath of the sea gods made the sea overflow into the land". King was adviced to make a sacrifice to the gods. A ship was prepared and was launched with Princess Devi, the daughter of the King. Immediately after the vessel was launched the ocean subsided. The ship with Devi was washed ashore along the southern coast and she married the ruler there and was named Viharamaha Devi. Her son Dutugemunu (137-161 BC) was a famous king who united whole of Sri Lanka.

It is not disputed that the there was a significant flood event at that time. However, it would not have been due to a tsunami considering the described time scales. A tsunami is a packet of waves. Data presented in this paper, and many others describing tsunamis, indicate that a tsunami is a series of waves which that force onshore-offshore movement of water onto the land (Figures 11 and 16). When a wave crest approach the coast there is flooding whist during the wave trough the water recedes (Figure 11). This intermittent flooding-receding process occurs at intervals of 5-10 minutes over a period 3-4 hours. There is no residual or pooling of water on land during this process. Now consider the narrative where the public approached the King to ask for a sacrifice and then a vessel was prepared and launched with the Princess onboard as a sacrifice. This whole process, if occurred today would take several days but over 2200 years ago it would have taken much longer. It could not be completed in a few hours. Also, it is stated that the water receded only after the vessel was launched which also implies that the flood event with residual water on land lasted several days which also contradicts the physical processes associated with tsunami waves.

7. DEVELOPMENT OF THE INDIAN OCEAN TSUNAMI WARNING SYSTEM

Immediately after the tsunami impact the countries around the Indian Ocean formed the Intergovernmental Coordinating Group (ICG) to develop an Indian Ocean Tsunami Warning and Mitigation System (IOTWS) under the auspices of the Intergovernmental Oceanographic Commission (IOC) of UNESCO. This included the establishment of an improved network of seismic stations; coastal and deep-water sea level recording stations; and the development of decision support tools for tsunami hazard and risk assessment for the region including tsunami hazard identification and characterisation, prediction, and scenario development. The senior author was the Chair of the working group: Modelling, forecasting and scenario development over the period 2005–2011. The main task of the working group was to build capacity in the Indian Ocean rim countries and develop tools to enable the construction of inundation maps for the coastal communities of the Indian Ocean region. It also included translation of the inundation projections to evacuation maps. As part of the working group, the tsunami community modeling tool Community Model Interface for

Tsunamis (ComMIT) was developed (Titov et al., 2011). It was designed for ease of use and allows dissemination of results to the community while addressing concerns associated with proprietary issues of bathymetry and topography. It uses initial conditions from a pre-computed propagation database, has an easy-to-interpret graphical interface (Figure 15), and requires only portable hardware. ComMIT was initially developed for Indian Ocean countries with support from the United Nations Educational, Scientific, and Cultural Organization (UNESCO), the United States Agency for International Development (USAID), and the National Oceanic and Atmospheric Administration (NOAA).

Model simulation results from an application of the ComMIT model to predict inundation due a moment magnitude 9.1 earthquake originating along the Sunda Arc, similar to the 2004 earthquake are shown on Figures 16-18. The model parameters include specification of the moment magnitude (9.1) and the fault characteristics that include 13-unit sources each 100x50 km with the length of the rupture being 500 km and the initial slip 19.276 m (Figure 15). This earthquake would create an Indian Ocean basin wide tsunami but with direct and largest impact on Sri Lanka (Figure 16). The tsunami waves reach Galle 2 hours and 9 minutes after the earthquake with inundation due to the first wave 8-11 minutes later (Figure 17). The water recedes 6 minutes later (at 2 h 27 min) as shown by the white areas close to the coast. The second high wave (at 2 h 45 min) has a major inundation with the cricket stadium and majority of the coastal regions inundated with up to 4m of water along the coastal areas. Note that the model grid does not capture the whole inundation due to this event due to insufficient

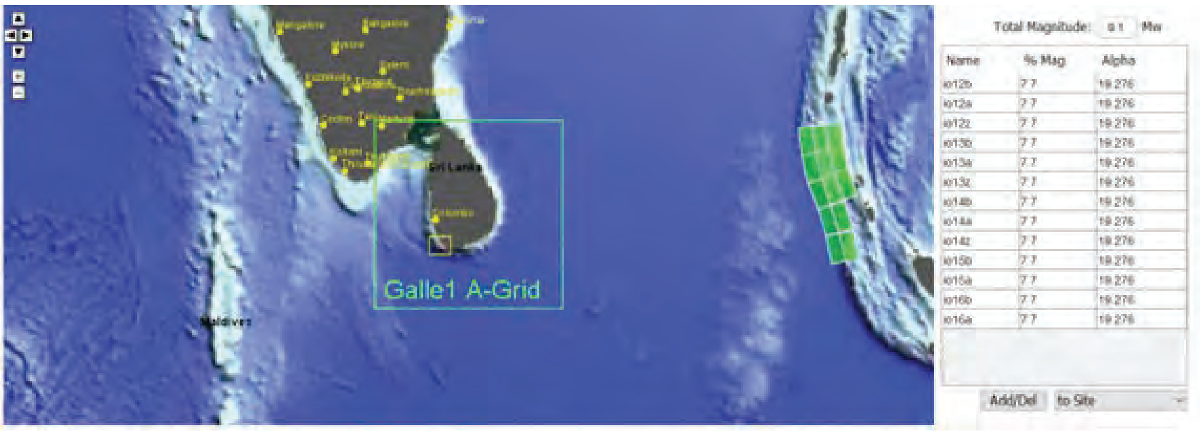

Figure 15. The ComMIT model interface showing a model run for Galle due to a 9.1 earthquake along the Sunda arc. The green boxes represent the earthquake rupture region.

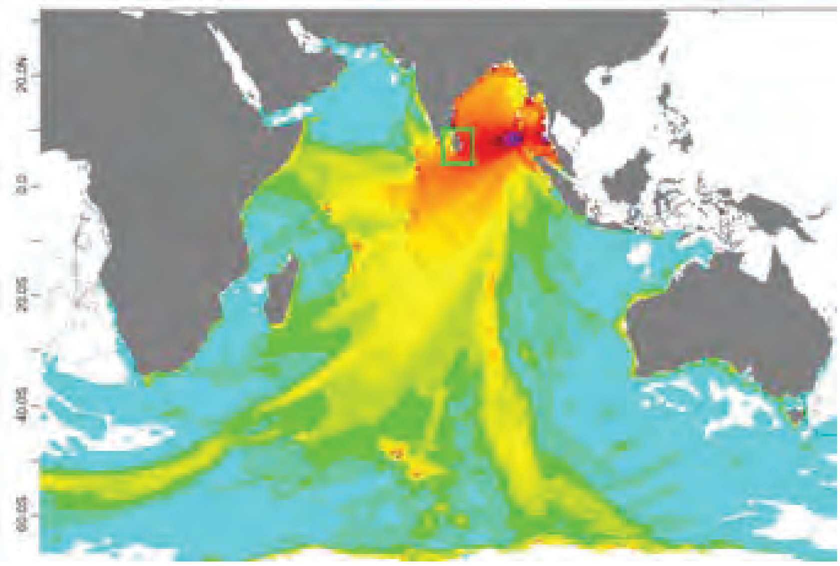

Figure 16. Maximum wave heights in the Indian Ocean for the scenario described in Figure 15

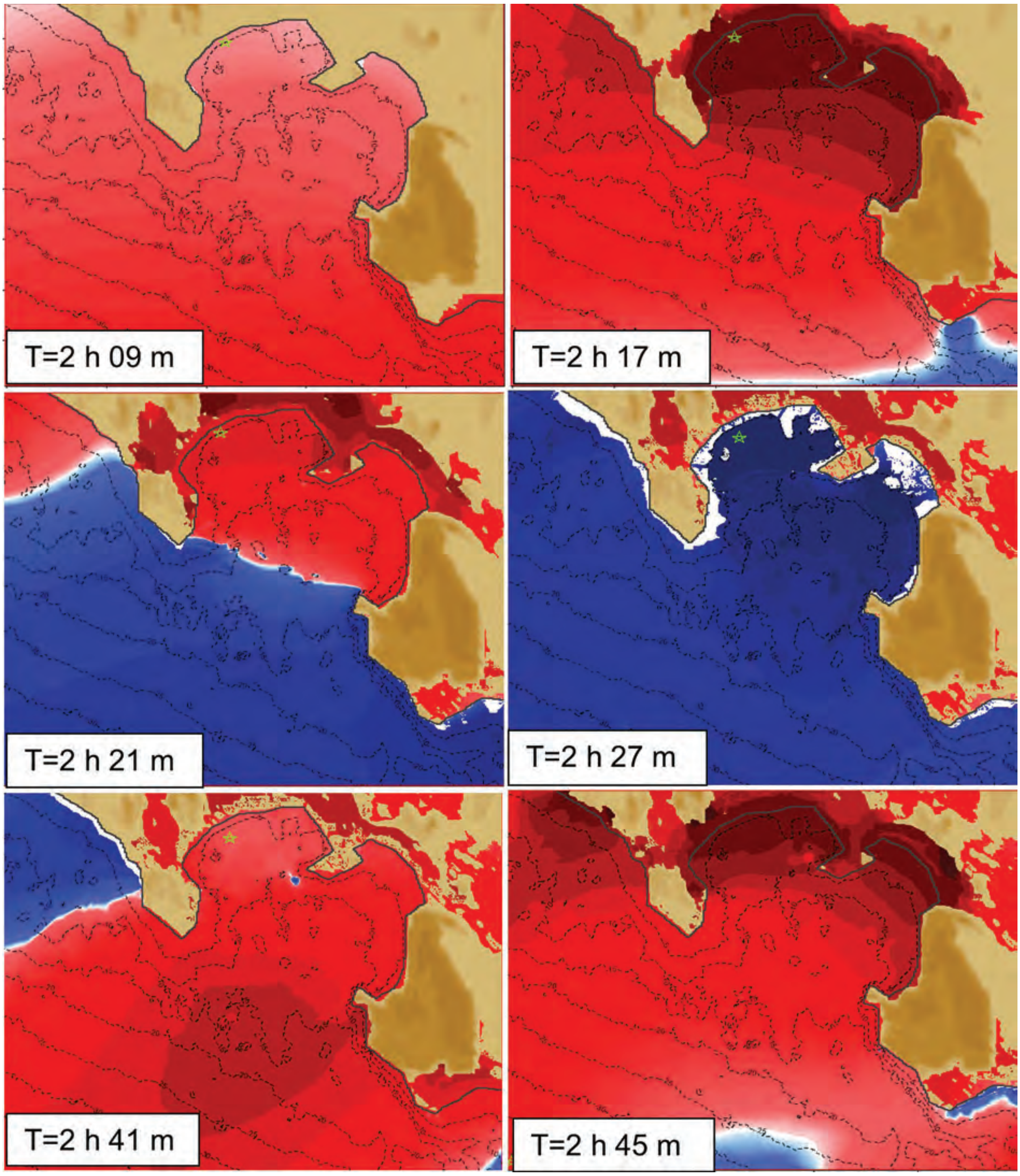

Figure 17. Time series of images from the Galle simulation over a period of 36 minutes showing the inundation for the scenario shown on Figures 15 and 16. T represent time since the earthquake. Brown colours represent land areas.

topography data. The maximum inundation for this scenario is shown on Figure 18 for Galle and Trincomalee superimposed on Google Earth with both locations showing significant inundation.

Two decades on we are still working to develop detailed inundation maps for Indian Ocean region, and we are still lagging behind. In many countries, including Sri Lanka even the fundamental data required to apply the models are unavailable. For example, oastal bathymetry data, including regions susceptible for inundation is unavailable to the required accuracy to undertake numerical modelling exercises required to predict tsunami risk, hazard, vulnerability, and exposure including tsunami run-up. This is a combination of the data unavailable or local authorities who are data curators unwilling to share data for a variety of reasons. Thus, it is imperative that an international cooperative effort is undertaken to acquire these data sets and develop expertise in the application of these model modelling techniques.

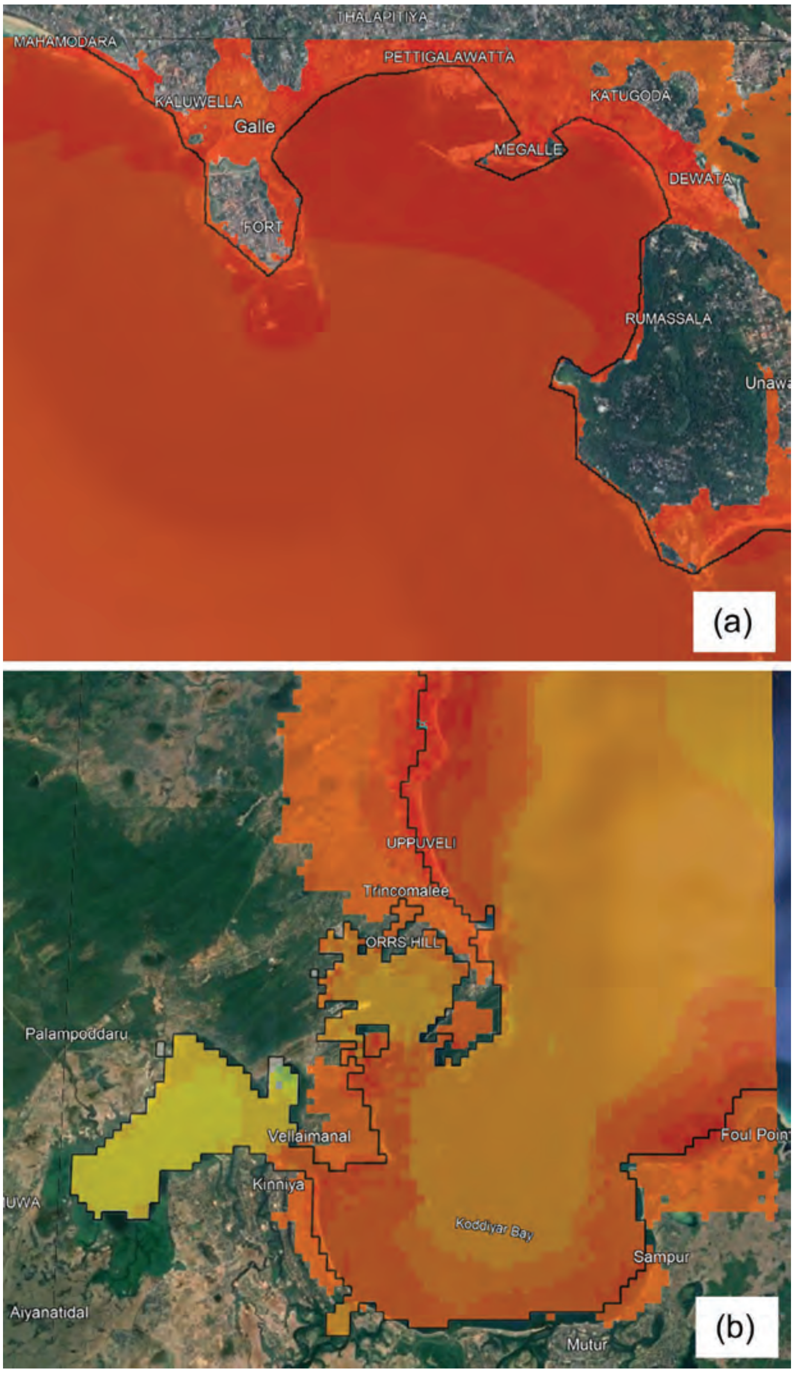

Figure 18. Predicted maximum inundation for (a) Galle; and, (b) Trincomalee from a ComMIT model simulation for the scenario shown on Figures 15 and 16.

The numerical modelling also contributed to the development of the tsunami warning system for Sri Lanka. The system is designed to provide at least a 90 min advanced alert or warning before the tsunami waves impact on Sri Lanka. We developed the 90-minute isochron to inform when tsunami waves cross this line (Figure 19). There is also a deep water tsunameter or DART buoy located at close to this isochron.

In addition to the Sunda Arc there is also the Makran subduction zone offshore Iran and Pakistan. Sri Lanka is not susceptible to tsunami waves originating from this region due to the presence of the Laccadive Islands and southern India which acts to dissipate and shelter tsunami wave energy before it impacts on Sri Lanka. This is demonstrated in a model simulation of a tsunami generated by a 8.7 moment magnitude tsunami (Figure 20). The tsunami wave propagate southward reaching the northern Laccadive Islands 180 minutes after the earthquake. The wave heights are significantly reduced as the

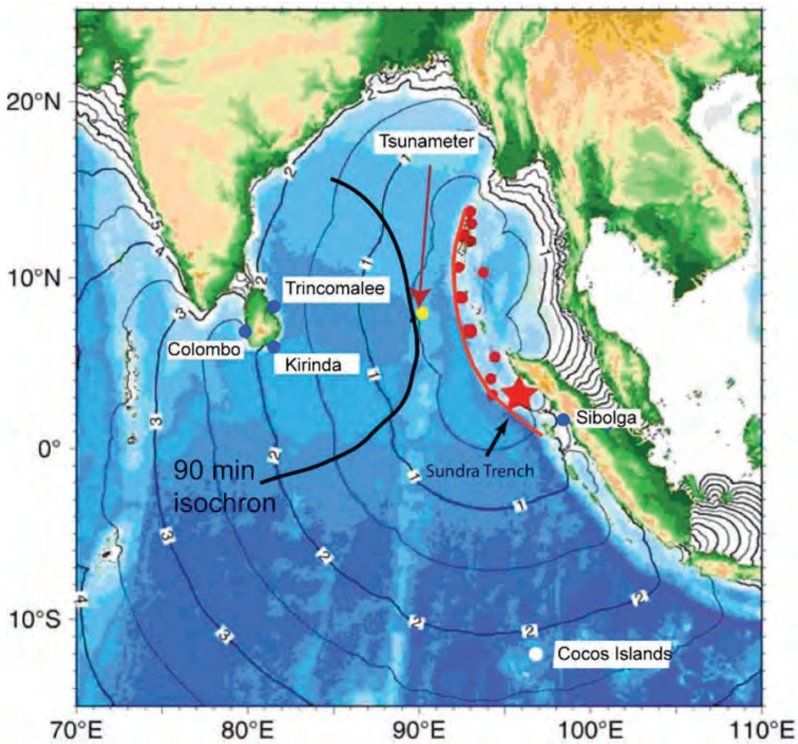

Figure 19. Development of the tsunami warning system for Sri Lanka. The system is designed such that there is a 90 min advanced warning alert before the tsunami waves impact on Sri Lanka.

tsunami waves cross the Laccadive Islands 280 minutes after the earthquake (Figure 20).

8. CONCLUSIONS

When the 2004 Indian Ocean tsunami waves impacted on Sri Lanka, almost two decades ago, very few people were familiar with the action of tsunamis lets alone understanding of their devastation and impact. In 2024, we have a a better knowledge base to deal with basin wide tsunamis in the Indian Ocean as summarised below:

1. Tsunamis impacting on Sri Lanka are those originating from a tsunamigenic earthquake from the Sunda Arc with moment magnitude > 7.5 and focal depth < 70 km.
2. Sri Lanka is largely unaffected by tsunamis originating from the northern Arabian sea – the Makran subduction zone due to the presence of Laccadive Islands.
3. The travel time to Sri Lanka from the origin varied with the tsunami impacting the east coast ~0855 (2 hours after the tsunami) and then propagated along the southern and the northern coasts reaching Colombo at ~1000 and Jaffna at ~1020.
4. The maximum run-up of > 10 m were recorded at Hambantota and Kahawa (location of the train disaster) and 11 m at Kalmunai. Other selected locations where measurements were available include: Nilaveli (5.1 m), Kirinda (9.1 m), Tangalle (3.7 m), Dickwella (4.9 m), Matara (5.8 m), Koggala (9.3 m), Galle (4.9 m), Payagala (6 m), Panadura (5.6 m) and Colombo (2.7 m).
5. The water level record from Mutwal Harbour indicated a highest water level of 3.13 m that occurred during the sixth wave, 3.5 hours after the first wave at 1330 local time. This was due the reflected waves from Maldives Island chain.
6. The tsunami warning system is operational at present and an advance alert/warning may be available 90 minutes to tsunami wave impact in Sri Lanka
7. Numerical modelling tools are available for simulating tsunamis and to develop inundation maps. Unfortunately, the high-resolution bathymetry and land topography data are not readily available to develop these maps.

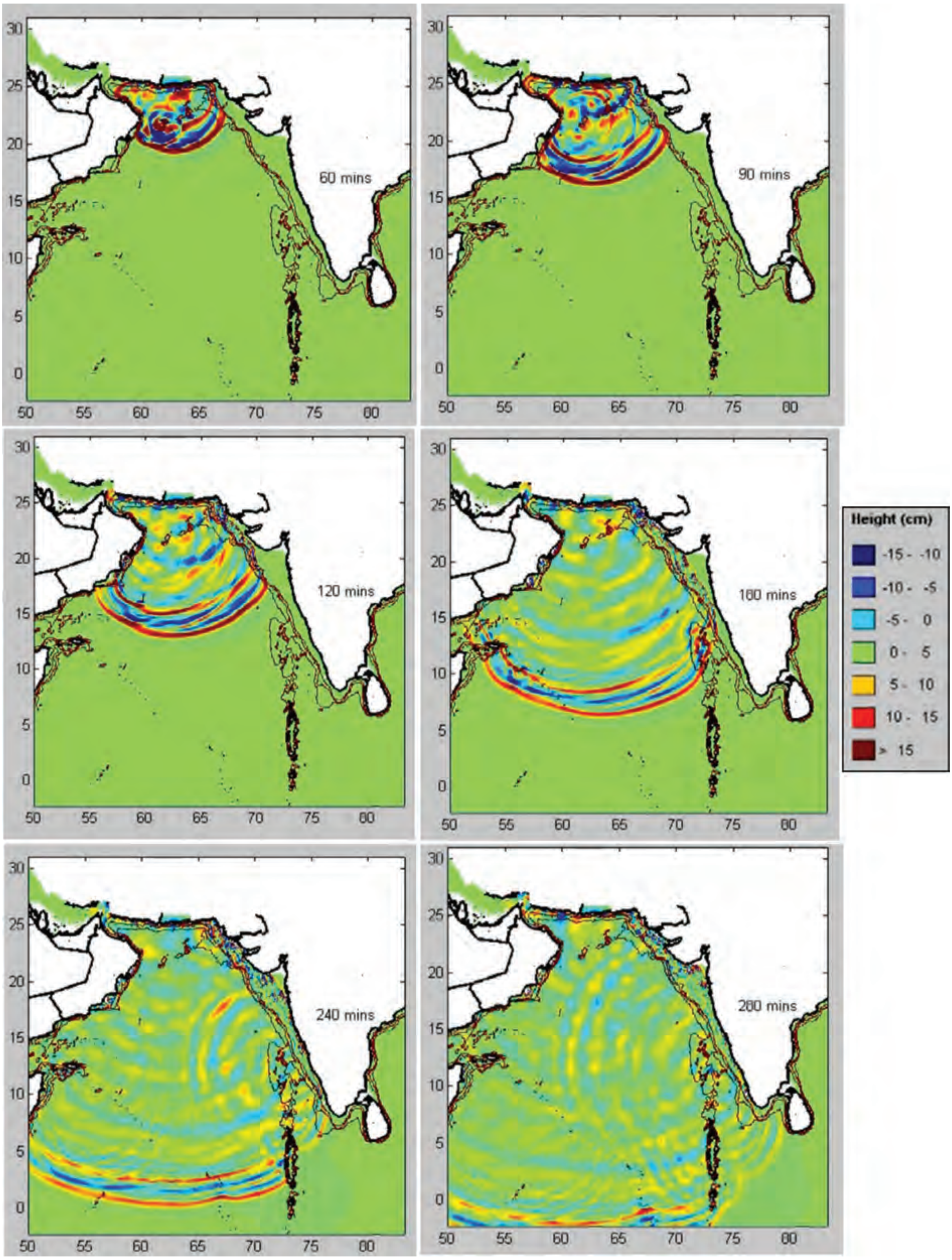

Figure 20. Time series of images form the ComMIT simulation of a tsunami originating from an earthquake in the Makran subduction zone

Figure 21. Tsunami affected area at Panadura. to the south of Colombo (Figure 1). The maximum run-up was ~5m. There were 184 houses located here.

9. REFERENCES

Inoue S., Wijeyewickrema A.C., Matsumoto H., Miura H., Gunaratne P.P., Madurapperuma M. and Sekiguchi T. (2007). Field survey of tsunami effects in Sri Lanka due to the Sumatra-Andaman earthquake of December 26, 2004. Pure and Applied Geophysics, 164, 395-412.

Lay T., Kanamori H., Ammon C.J., Nettles M., Ward S.N., Aster R.C., Beck S.L., Bilek S.L., Brudzinski M.R., Butler R., DeShon H.R., Ekstrom G., Satake K., Sipkin S. (2005). The great Sumatra-Andaman earthquake of 26 December 2004. *Science*, 308, 1127–1133.

Liu, P., Lynett L.-F. P., Fernando J., Jaffe B. E., Fritz H., Higman B., Morton R., Goff J., and Synolakis,C. (2005). Observations by the international tsunami team in Sri Lanka, *Science,* 308, 1595.

Mader C.L. (2004). *Numerical modelling of water waves,* 2nd Ed, CRC Press, New York, NY, USA, 274pp.

Miles J. (1974). Harbour seiching. *Annual Review of Fluid Mechanics*, 6, 17–33.

Okal E.A. (1988). Seismic parameters controlling far-field tsunami amplitudes: a review". Natural Hazards, 1, 67-96.

Pattiaratchi C.B. and Woo M. (2000). Risk of tsunami impact at the Port of Dampier, Centre for Water Research Report No. WP 1520 CP.

Pattiaratchi C.B. (2020). Influence of ocean topography on tsunami propagation in Western Australia. Journal of Marine Science and Engineering, 8(9), 629.

Pattiaratchi C.B. and Wijeratne E.M.S. (2015). Are meteotsunamis an underrated hazard? Philosophical Transactions of the Royal Society A, 373, 2053,

Pattiaratchi C.B. and Wijeratne E.M.S. (2014). Observations of meteorological tsunamis along the south-west Australian coast. Natural Hazards, 74, 281–303.

Pattiaratchi C.B. and Wijeratne E.M.S. (2009). Tide gauge observations of the 2004–2007 Indian Ocean tsunamis from Sri Lanka and Western Australia. Pure and Applied Geophysics, 166, 233–258.

Stein S. and Okal E.A. (2005). Seismology: Speed and size of the Sumatra earthquake.Nature, 434, 581-582.

Synolakis C.E. and Bernard E.N. (2006). Tsunami science before and after Boxing Day 2004, Phil. Trans. R. Soc. A 364(1845), 2231–2265.

Titov V., Rabinovich A.B., Mofjeld H.O., Thomson R.E., Gonzalez F.I. (2005). The global reach of the 26 December 2004 Sumatra tsunami. Science, 309, 2045–2048.

Titov V.V., Moore C.W., Greenslade D.J.M., Pattiaratchi C.B., Badal R., Synolakis C.E. and Kânoğlu U. (2011). A new tool for inundation mapping: Community Modeling Interface for Tsunamis (ComMIT). Pure and Applied Geophysics, 168, 2121–2131.

Voit S.S. (1987). "Tsunamis". Annual Review of Fluid Mechanics. 19, 217–236.

Wijeratne E.M.S. and Pattiaratchi, C.B. (2024). Numerical simulation of tsunamis observed in Sri Lanka by remote volcanic eruptions, *this issue*.

Wijetunge J.J. (2012). Nearshore tsunami amplitudes off Sri Lanka due to probable worst-case seismic scenarios in the Indian Ocean, Coastal Engineering, 64, 47-56

The Upstream-Interface-Downstream of the Tsunami Early Warning System: Sri Lanka Perspective

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ABSTRACT

The 2004 Indian Ocean Tsunami affected 14 countries and led to the deaths of more than 230,000 people. since then, several countries have come together to establish an effective tsunami warning system in the Indian Ocean region. An end-to-end tsunami early warning and mitigation system was accordingly established in 2008, and this became fully operational, covering all the affected countries in 2013.

A tsunami early warning system should be end-to-end in nature and should include several aspects of detection, warning, response and evaluation. Between detection and warning, there occurs the interface where the decision to warning is taken and an order for evacuation is given. The interface mechanism is a complex and dynamic process involving many stakeholders who operate at different levels. The decision-making involves technical knowledge as well as managerial and social skills to deal with emergencies 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. Although there are clear guidelines available at the national level, this complexity makes it difficult to operationalise the process and assess its effectiveness. Within this context, the purpose of this chapter is to deliver a detailed picture and an analysis of the functioning 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 its operation and identifies the stakeholders who must work together in a coordinated way and have a good understanding of each other's roles, responsibilities, authorities, and action during a tsunami event.

Key words: Tsunami, Early warning, Sri Lanka

1. END-TO-END TSUNAMI EARLY WARNING SYSTEM AND ITS COMPONENTS

In the face of worsening climate impacts and an increasing number of disasters, most countries in the world are preparing to mitigate and manage risks using early warning systems. An end-to-end tsunami early warning and mitigation system (TEWMS) is a risk reduction mechanism used in regions and countries prone to tsunami disasters. TEWMS are essentially end-to-end as it involve aspects of mitigation, preparedness, response and recovery. After the detection of tsunami by the warning centre, the regional tsunami service provider communicates the warning to the national tsunami warning centre (NTWC) in each country. An effective end-to-end tsunami warning system begins with the upstream rapid detection of a tsunami wave, including detection, verification, threat evaluation, and forecasting. It ends with a well-prepared community that is capable of responding appropriately to a warning, including delivery of public safety messages, risk assessment and management, initiating counter-measures, and standardised reactions.

An end-to-end tsunami warning (Figure 1) involves several stakeholders who must work together in a coordinated way and have

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Figure 1. End-to end tsunami warning system

a good understanding of each other's roles, responsibilities, authorities, and actions during a tsunami event. Planning and practising in advance of the real event helps to familiarise agencies and their staff with the steps and decision-making that need to be carried out without hesitation in a real emergency. Tsunami resilience is built upon communities' awareness and response preparedness regarding the tsunami hazard (Disaster Management Centre, 2020). As effective TEWMS includes the following four components:

- Knowledge of the hazards and risks to coastal communities from tsunami inundation, and planning for them;
- Access to information from the Intergovernmental Coordination Group (ICG) Tsunami Service Providers (TSP) and/or NTWCs of the earthquake, tsunami assessment and prediction, and tsunami detection, and the capability of an NTWC to evaluate the information received in order to determine the threat to their communities;
- Ability to quickly disseminate and communicate clear, understandable, and actionable warnings to prepared coastal communities in advance of the oncoming tsunami; and
- Capacities at national, local and community levels for effective tsunami emergency response.

A typical end-to-end tsunami warning system begins with the upstream rapid detection of a tsunami wave, including detection, verification, threat evaluation, and forecasting. It ends with a well-prepared community that is capable of responding appropriately to a warning, including delivery of public safety messages, risk assessment and management, initiating national counter-measures, and preparing and implementing standardised reactions (Rahayu et al. 2019; Haigh et al., 2022). An end-to-end tsunami early warning and mitigation system (TEWMS) includes three main stages: upstream, downstream and the interface.

- **UPSTREAM:** The upstream includes detection of the wave by the tsunami service providers, verification, threat evaluation and forecasting. The threat evaluation and forecasting are transmitted to the National Tsunami Warning Centre (NTWC) for further evaluation and local impact within the country (Haigh et al., 2020; Haigh et al., 2029);

- **INTERFACE:** Interface is where the warning is received by the national focal point and processed, and the evacuation decision is taken before disseminating it to the public. This involves the three principal actions of issuing the warning, conveying the warning and ordering for evacuation. Typically, the downstream process starts at the national level and ends before the community and before the evacuation orders are disseminated (Sakalasuriya, et al., 2022; Sakalasuriya, et al., 2021 , Rahayu, et al., 2019);
- **DOWNSTREAM:** After the warning is disseminated and the decision to evacuate people is confirmed by the authorities, the downstream mechanism takes place including delivery of public safety messages, initiation of national counter-measures and preparation and implementation of standardised operation (Hemachandra et al., 2021; Dias et al., 2021)

Figure 2 illustrates the components of a typical end-to-end tsunami warning system (Haigh et al., 2020).

2. INDIAN OCEAN TSUNAMI EARLY WARNING SYSTEM

Prior to the catastrophic earthquake and tsunami of 26 December 2004, there was no ocean-wide tsunami warning system for countries with Indian Ocean coasts. The enormous loss of life caused by that tsunami triggered a rapid response from the global community, with planning commencing immediately for an Indian Ocean Tsunami Warning and Mitigation System (IOTWMS), to be built using a framework similar to that already established for the Pacific Ocean by UNESCO's Intergovernmental Oceanographic Commission (IOC). As a result, a tsunami early warning and mitigation system was introduced in the Indian Ocean region for the first time and the system became fully operational with the IOTWMS Tsunami Service Providers (TSPs) of Australia, India and Indonesia became fully integrated in 2013 (UNESCO, 2017). These TSPs now provide real-time tsunami threat information to the 28 countries bordering the Indian Ocean (UNESCO/IOC, 2019a).

2.1. Principal Stakeholders of the Indian Ocean Tsunami Early Warning System

IOTWMS involves many stakeholders who must be able to work in coordination and with a good understanding of each other's roles, responsibilities, authorities and actions during a tsunami event. For an end-to-end TWS, the principal stakeholders involved are:

- Tsunami Service Provider(s) (TSP);
- National Tsunami Warning Centres (NTWCs);
- Emergency Management Agencies (EMAs) such as National/Local Disaster Management Offices (NDMO/LDMO), Local Authorities, and Emergency Services/other stakeholders; and
- Public/ Community

2.1.1. Tsunami Service Provider (TSP)

The IOTWMS is a "system-of-systems" with operational robustness achieved through multiple TSPs, each of which has implemented an Indian Ocean tsunami threat assessment system providing real-time information to the NTWCs

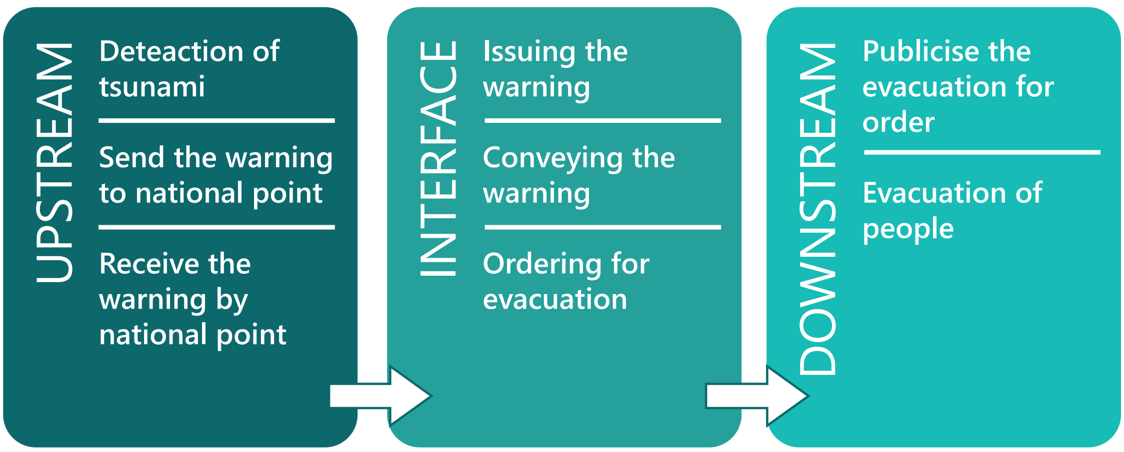

Figure 2. Components of a typical end-to-end tsunami warning system

of Indian Ocean countries during tsunami events. The following are the three TSPs which are part of the IOTWMS (UNESCO/IOC, 2019b) :

- Joint Australian Tsunami Warning Centre (JATWC) operated by Geoscience Australia (GA) and the Bureau of Meteorology (BoM)
- Indian Tsunami Early Warning Centre (ITEWC) operated by the Indian National Centre for Ocean Information Services (INCOIS)
- Indonesian Tsunami Early Warning System (InaTEWS) operated by the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG)

Each TSP provides threat information covering the entire Area of Service of the IOTWMS. The ICG/IOTWMS has specified that there must be at least two TSPs covering all parts of the Indian Ocean, to ensure redundancy and robust operations during tsunami events. This "system-of-systems" approach requires all seismic, sea level, and tsunami threat information provided by TSPs to be interoperable, i.e. TSPs are to use common and agreed formats for data and information exchange, are to meet agreed TSP Service Definition requirements, and are to share information on procedures and processes.

2.1.2. National Tsunami Service Provider

The National Tsunami Warning Centre (NTWC) is officially designated by the government with the purpose of monitoring and issuing earthquake information, tsunami threat and other related information within the country. It provides information for national emergency officials and may also provide information directly to the NDMO. Decisions made by the NTWC are assisted by the information from TSPs. The NTWC operates continuously on 24 hours a day/7 day a week basis to receive earthquake and tsunami information from the TSPs. This information is evaluated by the NTWC to decide whether there is a significant tsunami threat. NTWCs may use sea-level networks which stream data in real, or near-real time, to independently verify the generation of a tsunami and evaluate its severity. To achieve its objectives, NTWCs must have trained and experienced staff, adequate monitoring equipment, analysis tools, reliable communication systems and sustainable resources. Depending on the needs of the country and its resources, the NTWC may primarily rely on outside information sources such as TSPs. It may also conduct its own seismic and sea level analyses, and tsunami forecasting when it is necessary. Alternatively, a country may have sufficient resources to establish its own NTWC with the capability to monitor and detect earthquakes and tsunamis, forecast tsunami propagation, make threat assessments and issue warnings to relevant authorities and communities (UNESCO/IOC. 2019c). The core responsibilities of the NTWC are:

- To receive, directly the earthquake and tsunami information from the TSP(s) of its choice, and optionally, to monitor seismicity and tsunamis in real time as an independent agency
- To analyse all information received and assess the tsunami threat for the country
- To issue timely tsunami warnings or cancellations

2.1.3. National/Local Disaster Management Offices (NDMO/LDMO), Local Authorities

The National Disaster Management Offices (NDMOs) should play a key role in taking efficient and immediate actions to ensure public safety before, during, and after the event. NDMOs should understand the nature of tsunami disasters and act as translators of the scientific concept of tsunamis to the general public in an understandable manner by taking a lead role in efforts to increase community awareness. The NDMO should work in collaboration with the NTWC to receive the end-to-end delivery of a tsunami warning during an actual emergency. The NDMO must immediately interpret the science-based warnings issued by the NTWC, decide on the appropriate response action, and quickly disseminate warnings or other safety information to the stakeholders/Public on what to do. NDMO is also responsible for informing the public when it is safe for them to return to the evacuated coastlines due to structural damage, debris, and other life safety concerns after a tsunami. The "All Clear" to return may not be issued by the local authority for hours or even days after the event, depending on the situation (DMC, 2020).

2.1.4. Public/Community

An effective tsunami warning system is achieved when all people, especially those in coastal communities, respond appropriately to an official warning or upon recognition that a potentially destructive tsunami may be approaching. Raising public awareness of the tsunami hazard must, therefore be planned for, and mechanisms established for the promotion and monitoring of awareness on a community-led and community-owned, sustainable basis. The end receiver of warnings is the general public, and they are the recipients of any official and unofficial warnings. The public must understand how they will be warned on: how to react and respond; and where to go (evacuation zones, routes & Safe zones). To minimise confusion, they must be educated to understand Official warnings (how will they be warned); Natural warnings (what to look out for); Where and what to do; Evacuation zones; Routes and safe zones; and how to respond if evacuation zones are not defined.

3. SRI LANKA NATIONAL TSUNAMI EARLY WARNING SYSTEM

There is a variety of guidelines and frameworks to follow to implement the TEWMS in a country. However, due to the large number of actors and complex procedures entailed within the TEWMS, each country has its own mechanisms for managing a tsunami situation. Once the regional tsunami service provider (TSP) sends the warning alert to a country, it is up to each country's national warning centres to process the warning information and alert the public. There are various technical, legal and socio-cultural complexities involved in communicating the rapid detection of a tsunami wave to jurisdictional agencies and response partners in affected countries, focusing on upstream detection of the earthquake and tsunami threat to the downstream response, including potential evacuation of the exposed communities. It is often not clear how the decisions are made and the warning and evacuation orders are disseminated at the country level. It was therefore needed to investigate and analyse how the decision-making process and the warning dissemination are carried out in countries so that clear guidelines can be provided for an effective warning system within the countries. There are two significant phases of TEWMS that occur at the country level: firstly, the interface where the regional warning is evaluated and the decision to evacuate is taken; and secondly, the downstream where the order for evacuation is disseminated to the public and people are evacuated to safer places.

3.1. Methodology

Sri Lanka, benefitting from the Indian Ocean TEWMS was used as the case in order to analyse how upstream-interface-downstream the downstream phases of the end-to-end TEWMS operate in the Sri Lankan context. Two studies on the Sri Lankan end-to-end tsunami early warning system were undertaken. These focused on separate aspects of the early warning chain:

- The Interface arrangements, from receipt of the regional bulletins provided by tsunami services providers in Australia, India and Indonesia, to the decision-making at the national/sub-national level and issue of warning was studied as part of the project: "A study of the upstream-downstream interface in end-to-end tsunami early warning and mitigation systems, University of Huddersfield, UK; and
- The Downstream arrangements that disseminate the warning to the communities at risk were studied as part of: "Tsunami Early Warning Interface: Governance of the upstream-downstream interface in end-to-end Tsunami Early Warning Systems" and "Localising Tsunami Early Warning" University of Huddersfield, UK

A detailed literature review of the state of the art in tsunami early warning and a further detailed document review was carried out, including the National Emergency Operational Plan (NEOP), Disaster Management Act, information published by INCOIS, IOC-UNESCO guidelines to develop the criteria against which Sri Lanka's National Tsunami Early Warning System can be assessed was developed. There was also a review of reports and lessons learnt from previous tsunami exercises conducted including Exercise Indian Ocean Wave 2018: An Indian Ocean-wide Tsunami Warning and Communications (Haigh et al, 2018), and table-top exercises (e.g. Jayaweera et al, 2019).

Expert interviews were conducted with key personnel in relevant Ministries and Institutions, and who are directly involved in early warning activities before during, and after a tsunami. Participating Agencies included: Chamber of Commerce, Sri Lanka; Coast Conservation Department; Department of Fisheries; Department of Meteorology; Disaster Management Centre (DMC); Geological Survey and Mines Bureau; Government Information Department (Media); Marine Environmental Protection Agency; Ministry of Civil Aviation; Ministry of Defence - Disaster Management Division; Ministry of Education; Ministry of Fisheries and Aquatic Resources Development New Secretariat; Ministry of Foreign Affairs; Ministry of Highways; Ministry of Health; Ministry of Power and Energy; Ministry of Public Administration; Ministry of Transport; National Aquatic Resources and Development Agency (NARA); National Disaster Relief Service Centre; National Institute of Oceanography Marine Services National Aquatic Resources; Research and Development Agency; National Water Supply and Drainage Board; Office of the Chief of Defence (OCDS), Sri Lanka Army, Navy, Airforce, Police, Coast Guard; Sri Lanka Railway; Sri Lanka Tourism Development Authority; Sri Lanka Ports authority; Suwasariya (Ambulance); University of Moratuwa, Colombo, Peradeniya; NGOs/INGOs/CBO/Other Humanitarian Agencies; Centre for Development Research & Interventions; Association of Disaster Risk Management Professionals, Sri Lanka; Federation of Sri Lankan Local Government Authorities. External Organisations that were consulted included: the Intergovernmental Oceanographic Commission (IOC) of UNESCO, Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System (ICG/IOTWMS); ICG/IOTWMS Working Group 1: Tsunami Risk, Community Awareness and Preparedness & Institute of Technology, Bandung; Asian Disaster Preparedness Centre, Thailand; Indian Ocean Tsunami Warning and Mitigation System Secretariat; United Nations Office for Disaster Risk Reduction.

The two studies were designed and planned, and the results were analysed and reported, by an international group of experts drawn from Sri Lanka, Thailand, Indonesia and the United Kingdom (Sakalasuriya et al, 2018). Based on the findings, a more detailed analytical framework that depicts Sri Lanka's National Tsunami Early Warning System was arrived at.

4. SRI LANKA END-TO-END TSUNAMI EARLY WARNING AND MITIGATION SYSTEM (TEWMS) STAGES AND ASSOCIATED ORGANISATIONS

4.1. Upstream

As already detailed above, IOC-UNESCO has the mandate to develop and implement the establishment of the Tsunami Warning and Mitigation System in the Indian Ocean (IOTWMS). The IOTWMS involves international and multilateral cooperation with strong governance provided by IOC. It is a System that is a fully inter-operable network of tsunami service providers (TSPs) and national tsunami warning centres (NTWCs). It is fully owned by the countries, protects all countries, and has free and open data exchange. The TSPs only advise (Threat/No Threat). Warnings are the sovereign responsibility of NTWCs. In Sri Lanka, the Department of Meteorology is officially designated by the Government of Sri Lanka to monitor and issue tsunami warnings as the National Tsunami Warning Centre (NTWC), which functions twenty-four-seven (24/7). TSPs are directly linked with the Department of Meteorology as the National Tsunami Warning Centre. The websites of those TSPs (INCOIS, BMKG and BOM) are password-protected, and only DoM can receive information from TPSs. Emails, faxes and telephone numbers of authorised officials at DoM are registered with those centres, and messages are received during an earthquake via SMS, email and fax (DMC, 2020).

4.2. Interface

The Interface arrangement is defined from receipt of the regional bulletins provided by tsunami services providers (TSP) in Australia, India and Indonesia, to the decision-making at the national level and issue of warning. Tsunami Service Providers for the IOTWMS, based in India, Indonesia and Australia, have the most sophisticated technical information available to issue warnings. However, national legal frameworks within member states do not enable them to issue evacuation warnings directly.

The interface between upstream and downstream activities is vital, as it involves a wide array of jurisdictional agencies and response partners, information providers at the regional and national levels, tsunami national contact points and warning centres, and a range of sub-national emergency operational centres and related actors. The tsunami early warning interface is a complex process that encompass not only technical aspects but also political, social and cultural factors that vary according to the country's situation. The human involvement is high in decision-making and dissemination, and it is also influenced by the administrative structures, demography of the country and geographical properties. Therefore, the interface mechanisms tend to vary significantly across countries. It is the responsibility of each country, which has varying legal frameworks and technical capacities to forecast potential impacts and socio-cultural approaches. For example, the ability to create accurate, real-time tsunami warning information through tsunami energy estimates, flooding maps, and tsunami-induced currents, varies across member states but can be critical in determining potential local impacts (Sakalasuriya et al, 2018); Haigh et al, 2020).

4.2.1. Relevant Agencies

The decision-making at the Interface level is appropriately institutionalised at the national level in Sri Lanka. The Department of Meteorology (DoM) acts as the NTWC to receive Bulletins and other information generated by TSPs during tsunami events as guidance. NTWC uses the information from the TSP to assist its decision-making and to determine the possibility of a tsunami and its local impact. NTWC may consult the country's Tsunami technical evaluation committee and/or the relevant ministry responsible for Disaster Management (currently, it is the Ministry of Defence). The NTWC operates continuously on 24 hours a day /7 days a week basis to receive earthquake and tsunami information from the TSPs. NTWCs may use sea-level networks that stream data in real or near real-time, to independently verify the generation of a tsunami and evaluate its severity. DoM is officially identified as NTWC by Sri Lanka to monitor and issue tsunami warnings and other related statements. It provides the information to national emergency officials and may also provide it directly to other agencies, the media, and the public.

After analysing all information received and assessing the tsunami threat for Sri Lanka, NTWC issues timely tsunami warnings or cancellations (as bulletin information) to Sri Lanka's NDMO in accordance with its National Tsunami Warning and Emergency Response Plan. In Sri Lanka, the NDMO is the Disaster Management Centre (DMC). DMC takes necessary actions which include issuing warnings and evacuation orders to the public while informing all the relevant institutions at the national and local levels. The Emergency Operation Centre (EOC) at NDMO is working on a twenty-four-seven (24/7) basis. The Head (Director General) of the NDMO (DMC Sri Lanka) has the authority to issue tsunami warnings and evacuation orders to the public and stakeholders. The Director of the EOC and Duty Officer at DMC are authorised, with their approval, to issue evacuation orders on behalf of the Director General of DMC. Figure 3 below summarises the Interface of Sri Lanka's End-to-End Tsunami Early Warning and Mitigation System.

4.3 Downstream

Drawing from the above figure and previous research downstream of TEWMS is defined in this study as the process of decision-making and information dissemination starting after NDMC, going through provincial, district, municipal and village level actors to the public to take the necessary evacuation and precautionary actions. The downstream process begins after the decision to evacuate the public is taken, and in Sri Lanka, this is recognised as part of a tsunami warning that takes place below the district level, and communicating the warning message to other relevant stakeholder organisations by the DMC.

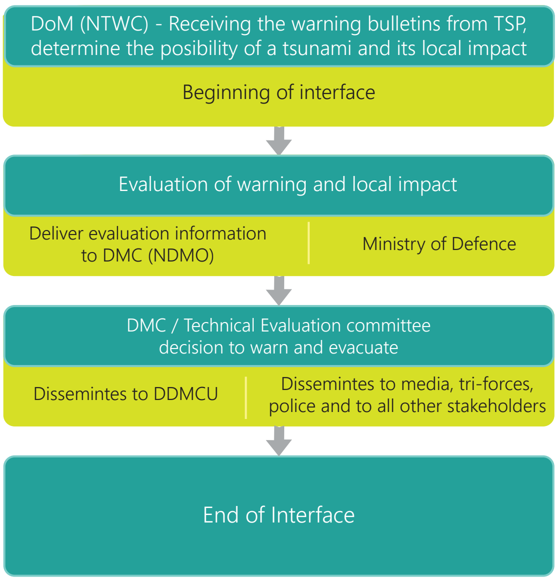

Figure 3. Summary of the interface

Decision-making from district DMCs to the lower levels is streamlined using multiple channels, and the information is passed both laterally, across different administrative domains, and vertically, from higher levels to lower levels right down to the community. Figure 4 explains the specific area dealt with in the downstream context, as well as the corresponding actors. Figure 5 illustrates the Early warning coordination framework from the national GM level in Sri Lanka.

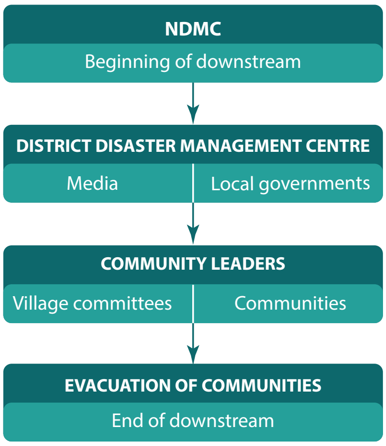

Figure 4. Downstream of end-to-end TEWMS in Sri Lanka

5. TSUNAMI EARLY WARNING SYSTEM IMPLEMENTATION

Overall, the Sri Lanka Tsunami warning system at the national, sub-national and local levels is outlined in Figure 6. Downstream dissemination of tsunami early warning is not merely a technical process, but a socio-technical process that interconnects communities, institutions and technology (Dias et al, 2024). In Sri Lanka, several local-level institutions are involved in the local dissemination process, including local governing bodies, armed forces, and national and local NGOs, and they all have the potential to play a significant role in disseminating tsunami early warnings to the local level. There are also various communication pathways and communication channels being used to disseminate early warnings to the local level, in Sri Lanka. Whilst it is not one of the objectives of this chapter to elaborate any prevailing gaps in

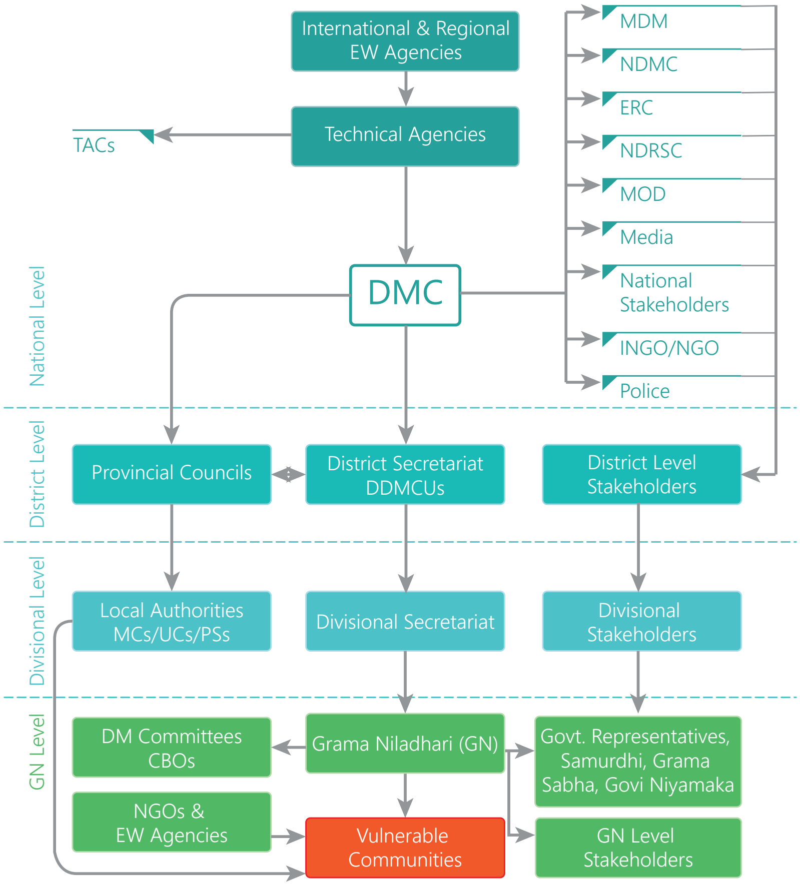

Figure 5. Early warning coordination framework from the national GM level in Sri Lank

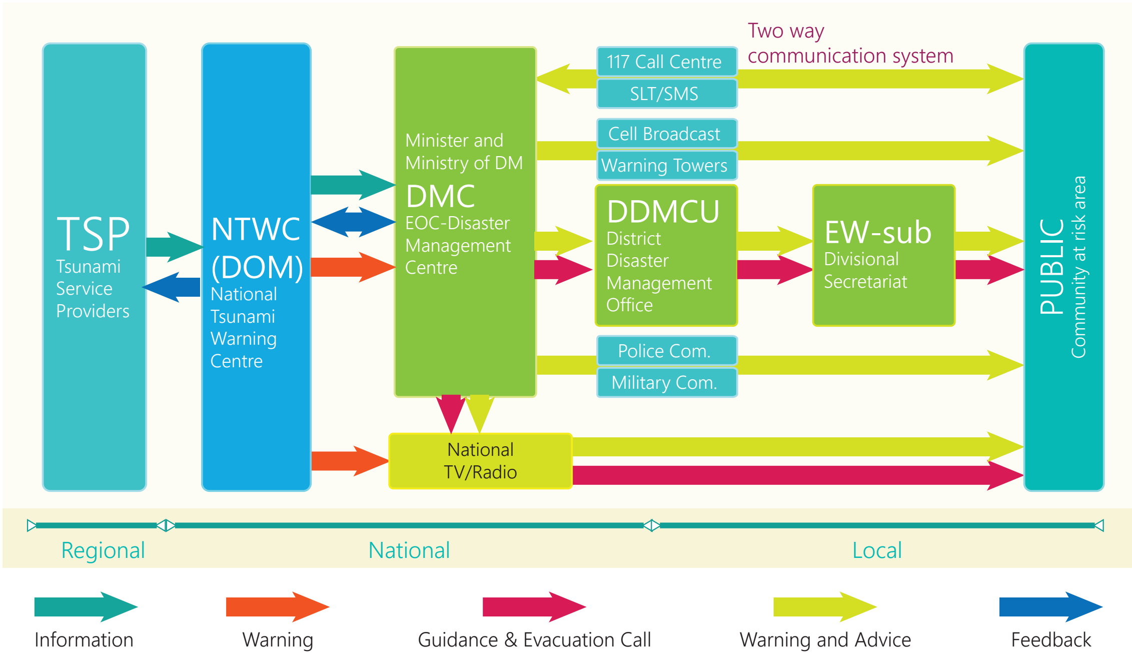

Figure 6. Tsunami early warning system implementation pathway

the downstream operationalisation of the end-to-end tsunami warning and mitigation system in Sri Lanka, Haigh et al (2020); Dias et al (2024); Sakalasuriya et al (2021); Haigh & Amaratunga (2018); Amaratunga et al (2020), highlight several of them, including a lack of synergy between the standard operating procedures (SOPs), inadequate technical and human resources, weak linkages to village level disaster management committees, a lack of sectoral integration in some instances, and public complacency towards drills.

6. TSUNAMI EARLY WARNING GOVERNANCE

The findings of this study further suggest that the complex relationships within the governance structure, the decision-making mechanism, institutional arrangements and political influence, can have a profound influence on the community responses in a TEWS. The interface is an important stage within the early warning process, as the rapidity and accuracy of decision-making and information dissemination determine the safety of the communities (Sakalasuriya, 2020). The TEWS is established within the existing Sri Lanka country governance structure for tsunami early warning, operating under the legal and administrative frameworks provided in the governance system (Dias et al., 2019).

Several parties are involved in this process, including community and citizens' groups, local governments, the private/corporate sector, national government, civil society organisations, professional groups and the media. There should be adequate coordination among the interested parties to overcome problems and face any challenges. Levels are equal in the administrative structure of Sri Lanka where decisions are translated from national government to local communities. Starting from the NCDM to community voluntary groups, there is a clear stratification at the national, provincial, district, divisional and village levels. Under each level, separate authorities and committees are responsible for engaging in the disaster management process. Within these structures, coordination of early warning initiatives, from national to local settings, is a complex task which requires serious efforts by a variety of stakeholders (Amaratunga et al, 2020). Figure 7 shows the links between national and local level structures through a top-down approach, and Amaratunga et al. (2020) analyse in detail, Sri Lanka's governance structure in detail, in particular, linking with the country's disaster management initiatives.

For an Early Warning System, Standard Operating Procedure (SOP) helps to ensure preparedness before a warning is issued and to facilitate an effective response during a hazard

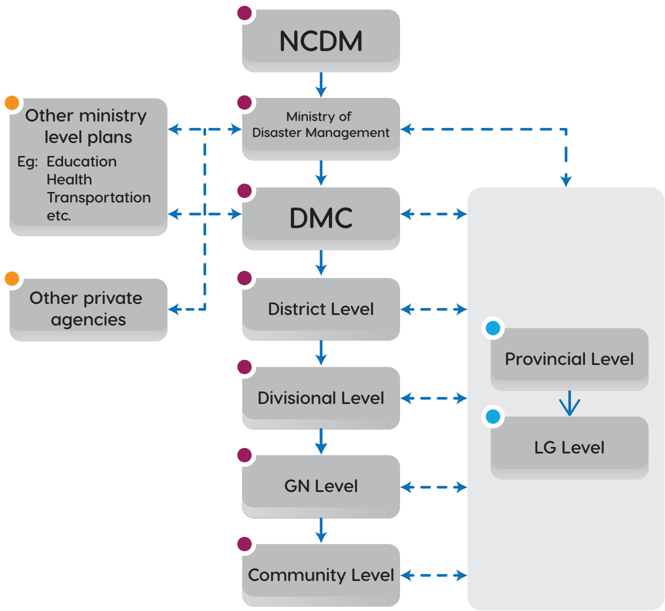

Figure 7. Disaster Management Structures at Different Levels

or potential disaster situation. For tsunami, it provides a description and procedure on agreed steps by institutions used in coordinating who, what, when, where and how for tsunami early warning and response. Based on the findings of this study, Sri Lanka DMC led the preparation of the synergised national SoP for Tsunami early warning for Sri Lanka, and related SOPs within Sri Lanka for generating and disseminating tsunami warnings to their relevant emergency response agencies have also been significantly updated and tested (Haigh, et al 2019). These SoPs are presented in DMC (2020), and were prepared as a result of this exercise, by consulting each institute responsible for tsunami activities and approved by a higher authority such as the National Disaster Management Council (NDMC) in Sri Lanka, to ensure the legal validity of the SOPs. This revised SOP was tested in IOWave 2018 and 2020 exercises (Haigh & Amaratunga, 2018; Amaratunga et al., 2020), which was used to simulate Indian Ocean countries being put in a tsunami warning situation, and subsequently, the synergised SoP was validated and adopted.

7. CONCLUSIONS AND RECOMMENDATIONS

Upstream-interface-downstream of the Sri Lanka tsunami early warning system will assist Sri Lankan institutions participating in the IOC-coordinated regional Tsunami Warning and Mitigation System. It strengthens the Sri Lankan tsunami warning and emergency response by providing detailed input towards SoPs for tsunami early warning. It also promotes alignment, interoperability and consistency among all Sri Lankan actors that have responsibilities in the end-to-end tsunami warning system.

Although this development of Sri Lanka tsunami early warning system is an important milestone in helping to protect the communities from the threat of tsunami, it is important that it remains a ‘live’ process, continuously updated to reflect regional protocols and following the results of evaluations and exercises. To ensure long-term sustainability, there should be regular exercises among the stakeholders, especially between NTWC and NDMO, to test communication, procedures, coordination, mobilisation and resource allocation, especially focusing on downstream activities. Planning and practising in advance of the real event will help to familiarise agencies and their staff with these steps and decision-making that need to be carried out without hesitation in a real emergency. Tsunami resilience is also built upon communities’ awareness and response preparedness regarding the tsunami hazard.

There also needs to be regular updates to protocols to reflect the latest updates from IOTWMS. SOPs should be considered as live documents, they need to remain up-to-date to be useful. Therefore, whenever procedures are changed (e.g., based on new guidelines issued by IOTWMS), SOPs should be updated and re-approved. If desired, only the pertinent section of an SOP can be modified, and the change recorded with a change date/revision number in the document control notation. SOPs should also be systematically reviewed on a periodic basis, e.g. every 1-2 years, to ensure that the policies and procedures remain up to date and appropriate.

8. REFERENCES

Amaratunga, D., High, R. Premalal, S. & Siriwardana, C. (2020). Observer Report on Exercise Indian Ocean Wave 2020: An Indian Ocean-wide Tsunami Warning and Communications Exercise, 13th October 2020 in Sri Lanka

Amaratunga, D., Malalgoda, C., Haigh, R., & De Silva, A. (2020) How do we Organise for DRR and Resilience? A Study on Disaster Reduction and Management Governance Profile of Sri Lanka, University of Huddersfield, UK, ISBN: 978-1-86218-171-7

Dias, N., Haigh, R., Amaratunga, D., & Rahayu, H. (2024). A review of tsunami early warning at the local level - Key actors, dissemination pathways, and remaining challenges. *International Journal of Disaster Risk Reduction*, *101*, [104195]. https://doi.org/10.1016/j.ijdrr.2023.104195

Dias, N., Haigh, R., Amaratunga, D., Sakalasuriya, M.M. (2021). A Cross Case Analysis of the Upstream–Downstream Interface in the Tsunami Early Warning Systems of Indonesia, Maldives, Myanmar and Sri Lanka. In: Amaratunga, D., Haigh, R., Dias, N. (eds) Multi-Hazard Early Warning and Disaster Risks. Springer, Cham. https://doi.org/10.1007/978-3-030-73003-1_51

Dias, N., Amaratunga, D., Haigh, R., Premalal, S. & Basnayake, S. (2019). Societal Impact of the Research Study on Governance of Upstream-Downstream Interface of Tsunami Early Warning – The Case of Sri Lanka. 2019 From Innovation to Impact (FITI),. 1-6.

Disaster Management Centre (2020), Standard Operating Procedures for Sri Lanka's Tsunami Early Warning System: Ministry of Defence, Government of Sri Lanka

Haigh, R., Amaratunga, D., Dias, N., Rahayu, H, (2022) A Systematic and Narrative Review of Local Dissemination in the Downstream of Tsunami Early Warning, University of Huddersfield & Institute of Technology Bandung, ISBN: 978-1-86218-210-3

Haigh, R., Sakalasuriya, M., Amaratunga, D., Basnayake, S., Hettige, S., Premalal, S. & Jayasinghe Arachchi, A (2020). The upstream-downstream interface of Sri Lanka's tsunami early warning system. International Journal of Disaster Resilience in the Built Environment, 11, 219-240.

Haigh, R., Amaratunga, D, Sakalsooriya, M., Premalal, S., Thillekeratne, H., Basnayake, S., Hettig,e S., Weerasena, N. & Rahayu, H. (2019), Briefing Paper on Developing a more integrated cross agency Standard operating Procedures (SoP) for Tsunami early warning in Sri Lanka

Haigh, R. & Amaratunga, D. (2018). Observer Report on Exercise Indian Ocean Wave 2018: An Indian Ocean-wide Tsunami Warning and Communications Exercise, 5th September 2018 in Sri Lanka

Hemachandra, K., Amaratunga, D., Haigh, R., Sakalasuriya, M.M. (2021). The Downstream Mechanism of Coastal Multi-Hazard Early Warning Systems. In: Amaratunga, D., Haigh, R., Dias, N. (eds) Multi-Hazard Early Warning and Disaster Risks. Springer, Cham. https://doi.org/10.1007/978-3-030-73003-1_43

Perera, C., Jayasooriya, D., Jayasiri, G., Randil, C., Bandara, C., Siriwardana, C., Dissanayake, R., Hippola, S., Sylva, K., Kamalrathne, T. and Kulatunga, A. (2020), "Evaluation of gaps in early warning mechanisms and evacuation procedures for coastal communities in Sri Lanka", International Journal of Disaster Resilience in the Built Environment, Vol. 11 No. 3, pp. 415-433. https://doi.org/10.1108/IJDRBE-07-2019-0048

Rahayu, H., Haigh, R., Amaratunga, D. & Sakalasuriya, M. (2019). A briefing paper for the interface of Ina-TEWS: Improving the upstream-downstream interface in the Indonesian end to end tsunami early warning and mitigation system (Ina-TEWS)

Sakalasuriya, M.M., Rahayu, H., Haigh, R., Amaratunga, D., Wahdiny, I.I. (2022). Post-tsunami Indonesia: An Enquiry into the Success of Interface in Indonesian Tsunami Early Warning System. In: Mardiah, A.N., Olshansky, R.B., Bisri, M.B. (eds) Post-Disaster Governance in Southeast Asia. Disaster Risk Reduction. Springer, Singapore. https://doi.org/10.1007/978-981-16-7401-3_8

Sakalasuriya, M.M., Haigh, R., Amaratunga, D., Hettige, S., Weerasena, N. (2021). An Analysis of the Downstream Operationalisation of the End-To-End Tsunami Warning and Mitigation System in Sri Lanka. In: Amaratunga, D., Haigh, R., Dias, N. (eds) Multi-Hazard Early Warning and Disaster Risks. Springer, Cham. https://doi.org/10.1007/978-3-030-73003-1_45

Sakalasuriya, M., Haigh, R., Hettige, S., Amaratunga, D., Basnayake, S. & Rahayu, H. P. (2020) Governance, organisations, community and power within the interface of the tsunami early warning system: a comparison of Indonesia and Sri Lanka In : Politics and Governance. 8, 4, Open Access.

Sakalasuriya, M., Amaratunga, D., Haigh, R. & Hettige, S. (2018), A Study of The Upstream-downstream Interface in End-to-end Tsunami Early Warning and Mitigation Systems, International Journal on Advanced Science Engineering Information Technology, Vol.8, No. 6, ISSN: 2088-5334. Indexed in SCOPUS

UNESCO (2017), PLANS AND PROCEDURES FOR TSUNAMI WARNING AND EMERGENCY MANAGEMENT, Manuals and Guides 76, Intergovernmental Oceanographic Commission

UNESCO/IOC (2019a). IOTWMS User Guide for National Tsunami Warning Centres: Version 2.0. Paris, UNESCO. IOC Technical Series No 145.

UNESCO/IOC (2019b). IOTWMS TSP Service Definition Document: Version 4.0. Paris, UNESCO-IOC. Technical Series

UNESCO/IOC. 2019c). IOTWMS User Guide for National Tsunami Warning Centres: Version 2.0. Paris, UNESCO. IOC Technical Series No 145.

Seismic Activity Onshore and Offshore Sri Lanka and Potential Tsunamigenic Events

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ABSTRACT

Sri Lanka is traditionally considered to lie in an aseismic zone, far from major plate boundaries and active faults. However, over the last three decades, several hundred earthquakes and tremors have been reported both onshore and offshore. This study explores seismic activity in Sri Lanka and its surrounding regions, with a focus on potential tsunamigenic events.

Seismic activity in the shallow part of the Sumatra subduction zone, particularly near the trench and outer-rise region, was analyzed using earthquake locations and focal mechanism solutions. The focal mechanisms in the shallow seismic zone near the trench are likely due to the bending of the subducting plate.

Offshore seismic activity, especially in the eastern and southeastern parts of Sri Lanka, has been significant over the past forty years. Global earthquake data analysis reveals scattered events in the southeastern offshore area, with a concentration of earthquakes along a belt to the south of Sri Lanka. These events align with the convergence boundaries of the Indo-Australian plate. The focal mechanisms of these earthquakes suggest strike-slip faulting, with a rotation of fault planes toward the India-Capricorn pole. The likelihood of significant tsunamigenic events from this region remains low.

In recent years, micro-earthquakes with magnitudes below 3 on the Richter scale have been recorded in various parts of Sri Lanka. These tremors primarily occur in the central region near hydroelectric plants, dams, the Highland-Wijayan boundary, and the Monaragala and Ampara districts. The waveform cross-correlation technique was employed to investigate these tremors, revealing many of them to be reservoir-induced earthquakes. Seismic activity in other regions of Sri Lanka may be related to the activation of old faults, lineaments, or weak geological zones, possibly triggered by large strike-slip earthquakes in the Sumatra subduction zone and the Turkey-Syria region.

Historical records, such as the Rajawaliya and Mahawamsa, suggest a tsunami over 2,200 years ago, The recurrence interval for megathrust earthquakes can exceed 1,000 years, raising the possibility of another tsunamigenic event in the Northern Arabian Sea, affecting western offshore Sri Lanka.

Seismic gaps in the Sumatra subduction zone, where areas that ruptured in 1907, 1935, 1797, and 1833 have not yet re-ruptured, present a strong possibility of future earthquakes. These could occur as individual events or as one large event, similar to the 1994 earthquake. A large dip-slip earthquake in this region has the potential to generate a tsunami.

Key words: Seismic activity, Subduction zones, Megathrust earthquakes, Tsunami, Sri Lanka

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1. INTRODUCTION

Seismology provides a wealth of information about seismic sources, the Earth's structure, and the relationship between earthquakes and tectonic processes. Studying earthquakes is crucial for understanding plate tectonics and the internal structure of the Earth. When an earthquake or explosion occurs within the Earth, part of the energy released is transmitted as elastic waves, which can be detected by instruments called seismometers that record ground motion. The speed of these waves depends on the density and elasticity of the rock through which they travel. Over the years, seismic wave analysis has led to many key discoveries in Earth science.

One significant breakthrough came in 1935 when Kiyoo Wadati proved the existence of deep earthquakes and identified an inclined seismic zone in Japan, known as the Wadati-Benioff zone, which dips westward from the Pacific Ocean. This discovery was instrumental in advancing our understanding of plate tectonics and subduction processes. Since then, many seismologists have worked to improve our understanding of these processes through various investigations.

In the 1960s, the introduction of computers revolutionized seismology, enabling more complex data analyses, such as calculating earthquake locations in complex velocity structures. With these computational advancements, the quality and quantity of seismic data have significantly improved over the past six decades, deepening our understanding of Earth's interior.

1.1. Seismic Activity of the Sumatra Subduction Zone

Subduction zones are generally characterized by inclined seismic zones that can extend to depths of around 700 km beneath the Earth's surface. The Sumatra subduction zone, where the Indo-Australian Plate subducts beneath the Sunda Plate and Andaman microplate, has a convergence rate of approximately 55 mm per year, causing significant seismic activity along the plate boundary (DeMets et al., 2005). Sumatra, an island in western Indonesia, lies within the Sunda arc, a subduction zone that extends over 5,600 km from the Andaman Islands to the Banda Arc in the east. This area is one of the most tectonically active regions in the world.

There are two major tectonic features affecting Sumatra Island: subduction zones and transform fault zones. Subduction zones are areas where oceanic plates are being subducted under a continental plate or an island arc, whereas transform fault zones occur where two lithospheric plates slide past each other.

The Sumatra subduction zone is one of the most active plate boundaries in the world, having experienced several major earthquakes in the last two centuries. Notable events include the magnitude 8.8–9.2 earthquake in 1833, the magnitude 8.3–8.5 earthquake in 1861, the 2004 magnitude 9.0–9.3 earthquake, and a magnitude 8.7 event in 2005 (Figure 2). In recent years, from 2000 to 2020, five large earthquakes with magnitudes greater than 8.0 were recorded in the region, including the devastating Sumatra-Andaman earthquake of December 26, 2004. This earthquake, with a magnitude of 9.3, was one of the most powerful recorded in the last two centuries and caused a massive tsunami.

The geometry of faulting during earthquake fault slip is denoted by focal mechanism solutions. Spatial distribution of focal mechanisms will give us information about earthquake generating stresses in and around the focal area. Information on stress distribution in the study region would improve the understanding of seismotectonics in the region. The main purpose of this study is to analyze the seismic activity of the shallow part of Sumatra subduction zone near the trench and outer-rise region (Figure 1). For this purpose, the offshore earthquake locations and their focal mechanism solutions were analyzed.

Seismic activity of the shallow part of Sumatra subduction zone near the trench and outer-rise region was analyzed (Gamage, 2017) by using earthquake locations and their focal mechanism solutions (Figure 1). Analyzed results show that normal faulting events are recorded than the reverse faulting events in the outer-rise region. In the near trench of the region, reverse faulting events were observed more than the normal faulting events and more reverse faulting events were observed in the shallow part of the trench. Patterns of hypocenter distribution and focal mechanisms found in the study are almost the same as that found under the outer-rise/outer-trench slopes of subduction zones by previous investigators of other subduction zones (Gemage

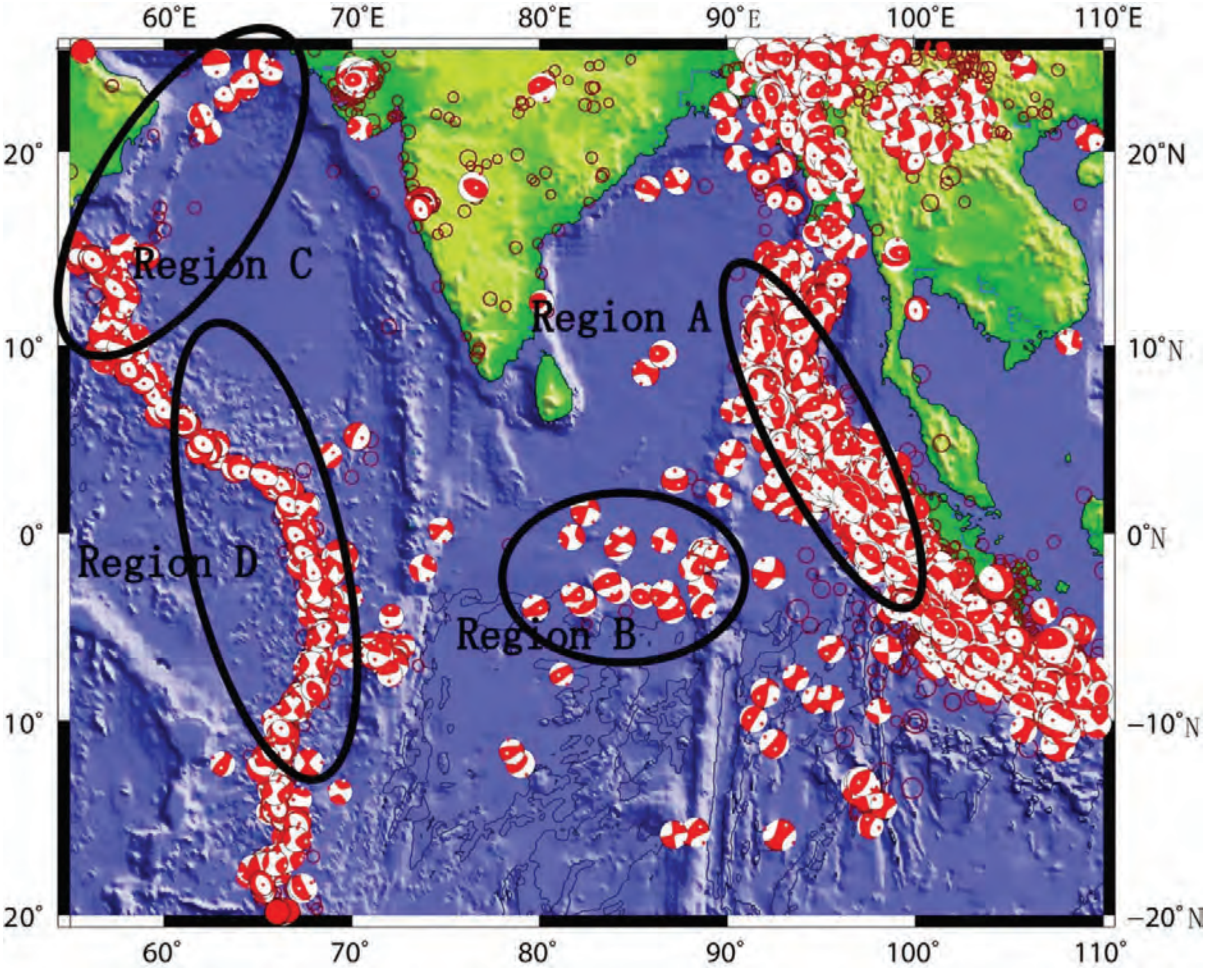

Figure 1. Distribution of focal mechanism solutions of the earthquakes (Magnitude > 3.0) that occurred from January 1976 to July 2012 in offshore of Sri Lanka. Harvard Centroid Moment Tensor (CMT) solutions are plotted at their epicenters. Beach-balls explain the geometry of faults. Specific region are named as Region A, Region B, Region C and Region D

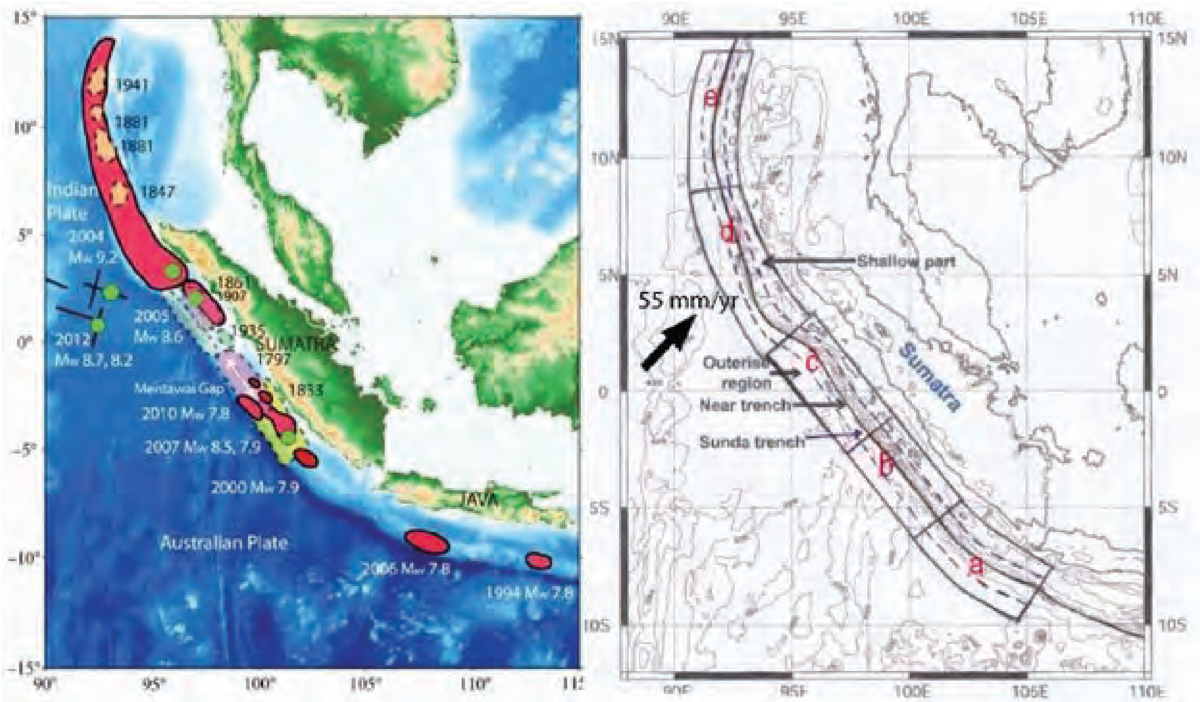

Figure 2. The map showing the study region. Left: Rupture areas of large earthquakes took place in the Sumatra subduction zone. Closed areas show the re-ruptured regions and dashed areas show the seismicity gaps. Right: Outer-rise, near trench and shallow part in the study region and sub-regions a, b, c, d and e

et al., 2008). The characteristics of these focal mechanisms for the shallow seismic zone near the trench region may be due to the bending of the subdcting plate near the trench.

1.2. Shallow Seismic Activity of Offshore Southeast of Sri Lanka

Sri Lanka is generally considered an aseismic zone, located away from major plate boundaries and active faults. However, over the past century, several hundred earthquakes and tremors have been reported in and around the island. Some of these events are documented in historical records, while more recent ones have been detected by global institutions like the United States Geological Survey (USGS) and the Japan Meteorological Agency (JMA). These seismic activities have been classified as shallow and intermediate-depth earthquakes, particularly in the offshore regions of Sri Lanka.

Despite this seismic activity, detailed investigations into the earthquakes occurring offshore of Sri Lanka have been limited. Therefore, this study focuses on analyzing the earthquake activity in the seismically active offshore region southeast of Sri Lanka. By examining tectonic settings, earthquake locations, and focal mechanism solutions, we aim to better understand the region's seismic behavior.

2. ANALYZING SEISMIC ACTIVITY OF THE SUMATRA SUBDUCTION ZONE

Hypocenter data obtained from the Data Management Center (DMC) at the Incorporated Research Institutions for Seismology (IRIS) were used for this study. All relevant data from January 1964 to April 2011 were included, covering a latitude range of 15°N to 12°S and a longitude range of 88°E to 110°E, with depths ranging from 0 to 700 km, across all magnitudes. Focal mechanism solutions for the same region were obtained from the Harvard CMT catalog for earthquakes of magnitude greater than 3.5 occurring between 1976 and 2011 (Figure 1).

The focal mechanism solutions of outer-rise, near-trench, and shallow parts near the Sunda and Andaman Trench regions were analyzed by dividing the region into five sub-regions, based on bathymetric depth variations (Figure 2). Two methods were used to analyze focal mechanisms, with the first being a graphical method. Topographic, bathymetric, and focal mechanism solutions data were combined, and maps were plotted for the study period, with individual maps created for each year. A map of all focal mechanism solutions is provided in Figure 1. The average focal mechanism solutions for all events were analyzed using fault plane solutions.

2.1. Results of Analyzing Seismic Activity in the Sumatra Subduction Zone

When analyzing the focal mechanism solutions prior to the Sumatra-Andaman earthquake of December 26, 2004, it was observed that all earthquakes occurring in the outer-rise region of Part a were normal faults. In the near-trench region, 81% of the earthquakes were reverse faults, while 19% were normal faults. The majority of earthquakes in the shallow part had fault geometries characterized by reverse faults, with a few being strike-slip faults. In Part b, normal and reverse faults were observed in equal proportions in the outer-rise region. All events in the near-trench region had reverse fault geometries, and the highest percentage of events in the shallow part were also reverse faults. No strike-slip faults were observed in Part b.

In Part c, no earthquakes were reported in the outer-rise region. The near-trench region had more reverse faults than normal faults. Comparing the normal faults in the near-trench and shallow parts, there were more normal faults in the near-trench region than in the shallow part. The highest percentage of events in the shallow part had reverse fault geometries. In Part d, the number of normal, reverse, and strike-slip faults was equal in the outer-rise region, while most earthquakes in the shallow part and near-trench region were reverse faults. In Part e, no events were reported in the outer-rise region, and all earthquakes in the near-trench were reverse faults. In the shallow part, 54.6% of earthquakes were reverse faults, with the remainder being normal faults.

Generally, many aftershocks are supposed to be occurring in the nearby regions after a major shock being taken place. These aftershocks can be appeared either in a few weeks or even in several years later (Gamage et al., 2009). Therefore, the analysis also considered data from before and after the 2004 Sumatra earthquake. The analysis revealed that normal faults were more prevalent than reverse faults in the outer-rise region. Fault geometries in the shallow part of the trench showed a predominance of normal faults over reverse faults (see Figures 3 & 4). However, in the near-trench region, reverse faults were more common than normal faults, which contradicts theoretical expectations. Before the December 26, 2004 earthquake, the percentage of normal faults in the near-trench region had increased compared to the period before the earthquake.

Pressure axes, Tensional axes, and Null axes of earthquake faults were plotted, and the distribution of focal mechanisms was analyzed using the method described by Gamage et al. (2009). The results are shown in Figure 5. Our analysis indicates that normal faults are more common than reverse faults in the outer-rise region. In the near-trench region, reverse faults were more frequently observed than normal faults, and a higher proportion of reverse faults were also observed in the shallow part of the trench.

The typical focal mechanisms for the near-trench and outer-rise regions are reverse fault types and normal fault types, respectively. To explain the distribution of focal mechanisms observed in this study, a plate bending model at the trench can be applied. The cold Indo-Australia Plate, having traveled a significant distance from the ridge, begins to subduct at the Andaman and Sunda trenches due to downward flexure. This bending may generate earthquake-stressing conditions in the plate near the trench.

This analysis utilized Harvard CMT catalog data, which records only high-magnitude earthquakes from 1976 to the present. The estimators involved may be subject to errors, so the results of this analysis may not be fully accurate.

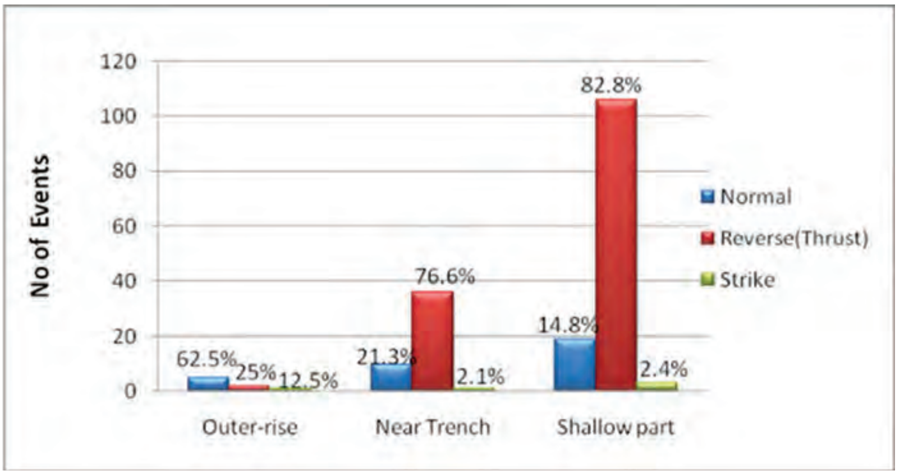

Figure 3. Distribution of number of events in faults with respect to the regions, outer-rise, near trench and shallow part for before the 26th December 2004 Sumatra earthquake. Colours are associated in such a way that, blue represents normal faults, red represents reverse(thrust) faults and green represents strike faults. Percentage values relevant to each region with contribution of faults are shown top of the each bar

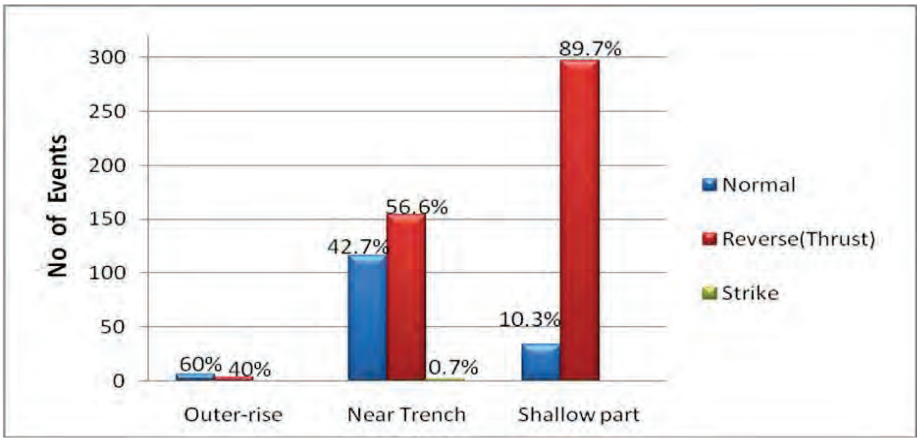

Figure 4. Distribution of number of events in faults with respect to the regions, outer-rise, near trench and shallow part for after the 26th December 2004 Sumatra earthquake. Colours are associated in such a way that, blue represents normal faults, red represents reverse(thrust) faults and green represents strike faults. Percentage values relevant to each region with the contribution of faults are shown top of the each bar

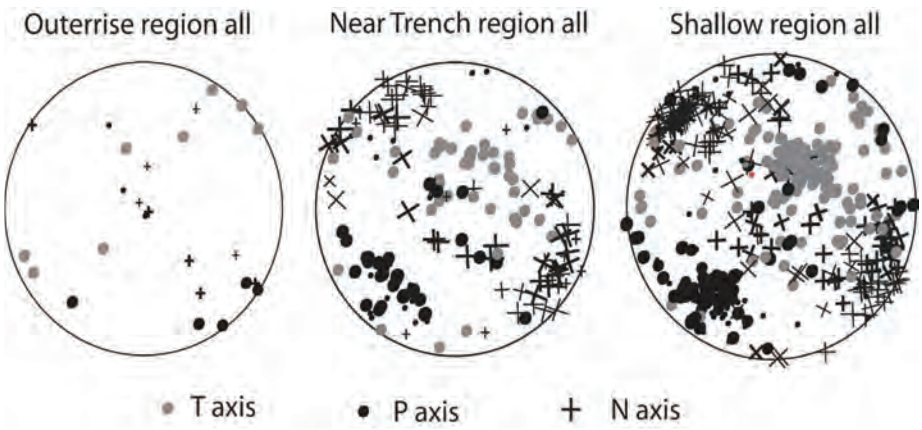

Figure 5. Distribution of the P, T and Null axes of focal mechanisms for events studied in the present study. Left, center and right figures are mechanisms related to outer rise, near trench and shallow earthquakes respectively. The location of each axis is projected on a lower focal hemisphere using an equal area projection. Black circles, grey circles and plus symbols denote P, T and Null axes, respectively

The data from various international networks have potential errors, including epicentral, focal depth, and magnitude errors. However, these errors were assumed to have negligible influence on this analysis.

Overall, normal faults were recorded more frequently than reverse faults in the outer-rise region, while reverse faults were predominant in the near-trench and shallow parts of the trench. Although the analysis focused on large events, the results are consistent with those from other subduction zones. The hypocenter distribution pattern and focal mechanisms identified in this study align with those found under the outer-rise/outer-trench slopes of subduction zones in previous studies (Stauder 1968; Chapple & Forsyth 1979; Gamage et al. 2009). The characteristics of focal mechanisms in the shallow seismic zone near the trench can be explained by the bending-unbending model of the subducting zone.

3. ANALYZING SEISMIC ACTIVITY OFFSHORE SOUTHEAST OF SRI LANKA

Seismological data can be accessed through a simple request from the Data Management Center (DMC) at the Incorporated Research Institutions for Seismology (IRIS). The IRIS DMC hosts events from multiple catalogs. For this study, we selected data from the NEIC catalog covering the period from January 1964 to January 2011.

The geometry of faulting during an earthquake is represented by focal mechanism solutions. Analyzing the spatial distribution of these focal mechanisms provides insights into the stress distribution that generates earthquakes in and around the focal area. Understanding this stress distribution helps enhance our knowledge of seismotectonics in the region.

Since there is no local station network in Sri Lanka to study fault plane solutions in detail, we rely on global data. Focal mechanism solutions were obtained from the Global Centroid Moment Tensor database, formerly known as the Harvard CMT catalog. We utilized focal mechanism solutions for earthquakes occurring from 1976 to January 2011.

3.1. Analyzing results of Seismic Activity of Offshore Southeast of Sri Lanka

We analyzed the shallow seismic activity of offshore of eastern and southern parts of Sri Lanka. The earthquake list distributed by the IRIS DMC made clear that there are sometimes multiple epicenter estimates for a single earthquake. We identified those errors and calculated them relative to the NEIC catalog epicenter. Since there are mis-locations of events, we tried to identify the magnitude of those errors. Then we analyzed the seismic activity region by region.

A significant number of offshore earthquakes have occurred near Sri Lanka during last 40 years. Earthquakes are mostly scattered in the Southeast offshore of Sri Lanka. Our finding of the analysis also shows that large number of earthquakes takes place at a belt lie in southern part of offshore Sri Lanka although some events are appeared to be scattered probably due to location errors mentioned above. These earthquakes seem to take place at the convergence boundaries at the Indo-Australia plate described by DeMets et al. (2005).

We also analyzed focal mechanisms of above earthquakes and observed that the earthquakes occurring in the offshore, about 1000 km away from southeastern coast of Sri Lanka, have equally-likely focal mechanism solutions which are similar to that of strike slip fault mechanisms. (see inside the circle B in Figure 1). In order to analyze focal mechanism solutions more closely, the region was divided in to three sub regions such as region K, region L and region M (Figure 6b). Pressure axes, Tensional axes and Null axes of earthquake faults were plotted and the distribution of the P, T, and Null axes of focal mechanisms (Figure 6a) were analyzed by the method described by Gamage et al. (2009). A rotation of fault planes towards the direction of India–Capricorn pole of rotation (Royer and Chang, 1991) can be seen from the results of present study. Therefore, it is clear that the earthquakes occurring in the identified belt in southeastern part of Sri Lanka may belong to the boundary of Indo-Australia plate. However, there is less possibility of occurring large events that may generate Tsunamis. This is because these earthquakes will not have a vertical displacement and thus not generating a tsunami.

4. SEISMIC ACTIVITY OF SRI LANKA

Sri Lanka is generally considered an aseismic zone, located away from major plate boundaries or active faults. However, over the last century, several hundred earthquakes and earth tremors have been reported in the country. Recent isolated earthquakes have occurred within Sri Lanka, but the reasons for these events are not fully understood. Most of the microseismic tremors

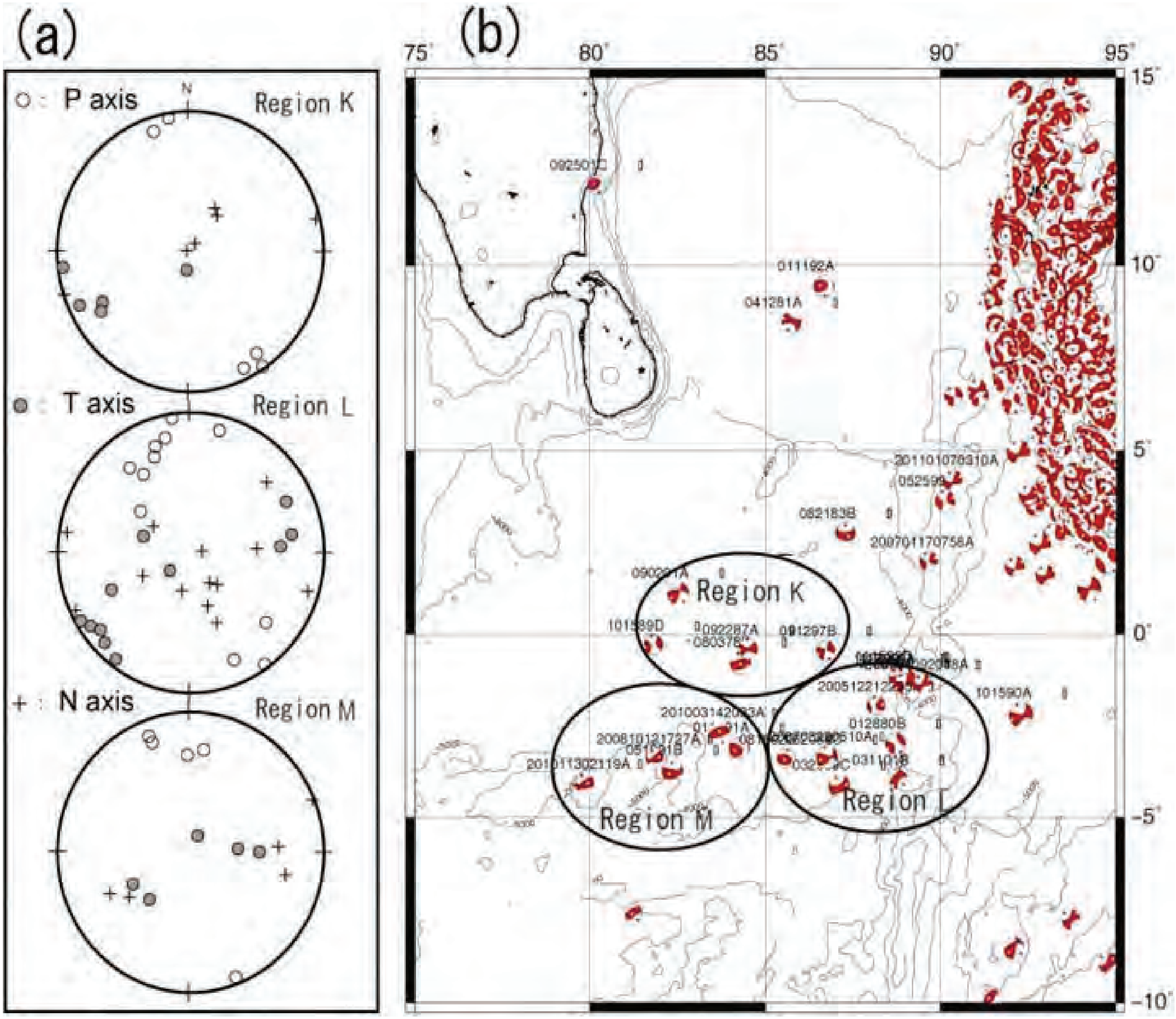

Figure 6. Distribution of the P, T, and Null axes of focal mechanisms for earthquakes that took place in the study region. (a). Region K, L and M represent the location of three study areas. Open circles, grey circles and plus symbols denote P, T. and Null axes, respectively. (b). Focal mechanism solutions of studied earthquakes are shown in region vice. Contour lines denote the iso-depth of the ocean floor. The date of the event is shown in each focal sphere

are either due to natural causes or are induced by human activities. A common example of an induced earthquake is a reservoir-triggered or induced earthquake, which occurs in conjunction with the impoundment of water or rapid water level changes behind large dams. Reactivation of lineaments can also trigger microseismic tremors. Many of these tremors are observed in the central part of Sri Lanka, particularly around Digana, Panwila, Walapane in the Kandy region, the Highland-Wijayan boundary, and the Wadinagala area in the Ampara district (Figure 7).

Most seismic activity has been concentrated in the central region, especially around Digana, Panwila, and Walapane in the Kandy region. This area is significant due to the presence of major power plants and dams. Recent tremors in Digana, Pallekele, Haragama, and Kandy were recorded on August 29, September 2, and November 18, 2020, with additional events noted in 2021. Studying microseismic activities, particularly those around Digana and Kandy, is valuable. These studies can help identify early signs of larger earthquakes and improve seismic risk assessments. Investigating the origins of these microearthquakes and their locations provides more reliable seismic risk statistics and helps minimize potential damage to existing hydroelectric power plants and dams.

4.1. Analyzing Seismic activity in Sri Lanka

To identify microearthquakes in the central region of Sri Lanka, we employed a statistical method known as waveform cross-correlation. This technique measures the similarity between two displacement time series as a function of time shift or time lag (Waldhauser et al., 2006). The cross-correlation method is highly sensitive, even in the presence of low background noise,

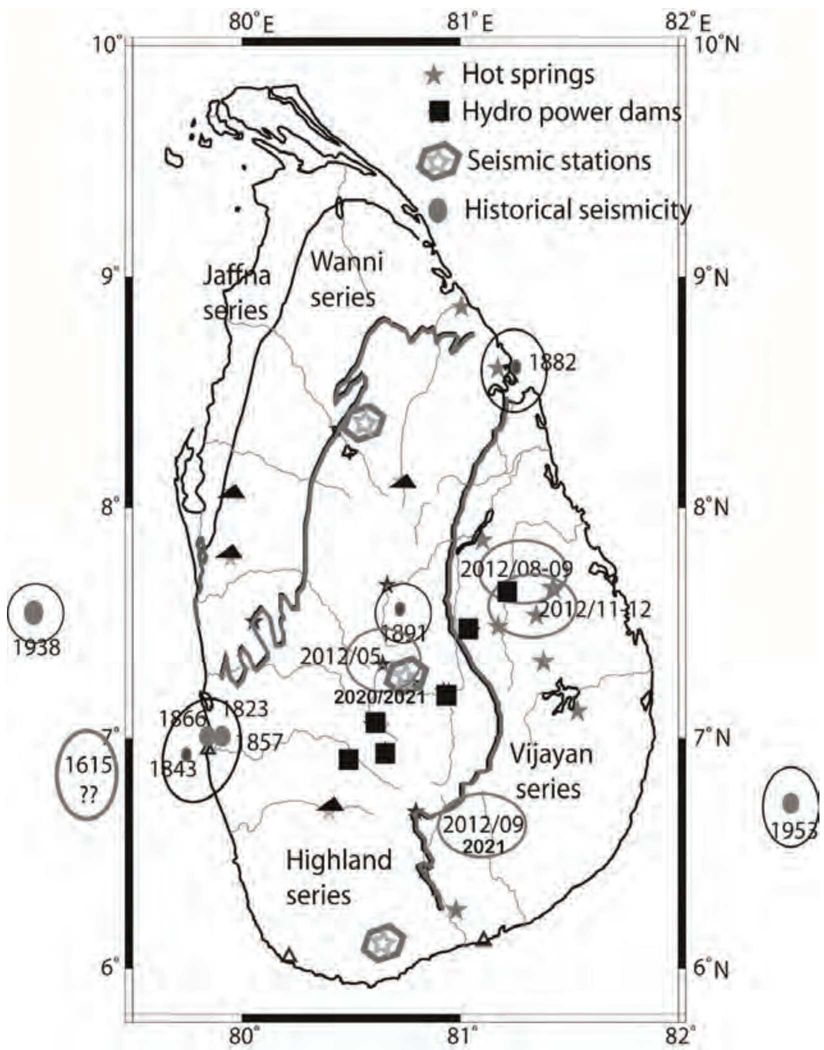

Figure 7. Specific geological places and regions of Sri Lanka. Stars represent hot springs, squares represent hydropower dams, open triangles represent harbors and closed triangles represent special geological features places. Seismically active regions and seismic stations are shown closed circles and polygons, respectively

as fluctuations do not significantly affect the peaks, which become attenuated. Identifying microearthquakes aids in understanding the structural behavior of the area, provides early warnings of larger earthquakes, and helps assess and mitigate seismic risks to critical infrastructure such as hydropower plants and dams (Kayal, 2008).

For this study, microseismic activities from January 2020 to June 2021 were analyzed. No significant microearthquakes were recorded in the central region after June 2021. The statistical analysis focused on ten events reported by civilians in the region. Tremors were considered independent of each other. Waveforms, which included background noise, were processed using a band-pass filter with a range of 2-9 Hz. The MALK and HALK stations have a maximum sample rate of 20 Hz, while the PALK station has a sample rate of 40 Hz. To avoid loss of information due to filtering, the Nyquist Theorem was applied. Different time windows were used for separate events.

Throughout the study, only P and P coda waves were used for correlation. For smaller events, P and S waves were selected due to their proximity in time. Using only P waves could introduce higher errors. Waveform cross-correlation (WCC) was conducted for each second over 24 hours, resulting in approximately 865,000 coefficients to identify higher values. To validate the events, cross-correlation (CC) was performed with data from other stations and channels. A time window with a slight time lag was used to correlate with other stations. Other than the PALK station, all other stations recorded lower coefficients, likely due to the decreased intensity of microseismic activities with increasing distance from the epicenter. Consequently, vertical components exhibited the highest coefficients compared to other stations.

4.2. Analyzing results and Seismic activity in Sri Lanka

In this study, we analyzed ten main seismic events, of which five new tremors were identified with coefficients (CC > 0.50) or higher. The study was conducted from January 2021 to June 2022. This timeframe suggests that additional unidentified microseismic events may have occurred in the past, and further seismic activity may yet arise. The increase in microseismic events in the central region may be attributed to the activation of old faults or the effects of large reservoirs. This technique is useful for analyzing Reservoir-Induced Seismicity (RIS) and identifying seismic swarms within the region. Reservoirs can exert substantial stress on the underlying rock due to the weight of the water column, potentially leading to seismic swarms or aftershocks. Given the very low magnitudes of these events, they may not be perceptible to residents in the area.

Recent earthquake activity has also increased in areas such as the Highland-Wijayan boundary and the Wadinagala area of the Ampara district. This increased activity could be due to the region's numerous faults, lineaments, and other geological weaknesses. Additionally, earthquakes occurring in the new plate zone offshore of eastern Sri Lanka may impact these faults and weak zones, potentially triggering tremors. Notably, four major earthquakes with magnitudes greater than 8 occurred in the Sumatra region between 2000 and 2014. These earthquakes include dip-slip events on December 26, 2004; March 28, 2005; and September 12, 2007, and a strike-slip event on April 11, 2012. Dip-slip events do not accumulate strain on plates, whereas strike-slip events create strain in the vicinity of the plate.

Pollitz et al. (2012) demonstrated that the rate of occurrence of remote M5.5 earthquakes within 500 km of the epicenter increased nearly fivefold for six days following the 2012 event, extending in magnitude up to M7.0. They suggest that the unprecedented delayed triggering power of the 2012 earthquake may have been due to its strike-slip source geometry or the fact that it occurred during a period of unusually low global earthquake activity, potentially increasing the number of nucleation sites that were close to failure. A statistical analysis of major earthquakes following the 2012 event shows a significant increase in seismic activity in the region after the April 11, 2012 earthquake (Gamage et al., 2018). However, no such increase was observed following other major events. This indicates that regional earthquake activity specifically increased after the 2012 M8.6 earthquake, likely due to the reactivation of old faults and weak zones triggered by the strike-slip event.

On February 6, 2023, an Mw 7.8 earthquake struck southern and central Turkey as well as northern and western Syria. The 2023 Kahramanmaraş Earthquake Sequence occurred along the East Anatolian Fault Zone, a left-lateral strike-slip fault that separates the Anatolian Plate from the northern part of the Arabian Plate, where Syria is located. Following this event, seismic activity in Sri Lanka, particularly in the eastern region, increased. This increase could also be explained by the reactivation of old faults and weak zones due to the 2023 strike-slip earthquake.

4.3. Challenges in Monitoring Regional Seismic Activity

Earthquake data represents a continuously growing repository of valuable earth science information, essential for post-processing and analysis. Earth scientists, geologists, and administrative officers utilize this data for both scientific research and planning purposes, making the collection of seismic data highly important. In recent decades, there have been a notable number of earthquakes and earth tremors reported in and around Sri Lanka. To effectively monitor these smaller events, a robust local seismic station network is necessary, in addition to the three (or four) global stations currently operational in Sri Lanka.

To address this need, seismic activity along the nearby Indo-Australian plate margin, as well as inland and offshore regions of Sri Lanka within the Indo-Australian plate, was analyzed. Based on these findings, particularly the distances to offshore events, several stations have been proposed for the eastern part of Sri Lanka. The installation of a broadband and short-period seismic station network would significantly enhance the ability to monitor offshore earthquake activity and inland tremors in Sri Lanka (Gamage and Premakumara, 2013).

4.4. Where Will the Next Regional Earthquake and Tsunami Occur?

For an earthquake to generate a tsunami, certain conditions must be met: the size, water depth, and type of movement must be suitable to create the large waves. The epicenter needs to be located beneath or near the ocean, and the fault must result in vertical displacement of the seafloor—several meters over a broad area. Additionally, the earthquake must have a large magnitude, and its focus should be shallow.

There are four seismically active offshore regions near Sri Lanka, as shown in Figure 1. Most of the regions within Area A have already ruptured. However, some seismic gaps remain in this area. As illustrated in Figure 2, the rupture zones of 1907, 1935, 1797, and 1833 have not re-ruptured yet. Therefore, there is a significant possibility of these areas rupturing either individually or as part of a larger event, similar to the one in 1994. If a large dip-slip earthquake occurs in this region, there is a high likelihood of generating a tsunami.

In contrast, there is no significant risk of a large tsunamigenic earthquake in Region B. However, if a major earthquake does occur there, while it may not generate a tsunami, the ground shaking could still affect Sri Lanka.

Ancient Sri Lankan chronicles, such as the *Rajawaliya* and the *Mahawamsa*, preserve accounts of ocean overflows occurring over 2,200 years ago during the reigns of King Kelanitissa in Maya Rata and King Kawantissa in Ruhunu Rata. The famous story of Viharamahadevi is linked to this tsunami event, which is referenced in historical works by Brohier (1935). If this event was indeed a tsunami, historical records suggest that the earthquake may have originated in Region C. Recent studies from other parts of the world show that the recurrence interval for megathrust earthquakes can sometimes exceed 1,000 years (Gamage et al., 2008). Thus, there is a potential for history to repeat, with a tsunamigenic megathrust earthquake occurring in the Makran Subduction Zone in the northern Arabian Sea, off the western coast of Sri Lanka.

Lastly, there is no high likelihood of large tsunamigenic earthquakes in Region D, although smaller seismic events may still occur there.

5. CONCLUSIONS AND RECOMMENDATIONS

The seismic activity of the shallow part of the Sumatra subduction zone near the trench and outer-rise regions was analyzed using earthquake locations and their focal mechanism solutions. The findings indicate that normal faults are more common in the outer-rise region, whereas reverse faults dominate the near-trench area, particularly in the shallow parts of the trench. While the focus was on large events, our results align with those observed in other subduction zones. The patterns of hypocenter distribution and focal mechanisms identified here are consistent with findings in outer-rise and outer-trench slopes of subduction zones, as reported by earlier researchers (Stauder, 1968; Chapple & Forsyth, 1979; Gamage et al., 2009). The focal mechanism characteristics in the shallow seismic zone near the trench may be explained by the bending-unbending model of subducting plates.

In addition, the seismic activity in the offshore region southeast of Sri Lanka was examined. The study reveals a notable concentration of earthquakes along a belt approximately 1,000 km southeast of Hambantota. While some events appeared scattered, likely due to location inaccuracies, the earthquake belt exhibits focal mechanism solutions characteristic of strike-slip faulting. Over 20 similar events were carefully analyzed, with the belt subdivided into multiple subregions. A rotation of fault planes in the direction of the India-Capricorn pole of rotation was observed, suggesting that these earthquakes may originate from the Indo-Australian plate boundary.

In the central region of Sri Lanka, the increase in microseismic events may be linked to the reactivation of old faults or the influence of large reservoirs. The cross-correlation technique employed in this study proved useful for analyzing Reservoir-Induced Seismicity (RIS) and identifying seismic swarms in the region. The stress exerted by these reservoirs on the underlying rock, due to the weight of the water column, could lead to seismic swarms or aftershocks, often with magnitudes too low to be felt by residents.

Earthquake activity in other regions of Sri Lanka may also be related to the reactivation of old faults, lineaments, and geological weak zones. These may have been triggered by large strike-slip earthquakes in distant regions such as the Sumatra subduction zone and the Turkey-Syria region.

Notably, seismic gaps exist in the Sumatra subduction zone, with areas that ruptured in 1907, 1935, 1797, and 1833 yet to re-rupture. There is a strong possibility that these areas could rupture individually or as one large event, similar to the 1994 earthquake. If a large dip-slip earthquake occurs in this region, it could generate a tsunami.

Additionally, there is a significant risk of a tsunamigenic megathrust earthquake in the Makran Subduction Zone, located in the Northern Arabian Sea, which could impact the offshore western part of Sri Lanka.

In conclusion, the following priorities are essential for advancing our understanding of regional seismic activity and improving preparedness:

1. **Scientific Goals:** Further research should focus on deepening our knowledge of mega-earthquake distributions across subduction zones and improving seismic methods for the early detection and warning of earthquakes and tsunamis.
2. **Operational Goals:** The installation and consistent maintenance of seismic networks are crucial for real-time alerts, as these networks are prone to rapid degradation.
3. **Societal Goals:** Education remains a vital component of disaster preparedness. Continuous efforts must be made to raise awareness about earthquake and tsunami risks, as education has proven to be a critical factor in saving lives during natural disasters.

6. REFERENCES

Brohier, R.V. (1935). *Ancient Irrigation Works in Ceylon*, Part III, p.1-2 & and Literary Register, Volume I, 1887, p. 62.

Chapple, W. M., & Forsyth, D. W. (1979). Earthquakes and bending of plates at trenches. *J. Geophys. Res.*, 84, 6729–6749.

De Mets, C., Gordon, R.G., & Royer, J.Y. (2005). Motion between the Indian, Capricorn and Somalian plates since 20 Ma: implications for the timing and magnitude of distributed lithospheric deformation in the equatorial Indian ocean, *Geophys. J. Int.*, 161, 445–468.

Gamage, S. N. (2011). Shallow seismic activity of offshore Southeast of Sri Lanka. 67th Annual session of the Sri Lanka Association for the Advancement of Science, 5-9th December, 2011, Colombo, Sri Lanka. 507 E.

Gamage, S. (2017) Seismic Activity near the Sunda and Andaman Trenches in the Sumatra Subduction Zone. *International Journal of Multidisciplinary studies*, 4 pp 49-54.

Gamage S. S. Dodangodage D, Ratnayake R. (2018), Regional Seismic Activity after 2012 M8. 6 Sumatra Earthquake. *Vidyodaya Journal of Science*, 21(1), pp 49-61.

Gamage, S. N., and H. J. Premakumara, (2013). Identification of suitable locations for seismic stations in Sri Lanka. 69th Annual session of the Sri Lanka Association for the Advancement of Science, 2-6th December, 2013, Colombo, Sri Lanka. 504 E.

Gamage, S. S. N, Umino, N., Hasegawa, A., & Kirby, S.H. (2009). Offshore double-planed shallow seismic zone in the NE Japan forearc region revealed by sP depth phases recorded by regional networks, *Geophys. J. Int.*, 178, 195-214.

Herath, P., Attanayake, J., & Gahalaut, K. (2022). A reservoir induced earthquake swarm in the Central Highlands of Sri Lanka. *Scientific Reports*, *12*(1), 18251.

Kayal, J. R. (2008). *Microearthquake seismology and seismotectonics of South Asia*. Springer Science & Business Media.

Pollitz, F. F., Stein, R. S., Sevilgen, V., & Bürgmann, R. (2012). The 11 April 2012 east Indian Ocean earthquake triggered large aftershocks worldwide. *Nature*, *490*(7419), 250-253.

Royer, J. Y., & Chang, T. (1991). Evidence for relative motions between the Indian and Australian plates during the last 20 my from plate tectonic reconstructions: Implications for the deformation of the Indo-Australian plate. *J. Geophys. Res.*, *96*, 11779-11802.

Stauder, W. (1968). Tensional character of earthquake foci beneath the Aleutian Trench with relation to sea-floor spreading. *J. Geophys. Res.*, *73*, 7693-7701.

Schaff, D. P., & Waldhauser, F. (2005). Waveform cross-correlation-based differential travel-time measurements at the Northern California Seismic Network. *Bulletin of the Seismological Society of America*, *95*(6), 2446-2461.

Influence of Mangrove Forests in Mitigating the Tsunami Risk in Coastal Areas of Sri Lanka

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ABSTRACT

Mangrove forests are essential elements of coastal ecosystems, offering critical defence against disasters like tsunamis. It is crucial to comprehend the precise contribution of mangroves in reducing tsunami risks in Sri Lanka, a country prone to coastal dangers. This study analyses the distinct role of mangrove forests in mitigating the detrimental impacts of tsunamis in Sri Lanka. The analysis reveals that mangrove ecosystems in Sri Lanka have unique physical and ecological characteristics that allow them to reduce the effects of tsunamis efficiently. Mangroves' ability to reduce wave energy and prevent coastal erosion makes them effective natural barriers against damaging tsunami waves. Additionally, the economic assessment of mangrove ecosystem services highlights their substantial impact on local economies. Community-based mangrove management projects enhance social resilience and empower coastal communities. However, deforestation, land-use disputes, and climate change threaten the viability of mangrove ecosystems in Sri Lanka. This study highlights the crucial importance of incorporating mangrove conservation into thorough coastal management systems. The organisation promotes collaboration across many disciplines, including stakeholders, and implementing sustainable management methods to protect mangrove ecosystems and enhance the long-term resilience of coastal communities against tsunamis and other coastal threats.

Key words: Mitigating tsunami risk, Mangrove forests, Coastal resilience, Tsunami risk reduction, Costal conservations

1. INTRODUCTION

Mangrove forests are crucial elements of coastal ecosystems, celebrated for their capacity to safeguard shorelines, sustain biodiversity, and offer a wide range of ecosystem services (Wells et al., 2006; Giri et al., 2011; Lee et al., 2014; Friess et al., 2020). The intertidal forests, consisting of trees and shrubs that can tolerate salt, are essential for reducing coastal erosion, improving water quality, and providing homes for a wide range of marine organisms (Duke et al., 2007; Gracia et al., 2018; Anu et al., 2024;). Mangroves have a broader importance beyond their ecological advantages. They function as natural defences against storm surges, cyclones, and tsunamis, effectively protecting coastal communities and infrastructure from significant harm (Kathiresan et al., 2005; Spalding et al., 2014; Asari et al., 2021; Temmerman et al., 2023;). The protective role of mangrove forests is crucial in regions that are susceptible to natural calamities, such as Sri Lanka (De Silva et al., 2023).

Sri Lanka, a country located on an island in the Indian Ocean, is at high risk of tsunamis and other dangers along its long coastline and low-lying land (Fernando et al., 2005; Wijetunge, 2014; Wijesundara et al., 2014; De Silva et al., 2023). The 2004 Indian Ocean tsunami had a significant impact on Sri Lanka's coastlines, causing unparalleled destruction. This event emphasised the urgent requirement for efficient natural defences. (Wijetunge, 2006; Illangasekare

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et al., 2009). This unfortunate incident emphasised the immediate need to comprehend and utilise the protective advantages of mangroves in order to reduce future hazards (Anu et al., 2024). Although the country has been acknowledged for its achievements, it continues to confront persistent dangers like as coastal erosion, climate change, and unsustainable land-use practices. These factors pose a risk to the well-being and ability to recover of its mangrove ecosystems (Feka et al., 2017; IUCN, 2020; Anu et al., 2024; Hernández-Delgado et al., 2024;).

The study seeks to clarify how mangroves, through their distinct physical and ecological features, reduce wave energy and protect coastlines from erosion, making them efficient natural barriers against tsunamis. In addition, the research aims to evaluate the economic worth of mangrove ecosystem services and their influence on local economies, while also assessing community-based management initiatives that improve social resilience. In conclusion, this study supports the inclusion of mangrove conservation in comprehensive coastal management policies in order to enhance the long-term resilience of Sri Lanka's coastal communities against tsunamis and other coastal hazards.

2. OBJECTIVE

The main objective of this study is to examine the detailed function of mangrove forests in mitigating tsunami hazards along the coastline of Sri Lanka.

3. METHODOLOGY

This systematic study involves a thorough gathering of reliable sources, such as peer-reviewed academic papers, conference proceedings, and technical reports, to investigate the contribution of mangrove forests in reducing the impact of tsunamis along the Sri Lankan coastline. The search criteria cover a substantial time period, ranging from 2000 to 2024. The research studies are obtained from reputable sources such as Google Scholar, ScienceDirect, and JSTOR. The keywords used in the search include "mangrove conservation," "tsunami mitigation," "coastal resilience," and "Sri Lanka." The selection criteria prioritised research that included empirical data, case studies, and theoretical ideas about the physical, ecological, and economic aspects of mangrove ecosystems. In addition, the review assessed community-based management strategies and transdisciplinary approaches to the conservation of mangroves. The process of data synthesis entailed analysing and contrasting the results from chosen studies in order to uncover recurring patterns, areas where knowledge is lacking, and optimal approaches.

4. CHARACTERISTICS OF MANGROVE FORESTS: PHYSICAL AND ECOLOGICAL

An estimate by Edirisinghe et al. (2010) indicates that mangrove distribution in Sri Lanka is approximately 15,670 hectares, with their distribution across the coastal districts illustrated in Figure 1. The mangrove forests of Sri Lanka consist of a wide variety of species, including Rhizophora, Avicennia, Bruguiera, and Sonneratia (Jayatissa et al., 2002; Alappatt, 2008; Arulnayagam et al., 2021; Wickramasinghe et al., 2022).

These species possess various adaptations that allow them to flourish in the intertidal areas of tropical and subtropical coastlines (Kathiresan et al., 2001; Nagelkerken et al., 2008). Rhizophora species, often known as red mangroves, are identified by their unique stilt roots, which serve to give structural support and increase the buildup of silt (Kathiresan et al., 2001; Nagelkerken et al., 2008; Boizard et al., 2011; Chaudhuri et al., 2019).

Figure 1. The mangrove distribution in Sri Lanka (Edirisinghe et al. (2010))

Avicennia species, sometimes known as black mangroves, have pneumatophores, which are specialised aerial roots that aid in gas exchange in low-oxygen sediments (Tomlinson, 1986; Primavera et al., 2004; Nelson et al., 2022).

The morphology of mangroves is essential for attenuating wave energy (Vo-Luong et al., 2008; Sánchez-Núñez et al., 2019; Amma et al., 2020). The intricate root systems of species such as Rhizophora form dense barriers that impede and decelerate incoming waves, diminishing their height and energy before reaching the coast (Massel et al., 1999; Spalding et al., 2014). The presence of mangroves plays a crucial role in reducing the impact of waves on coastal communities, especially during severe weather events like tsunamis and cyclones. This wave attenuation effect has been extensively studied by Mazda et al. (2006), Marois et al. (2015), Amma et al. (2020), and Chang et al. (2021). In addition, the complex root systems of plants capture sediments, contributing to the construction and stabilisation of coastlines. This process effectively prevents erosion and maintains the shape and structure of coastal landforms (Alongi et al., 2008; Marois et al., 2015; Amma et al., 2020; Chang et al., 2021). Mangrove areas provide vital habitats for a wide variety of fish, crabs, and molluscs, many of which have significant commercial value and depend on these areas for breeding and as nursery grounds (Nagelkerken et al., 2008). The decaying organic matter from mangrove leaves and wood plays a crucial role as a nutrient source for coastal food chains (Chen et al., 2017). In addition, mangroves contribute to carbon sequestration by absorbing substantial quantities of carbon dioxide from the atmosphere and retaining it in their biomass and sediment. This process helps to alleviate the effects of climate change (Donato et al., 2011; Soper et al., 2019; Nyanga, 2020; Zhu et al., 2022).

5. ROLE OF MANGROVES IN ALLEVIATING TSUNAMI IMPACT

Mangrove forests are essential in minimising the effects of tsunamis by employing various methods that decrease the energy of the waves (Alongi, 2008; Chen et al., 2024). The intricate root systems of mangroves, namely species such as Rhizophora with their long stilt roots and Avicennia with pneumatophores, form physical obstacles that impede and decelerate the flow of water (Mazda et al., 2006; De Deurwaerder, 2012; Hogarth, 2015; Kumari, et al., 2021). The roots of plants disperse the energy of incoming waves, diminishing their height and speed before reaching the coast (Quartel et al., 2007; McIvor et al., 2012).

The presence of mangrove tree canopies aids in reducing the force of waves by creating a rougher surface and facilitating the accumulation of sediment. This, in turn, improves the stability and ability of coastal areas to withstand disturbances. (Danielsen et al., 2005; Koh et al., 2018; Chang et al., 2021; Temmerman et al., 2023). Historical evidence from Sri Lanka and other South Asian countries emphasises the vital importance of mangroves in reducing the effects of tsunamis (Iftekhar, 2008; Ostling et al., 2009; Unnikrishnan et al., 2012; Jayatissa et al., 2016). The 2004 Indian Ocean tsunami caused less damage to coastal areas in Sri Lanka that had dense mangrove forests, particularly in the Eastern and Southern provinces, compared to regions without these natural barriers (Cochard et al., 2008; Kaplan et al., 2009; Venkatachalam, 2010; Jayatissa et al., 2016). In some locations such as Pottuvil and the Rekawa Lagoon, mangroves served as natural barriers, mitigating the destructive impact of the waves and leading to a lower number of victims and less damage to infrastructure (Dahdouh-Guebas et al., 2005; Appanah et al., 2005; MENRSL., 2005; Jayatissa et al., 2016).

Consistent patterns were noted throughout South Asia. According to a study conducted in Tamil Nadu, India, villages that had mangrove belts as a kind of protection experienced much lower casualties and less damage to property compared to nearby places without similar protection (Kathiresan & Rajendran, 2005). Mangroves in Phang Nga province in Thailand and Aceh province in Indonesia provided significant protection to coastal communities during the tsunami. In Phang Nga, the mangroves acted as a shield, minimising the impact of the waves. Similarly, in Aceh, the presence of mangroves reduced the extent of damage caused by the tsunami. These instances highlight the efficacy of mangroves as a natural means of protection throughout the area, emphasising the necessity of preserving and restoring them.

Yanagisawa et al. (2010) developed a model to assess the effectiveness of mangrove forests in reducing tsunami damage in Banda Aceh, Indonesia, utilising field data and numerical simulations. The research indicated that mangroves effectively diminished tsunami wave energy through the creation of physical drag and force dissipation, as evidenced by the data summarised in Table 1. The Wave period of the incident wave is 40 min. Values with more than 70% of the destruction rate are shown in bold.

6. THE ECONOMIC IMPLICATIONS OF THE SERVICES PROVIDED BY MANGROVE ECOSYSTEMS

Mangrove forests provide ecological services that bring economic benefits to local communities, including coastal defense, support for fishing activities, and potential for tourism. They play a crucial role in protecting against natural disasters like tsunamis, and reducing infrastructure and property damage costs. Mangroves also contribute to local economies by supporting fisheries and tourists, as their intricate root systems serve as breeding and nursery habitats for commercially significant fish and shellfish species. Mangrove-associated fisheries contribute an economic value of $750 to $16,750 per hectare per year to local economies. The unique biodiversity and picturesque allure of mangrove forests attract tourists, bolstering the eco-tourism sector. Maintaining mangrove ecosystems is cost-effective compared to repairing damage caused by tsunamis and other coastal disasters. Investing in mangrove conservation reduces potential losses and ensures a steady stream of economic benefits through sustained environmental services. The summary of the economic and ecological contributions of mangrove forests is shown in Table 2.

7. ENHANCING SOCIAL RESILIENCE THROUGH COMMUNITY-BASED MANGROVE MANAGEMENT

Community-based initiatives focused on the management of mangrove ecosystems have shown notable achievements in safeguarding and reviving these habitats, while also improving social resilience. An exemplary instance is the Sri Lankan Community Forestry Programme, which has engaged local communities in the rehabilitation and sustainable governance of mangrove forests. This effort has enabled communities to gain power and control by providing education and sharing resources. As a result, damaged mangrove habitats have been successfully restored and sustainable ways of making a living have been established (Samarakoon et al., 2012; Datta et al., 2012). The Mangrove Action Project (MAP) in Thailand is a highly effective initiative that prioritises community-led restoration and conservation endeavours. The organisation MAP has successfully supported the planting of a large number of mangrove seedlings, establishing nurseries and promoting the responsible utilisation of mangrove resources. This has resulted in improved ecological and economic stability in coastal regions, as documented by MAP in 2014, Lhosupasirirat et al. in 2023, and Blanton et al. in 2024.

Local people have a crucial role in safeguarding and reviving mangroves through their involvement in conservation efforts, monitoring the well-being of the environment, and adopting sustainable methods for harvesting. By engaging residents in these processes, projects guarantee that conservation efforts are culturally pertinent and economically advantageous, promoting a

Table 1. Reduction Rate of Hydrodynamic Force by the Assumed Mangrove Forest

Forest Age	**Width (m)**	**Tsunami Inundation Depth (m)**							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
10 Years	100	0.40	0.42	0.35	0.12	0.05	0.04	0.04	0.03
	300	0.60	0.60	0.58	0.30	0.11	0.08	0.07	0.07
	500	0.76	0.71	0.69	0.45	0.12	0.09	0.08	0.07
20 Years	100	0.33	0.34	0.33	0.26	0.13	0.07	0.04	0.03
	300	0.52	0.51	0.52	0.48	0.30	0.15	0.09	0.07
	500	0.69	0.63	0.62	0.59	0.42	0.18	0.10	0.09
30 Years	100	0.30	0.28	0.26	0.23	0.19	0.13	0.07	0.05
	300	0.48	0.46	0.45	0.43	0.37	0.28	0.17	0.10
	500	0.65	0.58	0.56	0.54	0.48	0.37	0.23	0.13

Table 2. The economic and ecological contributions of mangrove forests

Category	Details	Economic Value	References
Coastal Defence	Mitigation of natural disasters such as tsunamis is essential for minimising infrastructure and property damage expenses.	\$3,200 to \$5,400 per hectare per year	Barbier et al., 2011; Beever III et al., 2013; Zeng et al., 2021
Fisheries Support	Breeding and nursery environments for commercially important fish and shellfish species, enhancing fishing production.	\$750 to \$16,750 per hectare per year	Rönnbäck, 1999; Clavelle et al., 2013; Bhukta et al., 2022
Tourism and Eco-Tourism	Activities such as bird observation, paddling, and educational trips contribute to local economic development.	Revenue generation and employment creation	Rönnbäck et al., 2007; Uddin et al., 2013; Getzner et al., 2020
Restoration Costs	The expense of rehabilitating mangrove forests is contingent upon the degree of degradation and the methodologies employed.	\$225 to \$216,000 per hectare	Lewis, 2001; Gilman et al., 2007; Barbier et al., 2017; Zhang et al., 2023
Tsunami Damage Costs	Economic consequences of tsunami-induced destruction to infrastructure and real estate.	Amounts reaching billions of dollars (e.g., \$10 billion for the 2004 Indian Ocean tsunami)	UNEP, 2005; Cochard et al., 2011; Friess et al., 2016; Karanja et al., 2018
Cost-Benefit Analysis	Evaluating the cost-effectiveness of mangrove conservation/restoration in relation to tsunami damage repair.	Economically advantageous relative to post-disaster remediation costs	Karanja et al., 2018; Cochard et al., 2011; Friess et al., 2016

feeling of ownership and accountability towards the environment (Primavera, 2000; Aheto et al., 2016; Romañach et al., 2018; Arifanti et al., 2023; Akram et al., 2024). In the Philippines, community members have established Mangrove Management Committees to supervise local conservation initiatives, enforce regulations, and raise awareness about the significance of mangroves (Walters, 2004; Datta et al., 2012; Daupan et al., 2016). The active participation of local communities is essential for the sustained effectiveness of mangrove conservation efforts.

Community-based mangrove management has significant social and educational advantages, which contribute to the improvement of coastal resilience. Educational initiatives aim to increase knowledge and understanding of the ecological and economic significance of mangroves, encouraging the adoption of sustainable practices and fostering environmental responsibility across different age groups (Datta et al., 2012; Haque et al., 2016; Gevaña et al., 2011; Kongkeaw et al., 2019). These initiatives frequently incorporate instruction in mangrove planting, upkeep, and surveillance, which provide community members with the expertise needed to independently maintain conservation efforts. From a social perspective, these projects enhance community cohesion and offer economic prospects through eco-tourism, sustainable fishing practices, and the utilisation of mangrove-based products. Enhanced social cohesion and economic diversification contribute to the ability of communities to tolerate and recover from environmental and economic shocks, hence enhancing overall resilience (Ellison, 2000).

8. CHALLENGES FACING MANGROVE ECOSYSTEMS

Mangrove ecosystems encounter multiple hazards that endanger their existence and the essential functions they offer. Deforestation, caused by coastal development, aquaculture, and agricultural growth, is a major hazard (Ahmed et al., 2016; Richards et al., 2016; Ahmed et al., 2019). Mangroves in numerous areas are removed to accommodate shrimp farms, urban infrastructure, and tourism amenities, resulting in substantial depletion of these crucial ecosystems. During the period from 1980 to 2005, the global mangrove forest cover decreased by almost 20%. Southeast Asia witnessed the most significant deforestation rates during this time, as reported by Valiela et al. (2001), Richards et al. (2016), and Thomas et al.

(2017). Mangrove deforestation in Sri Lanka has been especially significant in regions experiencing fast urbanisation and industrialisation, which has worsened land-use conflicts and environmental deterioration (Kumara et al., 2010).

Climate change presents extra risks to mangrove ecosystems due to rising sea levels and an increase in the frequency of storms (Michener et al., 1997; Ghorai et al., 2015). Elevated sea levels have the potential to flood mangrove environments, leading to changes in the levels of saltiness and the submersion of root systems. This, in turn, impairs the ability of mangrove trees to develop and survive. In addition, the more frequent and severe storms can result in physical harm to mangrove forests, including the uprooting of trees and erosion of soil (Ghorai et al., 2015; Lovelock et al., 2016; Srikanth et al., 2016). The climatic changes have a dual influence on mangroves. They not only alter the structural integrity of mangroves but also have an impact on the biodiversity they support. This leads to changes in the composition of species and the functions of the ecosystem (Alongi, 2008). The effects of climate change in Sri Lanka are already apparent, as evidenced by the erosion of coastlines and the loss of habitats, which pose a danger to the resilience of mangrove ecosystems (Edirisinghe, 2014; Dananjaya, 2017; Khaniya et al., 2021).

9. CONCLUSION

This study has emphasised the crucial significance of mangrove forests in reducing the impact of tsunamis and bolstering the ability of coastal populations in Sri Lanka to recover and adapt. The key findings highlight that the distinctive physical and ecological attributes of mangroves, such as their capacity to disperse wave energy and mitigate coastal erosion, render them very efficient natural defences against tsunamis and other coastal dangers. Mangroves offer substantial economic advantages by offering vital services that bolster local fisheries, tourism, and coastal protection. Moreover, community-based management initiatives have demonstrated efficacy in fostering the preservation of mangroves, bolstering societal adaptability, and guaranteeing the long-term viability of these crucial ecosystems.

Policymakers, stakeholders, and researchers must prioritise mangrove conservation in coastal management policies by taking immediate action. Policymakers must implement more stringent laws for coastal development and provide assistance to projects that encourage sustainable land use and the restoration of habitats. It is important for stakeholders, such as local communities and companies, to actively engage in conservation initiatives, acknowledging the lasting advantages of safeguarding mangrove ecosystems. Researchers are encouraged to persist in investigating the various complex functions of mangroves, supplying the data and understanding necessary to guide efficient conservation policies and practices. Through collaboration, we can guarantee the ongoing protection and sustenance of coastal populations for future generations by preserving mangrove forests.

10. REFERENCES

Aheto, D. W., Kankam, S., Okyere, I., Mensah, E., Osman, A., Jonah, F. E., & Mensah, J. C. (2016). Community-based mangrove forest management: Implications for local livelihoods and coastal resource conservation along the Volta estuary catchment area of Ghana. *Ocean & coastal management*, *127*, 43-54.

Ahmed, N., & Glaser, M. (2016). Coastal aquaculture, mangrove deforestation and blue carbon emissions: is REDD+ a solution?. *Marine Policy*, *66*, 58-66.

Ahmed, N., & Thompson, S. (2019). The blue dimensions of aquaculture: A global synthesis. *Science of the Total Environment*, *652*, 851-861.

Akram, H., Hussain, S., Mazumdar, P., Chua, K. O., Butt, T. E., & Harikrishna, J. A. (2023). Mangrove health: A review of functions, threats, and challenges associated with mangrove management practices. *Forests*, *14*(9), 1698.

Alappatt, J. P. (2008). Structure and species diversity of mangrove ecosystem. In *Biodiversity and Climate Change Adaptation in Tropical Islands* (pp. 127-144). Academic Press.

Alongi, D. M. (2008). Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science*, 76(1), 1-13. https://doi.org/10.1016/j.ecss.2007.08.024

Amma, P. K. G., & Bhaskaran, P. K. (2020). Role of mangroves in wind-wave climate modeling–A review. *Journal of Coastal Conservation*, *24*(2), 21.

Anu, K., Sneha, V. K., Busheera, P., Muhammed, J., & Augustine, A. (2024). Mangroves in environmental engineering: Harnessing the multifunctional potential of Nature's coastal architects for sustainable ecosystem management. *Results in Engineering*, 101765.

Appanah, S. I. M. M. A. T. H. I. R. I. (2005). Assessment of forestry-related requirements for rehabilitation and reconstruction of tsunami-affected areas of Sri Lanka. Mission Report, Food and Agriculture Organization of the United Nations, 10-24.

Arifanti, Virni Budi, Frida Sidik, Budi Mulyanto, Arida Susilowati, Tien Wahyuni, Naning Yuniarti, Aam Aminah et al. "Challenges and strategies for sustainable mangrove management in Indonesia: a review." *Forests* 13, no. 5 (2022): 695.

Arulnayagam, A., Khim, J. S., & Park, J. (2021). Floral and faunal diversity in Sri Lankan mangrove forests: a systematic review. *Sustainability*, *13*(17), 9487.

Asari, N., Suratman, M. N., Mohd Ayob, N. A., & Abdul Hamid, N. H. (2021). Mangroves as a natural barrier to environmental risks and coastal protection. *Mangroves: Ecology, Biodiversity and Management*, 305-322.

Barbier, E. B. (2017). Valuation of mangrove restoration. In *Oxford Research Encyclopedia of Environmental Science*.

Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., & Silliman, B. R. (2011). The value of estuarine and coastal ecosystem services. *Ecological Monographs*, 81(2), 169-193. https://doi.org/10.1890/10-1510.1

Beever III, J., & Walker, T. (2013). Estimating and Forecasting Ecosystem Services within Pine Island Sound, Sanibel Island, Captiva Island, North Captiva Island, Cayo Costa Island, Useppa Island, Other Islands of the Sound, and the Nearshore Gulf of Mexico. *Southwest Florida Beever and Walker Total ecosystem services*.

Bhukta, A., & Bhukta, R. (2022). Valuation of mangrove ecosystems in South Asian Countries: a review. *The Blue Economy: An Asian Perspective*, 201-217.

Blanton, A., Ewane, E. B., McTavish, F., Watt, M. S., Rogers, K., Daniel, R., ... & Mohan, M. (2024). Ecotourism and mangrove conservation in Southeast Asia: Current trends and perspectives. *Journal of Environmental Management*, *365*, 121529.

Boizard, S. D., & Mitchell, S. J. (2011). Resistance of red mangrove (Rhizophora mangle L.) seedlings to deflection and extraction. *Trees*, *25*, 371-381.

Chang, C. W., & Mori, N. (2021). Green infrastructure for the reduction of coastal disasters: A review of the protective role of coastal forests against tsunami, storm surge, and wind waves. *Coastal Engineering Journal*, *63*(3), 370-385.

Chaudhuri, P., Chaudhuri, S., & Ghosh, R. (2019). The role of mangroves in coastal and estuarine sedimentary accretion in Southeast Asia. *Sedimentary Processes-Examples from Asia, Turkey and Nigeria*, 203-218.

Chen, L., Yan, T., Xiong, Y., Zhang, Y., & Lin, G. (2017). Food sources of dominant macrozoobenthos between native and non-native mangrove forests: A comparative study. *Estuarine, Coastal and Shelf Science*, *187*, 160-167.

Chen, X., Yin, Z., Li, Z., Wang, B., Tao, A., Guo, Z., ... & O'Driscoll, K. (2024). Overview on Mangrove Forest Disaster Prevention and Mitigation Functions. *Journal of Ocean University of China*, *23*(1), 46-56.

Clavelle, T., & Jylkka, Z. (2013). Ecosystem service valuation of proposed protected areas in Abaco, The Bahamas.

Cochard, R. (2011). The 2004 tsunami in Aceh and Southern Thailand: coastal ecosystem services, damages and resilience. *The Tsunami Threat-Research and Technology*, 179-216.

Cochard, R., Ranamukhaarachchi, S. L., Shivakoti, G. P., Shipin, O. V., Edwards, P. J., & Seeland, K. T. (2008). The 2004 tsunami in Aceh and Southern Thailand: a review on coastal ecosystems, wave hazards and vulnerability. *Perspectives in Plant Ecology, Evolution and Systematics*, *10*(1), 3-40.

Dahdouh-Guebas, F., Jayatissa, L. P., Di Nitto, D., Bosire, J. O., Seen, D. L., & Koedam, N. (2005). How effective were mangroves as a defence against the recent tsunami? *Current Biology*, 15(12), R443-R447. https://doi.org/10.1016/j.cub.2005.06.008

Dananjaya, K. A. J. (2017). Climate change impacts on biodiversity and ecosystems in Sri Lanka: a review. *Nature Conservation Research. Заповедная наука*, *2*(3), 2-22.

Danielsen, F., Sørensen, M. K., Olwig, M. F., Selvam, V., Parish, F., Burgess, N. D., ... & Quarto, A. (2005). The Asian tsunami: A protective role for coastal vegetation. *Science*, 310(5748), 643. https://doi.org/10.1126/science.1118387

Datta, D., Chattopadhyay, R. N., & Guha, P. (2012). Community based mangrove management: A review on status and sustainability. *Journal of environmental management*, *107*, 84-95.

Daupan, S. M. M. A. V. (2016). *Community participation in mangrove forest management in the Philippines: management strategies, influences to participation,* *and socio-economic and environmental impacts* (Doctoral dissertation).

De Deurwaerder, H. (2012). How are anatomical and hydraulic features of Avicennia marina and Rhizophora mucronata trees influenced by siltation?. *University of Ghent, Brussels*.

De Silva, W., & Amarasinghe, M. D. (2023). Coastal protection function of mangrove ecosystems: a case study from Sri Lanka. *Journal of Coastal Conservation*, *27*(6), 59.

Donato, D. C., Kauffman, J. B., Murdiyarso, D., Kurnianto, S., Stidham, M., & Kanninen, M. (2011). Mangroves are among the most carbon-rich forests in the tropics. *Nature Geoscience*, 4(5), 293-297. https://doi.org/10.1038/ngeo1123

Duke, N. C., Meynecke, J. O., Dittmann, S., Ellison, A. M., Anger, K., Berger, U., ... & Dahdouh-Guebas, F. (2007). A world without mangroves? *Science*, 317(5834), 41-42. https://doi.org/10.1126/science.317.5834.41

Edirisinghe, E. A. P. N. (2014). Assessment of climate change impacts on coastal communities in Sri Lanka. *Journal of Coastal Conservation*, 18, 241-248. https://doi.org/10.1007/s11852-014-0327-3

Edirisinghe, E.A.P.N., Ariyadasa, K.P., Chandani, R.P.D.S. 2012. Forest Cover Assessment of Sri Lanka, The Sri Lankan Forester, Journal of Sri Lanka Forest Department

Ellison, A. M. (2000). Mangrove restoration: Do we know enough? *Restoration Ecology*, 8(3), 219-229. https://doi.org/10.1046/j.1526-100X.2000.80033.x

Feka, Z. N., & Morrison, I. (2017). Managing mangroves for coastal ecosystems change: A decade and beyond of conservation experiences and lessons for and from west-central Africa. *Journal of Ecology and The Natural Environment*, *9*(6), 99-123.

Fernando, H. J. S., McCulley, J. L., Mendis, S. G., & Perera, K. (2005). Coral poaching worsens tsunami destruction in Sri Lanka. *Eos, Transactions American Geophysical Union*, 86(33), 301-304. https://doi.org/10.1029/2005EO330002

Friess, D. A., & Thompson, B. S. (2016). Mangrove payments for ecosystem services (PES): a viable funding mechanism for disaster risk reduction?. *Ecosystem-Based Disaster Risk Reduction and Adaptation in Practice*, 75-98.

Friess, D. A., Yando, E. S., Alemu, J. B., Wong, L. W., Soto, S. D., & Bhatia, N. (2020). Ecosystem services and disservices of mangrove forests and salt marshes. *Oceanography and marine biology*.

Gedan, K. B., Kirwan, M. L., Wolanski, E., Barbier, E. B., & Silliman, B. R. (2011). The present and future role of coastal wetland vegetation in protecting shorelines: Answering recent challenges to the paradigm. *Climatic Change*, 106, 7-29. https://doi.org/10.1007/s10584-010-0003-7

Getzner, M., & Islam, M. S. (2020). Ecosystem services of mangrove forests: Results of a meta-analysis of economic values. *International Journal of Environmental Research and Public Health*, *17*(16), 5830.

Gevaña, D. T., Camacho, L. D., & Pulhin, J. M. (2018). Conserving mangroves for their blue carbon: Insights and prospects for community-based mangrove management in Southeast Asia. *Threats to Mangrove Forests: Hazards, Vulnerability, and Management*, 579-588.

Ghorai, D., & Sen, H. S. (2015). Role of climate change in increasing occurrences oceanic hazards as a potential threat to coastal ecology. *Natural Hazards*, *75*, 1223-1245.

Gilman, E., & Ellison, J. (2007). Efficacy of alternative low-cost approaches to mangrove restoration, American Samoa. *Estuaries and Coasts*, *30*, 641-651.

Giri, C., Ochieng, E., Tieszen, L. L., Zhu, Z., Singh, A., Loveland, T., ... & Duke, N. (2011). Status and distribution of mangrove forests of the world using earth observation satellite data. *Global Ecology and Biogeography*, 20(1), 154-159. https://doi.org/10.1111/j.1466-8238.2010.00584.x

Gracia, A. D., Rangel-Buitrago, N., Oakley, J. A., & Williams, A. T. (2018). Use of ecosystems in coastal erosion management. *Ocean & coastal management*, *156*, 277-289.

Haque, M. A., Rahman, D., & Rahman, M. H. (2016). The importance of community based approach to reduce sea level rise vulnerability and enhance resilience capacity in the coastal areas of Bangladesh: a review.

Harborne, A. R., Mumby, P. J., Micheli, F., Perry, C. T., Dahlgren, C. P., Holmes, K. E., & Brumbaugh, D. R. (2006). The functional value of Caribbean coral reef, seagrass and mangrove habitats to ecosystem processes. *Advances in marine biology*, *50*, 57-189.

Hernández-Delgado, E. A. (2024). Coastal Restoration Challenges and Strategies for Small Island Developing States in the Face of Sea Level Rise and Climate Change. *Coasts*, *4*(2), 235-286.

Hogarth, P. J. (2015). *The biology of mangroves and seagrasses*. Oxford university press.

Iftekhar, M. S. (2008). An overview of mangrove management strategies in three South Asian countries: Bangladesh, India and Sri Lanka. *International Forestry Review*, *10*(1), 38-51.

Illangasekare, T., Obeysekera, J., Hyndman, D., Perera, L., Vithanage, M., & Gunatilaka, A. (2009). Impacts of the 2004 Tsunami and Subsequent Water Restorations Actions in Sri Lanka. In *Decision Support for Natural Disasters and Intentional Threats to Water Security* (pp. 3-28). Springer Netherlands.

IUCN. (2020). *Mangrove Conservation and Restoration*. International Union for Conservation of Nature. Retrieved from https://www.iucn.org/theme/marine-and-polar/our-work/climate-change-and-oceans/mangrove-conservation-and-restoration

Jayatissa, L. P., Dahdouh-Guebas, F., & Koedam, N. (2002). A review of the floral composition and distribution of mangroves in Sri Lanka. *Botanical Journal of the Linnean Society*, 138(1), 29-43. https://doi.org/10.1046/j.1095-8339.2002.00002.x

Jayatissa, L. P., Kodikara, K. A. S., Dissanayaka, N. P., & Satyanarayana, B. (2016). Post-Tsunami assessment of coastal vegetation, with the view to protect coastal areas from ocean surges in Sri Lanka. *Tsunamis and Earthquakes in Coastal Environments: Significance and Restoration*, 47-64.

Kaplan, M., Renaud, F. G., & Lüchters, G. (2009). Vulnerability assessment and protective effects of coastal vegetation during the 2004 Tsunami in Sri Lanka. *Natural Hazards and Earth System Sciences*, *9*(4), 1479-1494.

Karanja, J. M., & Saito, O. (2018). Cost–benefit analysis of mangrove ecosystems in flood risk reduction: a case study of the Tana Delta, Kenya. *Sustainability Science*, *13*, 503-516.

Kathiresan, K., & Bingham, B. L. (2001). Biology of mangroves and mangrove ecosystems.

Kathiresan, K., & Rajendran, N. (2005). Coastal mangrove forests mitigated tsunami. *Estuarine, Coastal and Shelf Science*, 65(3), 601-606. https://doi.org/10.1016/j.ecss.2005.06.022

Khaniya, B., Gunathilake, M. B., & Rathnayake, U. (2021). Ecosystem-Based Adaptation for the Impact of Climate Change and Variation in the Water Management Sector of Sri Lanka. *Mathematical problems in engineering*, *2021*(1), 8821329.

Koh, H. L., Teh, S. Y., Kh'Ng, X. Y., & Raja Barizan, R. S. (2018). Mangrove forests: Protection against and resilience to coastal disturbances. *Journal of Tropical Forest Science*, *30*(5), 446-460.

Kongkeaw, C., Kittitornkool, J., Vandergeest, P., & Kittiwatanawong, K. (2019). Explaining success in community based mangrove management: Four coastal communities along the Andaman Sea, Thailand. *Ocean & Coastal Management*, *178*, 104822.

Kumara, M. P., Jayatissa, L. P., Krauss, K. W., Phillips, D. H., & Huxham, M. (2010). High mangrove density enhances surface accretion, surface elevation change, and tree survival in coastal areas susceptible to sea-level rise. *Oecologia*, 164, 545-553. https://doi.org/10.1007/s00442-010-1705-2

Kumari, A., & Rathore, M. S. (2021). Roles of Mangroves in Combating the Climate Change. *Mangroves: Ecology, Biodiversity and Management*, 225-255.

Lee, S. Y., Primavera, J. H., Dahdouh-Guebas, F., McKee, K., Bosire, J. O., Cannicci, S., ... & Record, S. (2014). Ecological role and services of tropical mangrove ecosystems: a reassessment. *Global ecology and biogeography*, *23*(7), 726-743.

Lewis, R. R. (2001). Mangrove restoration—Costs and benefits of successful ecological restoration. In *Proceedings of the Mangrove Valuation Workshop*, (pp. 18-23). International Society for Mangrove Ecosystems, Japan.

Lhosupasirirat, P., Dahdouh-Guebas, F., Hugé, J., Wodehouse, D., & Enright, J. (2023). Stakeholder perceptions on Community-Based Ecological Mangrove Restoration (CBEMR): a case study in Thailand. *Restoration Ecology*, *31*(5), e13894.

Lovelock, C. E., Krauss, K. W., Osland, M. J., Reef, R., & Ball, M. C. (2016). The physiology of mangrove trees with changing climate. *Tropical tree physiology: adaptations and responses in a changing environment*, 149-179.

Mangrove Action Project (MAP). (2014). Community-based ecological mangrove restoration (CBEMR). Retrieved from https://mangroveactionproject.org

Marois, D. E., & Mitsch, W. J. (2015). Coastal protection from tsunamis and cyclones provided by mangrove wetlands–a review. *International Journal of Biodiversity Science, Ecosystem Services & Management*, *11*(1), 71-83.

Massel, S. R., & Massel, S. R. (1999). Tides and Waves on Vegetated Coasts. *Fluid Mechanics for Marine Ecologists*, 417-452.

Mazda, Y., Magi, M., Kogo, M., & Hong, P. N. (2006). Mangroves as a coastal protection from waves in the Tong King delta, Vietnam. *Mangroves and Salt Marshes*, 1(2), 127-135. https://doi.org/10.1023/A:1009943530251

McIvor, A. L., Möller, I., Spencer, T., & Spalding, M. (2012). *Reduction of wind and swell waves* *by mangroves*. The Nature Conservancy and Wetlands International.

Michener, W. K., Blood, E. R., Bildstein, K. L., Brinson, M. M., & Gardner, L. R. (1997). Climate change, hurricanes and tropical storms, and rising sea level in coastal wetlands. *Ecological applications*, *7*(3), 770-801.

Moberg, F., & Rönnbäck, P. (2003). Ecosystem services of the tropical seascape: interactions, substitutions and restoration. *Ocean & Coastal Management*, *46*(1-2), 27-46.

Nagelkerken, I., Blaber, S. J. M., Bouillon, S., Green, P., Haywood, M., Kirton, L. G., ... & Somerfield, P. J. (2008). The habitat function of mangroves for terrestrial and marine fauna: A review. *Aquatic Botany*, 89(2), 155-185. https://doi.org/10.1016/j.aquabot.2007.12.007

Nelson, D. R., Chaiboonchoe, A., Hazzouri, K. M., Khraiwesh, B., Alzahmi, A., Jaiswal, A., ... & Salehi-Ashtiani, K. (2022). Tissue-specific transcriptomes outline halophyte adaptive strategies in the gray mangrove (Avicennia marina). *Agronomy*, *12*(9), 2030.

Nyanga, C. (2020). The role of mangroves forests in decarbonizing the atmosphere. In *Carbon-Based Material for Environmental Protection and Remediation*. IntechOpen.

Ostling, J. L., Butler, D. R., & Dixon, R. W. (2009). The biogeomorphology of mangroves and their role in natural hazards mitigation. *Geography Compass*, *3*(5), 1607-1624.

Primavera, J. H. (2000). Development and conservation of Philippine mangroves: Institutional issues. *Ecological Economics*, 35(1), 91-106. https://doi.org/10.1016/S0921-8009(00)00170-1

Primavera, J., Sadaba, R., Lebata, M. J. H. L., & Altamirano, J. (2004). *Handbook of mangroves in the Philippines-Panay*. Aquaculture Department, Southeast Asian Fisheries Development Center.

Quartel, S., Kroon, A., Augustinus, P. G. E. F., Van Santen, P., & Tri, N. H. (2007). Wave attenuation in coastal mangroves in the Red River Delta, Vietnam. *Journal of Asian Earth Sciences*, *29*(4), 576-584.

Richards, D. R., & Friess, D. A. (2016). Rates and drivers of mangrove deforestation in Southeast Asia, 2000–2012. *Proceedings of the National Academy of Sciences*, *113*(2), 344-349.

Romañach, S. S., DeAngelis, D. L., Koh, H. L., Li, Y., Teh, S. Y., Barizan, R. S. R., & Zhai, L. (2018). Conservation and restoration of mangroves: Global status, perspectives, and prognosis. *Ocean & Coastal Management*, *154*, 72-82.

Rönnbäck, P. (1999). The ecological basis for economic value of seafood production supported by mangrove ecosystems. *Ecological Economics*, 29(2), 235-252. https://doi.org/10.1016/S0921-8009(99)00016-6

Rönnbäck, P., Crona, B., & Ingwall, L. (2007). The return of ecosystem goods and services in replanted mangrove forests: perspectives from local communities in Kenya. *Environmental Conservation*, *34*(4), 313-324.

Samarakoon, J. I., & Samarawickrama, S. P. (2012). The role of community in mangrove conservation in Sri Lanka. *Ocean & Coastal Management*, 57, 26-33. https://doi.org/10.1016/j.ocecoaman.2011.12.008

Sánchez-Núñez, D. A., Bernal, G., & Mancera Pineda, J. E. (2019). The relative role of mangroves on wave erosion mitigation and sediment properties. *Estuaries and Coasts*, *42*, 2124-2138.

Soper, F. M., MacKenzie, R. A., Sharma, S., Cole, T. G., Litton, C. M., & Sparks, J. P. (2019). Non-native mangroves support carbon storage, sediment carbon burial, and accretion of coastal ecosystems. *Global Change Biology*, *25*(12), 4315-4326.

Spalding, M., Mcivor, A., Tonneijck, F., Tol, S., & Eijk, P. V. (2014). Mangroves for coastal defence.

Sri Lanka. Ministry of Environment & Natural Resources. (2005). *Sri Lanka: Post-tsunami Environmental Assessment* (Vol. 882). UNEP/ Earthprint.

Srikanth, S., Lum, S. K. Y., & Chen, Z. (2016). Mangrove root: adaptations and ecological importance. *Trees*, *30*, 451-465.

Temmerman, S., Horstman, E. M., Krauss, K. W., Mullarney, J. C., Pelckmans, I., & Schoutens, K. (2023). Marshes and mangroves as nature-based coastal storm buffers. *Annual Review of Marine Science*, *15*(1), 95-118.

Thomas, N., Lucas, R., Bunting, P., Hardy, A., Rosenqvist, A., & Simard, M. (2017). Distribution and drivers of global mangrove forest change, 1996–2010. *PloS one*, *12*(6), e0179302.

Tomlinson, P. B. (1986). *The botany of mangroves*. Cambridge University Press.

Uddin, M. S., Van Steveninck, E. D. R., Stuip, M., & Shah, M. A. R. (2013). Economic valuation of provisioning and cultural services of a protected mangrove ecosystem: A case study on Sundarbans Reserve Forest, Bangladesh. *Ecosystem Services*, *5*, 88-93.

United Nations Environment Programme (UNEP). (2005). *After the tsunami: Rapid environmental* *assessment*. Nairobi, Kenya. Retrieved from https://wedocs.unep.org/handle/20.500.11822/8746

Unnikrishnan, S., Singh, A., & Kharat, M. G. (2012). The role of mangroves in disaster mitigation: a review. *international Journal of Environment and Sustainable development*, *11*(2), 164-179.

Valiela, I., Bowen, J. L., & York, J. K. (2001). Mangrove forests: One of the world's threatened major tropical environments. *BioScience*, 51(10), 807-815. https://doi.org/10.1641/0006-3568(2001)051[0807:MFOOTW]2.0.CO;2

Venkatachalam, A. J. (2010). *Environmental assessment of the south coast of Sri Lanka, with special reference to the 2004 tsunami* (Doctoral dissertation, University of Warwick).

Vo-Luong, P., & Massel, S. (2008). Energy dissipation in non-uniform mangrove forests of arbitrary depth. *Journal of Marine Systems*, *74*(1-2), 603-622.

Walters, B. B. (2004). Local management of mangrove forests in the Philippines: Successful conservation or efficient resource exploitation? *Human Ecology*, 32(2), 177-195. https://doi.org/10.1023/B:HUEC.0000019768.91962.e4

Wells, S., & Ravilious, C. (2006). *In the front line: shoreline protection and other ecosystem services from mangroves and coral reefs* (No. 24). UNEP/Earthprint.

Wickramasinghe, S., Wijayasinghe, M., & Sarathchandra, C. (2022). Sri Lankan mangroves: biodiversity, livelihoods, and conservation. In *Mangroves: Biodiversity, Livelihoods and Conservation* (pp. 297-329). Singapore: Springer Nature Singapore.

Wijesundara, A., & Ranagalage, M. (2014). Identification of tsunami risk area using geographical information systems & remote sensing (a case study of Weligama coastal belt area, Sri Lanka).

Wijetunge, J. J. (2006). Tsunami on 26 December 2004: spatial distribution of tsunami height and the extent of inundation in Sri Lanka. *Science of Tsunami Hazards*, 24(3), 225-239. Retrieved from http://tsunamisociety.org/243jijetunge.pdf

Wijetunge, J. J. (2014). A deterministic analysis of tsunami hazard and risk for the southwest coast of Sri Lanka. *Continental Shelf Research*, *79*, 23-35.

Yanagisawa, H., Koshimura, S., Miyagi, T., & Imamura, F. (2010). Tsunami damage reduction performance of a mangrove forest in Banda Aceh, Indonesia inferred from field data and a numerical model. *Journal of Geophysical Research: Oceans*, *115*(C6).

Zeng, Y., Friess, D. A., Sarira, T. V., Siman, K., & Koh, L. P. (2021). Global potential and limits of mangrove blue carbon for climate change mitigation. *Current Biology*, *31*(8), 1737-1743.

Zhang, Z. (2023). *Mitigating Investment Risks in Nature-Based Solutions: A Strategic Approach Towards Sustainable Project Implementation* (Doctoral dissertation, Massachusetts Institute of Technology).

Zhu, J. J., & Yan, B. (2022). Blue carbon sink function and carbon neutrality potential of mangroves. *Science of the Total Environment*, *822*, 153438.

Systems Perspectives on Tsunami Risk for Coastal Hospitals

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ABSTRACT

The authors present a commentary to their recently proposed Tsunami Relative Risk Index (TRRI) for coastal hospitals exposed to the threat of tsunami. The aim of this paper is to discuss the 'nested' nature of TRRI, which progresses from reflecting the risk to the structure that envelopes an individual critical care unit, to that of the entire building, and then to the functioning of that unit. A procedure for computing the overall risk to a network of such units is also presented. Uncertainty is dealt with, not through a probabilistic framework, but rather through the combination of three hazard level scenarios and three "What-if" mitigation measures plus a baseline case. Such a scenario-based approach can give more insight into the resilience of the system than would be reflected through probabilistic risk analysis. The scenarios also allow for the cotemporaneous assessment of the network of service across geographical locations. The TRRI, characterized by its 'nested' nature, is compared with other risk indices, where contributions to risk (or safety) are made through a 'parallel' consideration of the various contributory aspects. Finally, the importance of visualization is demonstrated, for presenting risk and mitigation information to hospital administrators.

Key words: Hospital network, Critical care unit, Hazard levels, What-if scenarios, Hierarchical structuring

1. INTRODUCTION

Hospitals have attracted much attention in the context of Disaster Risk Reduction (DRR). The Pan American Health Organization (PAHO) and World Health Organization (WHO) have recently developed a tool to assess the level of hospital safety (WHO and PAHO 2015). This tool has four modules, for which information has to be collected by evaluators. The first relates to hazards; and the other three to structural, non-structural and emergency & disaster management aspects. The hazards considered are geological (e.g. earthquakes and tsunamis), hydro-meteorological (e.g. cyclones), biological (e.g. pandemics), technological (e.g. fire), and societal (e.g. armed conflict and social unrest). The scope of this survey tool includes the safety of the hospital itself, as well as the requirement that it be equipped to deal with patients arising from the hazard events. This twofold perspective is an important one that is of particular importance to hospital buildings, and one that has promise for greater exploration, although not pursued herein. In addition, the module on hazards has a separate section on the geotechnical properties of the soils that the hospital is located on. This can be seen as an exposure aspect, especially for earthquake hazards.

Although hazard (and exposure) are covered to some extent in the PAHO assessment tool, the safety index is computed mainly on the basis of data pertaining to structural, non-structural and emergency & disaster management aspects. For example, the structural module has questions regarding structural redundancy, horizontal and vertical irregularity, and ratio of column to beam

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strength. It is reminiscent of aspects covered in FEMA P-154 for the rapid visual screening of buildings for seismic hazards (FEMA 2015). The non-structural module has questions regarding architectural elements (such as partition walls and roofs), access routes, and backup systems such as electricity, water supply, HVAC, firefighting and medical gases. The emergency & disaster management module deals with planning, coordination, evacuation and human resources.

Since the computation of the safety index is only marginally based on hazard, the PAHO index primarily reflects inherent vulnerability, or rather robustness. It is computed by assigning weights to the three modules, e.g. 0.50 or 0.33 for structural aspects, 0.30 or 0.33 for non-structural aspects, and 0.20 or 0.33 for emergency & disaster management aspects, depending, respectively, on whether there would be a higher risk of earthquakes and/or cyclones or not. Although this is the only computation where a dependence on the hazard is involved, it nevertheless introduces a risk dimension to the index as well. The unit of analysis is a given hospital (in its entirety), with the final scores used to classify the hospital as Class A (index of 0.66 to 1.00), needing little or no interventions; Class B (index of 0.36 to 0.65), requiring short term interventions; or Class C (index of 0.00 to 0.35), demanding urgent interventions.

Civil and structural engineers engaging with the PAHO assessment tool will be rightly forced to consider multi-disciplinary aspects of hospital risk. In order to assign weights to and compare the influence of different aspects, they would need to move away from rigorous, though reductionist, approaches such as numerical analysis (e.g. Proença et al. 2004, Casarotti et al. 2009), to index based methods following rapid visual screening, such as those proposed in FEMA P-154 (FEMA 2015) for earthquake hazards and PTVA-4 (Dall'Osso et al. 2016) for tsunami ones. Although both the FEMA P-154 and PTVA-4 schemes appear to be vulnerability indices, the use of a 'basic score' that is dependent on seismicity in the former, and an inundation depth in the latter, transform them into risk indices of a sort, not unlike the PAHO tool.

Suggestions (e.g. Dias and Edirisooriya 2019) and alternatives (e.g. Hasalanka et al. 2021) have been proposed for improvements of the PTVA-4 approach. However, one of the biggest shortcomings of such index based tools is that the aggregation of scores can be seen as being in 'parallel' mode – as illustrated in Figure 1 for the PAHO assessment tool. For example, the non-structural module contains aspects related to backup systems (e.g. electricity and water supply etc.). If both the regular and backup systems are liable to fail as a result of water inundation during a tsunami, the hospital would not be able to function, and the 'safety index' would in fact be zero. However, in the recommended 'parallel mode' computation, it is only the scores contributed by the non-structural module that would be lowered, while the computed safety index may still be very high, thus not genuinely reflecting the inherent safety (or risk). Similarly, in the PTVA-4 scheme (Dall'Osso et al. 2016), a weight of 0.33 is assigned to 'water vulnerability' (WV), with the rest being assigned to 'structural vulnerability' (SV). PTVA-4 is admittedly not designed specifically for hospitals, but if applied to these facilities, even a very high WV score will not increase the overall vulnerability by much, because WV is weighted by only 0.33. In a hospital however, inundation of critical care units would completely disrupt their function, even if the structure was very robust against tsunami forces.

The main objective of this paper is to present the relatively new Tsunami Relative Risk Index (TRRI), to highlight the fact that hierarchical or nested risk indices, as represented in Figure 2 below, are needed for more realistic estimates of risk. There are two aspects to the methodology. First, the methodology of the TRRI (Baiguera

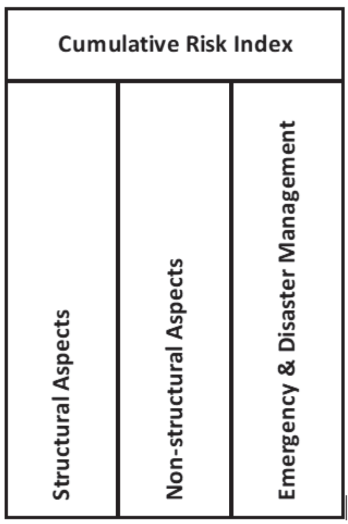

Figure 1. Parallel Aggregation of Risk Scores

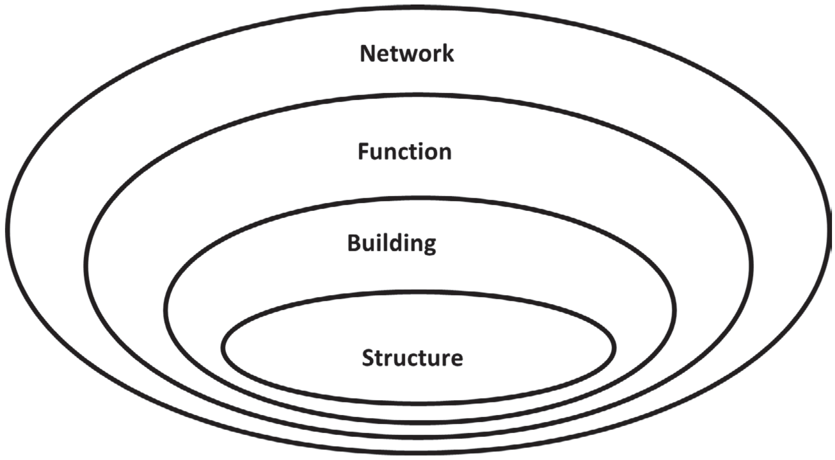

Figure 2. Nested Aggregation of Risk Scores

et al. 2021) is summarised in Section 2. Second, some results are generated from the application of the TRRI method to a set of three coastal hospitals in Sri Lanka, in order to highlight some insights that would otherwise be missed (Section 3). The TRRI method treats each critical care unit as part of a wider system, and hence can also be seen as an example of a systems approach to risk assessment.

2. THE TSUNAMI RELATIVE RISK INDEX (TRRI) APPROACH

Previous work by the authors (Baiguera et al. 2021) has tackled some of the issues raised above, through an approach called the Tsunami Relative Risk Index (TRRI). There are some key differences between the TRRI approach and those of WHO and PAHO (2015) and PTVA-4 (Dall'Osso et al. 2016). The most important difference is that it uses a 'nested' or hierarchical mode of risk aggregation, as depicted in Figure 2 and explained below. Another key difference is that simple engineering computations are performed wherever possible, rather than relying solely on scores based on qualitative judgements as in the other approaches. Finally, the unit of analysis is not the entire hospital as in WHO and PAHO (2015) or even a single building as in PTVA-4 (Dall'Osso et al. 2016), but rather on important critical care units of the hospital such as Intensive Care Units (ICU), Labour Rooms (LR), Maternity Wards (MW), Pediatric Wards (PW) and Operating Theatres (OT).

While a full description of the TRRI approach is given elsewhere (Baiguera et al. 2021), a brief outline follows, with Figure 2 as a guide. The approach starts by evaluating the Relative Risk Index (RRI) of the structure that envelopes a critical care unit of interest. Hydrodynamic impact on the lower floors of buildings under tsunami loading would cause large shear forces on the columns; this would be the failure precipitating phenomenon for the structure (Petrone et al. 2017). The index for structural performance is simply the hydrodynamic force exerted by the tsunami (F_{TSU}) divided by the total shear capacity of all columns, Q_C. The calculation procedure is given by Baiguera et al. (2021), based on the provisions of ASCE/SEI 7-16 (2017). We can thus obtain the index RRI_{struct} as

$$RRI_{struct} = F_{TSU}/Q_C \quad (1)$$

The structure itself is part of the building, which has at least two other potential failure modes, namely the undermining of foundations via scour and the threat to columns via debris loading. The index RRI_{scour} is obtained as the ratio between the undermined columns (N_{scour}) and the total number of columns (N_C) as in equation (2), provided the percentage of foundations that could be undermined is below 50%; else guidance is given in Baiguera et al. (2021).

$$RRI_{scour}=N_{scour}/N_C \quad (2)$$

The index RRI_{debris} can be obtained as the ratio between columns collapsed by debris loads (N_{debris}) and total number of columns (N_C) as in equation (3), with details given once again in Baiguera et al. (2021).

$$RRI_{debris}=N_{debris}/N_c \quad (3)$$

The final RRI for the building is taken as the maximum RRI value from the three separate possible modes of failure. In other words, the individual risks are combined by using their maximum value, i.e.:

$$RRI_{bldg} = \max(RRI_{struct}, RRI_{scour}, RRI_{debris}) \quad (4)$$

It is the use of such 'max' functions across several relative risk measures that bestows upon the TRRI approach a 'nested' or hierarchical mode of risk aggregation, rather than the somewhat inadequate 'parallel' one, as argued before. There is another hierarchical level as one progresses from the *building* that houses a given hospital unit to the *function* of that unit (Figure 2). Even though the building may have only a low relative risk, the risk to the operation of that unit could be increased either by the inundation of the unit itself; or failure (once again though inundation) of the backup systems serving the unit. If the envisaged inundation depth will reach the floor level of the unit concerned, it will not be able to function, and RRI_{water} is set to unity; else, it will be zero.

Within the TRRI approach, eight backup critical systems (BCS) are identified as contributing to the functioning of critical units. These are: Power, Air conditioning, Telecommunications, Water Supply, Fire Protection, Waste Water, Medical Gas, and Fuel and Gas reserves (WHO and PAHO, 2015). These are first weighted (w_i) for relative importance (Baiguera et al. 2021) and then each of the eight $(BCS)_i$ is assigned a value of unity or zero, depending on whether the relevant backup system is affected or not by the anticipated inundation. RRI_{bcs} is computed as

$$RRI_{bcs} = \Sigma_{i=1to8}(BCS)_i.w_i \quad (5)$$

The final TRRI for the functioning of the unit concerned is taken as the maximum RRI value from the building, inundation and backup critical systems. In other words, the individual risk indices are combined once again by using their maximum value, i.e.

$$TRRI = \max(RRI_{bldg}, RRI_{water}, RRI_{bcs}) \quad (6)$$

Baiguera et al (2021) computed the TRRI values for 22 critical units housed within reinforced concrete buildings in three coastal hospitals on the southern coast of Sri Lanka, namely the District General Hospital in Matara and two Base Hospitals in Balapitiya and Tangalle. Critical care units housed in unreinforced masonry buildings were not analysed, since the resistance of such buildings to tsunami forces is likely to be minimal. Recall again that these TRRI values relate to the hospital units rather than to entire buildings or hospitals. The distribution of the units across the hospitals is given in Table 1.

Table 1. Number of critical care units in the hospital network

Unit Type	BH Balapitiya	DGH Matara	BH Tangalle	TOTAL
ICU	4	4	1	**9**
LR	1	1	0	**2**
MW	1	2	2	**5**
OT	2	2	0	**4**
PW	0	0	2	**2**

Risk indices can embody uncertainty via probabilistic analysis or scenario analysis. The problems with using a purely probabilistic approach to risk have been highlighted by Elms (2019), one of which is the difficulty in dealing with high impact low occurrence (HILO) events - such as tsunami inundation on Indian Ocean coastlines, the *probabilities* of which are difficult to quantify with accuracy. The TRRI computations used the scenario approach, employing three inundation depth scenarios. Hazard Level 1 constituted the depths recorded for the 2004 Indian Ocean tsunami; while Hazard levels 2 and 3 assumed depths of 1.5 m and 3.0 m over and above the Hazard 1 depths. The effect of three separate mitigatory measures, or "What-If" (WI) measures, was also studied, in addition to the "as present" baseline. The first (WI1) involved the relocation of backup systems to elevations above the inundation zone. The second (WI2) envisaged the relocation of the critical hospital units by a single floor over and above the floor it was currently housed in; unless they were already housed on the top floor, in which case it remained there. The third (WI3) was a combination of both measures. These measures did not involve significant structural retrofit, and were hence considered realistic to implement. In the above context, each hospital unit had 12 computed TRRI values when the three scenarios were combined with the baseline plus three "What-if" measures. These scenario cum mitigation combinations can be seen as embodying a *resilience* approach to infrastructure, since a range of *possible* eventualities are considered and analysed (Elms et al. 2019).

The final hierarchical level in Figure 2 (i.e. that of network risk) does not involve the computation of TRRI values, but rather that of the proportion of different critical units that would not be functional under each of the hazard cum mitigation combinations. This is also an exploration of how the three coastal hospitals could offer their critical services in a combined fashion, rather than in isolation; and a quantification of the risk to that combined service as a result of tsunami hazards. There is, of course, a much wider network of hospitals in southern Sri Lanka, but this analysis is a 'proof of concept' for the approach. The question of transport availability during tsunami inundation has not been considered either, but could be incorporated in future work.

3. SYSTEMS INTERPRETATIONS OF RESULTS FROM BAIGUERA ET AL. (2021)

This section presents some visualizations and interpretations of the results already presented in Baiguera et al. (2021). They emphasise some of the systems concepts described above. Figure 3 shows how the risk index changes as we progress from the inner to outer hierarchical layers (see Figure 2) for a single maternity ward (MW) located on the first floor of a reinforced concrete building (M27) in the District General Hospital at Matara. Under Hazard Level 1 (inundation levels from the 2004 Indian Ocean tsunami), the risk is low for the structure, but increases somewhat at the building level, due to some scour risk. At

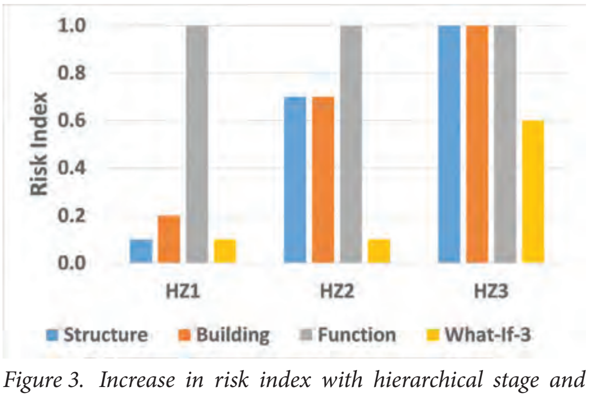

Figure 3. Increase in risk index with hierarchical stage and reduction through mitigation at various hazard levels

the function level, the risk index is maximum (= 1.0), because the inundation of critical backup systems would not allow the unit to be functional. This risk can be reduced to a very low level once again, if the "What-if-3" measure is deployed. This involves the relocation of backup systems to elevations above the inundation zone, which is sufficient to reduce the risk, even though the ward could not be relocated at a higher level, since the first floor was the highest available in the building. For Hazard Levels 2 and 3 (higher inundation depths) the structure and building risk indices are correspondingly higher; but the "What-if-3" measure is still able to reduce them. What is important is that when the hierarchical nature of risks, as embodied in Figure 2, are accounted for, the risk indices can soon reach their maximum values (as shown in Figure 3). This would not be the case when using a 'parallel' aggregation of risk scores, as depicted in Figure 1.

Table 2 gives the proportions of the Intensive Care Units (ICUs) that would survive (i.e. have risk indices less than unity) under all the combinations of Hazard Levels and "What-if" measures. The distribution of units across the three hospitals is given in Table 1. Note that the efficacy of "What-if-1" measures, i.e. the relocation of backup systems, appears to be marginally greater in general than those of "What-if-2", i.e. the relocation of the critical care units where possible.

Figure 4 shows the risk to the Intensive Care Units (ICUs) in the three-hospital network under combinations of the three hazard levels and "What-if" measures. Risk is defined as the proportions of the units that would have individual TRRIs of unity for the above combinations. As expected, the risk indices increase for increasing Hazard Levels, but decrease for increased "What-if" measures. However, visualisations such as the one shown in Figure 4 can bring out some subtle insights - for instance, that the increase of "What-if" measures will make significant reductions in network risk at

Table 2. Number of critical care units that would be functional under various hazard and mitigation scenarios

Critical Unit	Total	Functional Units under HZ1				Functional Units under HZ2				Functional Units under HZ3			
		baseline	WI-1	WI-2	WI-3	baseline	WI-1	WI-2	WI-3	baseline	WI-1	WI-2	WI-3
ICU	9	5	7	5	9	5	5	5	6	0	0	1	2
LR	2	1	1	1	2	1	1	1	2	0	0	1	1
MW	5	3	4	3	4	2	3	3	4	0	1	0	2
OT	4	2	3	2	4	2	3	2	4	0	0	1	1
PW	2	2	2	2	2	2	2	2	2	0	1	1	2

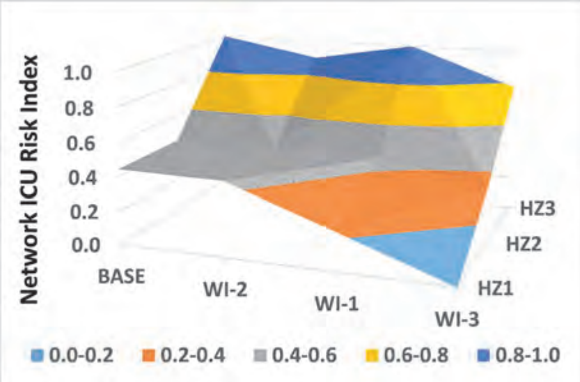

Figure 4. Risk index for ICU network with hazard level and mitigation measures

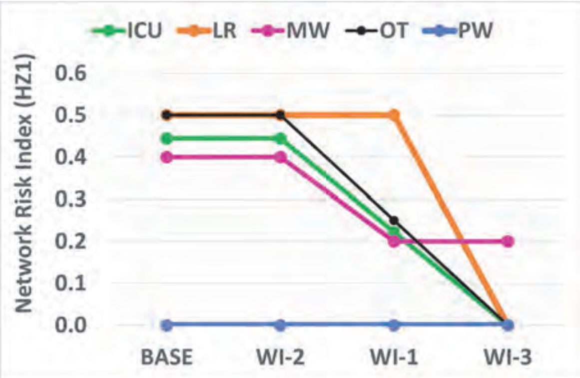

Figure 5. Network risk index for various critical care units at Hazard Level 1

Hazard Level 1, but not so much at Hazard Levels 2 and 3.

Another visualisation is presented in Figure 5 for (the lowest) Hazard Level 1, arguably the only one that may be taken up for mitigation by invariably cash strapped administrators, especially since that level corresponds to a tsunami generated by one of the largest earthquake magnitudes experienced to date (i.e. Mw=9.3). Figure 5 indicates that a "What-if 1" intervention (more effective than "What-if 2") may be sufficient to bring down the network risk to fairly acceptable levels (i.e. an index of 0.20-0.25) for all critical care units other than Labour Rooms (LR), which may need mitigation via a "What-if 3" intervention. Where practical implementation is concerned, the information in Figure 5 can be used by hospital administrators in the three hospitals, acting in concert, to appropriately prioritize the "What-if" measures related to the critical care units during their next cycles of maintenance operations. It must be emphasised that these computations are confined to a network of only three hospitals and their critical care units. They are presented as a proof of concept for using a network approach to hospital risk.

4. CONCLUDING DISCUSSION

The main systems contribution of this paper is to highlight the fact that hierarchical or nested risk indices, as represented in Figure 2, are needed for more realistic estimates of risk. Risk indices computed on the basis of 'parallel' aggregation of scores (represented in Figure 1) will arguably be misleading, especially when envisaging the actual functioning of critical care units.

Secondly, embedded in the approach presented here is the idea that the unit of risk analysis is the critical care unit (rather than a building or a hospital); also, that risk can be spread across a network of such units in adjacent hospitals.

In order to incorporate uncertainty, the TRRI relies on scenarios, whether for hazards or mitigation measures, rather than on probabilistic computations of risk. It could be argued that this constitutes a resilience rather than risk approach, although the term 'risk' is maintained. Resilience approaches are more appropriate for High Impact Low Occurrence (HILO) events, such as disasters in general, and Indian Ocean tsunamis in particular.

Finally, appropriate visualizations can help to communicate how the network or system will respond to various hazards and mitigations, thus helping administrators to take informed and appropriate decisions.

An area to which further attention needs to be paid is to validate some of these conclusions. One approach could be to compare the outputs of the approach proposed here with perceptions of the medical administrators of the three hospitals studied.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

ASCE (2017) Minimum Design Loads and Associated Criteria for Buildings and Other Structures. ASCE/SEI 7-16. Reston, VA, USA.

Baiguera, M., Rossetto, T., Palomino, J., Dias, P., Lopez-Querol, S., Siriwardana, C., Hasalanka, H., Ioannou, I. and Robinson, D. (2021) A New Relative Risk Index for Hospitals Exposed to Tsunami, Frontiers in Earth Sciences, 9: 626809.

Casarotti C., Pavese A. and Peloso S. (2009). "Seismic Response of the San Salvatore Hospital of Coppito (L'Aquila) during the 6th April 2009 earthquake", Progettazione Sismica, Issue 3, Special Abruzzo, Italian (pp.163-176) and English (pp.159-172).

Dall'Osso, F., D. Dominey-Howes, C. Tarbotton, S. Summerhayes, and G. Withycombe. 2016. "Revision and Improvement of the PTVA-3 Model for Assessing Tsunami Building Vulnerability Using 'International Expert Judgment': Introducing the PTVA-4 Model." *Natural Hazards* 83 (2): 1229–56. https://doi.org/10.1007/s11069-016-2387-9.

Dias, W.P.S., and U. Edirisooriya. 2019. "Derivation of tsunami damage curves from fragility functions." *Natural Hazards* 96: 1153–66.

Elms, D. (2019) Limitations of risk approaches, Civil Engineering and Environmental Systems, 36:1, 2-16, DOI: 10.1080/10286608.2019.1615474.

Elms, D., I. McCahon & R. Dewhirst (2019) Improving infrastructure resilience, Civil Engineering and Environmental Systems, 36:1, 83-99, DOI: 10.1080/10286608.2019.1615479

FEMA. 2015. *Rapid Visual Screening of Buildings for Potential of Seismic Hazards: A Handbook (FEMA P-154)*. 3rd ed. Federal Emergency Management Agency (FEMA).

Hasalanka, H., Siriwardana, C.S.A., Kularatne, D. and Dias, W.P.S. (2021): Development of a Structural Robustness Index against tsunamis for hospitals, Civil Engineering and Environmental Systems, 38(2): 85-101. DOI: 10.1080/10286608.2021.1890045

Petrone C., Rossetto T., & Goda K. (2017). "Fragility assessment of a RC structure under tsunami actions via nonlinear static and dynamic analyses". Engineering Structures, 136, 36-53.

Proença, J., Oliveira, C. S. and Almeida, J. P. (2004). "Performance-Based Seismic Assessment of Reinforced Concrete Structures with Masonry Infilled Panels: The Case of Block Number 22 of the Santa Maria Hospital in Lisbon", ISET Journal of Earthquake Technology, 41, pp.233-247.

WHO and PAHO. 2015. *Hospital Safety Index Guide for Evaluators*. 2nd ed. World Health Organization.

Tsunami Risk for School Buildings on the Sri Lankan Coast

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ABSTRACT

This paper reports multi-disciplinary studies on tsunami risk for school buildings in Sri Lanka. The study includes questionnaire surveys to establish risk perception, through classification of building types to identify school building typologies and empirical fragility analysis based on historical records, for tsunami loading to identify inundation depths that would cause buildings to reach various damage states. The Galle, Batticaloa and Ampara districts were selected for both sociology and engineering surveys, on the basis that they were the worst affected by the 2004 Indian Ocean tsunami. The questionnaire survey was carried out among twenty five school principals in these districts and established that tsunami is still perceived as the greatest risk to schools. The school building survey, carried out on the same school dataset, identified three main reinforced concrete typologies, with some variations in masonry infill patterns. The empirical fragility analysis collates data from school building damage surveys conducted soon after the 2004 tsunami and a high-resolution numerical tsunami model. This dataset provides key information on the behaviour of single-storey masonry buildings under variable tsunami inundation depths.

Key words: Tsunami, School buildings, Risk perception, Exposure, Damage states, Fragility

1. INTRODUCTION

The 2004 Indian Ocean tsunami (IOT), is the deadliest natural disaster in Sri Lanka's history, which claimed over 35,000 casualties and missing persons (with an additional 23,000 injured); internally displaced over one million people; and caused economic losses of approximately $2.2 billion (Pomonis et al., 2006). The infrastructure recovery from this disaster took about three to six years; and many countries, donor agencies and non-governmental organisation (NGOs) facilitated the recovery processes in Sri Lanka (Suppasri et al., 2015). While the tsunami risk was unfamiliar till then, the devastation it wrought led to a recognition of the need for greater national level disaster preparedness, which resulted in the establishment of the National Council for Disaster Management and the Disaster Management Centre (DMC) of Sri Lanka. The importance of disaster resilient critical infrastructure such as schools, hospitals and transportation systems was realised in the country and some actions have been taken to "build back better" (Dharmadasa et al., 2024).

The exposure, preparedness and vulnerability of schools in Sri Lanka against tsunami risk are explored in this paper. Uninterrupted functioning of schools is vital for community resilience and post-disaster recovery. The significance of disaster resilient school infrastructures have been stated

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in prominent global frameworks for disaster risk reduction, such as the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015), and the Comprehensive School Safety Framework (CSSF) (UNISDR & GADRRRES, 2017). In particular, the CSSF outlines three pillars of actions to facilitate the reduction of risks to education due to disasters, namely (1) Safe Learning Facilities, (2) School Disaster Management, and (3) Risk Reduction and Resilience Education (UNISDR & GADRRRES, 2017).

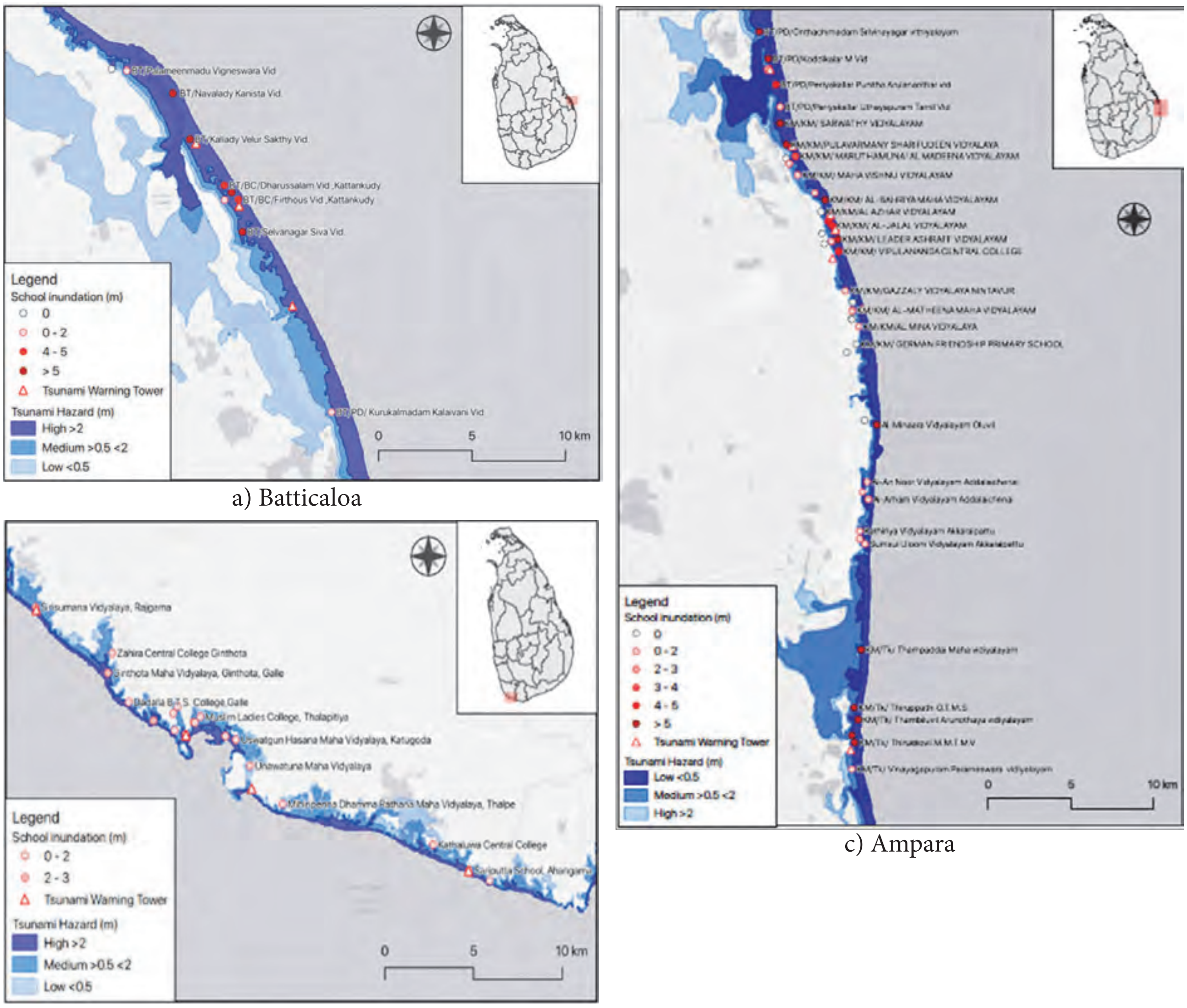
The 2004 IOT caused immediate disruption to education across Sri Lanka's coastal regions, directly affecting 5% of the country's schools. More details on the impacts of schools due to 2004 IOT are outlined in Section 2. Twenty years have passed since this catastrophic disaster, and significant progress has been made to reduce the tsunami risks in the region, by setting up early warning systems and community preparedness programmes. Nonetheless, Sri Lanka is still vulnerable to tsunami generated by subduction earthquakes in the Northern Andaman-Myanmar, Northern Sumatra-Andaman, and Southern Sumatra trenches, in addition to the Makran Trench in the Northern Arabian Sea. To the authors' best knowledge, hitherto no systematic studies have been conducted to gauge the exposure, preparedness and vulnerability of reconstructed/rehabilitated schools in the affected regions. These aspects have been systematically assessed in this research, using the CSSF as a guiding framework. The application of all three pillars of actions (stated in the CSSF) to the coastal schools of Sri Lanka has been undertaken. For these purposes, schools in three districts (Galle, Batticaloa and Ampara) were selected, based on the evidence that they were the most affected by the 2004 IOT.

The work reported in this paper is part of an ongoing collaborative research project titled "Resilience of Schools to Extreme Coastal Flooding – ReSCOOL", between the University College London, University of Naples Federico II, University of Moratuwa, University of Peradeniya, and South Eastern University of Sri Lanka. In order to apply the CSSF to the Sri Lankan education system, a series of systematic investigations were formulated to evaluate the following: (1) exposure of the school buildings to tsunami (related to the first pillar, i.e. Safe Learning Facilities); (2) preparedness of schools (that covers the second and third pillars, i.e. school disaster management, and risk reduction and resilience education, respectively); and (3) fragility of school buildings to tsunami (that provides a quantification of the first and second pillars). The exposure details of the schools in these coastal districts are described in Section 3. The outcomes of the questionnaire survey to establish tsunami risk perception and preparedness of schools are given in Section 4. The method followed to understand the tsunami vulnerability of typical single-storey school buildings in the country are elaborated in Section 5.

2. SCHOOLS AFFECTED DURING 2004 INDIAN OCEAN TSUNAMI

The 2004 IOT completely destroyed 74 schools and severely damaged a further 108 schools in Sri Lanka (UNICEF, 2009). Approximately 80,350 students and 3300 teachers were displaced from their schools across ten districts. The locations of the affected (destroyed and damaged) schools in three districts are indicated in Figure 1, including the schools that were used as Internally Displaced Person (IDP) camps. With great efforts, education activities of the affected schools were resumed in the third week of January 2005 and nearly 85% of the affected students were brought back to their studies by the end of March 2005 (UNICEF, 2009). Within four months, all the affected schools were put to function either through temporary facilities or amalgamating with the closest unaffected inland schools (The Education Rehabilitation Monitor, 2009). The school enrolment rates returned to normal within a year from the disaster. Many NGOs and donor agencies aided to reconstruct and rehabilitate the affected schools, and most of this work was completed within two to five years, as per the agency set up to monitor the rehabilitation programme of tsunami affected schools in Sri Lanka (The Education Rehabilitation Monitor, 2009).

The government enacted buffer zones of 100 m and 200 m from the coastal line in South/South-Western and East/North coasts, respectively, to discourage properties being reconstructed in tsunami hazard zones; this included schools. However, the policy of buffer zones and relocation of affected schools largely failed, and most of the schools had to be built at the same locations, due to resistance from local communities and difficulties in land procurements. The mapping



a) Batticaloa

b) Galle

c) Ampara

Figure 1. Destroyed/damaged schools (and schools used as IDP camps) in the three regions studied

of current schools in these regions indicates that there are 430 coastal schools in Sri Lanka that situated within the DMC's map of tsunami inundation; this implies that a future tsunami with similar intensity could potentially affect over 193,000 pupils. This highlights the importance of assessing the tsunami risk to schools and the education system in Sri Lanka.

3. EXPOSURE OF SCHOOLS

The exposure of schools in Sri Lanka to tsunami was assessed to understand the current state of the school infrastructures and to later use them for evaluating their structural vulnerability to tsunami. Rapid Visual Surveys (RVS) have been adopted in many past studies to gather exposure data for earthquake risk assessments (e.g. Karafagka et al. 2024), qualitatively assess seismic vulnerability of buildings (e.g. Clemente and Concha, 2020) and also for the identification or predominant building types (and their characteristics) for the development of index buildings to representing building classes in seismic fragility assessments (e.g. Gentile et al., 2019, amongst others). A small subset of RVS have been developed for schools considering earthquakes and tsunami (e.g. Gentile et al., 2019). However, it is found that these do not sufficiently capture features of the school buildings, school compound and surroundings, that can affect the school vulnerability and functionality in tsunami. Recently, a RVS method was developed specifically for masonry infilled reinforced concrete school buildings by Sathurshan et al (2023) against seismic risk, however tsunami risk in the RVS was not considered. Hence, a new RVS tool was purposely developed for capturing information both about the school as a whole, and the individual buildings within the school premises. The advantages of this newly developed RVS tool over existing ones have been clearly explained in work reported before (Cels et al., 2023a). The developed RVS tool was used to survey 38 schools (86 buildings in total) in the three coastal districts mentioned before, between June and November 2020. The schools surveyed were affected by the 2004 IOT, and many of the existing buildings have been reconstructed, while others have been rehabilitated. The structural and non-structural exposure information related to tsunami response of the schools were charted during the survey using the RVS tool. The information on physical resource management of the schools including energy, water and preparedness for tsunami was also collated. They allowed the development of multi-disciplinary repositories of exposure information, aimed at improving disaster risk reduction efforts for evacuation and maintaining/restoring school functionality after a natural hazard event. More details on the exposure studies can be referred from Cels et al. (2023a). This phase of the research study is directly related to the first pillar outlined in the CSSF for disaster risk reduction of schools. Although this RVS tool was developed specifically for school buildings in Sri Lanka, it can be used worldwide for rapid on-site collection of data regarding schools exposure to tsunami. Although data was collected on the masonry buildings in the school compound, the detailed exposure surveys of the schools focused on moment-resisting reinforced concrete frame school buildings, as these are considered to be more resilient to tsunami. The survey revealed that, most of the reinforced concrete school buildings are built according to three different typologies as shown in Figure 2.

The Type 1 buildings (see Figure 2a), have two rows of columns aligned with the longer dimension of the building, whereas the Type 2 buildings (see Figure 2b) have similar layout as Type 1, but are designed with an additional row of columns built along the corridor. This additional row of columns in Type 2 buildings could have been introduced to improve the robustness to tsunami-like lateral actions. All the buildings surveyed are two to three storeys high, and their architectural layout encompasses a central staircase with two or three classrooms on either side connected by a longitudinal corridor. A classroom of Sri Lankan schools typically spans two structural bays, and their dimensions are 6 m × 6.5 m. Among the schools surveyed, Type 1 is the most prevalent typology, while most of the Type 2 buildings have been reconstructed after the 2004 IOT.

Parapet and partition walls of the classrooms are constructed using brickwork/blockwork. Different patterns of openings and thicknesses are used for these parapet walls (front and rear sides). Although these walls are considered as non-structural elements, they play a vital role in resisting tsunami loads. Some non-structural aspects noted during the survey are shown in Figure 3.

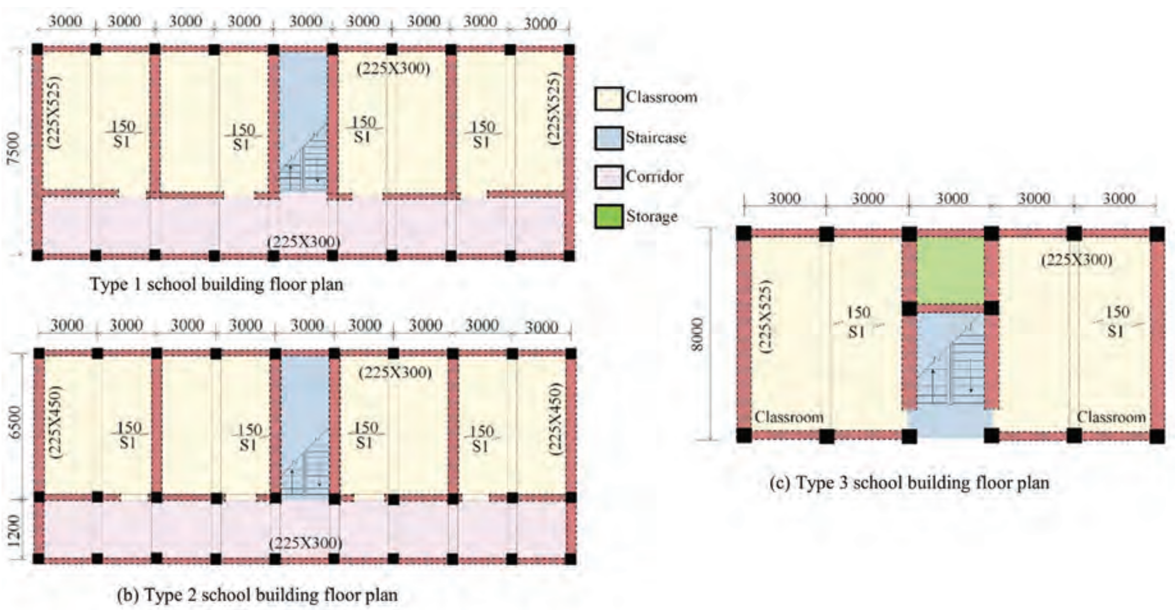


Figure 2. The floor plans of the three school building typologies identified

Figure 3. Non-structural aspects noted during exposure survey for infills and roofs

Figure 4. Example of school details retrieved through Google Earth satellite imagery, for a school in Batticaloa

To retrieve the status of other schools along the coast of Sri Lanka (that are not covered in the physical survey), and for further vulnerability and loss assessments, a digitalized database is developed comprising, locations of the school compounds, the number of buildings in each compound and their characteristics (building type, distance from coast, and orientation), using Google Earth satellite imagery tools, website searches, and school census data. Figure 4 shows the details looked through the Google Earth satellite imagery of a school in the Batticaloa district.

4. TSUNAMI PREPAREDNESS OF SCHOOLS

In order to gauge the preparedness of the school education system in Sri Lanka to tsunamis (reflecting the second and third pillars in the CSSF), two sets of semi-structured interviews were conducted. The first set of interviews were aimed at comprehending the government policies and regulations towards tsunami risk, and to understand existing contingency measures and disaster management protocols in Sri Lanka for schools. Eight regional education, national education and disaster management officials were interviewed. The questions were specifically designed to gather information on three aspects from these officials, namely: (1) official guidelines issued to schools on tsunami preparedness, 2) mechanisms in place to evaluate the preparedness, and 3) rehabilitation practices after a tsunami event. The second set of interviews were conducted with twenty five principals of coastal schools (covered in the exposure studies) in the three districts mentioned. The purpose of this set of interviews was to gather information regarding school level preparedness to tsunami, including preparedness against multiple hazards in the schools such as fire and flooding. In addition, questions were asked on whether the schools have the necessary level of awareness, capacity, and practice, to ensure the safety of students and staff during a tsunami. On behalf of the authors, the interviews were conducted between July and August 2020 by Vanguard Survey Ltd, which is a Sri Lankan survey agency with experience of conducting surveys dating back to the 2004 IOT. These two sets of interviews provided insights into the official procedures and measures that are in place at school level, as well as the communication protocols between schools and their respective disaster management services.

Based on both sets of interviews, it could be perceived that in general, the baseline tsunami preparedness is low. The tsunami risk perception among the officials has dropped down their list of priorities (perhaps due to competing concerns as well), and subsequent preparedness measures for tsunami have received limited funds. The DMC selects a number of coastal schools for tsunami drills and training each year; however the interviews indicate that these efforts are sporadic. Earlier efforts to train teachers in risk reduction and disaster management activities following the 2004 IOT have waned, thus causing a knowledge and experience drain.

Nonetheless, the principals interviewed recognise that they are least prepared for tsunami risk, among the set of multi-hazard scenarios presented. All twenty five principals indicated that a tsunami is a threat to their schools, while twenty of them thought it constituted the greatest risk. There is a strong connection between the perceived risk of a hazard and the school's experience of that hazard, as all those schools were affected by the 2004 IOT. The interviews implied that many of the risk reduction, management and preparedness responsibilities fall directly onto schools. The principals are reportedly responsible for the disaster management protocols at the school level, for conducting drills, and identifying the risks threatening the school. While teachers are provided first-aid training systematically, tsunami specific training is not given. Schools, through their safety committees, are expected to plan for and handle emergencies, including the development of their own emergency plans. There is no indication however, that schools receive the necessary support to draw up these plans. Most principals allude to sporadic teacher training with regard to hazard management, with intervals between trainings usually spanning several years, except for first aid training which is mostly given yearly or "on occasion". More analyses of the interviews conducted can be referred from Cels et al. (2023b).

Overall, it can be said that the school principals have much of the responsibility for preparing their schools against tsunami risk. The principals interviewed are aware of the tsunami risks to their schools and have acknowledged that tsunami is a significant hazard that could affect their schools. This can be seen as a positive indication, since risk awareness is the first step to engaging with or adopting risk reduction measures. However, limitations in physical and human resources in the schools are likely to affect the preparation and adoption of such measures, especially against tsunami. Therefore, it is recommended to place greater priority on tsunami disaster risk reduction training; and provide more resources at school level for greater empowerment and development of contextualised solutions.

5. VULNERABILITY OF SCHOOLS TO TSUNAMI

Once the exposure and preparedness of schools were understood, the vulnerability of the schools to tsunami scenarios were assessed, since understanding the vulnerability of school buildings to tsunami inundations is vital, as outlined in the first and second pillars of the CSSF. In particular, the physical vulnerability of the schools were assessed by modelling their fragility to tsunami. A limited number of studies have attempted to characterise tsunami vulnerability of Sri Lankan buildings in terms of fragility functions in the past, with most of them employing empirical datasets on masonry residential buildings (Peiris and Pomonis, 2005; Dias et al., 2009; Murao and Nakazato, 2010). Hence, this consortium embarked upon the development of fragility functions for Sri Lankan schools using different approaches. Firstly, Del Zoppo et al. (2021) developed analytical fragility functions for a typical reinforced concrete school building in Sri Lanka. This study adopted a variable depth pushover approach, which does not require detailed information of the tsunami inundation to analyse the building's response. This approach is currently being expanded to develop fragility functions for all three types of school buildings identified as being the predominant multi-storey reinforced concrete building typologies in Section 3.

In order to complement the ongoing work on the multi-storey reinforced concrete building types, the team also developed tsunami fragility functions for single-storey masonry school buildings using an empirical approach. For this, a set of damage surveys conducted by the Sri Lankan Ministry of Education (2005) in the aftermath of the IOT for 154 schools across nine districts was used. The methodology followed to establish tsunami empirical fragility functions is presented in Figure 5.

Initially, the hand written school damage data was digitized. The damage survey forms consisted of seven sections, namely (1) school information, (2) school building layout, (3) buildings in need of reconstruction/rehabilitation, (4) building damage levels, (5) damages to school furniture, (6) incomplete buildings, and (7) a building inventory. For this analysis, a sample of 96 school surveys, with an average of eight buildings per school, were taken. While digitizing the data, the survey reports were also cross-checked with school location (Sri Lankan Disaster Management Centre, 2020), census data (Department of Census & Statistics, 2019), and reconstruction monitoring data (The Education Rehabilitation Monitor, 2009), as well as Google Earth satellite imagery between 2002 and 2022. In the survey reports, damages to buildings were rated between 0 (no damage) to 10 (complete damage). These rating were converted

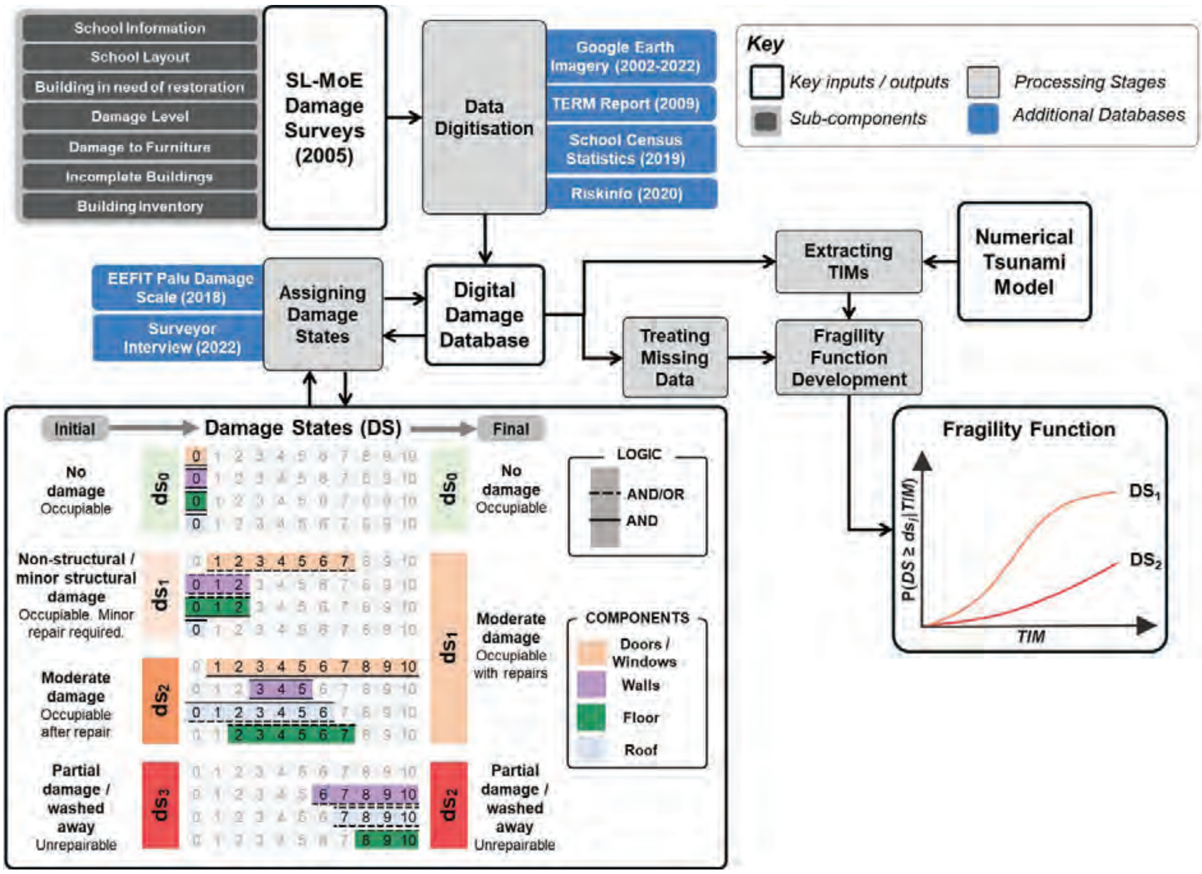


Figure 5. Method for empirical fragility function development for masonry school buildings

to damage states, using damage scale descriptions given in the Earthquake Engineering Field Investigation Team (EEFIT) report by Rossetto et al. (2019), supplemented with an interview with three members of the survey teams (Fernando et al., 2022). Four conceptual damage states (DS) were subsequently defined and coalesced into three damage states (see Figure 5), due to the polarised distribution of damage ratings.

Single-storey buildings, excluding temporary buildings, water wells and water tanks, were filtered to develop a representative building class for masonry school buildings (Dias et al., 2006). Considering the approximate standard area of a classroom in Sri Lanka, buildings with footprints ≥ 37 m^2 were selected (Sathurshan et al., 2023). Where building damage ratings were known, a DS was assigned. Detailed numerical simulations of the tsunami inundation from the 2004 IOT were conducted to determine the tsunami intensity level at each school site. The numerical simulations were conducted using an inverted source model to determine slip distribution, with results validated against GPS and DART buoy data. The vertical co-seismic dislocation was calculated using a homogeneous elastic half-space model. The Kajiura filter was applied for ocean surface deformation to set initial conditions. The Thetis model with an unstructured mesh provided detailed tsunami propagation and inundation simulations. Bathymetric data from GEBCO and SRTM+ were blended using the HRDS Python package for accurate coastal modeling (Baskaran et al., 2023). Tsunami inundation height was considered as the intensity measure in the fragility analyses, as it is commonly used in this field. Maximum inundation depth values (h_{max}) were subsequently assigned to each school complex, where pre-tsunami coordinates were known. As detailed by Baskaran et al. (2023), DSs were then aggregated by school complex, and a h_{max} < 2 m constraint applied, before representative empirical fragility functions were developed for ds_1 and ds_2.

Likelihood ratio tests were conducted on the empirical fragility functions produced in this study, with ds_2 identified as the only curve of statistical significance at the p = 0.05 threshold. This curve is plotted in Figure 6 with its 90% confidence interval (CI), and compared with fragility functions developed in previous studies on comparable tsunami events. Alignment with previous studies is observed at h_{max} > 1.6 m, which could be attributed in part to the uncertainty in damage rating assignment at shallow inundation depths (Murao and Nakazato, 2010). In this range, the 'Partial Damage/washed away' (ds_2) fragility curve of this study lies between the 'Severe' (ds_4) and 'Collapse' (ds_5) curves developed by Reese et al. (2011) for masonry residential buildings. This also observed between RC building curves: 'Damage to primary members' (ds_2) and 'Collapse' (ds_3), from Lahcene et al. (2021). As expected, the masonry, residential building curves show a close proximity to the 90% CI of ds_2, whilst the

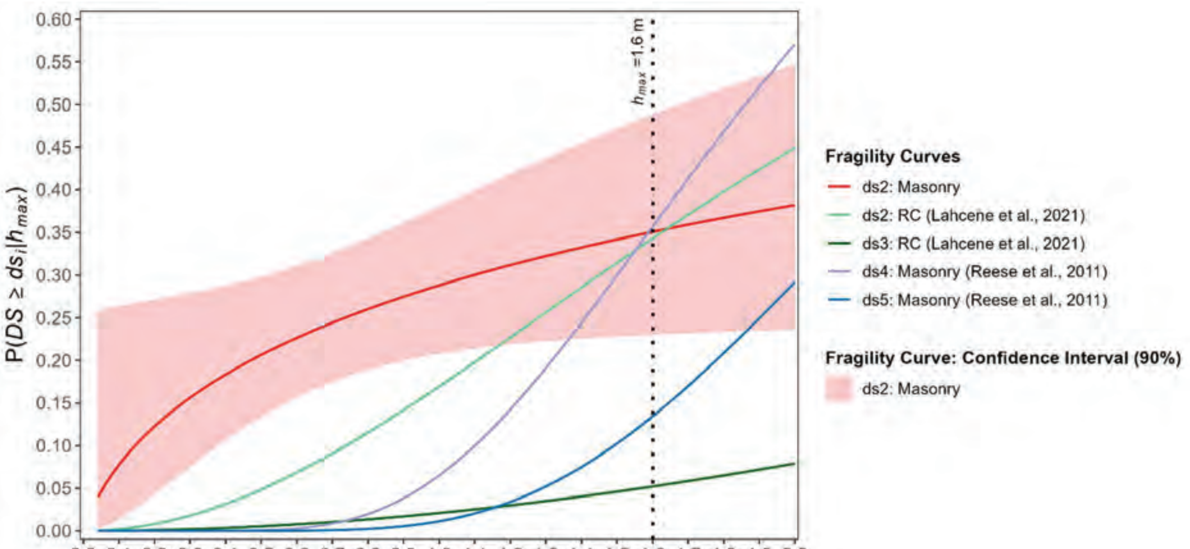


Figure 6. Empirical tsunami fragility function and 90% confidence interval for ds2, compared with those from previous studies

'Collapse' DS of RC buildings lies well below this interval. Multi-storey RC buildings have been shown to have higher structural stability compared to single-storey masonry structures (Dias et al., 2006), which justifies their lower fragility.

6. SUMMARY AND CONCLUSIONS

Schools generally facilitate community recovery and educational continuity in the aftermath of natural hazard events. Hence, school education management and infrastructures should be planned to mitigate imminent disasters. The 2004 IOT exposed several shortcomings in the school management and infrastructure in Sri Lanka. Measures have been taken subsequently to build back better the education system, although their relevance (e.g. to the CSSF) has not been well verified. Although the material presented in this paper may appear to be isolated aspects of school tsunami resilience, the way the exposure, preparedness and vulnerability studies reported herein relate to the three pillars of the CSSF has been clearly spelt out. Through exposure surveys, the current state of the rebuilt/rehabilitated school buildings and their structural and non-structural features were documented. The semi-structured interviews conducted to gauge the preparedness of schools to tsunami revealed that on the one hand principals rate tsunami risk as very high, though they are least prepared and resourced for it; while on the other hand, tsunami risk has dropped down the list of priorities among school zonal officials, which has led to limited resource allocation in the education system. The vulnerability of schools to tsunami, in particularly those of single-storey masonry buildings, was assessed by developing empirical fragility functions. These clearly imply that masonry school buildings can be fully damaged even under low level of tsunami inundation. Due to this conclusion, it can be assumed that all structures of this type will not survive future tsunami and that students using these buildings will need to be evacuated elsewhere. Thus, assessments were made to comprehend the tsunami risk on three fronts, namely (1) exposure, (2) preparedness and (3) vulnerability of buildings (though focused only on masonry buildings, here). Meanwhile, research work is still underway on developing analytical fragility function for the three identified predominant reinforced concrete school typologies. Such schools have a higher likelihood of survival, and may, under certain conditions, be adequate for use as vertical evacuation. A full comprehension of the likely damage to school structures will allow for evidence-based decisions on evacuation and on what actions need to be taken to ensure education can resume soon after a tsunami. Although twenty years have passed since the 2004 IOT, Sri Lanka is still inevitably exposed to tsunami risk. The outcomes of these studies can be used in the future to take informed decisions by policy makers to prepare Sri Lankan schools against such tsunami risk.

7. ACKNOWLEDGMENTS

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8. REFERENCES

Pomonis., A, Rossetto, T., Wilkinson, S, Del Re, D., Gallocher, S., Peiris, N., & et al. (2006). The Indian Ocean tsunami of 26 December 2004: Mission findings in Sri Lanka and Thailand. Available at: https://www.istructe.org/IStructE/media/Public/Resources/report-eefit-Indian-Ocean-tsunami-20190815.pdf

Suppasri, A., Goto, K., Muhari, A., Ranasinghe, P., Riyaz, M., Affan, M., Mas, E., Yasuda, M., & Imamura, F. (2015). A decade after the 2004 Indian Ocean Tsunami: The progress in disaster preparedness and future challenges in Indonesia, Sri Lanka, Thailand and the Maldives. *Pure Appl. Geophys*, 172, 3313–3341.

Dharmadasa, K., Kulatunga, U., & Eranga, I. (2024). Significance of critical infrastructure development in post-disaster resettlement in Sri Lanka. *International Journal of Construction Management*, 1–10. https://doi.org/10.1080/15623599.2024.2320972

UNISDR (2015). Sendai Framework for Disaster Risk Reduction 2015-2030. Available at: https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030.

UNISDR & GADRRRES (2017). Comprehensive school safety: a global framework in support of the The Global Alliance for Disaster Risk Reduction and Resilience in the Education Sector and The Worldwide Initiative for Safe Schools. Available at : https://www.undrr.org/publication/comprehensive-school-safety-framework-2017.

UNICEF (2009). Children and the 2004 Indian Ocean Tsunami: Evaluation of UNICEF's Response in Sri Lanka (2005-2008). Country Synthesis Report. New York.

The Education Rehabilitation Monitor (2009). Reconstruction and Rehabilitation Program of Tsunami Affected Schools.

Karafagka, S., Riga, E., Oikonomou, G. et al. (2024) RiskSchools: A prioritization-based system for the risk assessment of school buildings combining rapid visual screening smartphone app and detailed vulnerability analysis. *Bulletin of Earthquake Engineering,* 22, 2951–2980. https://doi.org/10.1007/s10518-024-01889-x

Clemente J.C., and Concha N.C., (2020) Assessment of Seismic Vulnerability of Public Schools in Metro Manila within 5 Km from the West Valley Fault Line using Rapid Visual Survey (RVS). *IEEE 12th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management (HNICEM)*, Manila, Philippines, 2020, pp. 1-4, doi: 10.1109/HNICEM51456.2020.9400131.

Gentile, R., Galasso, C., Idris, Y., Rusydy, I. and Meilianda, E., 2019. From rapid visual survey to multi-hazard risk prioritisation and numerical fragility of school buildings. *Natural Hazards and Earth System Sciences*, 19(7), pp.1365-1386.

Sathurshan M, Thamboo J, Mallikarachchi C, et al (2023) Rapid seismic visual screen method for masonry infilled reinforced concrete framed buildings: Application to typical Sri Lankan school buildings. *International Journal of Disaster Risk Reduction,* 92:103738. https://doi.org/10.1016/j.ijdrr.2023.103738

Cels, J., Rossetto. T., Dias, P., Thamboo, J., Wijesundara, K., Baiguera, M., & Del Zoppo, M. (2023a). Engineering surveys of Sri Lankan schools exposed to tsunami. *Frontiers in Earth Science*, 11, 1075290. https://doi.org/10.3389/feart.2023.1075290.

Cels, J., Rossetto, T., Little, A.W., Dias, P. (2023b). Tsunami preparedness within Sri Lanka's education system. *International Journal of Disaster Risk Reduction,* 84, 103473. https://doi.org/10.1016/j.ijdrr.2022.103473.

Peiris, N., & Pomonis, A. (2005). December 26, 2004 Indian Ocean Tsunami: Vulnerability functions for loss estimation in Sri Lanka. *In Geotechnical Engineering for Disaster Mitigation and Rehabilitation - Proceedings of the 1st International Conference. Singapore: World Scientific Publishing* Co. Pte. Ltd., pp. 411–416. Available at: https://doi.org/10.1142/9812701605_0048.

Dias, W.P.S., Yapa, H.D., & Peiris, L.M.N. (2009). Tsunami vulnerability functions from field surveys and Monte Carlo simulation. *Civil Engineering and Environmental Systems*, 26(2), 181–194. https://doi.org/10.1080/10286600802435918.

Murao, O., & Nakazato, H. (2010). Vulnerability functions for buildings based on damage survey data in Sri Lanka after the 2004 Indian Ocean Tsunami. Proceedings of *International Conference on Sustainable Built Environment (ICSBE-2010)*. Kandy, pp. 371–378.

Del Zoppo, M., Wijesundara, K., Rossetto, T., Dias, P., Baiguera, M., Di Ludovico, M., Thamboo, J., & Prota, A., (2021). Influence of exterior infill walls on the performance of RC frames under tsunami loads: Case study of school buildings in Sri Lanka. *Engineering Structures*, 234, 1–15. https://doi.org/10.1016/J.ENGSTRUCT.2021.111920.

Sri Lankan Ministry of Education (2005). Post-Tsunami School Damage Surveys.

Sri Lankan Disaster Management Centre (2020). Riskinfo. Available at: http://riskinfo.lk/ (Accessed: 29 January 2020).

Department of Census & Statistics (2019). School List 2019. Battaramulla, Sri Lanka.

Rossetto, T., Raby, A., Brennan, A., Lagesse, R., Robinson, D., Adhikari, R.K., Rezki-Hr, M., Meilianda, E., Idris, Y., Rusydy, I., & Kumala, I.D. (2019). The Central Sulawesi, Indonesia Earthquake and Tsunami of 28th September 2018 – A Field Report by EEFIT-TDMRC. London. Available at: https://www.istructe.org/IStructE/media/Public/Resources/report-eefitmission-sulawesi-indonesia-20200214.pdf.

Fernando, L., Wanasinghe, S., & Inoka, A. (2022). 2005 Damage Survey Interview. Online.

Dias, P., Dissanayake, R., and Chandratilake, R. (2006). Lessons learned from tsunami damage in Sri Lanka, *Proceedings of the Institution of Civil Engineers - Civil Engineering*, 159(2), 74–81. https://doi.org/10.1680/cien.2006.159.2.74.

Sathurshan, M., Thamboo, J., Mallikarachchi, C., Wijesundara, K., Dias, P. (2023). Rapid seismic visual screen method for masonry infilled reinforced concrete framed buildings: application to typical Sri Lankan school buildings. International Journal of Disaster Risk

Reduction, 92:103738. https://doi.org/10.1016/j.ijdrr.2023.103738

Baskaran, H., Salah, P., Sathurshan, M., Cels, J., Ioannou, I., Rossetto, T., Thamboo, J., Dias, P., Warder, S., & Piggott, M. (2023). Empirical tsunami fragility assessment of masonry schools in Sri Lanka. *Proceedings of Earthquake Engineering & Dynamics for a Sustainable Future (SECED 2023)*, Cambridge, UK. https://seced.org.uk/index.php/seced-2023-proceedings/67-fragility-vulnerability-infrastructure-resilience/827-empirical-tsunami-fragility-assessment-of-masonry-schools-in-sri-lanka.

Reese, S., Bradley, B.A., Bind, J., Smart, G., Power, W., & Sturman, J. (2011). Empirical building fragilities from observed damage in the 2009 South Pacific tsunami. *Earth-Science Reviews*, 107(1–2), 156–173. https://doi.org/10.1016/J.EARSCIREV.2011.01.009.

Lahcene, E., Ioannou, I., Suppasri, A., Pakoksung, K., Paulik, R., Syamsidik, S., Bouchette, F. and Imamura, F. (2021). Characteristics of building fragility curves for seismic and non-seismic tsunamis: case studies of the 2018 Sunda Strait, 2018 Sulawesi–Palu, and 2004 Indian Ocean tsunamis. *Natural Hazards and Earth System Sciences*, 21(8), 2313–2344. https://doi.org/10.5194/nhess-21-2313-2021.

Numerical Simulation of Tsunamis Observed in Sri Lanka Generated by Remote Volcanic Eruptions

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ABSTRACT

Earthquakes beneath the ocean floor, volcanic eruptions and landslides are the main causes of tsunamis. In this study, we investigate whether tsunami waves along the coastline of Sri Lanka could be caused by remote volcanic eruptions. Two super volcano eruptions such as August 1883 Krakatoa and January 2022 Hunga Tonga–Hunga Ha'apai, were selected for the numerical simulations. Both events generated basin-wide tsunamis and signals were also recorded along the coastline of Sri Lanka. A range of simulations were performed to determine whether the tsunami signals along the coastline of Sri Lanka were caused by: (1) tsunami that were originated at the erupted area due to the verity of mechanisms; or (2) oceanic response to outward radiating atmospheric pressure waves and Proudman resonance (meteotsunami).

The simulation results suggest that the tsunami waves (height over 0.9 m) that hit the Sri Lanka coastline during the Krakatoa event was generated at eruptive site (conventional volcanic tsunami) and propagated as a free wave towards the Sri Lanka. The wave amplification through the Proudman resonance condition may not have been satisfied by the fast-moving atmospheric waves between Krakatoa and Sri Lanka. However, the simulation results from the Tonga event indicated that the time and amplitude of the observed sea-level changes were consistent with the simulated sea-level changes forced by the atmospheric forcing, whereas wave was generated through air-sea interaction and amplified through the near Proudman resonance in the deep ocean. A set of experiments with different bandwidth atmospheric pressure jumps revealed the importance of amplification due to near-Proudman resonance over deep ocean basins and the shoaling effect over the continental slope.

Key words: Tsunami, Volcanic eruption, Krakatoa, Tonga, Numerical simulations

1. INTRODUCTION

Volcanic tsunamis can be generated by several mechanisms within one eruptive sequence and are typically characterized by relatively short period, dispersive waves whose destructive potential is limited to the near field. Typically, such near filed, or non-transoceanic tsunamis are generated by underwater explosion and mass collapses such as flank, pyroclastic flow, eruptive column, and caldera. In a supper volcanic eruption, the excitation of atmospheric oscillations includes the near-source acoustic waves and internal gravity waves, as well as planetary scale atmospheric waves (also known as Lamb waves) which can excite tsunami waves far away (Kanamori et al., 1994). However, super volcano eruptions can produce a large near field atmospheric pressure disturbance and outward radiating fast moving atmospheric waves. The outward fast moving atmospheric waves can cause global tsunamis due the inverted barometric effect and wave amplification at deep sea through resonance conditions (Proudman, 1929). Tsunamis that generated by atmospheric forcing can be considered as meteotsunamis and are the only tsunamis that may have a global propagation, as appear to have been the case for 1983 Krakatoa and 2022 Hunga Tonga–Hunga Ha'apai Hunga Tonga events (Harkrider & Press, 1967, Wright et al., 2022).

The effects of the volcanic explosions and collapses of the volcano of Krakatoa (6.1021°S, 105.4230°E) in Indonesia on August 26-27, 1883,

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including the effects of its destructive tsunami, were extensively reported in early scientific reports based on geological surveys and data collected in the affected area (Warton and Evans, 1888). It was revealed that approximately 10 km^3 of solid rock was blown out of the volcano and about 20 km^3 of pyroclastic deposits spread out over 300 km^2 to an average depth of 40 m (Bryant, 2001). A caldera 6 km in diameter and 270 m deep was formed where the central island had once stood (Bryant, 2001). The eruption generated atmospheric shock waves that travelled around the world several times (Bryant, 2001). Hunga Tonga–Hunga Ha'apai (20.54°S, 175.38°W, hereafter '2022 Tonga') is one of several active volcanoes in the South Pacific and it erupted on 15 January 2022. This volcanic explosion was thought to be equivalent to VEI 5, this eruption was an order of magnitude greater than the 1991 eruption of Pinatubo in The Philippines (Cronin et al., 2022) and represents the biggest eruption of a submarine volcano for nearly one and a half centuries since the cataclysmic destruction of Krakatoa in Indonesia in 1883. The eruption produced a plume that elevated 58 km into the troposphere and a broad spectrum of waves was triggered by the initial explosion, including Lamb waves propagating at phase speeds of $318.2 \pm 6\ ms^{-1}$ at surface level and between 308 ± 5 to $319 \pm 4\ m\,s^{-1}$ in the stratosphere, and gravity waves propagating at 238 ± 3 to $269 \pm 3\ m\,s^{-1}$ in the stratosphere (Harrison, 2022; Yuen et al., 2022). These atmospheric pressure waves were captured at weather stations around the world and were found circling the Earth at least five times over several days following the explosion (Amores et al., 2022).

Both 1883 Krakatoa and 2022 Tonga caused global tsunamis through outward travelling atmospheric pressure waves. The main mechanism of tsunami generation is called the Proudman resonance (Proudman, 1929; Pattiaratchi and Wijeratne, 2015), a physical process where pressure perturbations of atmospheric waves amplify oceanic waves that have close phase speeds. The Froude number, $F_r = U/C$, defined as the ratio between the propagating pressure jump's propagation speed (U) and the long wave propagation speed (C), is the measure of the relative effects of inertia on the gravitational forces. The simplified, one-dimensional form of the water level change due to the propagating pressure jump over the shallow seas is defined as $\eta_c = \frac{1}{1-F_r}\eta_o$, where $\eta_o = \left(\frac{\Delta p}{\rho g}\right)$ water level change due to the inverted barometric effect by a change of sea level pressure Δp (ρ = water density). When $0 \le F_r < 1$, the system becomes subcritical, and a negative water elevation id formed below the positive pressure jump, which is directly correlated with the atmospheric pressure distribution and vice versa. The direct sea level response to changes in atmospheric pressure is approximately 1 cm for each hPa of change in the pressure exerted by the air column above (usually referred to as the inverted barometer response). For subcritical conditions, gravity plays the main role in water level change, and most of the energy is used to depress or increase the water level, which is also determined by the length scale of the atmospheric forcing (e.g., wavelength or bandwidth of the pressure jump). In the case of supercritical conditions ($F_r > 1$), kinetic energy dominates the total energy, and a positive or negative water level will be generated ahead of a positive or negative pressure jump. When $F_r \sim 1$, Proudman resonance occurs with amplification of the surface water waves.

This study focuses on the tsunami generated by fast travelling atmospheric pressure jumps and attempts to reveal whether the tsunami waves along the coast of Sri Lanka could be generated through remote volcanic eruptions.

2. NUMERICAL MODEL

We used the Regional Ocean Modelling System (ROMS; www.myroms.org) to perform the numerical simulations. ROMS is a three-dimensional, free-surface, split-explicit primitive equation model with Boussinesq and hydrostatic approximation (Shchepetkin and McWilliams, 2005). ROMS provides an accurate and stable numerical representation of the inverted barometric effect and resonance amplification (Renault et al., 2011; Ličer et al., 2017; Bubalo et al., 2018). The model bathymetry was constructed using GEBCO 2023 data. The model domain covers whole of the Indian Ocean and western part of the Pacific Ocean basin (Figure 1). The minimum depth in the model was set to 1m and maximum depth was set to ocean full depth (10,500 m). A variable horizontal model resolution was chosen to capture the coastline, shelf slope, and shelf bathymetry. The model

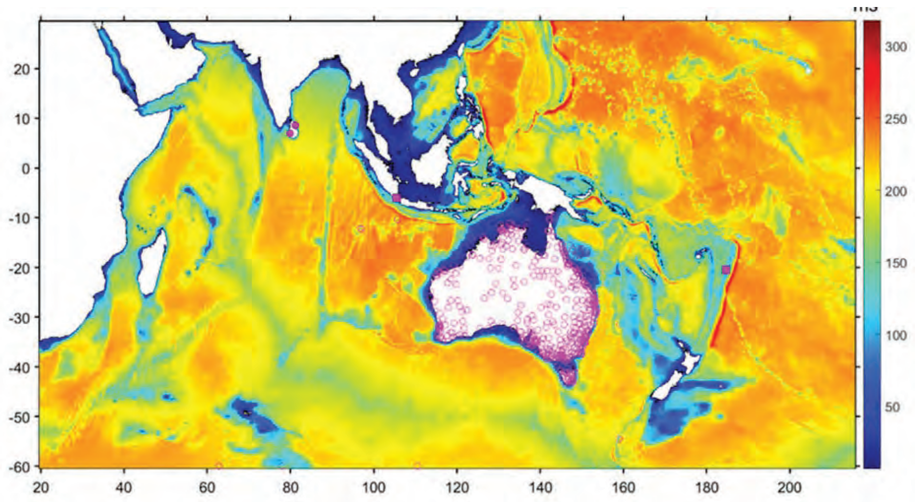

Figure 1. Map of long wave speed (√gh), g is 9.81 ms^{-2}, h (m) is depth. Krakatau (105.4230° E, 6.1021° S) and Tonga (184.62º E, 20.54º S) volcano locations are denoted in purple squares. Tide gauge stations in Sri Lanka (Trincomalee on the east coast and Colombo on the west coast) are denoted in face filled purple circles. Atmospheric pressure observation stations are denoted in purple circles. The pressure data was obtained from the weather monitoring network in Australia (see details Davies, 2024).

had 2160 x 2160 horizontal dimensions and 15 S vertical levels in terrain-following coordinates. Potential horizontal gradient errors were minimised by smoothing the bathymetry slope factor (Beckmann and Haidvogel, 1993) rx0 = 0.12 and the Haney number, rx1 = 4.0, which ensured numerical stability for the ROMS grid. HyCOM model data, was used to define the initial and open boundary fluxes, salinity, and temperature. TPXO global tidal model solutions were used to construct the open boundary tidal forcing (Egbert and Erofeeva, 2002).

The atmospheric pressure forcing P was imposed as an external surface forcing and assumed to be an outward radiating pressure jump from the eruption location (Figure 2), the amplitude of the atmospheric pressure jump decreased from the eruption location as shown in the Figure 2. For the 2022 Tonga event, ~ ten hours after the explosion, the jump propagated over Sri Lanka, where pressure jump was approximately 1.5 hPa. For the 1983 Krakatoa event, after ~ 3 hours of the explosion, the jump propagated over Sri Lanka, where jump was ~ 3.5 hPa. To create an initial artificial water displacement due to the eruption process, we included a large pressure disturbance/jump (40 mb) for 15 min at the time of explosion. Literature suggests that speed of the pressure wave from Krakatoa was ~ 301 ms^{-1} from east to west and 316ms^{-1} from west to east. The violent eruption of the volcano 2022 Tonga generated an intense pressure wave registered by instruments globally. The observations revealed that travelling speed was 300-330 ms^{-1} for the 2022 Tonga event. For the validation simulations, the bandwidth of the pressure jump was set to 300km. Global meteorological observations revealed that the atmospheric pressure wave propagated several times around the Earth. Our simulation, however, was limited to the initial propagation of pressure waves across the model domain (Figure 1).

The synthetic simulations were also conducted to examine the sensitivity the bandwidth of propagating pressure jumps influence the wave amplification through near Proudman Resonance and shoaling of free waves on ocean slopes and shelf slopes. The bandwidth of the pressure jump defines the rate-of-change of the pressure within the jump.

3. RESULTS

3.1. Atmospheric pressure wave characteristics

The pressure wave travelling speed, wave period, and wave height have been estimated using Australian atmospheric pressure gauge records during the 2022 Tonga event, which were compiled by Davis et al. (2024). First, the arrival times of the first peaks of the pressure wave are extracted from the data with respect to 04:15 UTC as the event origin time at Tonga. Based on the arrival times and the distances from the volcano, the average traveling speeds for the pressure wave were derived (Figure 3). The maximum peak and trough values from the pressure time series were extracted to derive a relation for the amplitude of the pressure wave as a function of distance from the volcano. The atmospheric pressure

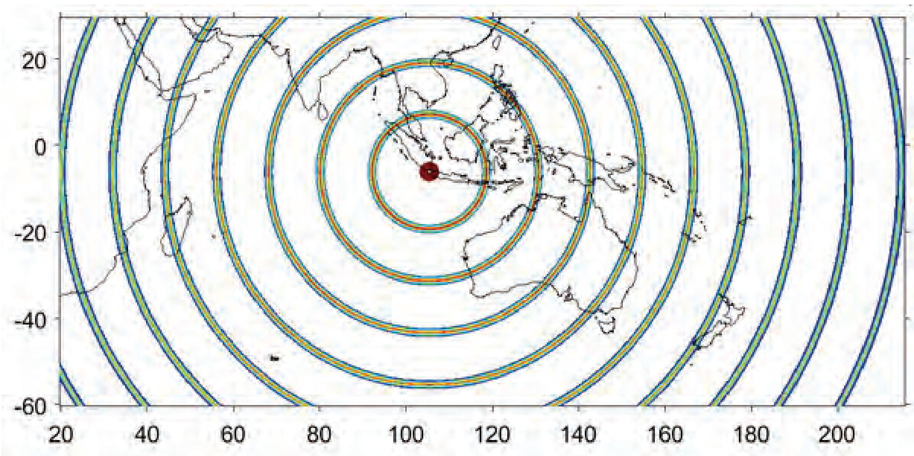

Figure 2. (a) Constructed atmospheric pressure wave propagation for 1883 Krakatoa event

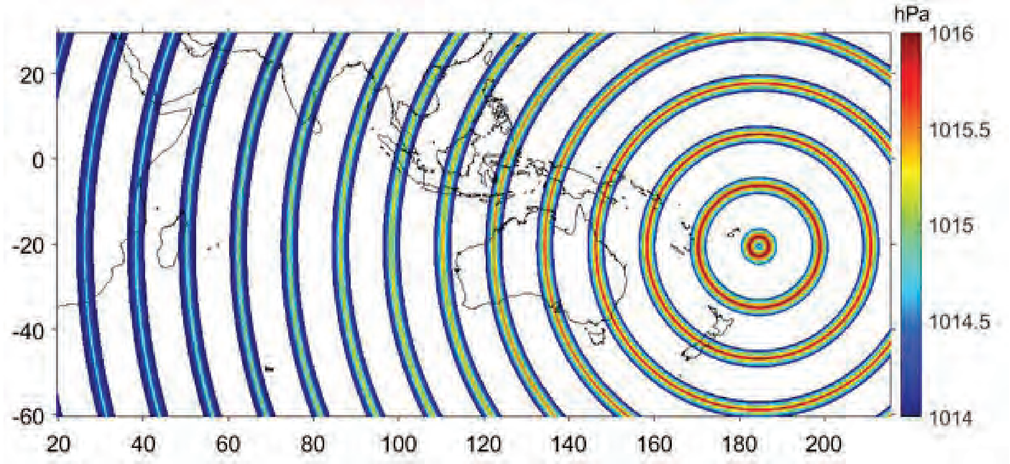

Figure 2. (b) Constructed atmospheric pressure wave propagation for 2022 Tonga event

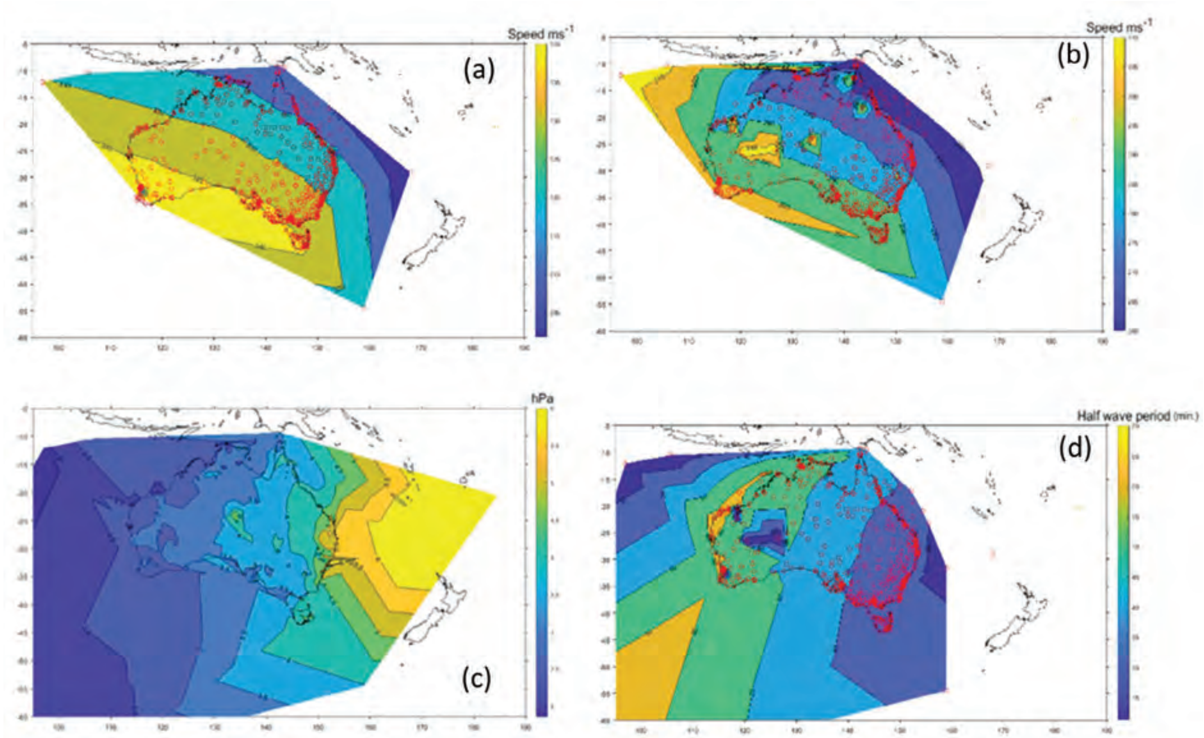

Figure 3. Atmospheric pressure wave crest travelling speed (a), trough travelling speed (b) wave height (c) and half wave period (d) estimated from Australian weather observation network (Davis et al., 2024).

jump propagation speed slightly increases as it moves away from the eruption location (Figure 3). The speed of crest propagation was marginally greater than the speed of trough (Figures 3a and b). The estimated average speed was ~ 320 $m\,s^{-1}$. Meanwhile, the height of pressure disturbance decreases as the distance increases, as shown in Figure 3c. The half wave period (time difference between the first crest and the first trough) varies from 30 to 60 min (Figure 3d). The estimated bandwidth of the atmospheric pressure jump varies from 300–750 km. Synthetic model simulations (Section 3.2) provided a better understanding of the meteotsunami generation process and wave height sensitivity to the propagating pressure jumps.

3.2. Synthesis Simulation

The earlier study demonstrated that magnitude, speed, and bandwidth of propagation pressure jump influenced the wave amplification through Proudman Resonance (Wijeratne and Pattiaratchi, 2024). However, previous simulations were limited to the shallow shelf with relatively low speed propagating (<50ms^{-1}) and narrow bandwidth (<50 km) pressure jumps. It is known that a decrease of atmospheric pressure with 1 hPa will lead to about 1 cm elevation of water level in static equilibrium, but when the disturbance moves with a similar speed of the free water waves, waves height can be reached to more than 20 times of the equilibrium height due to the Proudman resonance (Vilibić, 2008). Here, the results from synthetic simulations were presented to examine how Proudman Resonance response at deep for the wave amplification. We also examined how the bandwidth of propagating pressure jumps influences the wave amplification through Proudman resonance at deep see (>3000m depths). The synthetic pressure jump parameters were chosen based on travelling pressure jump data described in Section 3.1. We defined synthetic pressure jump with the magnitude of 4 hPa moving at a constant velocity (320ms^{-1}). We performed the simulation with various water depths (3000, 5000, 6500, 8000, and 10.500 km) and different bandwidth pressure jumps (400 and 750 km). In relation to depths, the corresponding Froud numbers (Fr) were 1.86, 1.44, 1.26, 1.14, and 1.00. As expected, the amplification was greatest for Fr = 1 (Figures 4 and 5). The amplification factor decreased with the increase of Fr from 1 to 1.86. Nonetheless, there was a notable amplification of waves for Fr < 1.4. The bandwidth of the pressure jumps also influence the wave amplification (Figures 4 and 5). The long wave speed between Krakatoa and Sri Lanka is about 210 ms^{-1} on average. Therefore, for a pressure jump moving at 320 ms^{-1}, the Froud number, Fr is ~ 1.5. As the supercritical situation

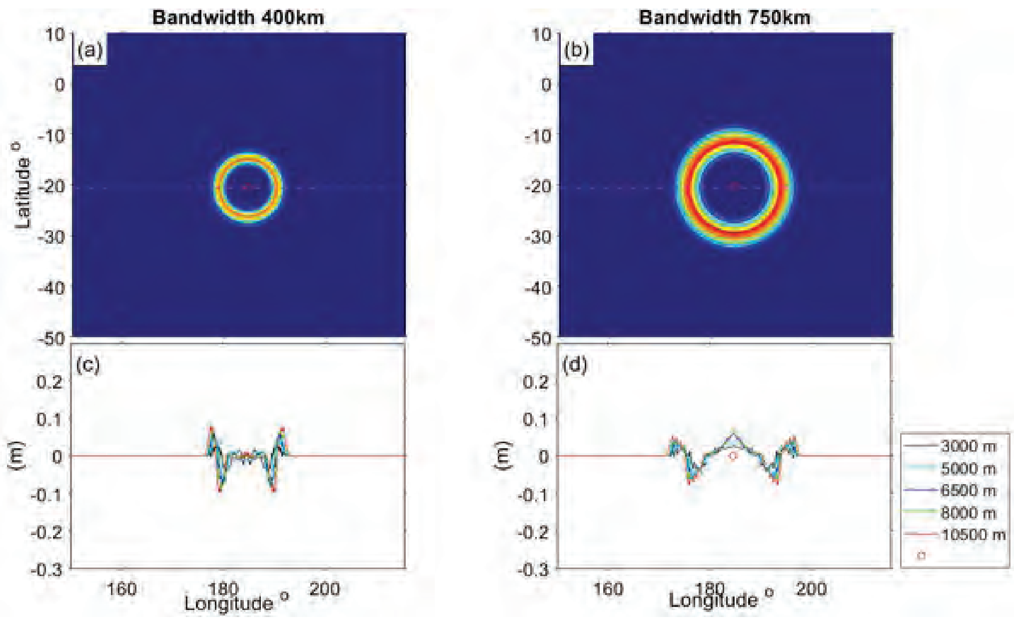

Figure 4. Simulation results showing wave amplification with the moving atmospheric pressure jump with different water depths. Upper panels (a and b) are showing outward radiating pressure jump (4 hPa) after 30 min with a speed of 320 ms^{-1}. Extracted water profiles along the dash line after 30 min (c) for 400 km bandwidth jump propagating at different depths and (d) for 750 km bandwidth jump propagating at different depths. The red circles show the centre of the eruption. The dash line shows the sea level profiling section.

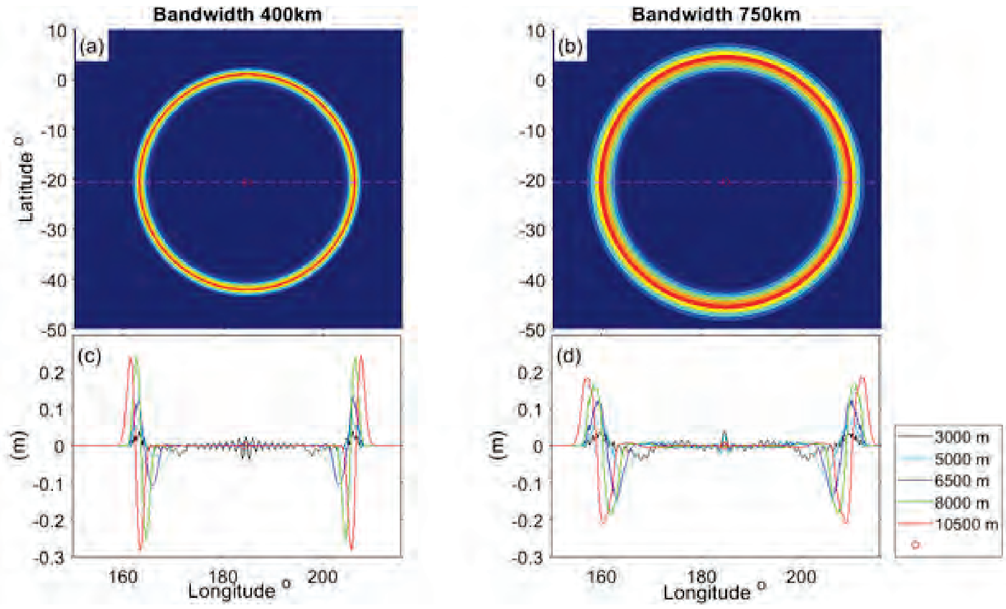

Figure 5. Simulation results showing wave amplification with the moving atmospheric pressure jump with different water depths. Upper panels (a and b) are showing outward radiating pressure jump (4 hPa) after 02 hrs with a speed of 320 ms^{-1}. Extracted water profiles along the dash line after 30 min (c) for 400 km bandwidth jump propagating at different depths and (d) for 750 km bandwidth jump propagating at different depths. The red circles show the centre of the eruption. The dash line shows the sea level profiling section

Fr >1, the classic Proudman resonance is not satisfied, and significant tsunami waves are hard to generate between Krakatoa and Sri Lanka with an atmospheric wave travelling with a speed of 320 ms^{-1}.

3.3. 1883 Krakatoa tsunami simulation

The Krakatoa is located approximately 3000km from Sri Lanka. The major volcano blast occurred at 03:00 (UTC) 27th August 1883 was largest from the series of the four main explosions during 26th and 27th (Bryant, 2001). The tsunami signals were recorded along the coastline of Sri Lanka (https://www.ngdc.noaa.gov/hazel/view/hazards/tsunami/related-runups/1142). The wave height recorded on the coast of Southern Sri Lanka was 1.2 m at Galle, while on the eastern and western coasts 0.9 m (Batticaloa) and 1.0 (Colombo), respectively. The specific features of the waves and the quality of the records remain unknown, though. The predicted snapshots of the tsunami waves in the Indian Ocean for the 300 km bandwidth propagation pressure jump are shown in Figure 6. The tsunami waves originate in the vicinity the volcano, where the amplitude is large due to the large atmospheric pressure disturbance at the time of eruption, which propagate as a free wave with the long wave speed. The wave that generated through the fast-travelling atmospheric wave under super critical state (Fr>1) propagates ahead of the free wave.

Snapshots of simulation results for the atmospheric wave propagation speeds 320 ms^{-1} and 270 ms^{-1} are shown in Figures 6 and 7, respectively. The first wave reached the coast of Sri Lanka at about 3 hrs after the eruption for the pressure jump speed of 320ms^{-1} and 3 hrs and 30 min for the 270 ms^{-1}. The first water level signal arrival time coincided with the atmospheric wave arrival time, which was not maximal wave. The large tsunami signals were recorded approximately 1 hr and 2 hrs after the first signal for the jump speed 320 ms^{-1}, 270 ms^{-1}, respectively (Figures 6 and 7). It was evident that a larger eruption could yield large atmospheric pressure changes over the erupted region, yielding a significant near-field inverse barometric water displacement in addition to water displacement due to the other mechanisms (landslides, collapses etc.). Time series of predicted tsunami waves at Trincomalee and Colombo for the travelling speeds 320 and 270 ms^{-1} are shown in Figures 8 and 9, respectively. Snapshots of results for the 750 km bandwidth pressure jumps propagating with a speed of 270 ms^{-1} is shown in Figures 10. The initial large pressure displacement with a broad bandwidth (750 km) caused the larger tsunami wave to be

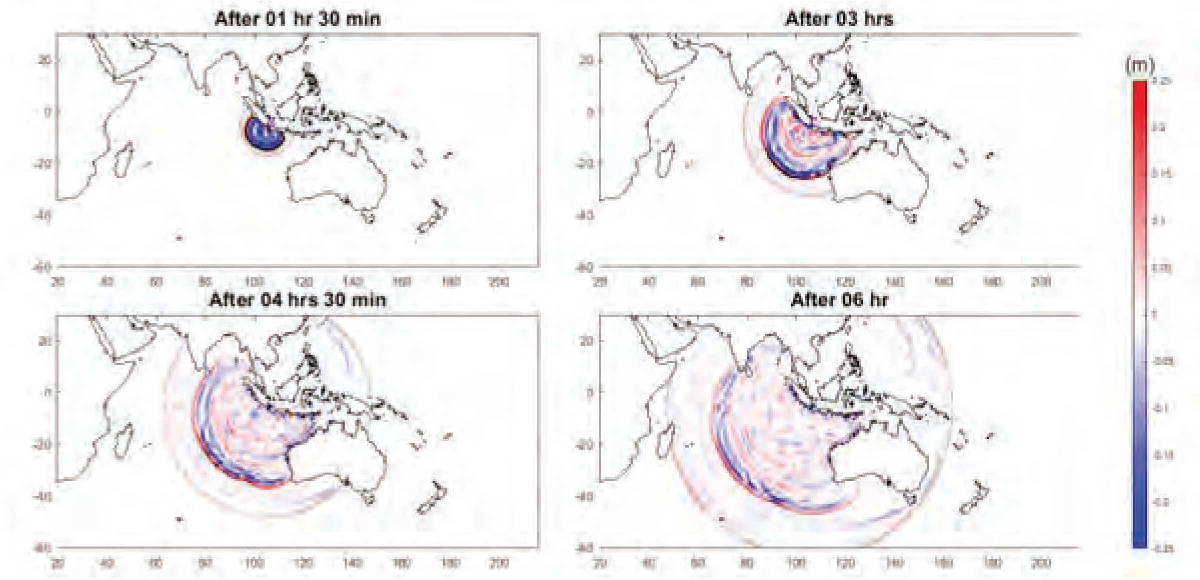

Figure 6. Snapshots of predicted tsunami wave propagation in the Indian Ocean during 1883 Krakatoa eruption for the 300 km bandwidth pressure jump and travelling speed 320 ms^{-1}

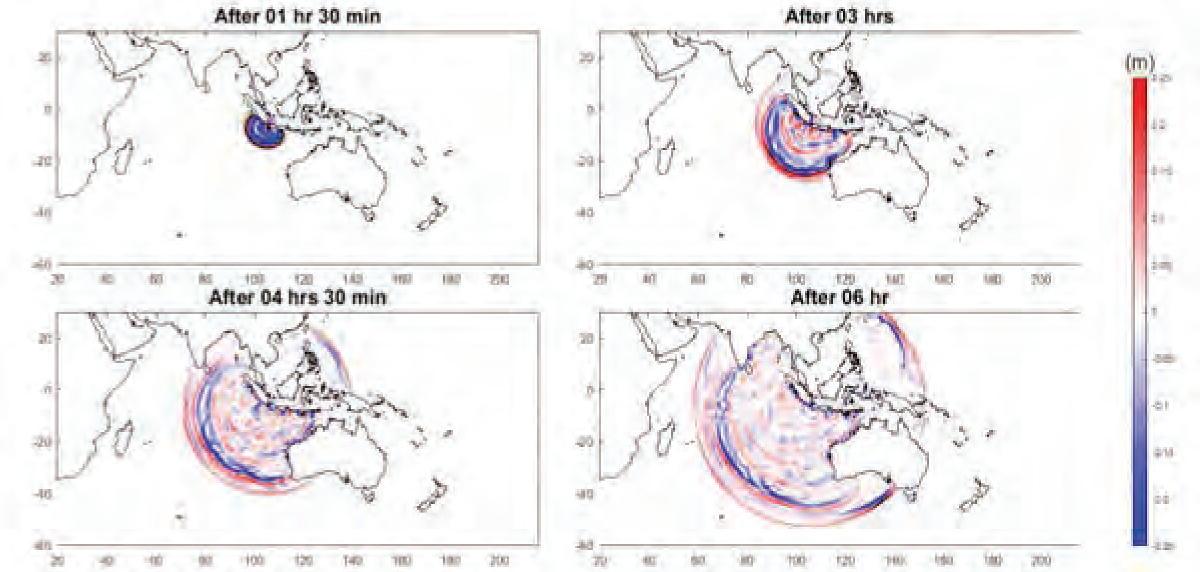

Figure 7. Snapshots of predicted tsunami wave propagation in the Indian Ocean during 1883 Krakatoa eruption for the 300 km bandwidth pressure jump and travelling speed 270 ms^{-1}

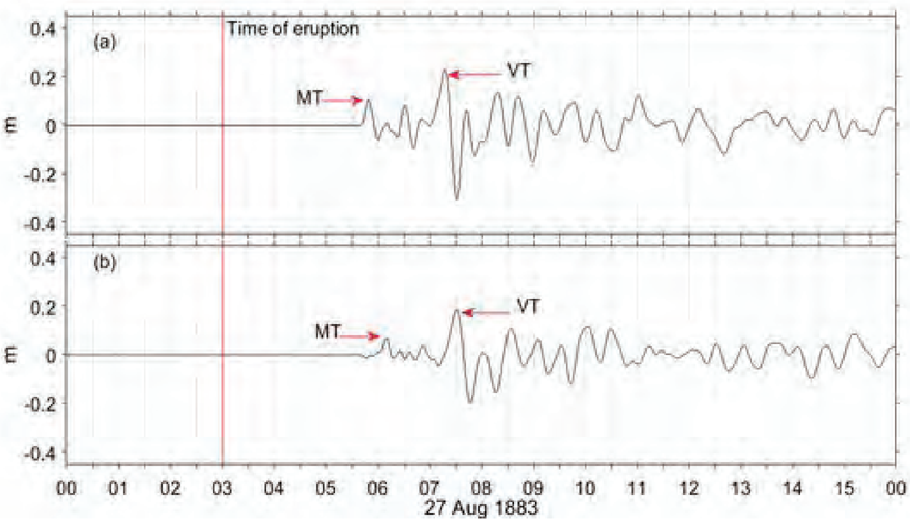

Figure 8. Numerically simulated time series of tsunami wave at Trincomalee (a) and Colombo (b) during 1883 Krakatoa eruption. The model was forced with a bandwidth of pressure jump of 300 km and travelling speed of 320 ms^{-1}. MT is Meteotsunami and VT is tsunami that generated at eruption site and propagated as a free wave

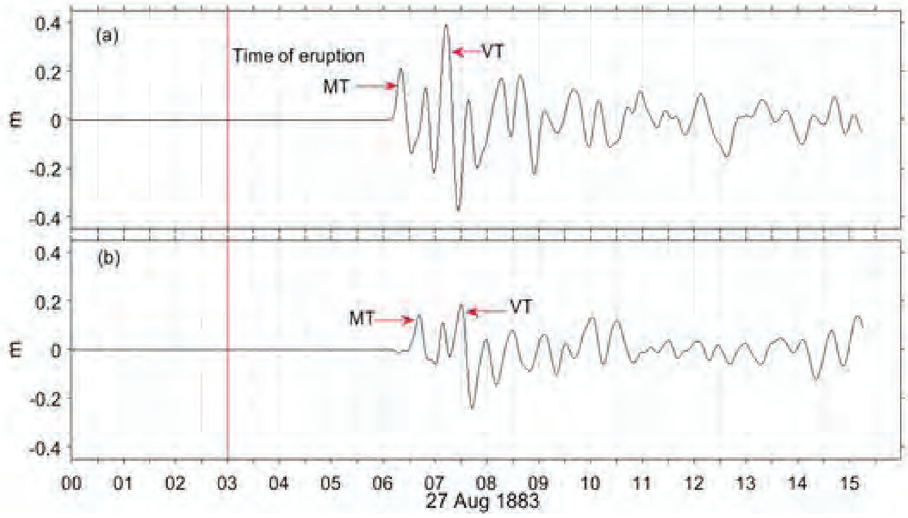

Figure 9. Numerically simulated time series of tsunami wave at Trincomalee (a) and Colombo (b) during 1883 Krakatoa eruption. The model was forced with a bandwidth of pressure jump of 300 km and travelling speed of 270 ms^{-1}. MT is Meteotsunami and VT is tsunami that generated at eruption site and propagated as a free wave

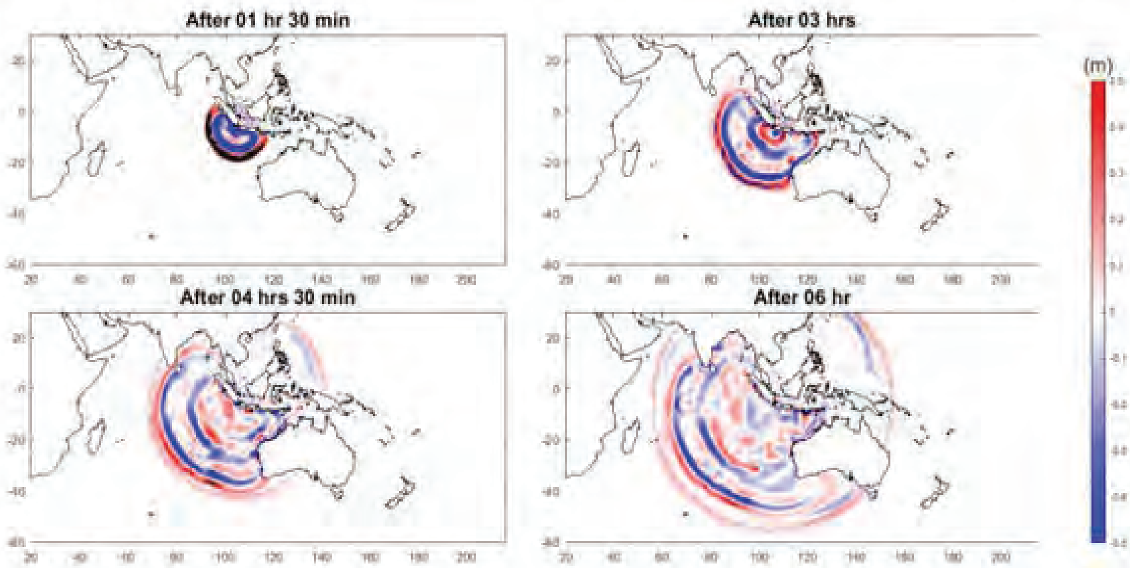

Figure 10. Snapshots of predicted tsunami wave propagation in the Indian Ocean during 1883 Krakatoa eruption for the 750 km bandwidth pressure jump

formed at the erupted region and propagated as free wave.

3.4. 2022 Tonga tsunami simulation

The volcanic eruption in Tonga occurred approximately 13,000 kilometres from Sri Lanka's shortest sea route and 11,500 kilometres from its strait (air route). The initial explosion and subsequent plume triggered atmospheric waves that propagated around the world multiple times (Yamada, 2022). Following the eruption, tsunami signals were recorded in Sri Lanka tide gauges, much earlier than expected based on the oceanic long-wave propagation from Tonga. The eruption occurred at 04:15 UTC (USGS, 2022) on 15 Jan 2022 and tsunami signals occurred at Trincomalee tide gauge at 14:35 UTC, so the tsunami wave travel time was ~ 10hrs and 20 min.). The pressure fluctuations travelled for ~ 09 hours and 40 min over 11,500 km from Tonga to Sri Lanka (strait distance) with a speed of 320 ms^{-1}. However, it takes approximately 17 hours for long free waves to travel from Tonga to Sri Lanka (~13,000km) with a wave speed ($C=\sqrt{gh}$) of 210 ms^{-1} (h=average water depth of 4500m between Sri Lanka and Tonga). Therefore, the observed sea-level fluctuations can be considered as meteotsunamis forced by the pressure perturbation rather than tectonically forced tsunami at eruption site. The simulation results are shown in Figures 11 and 12. Two main components of tsunami waves, phase-locked waves and free gravity waves were identified by significant differences in propagating speeds across the Indian Ocean. The long ocean wave propagated with the pressure jump in the deep ocean (>6000 m) and propagated behind the pressure jump in the shallow depth, which resulted in refraction of the long ocean wave due to bottom topography (Figure 11). The results show that the time and amplitude of the observed sea-level changes at Trincomalee and Colombo were consistent with a traveling atmospheric pressure jump, having a half wavelength of 300 km (Figure 12). The simulation reconstructs the tsunami waves induced by pressure disturbance well, thus we can discuss the mechanisms of near Proudman resonance amplification at deep sea and shoaling amplification at the slope through the model.

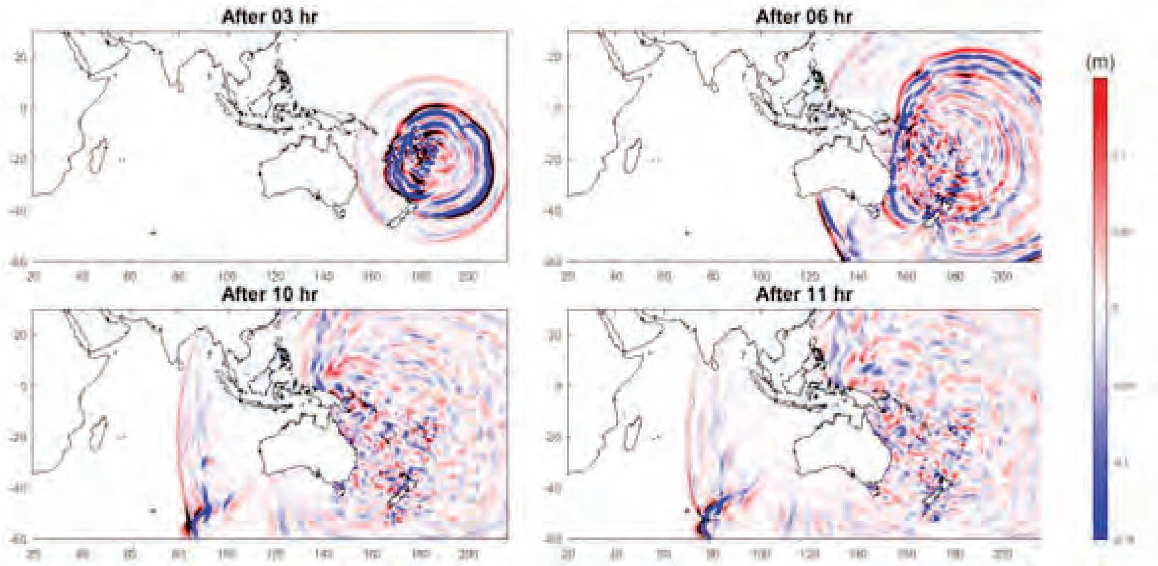

Figure 11. Snapshots of predicted tsunami wave propagation in the Indian Ocean during 2022 Tonga eruption for the 300 km bandwidth pressure jump

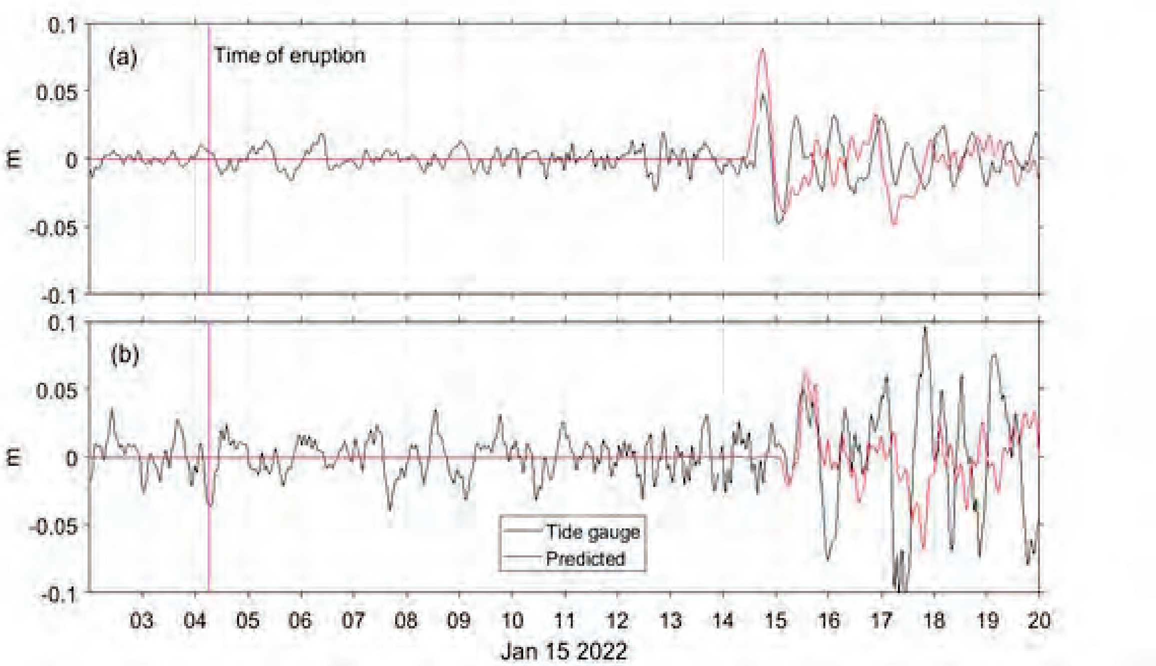

Figure 12. Comparisons of the measured and the predicted tsunami waves at Trincomalee (a) and Colombo (b) during 2022 Tonga eruption. The model was forced with a bandwidth of pressure jump of 300 km and travelling speed of 330 ms^{-1}

4. DISCUSSION

In this study, focus was whether the notable tsunami waves along the coastline of Sri Lanka could be caused by remote volcanic eruptions. The propagation of the tsunami waves generated by the Krakatoa and Tonga volcanic eruptions are studied numerically using Regional Ocean Modelling System (ROMS). It was revealed that rapidly moving atmospheric waves associated with volcano eruptions can trigger global scale meteotsunamis, as recorded after the 1883 Krakatoa eruption and after the 2022 Tonga eruption (Garrett, 1970; Omira et al., 2022; Yamada et al., 2022, Wijeratne and Pattiaratchi, 2023). It can be clearly shown that a pressure disturbance radiating from the volcanic eruption spread rapidly over the Indian Ocean with an average speed of 320 ms^{-1}, while a group of tsunami waves closely following the atmospheric disturbance. In the Indian Ocean, the pressure disturbance moved too fast to satisfy the full Proudman resonance condition (Fr=1), Fr, was larger than 1.2. However, simulation results shown that the waves were amplified with Fr=1.4 through near Proudman resonance condition. A large initial pressure disturbance associated with super volcanos has the potential to generate a large tsunami (Devlin, 2022). The simulation results show that relatively large tsunami waves were generated at the Krakatoa eruption region and were propagated to Sri Lanka as free waves.

A set of idealised simulations was conducted to examine the sensitivity of wave amplification to different bandwidths of propagating pressure jumps as observed during 2022 Tonga event. Free waves generated by other tsunami generation mechanisms such as underwater explosion and mass collapses, pyroclastic flow etc., which have not been considered in the simulation.

5. CONCLUSIONS

A numerical model was configured to investigate the generation mechanisms and propagation of tsunami waves over the Indian Ocean and towards the Sri Lanka coast by remote volcanic eruptions. The main conclusions are as follows:

- Numerical simulations shows that the observed large tsunami waves (~ 1m) along the Sri Lanka coastline during 1883 Krakatoa eruption cannot be attributed to the Proudman resonance (meteotsunami). They were generated at source location and propagated to towards the Sri Lanka as free waves.
- A larger eruption (such as the Krakatoa eruption of 1883) could yield atmospheric pressure changes up to 30 mb, yielding a 0.3 m near-field water displacement that would also propagate as a free wave.
- The results from numerical simulations suggested that the recorded tsunami signals that occurred on 15 Jan 2022 due to the Tonga eruption, was generated by amplification of long waves on the at deep sea (> 5000 m) through near Proudman resonance, shoaling and refracted free waves.
- The numerical results show clearly that the long waves amplified at deep ocean through Proudman resonance with large Froude number (Fr~1.4).
- The simulations revealed that the resonance and shoaling amplification were determined by bandwidth of the propagating pressure jump. The pressure jump with constant translational speed can cause significantly different wave amplification through Proudman Resonance and shoaling when the bandwidths were different.

6. ACKNOWLEDGMENTS

The atmospheric pressure data that support the analysis of this study are openly available from the Davies et al (2024). Sea level data from Sri Lanka were derived from IOC sea level monitoring facility, tide gauges are managed by National Aquatic Resources Agency. Access to the supercomputing facilities of the Pawsey Centre was enabled through the partner allocation scheme..

7. REFERENCES

Abbrescia, M., Avanzini, C., Baldini, L. et al. (2022). Observation of Rayleigh-Lamb waves generated by the 2022 Hunga-Tonga volcanic eruption with the POLA detectors at Ny-Ålesund. Sci Rep 12, 19978. https://doi.org/10.1038/s41598-022-23984-2.

Amores, A. et al. (2022). Numerical simulation of atmospheric lamb waves generated by the 2022 Hunga-Tonga Volcanic Eruption. Geophys Res. Lett. 49,e2022GL098240.

Beckmann, A., & Haidvogel, D. B. (1993). Numerical simulation of flow around a tall isolated seamount. Part I: problem formulation and model accuracy. Journal of Physical Oceanography, 23(8), 1736–1753. https://doi.org/10.1175/1520-0485(1993)023<1736:NSOFAA>2.0.CO;2.

Bubalo, M., Janeković, I., & Orlić, M. (2018). Chrystal and Proudman resonances simulated with three numerical models. Ocean Dynamics, 68(4–5), 497–507. https://doi.org/10.1007/s10236-018-1146-8.

Bryant, E. (2001). Tsunami: the underrated hazard, Pp320 (Cambridge University Press, New York.

Choi, B. H., Pelinovsky, E., Kim, K. O., & Lee, J. S. (2003). Simulation of the trans-oceanic tsunami propagation due to the 1883 Krakatoa volcanic eruption. Natural Hazards and Earth System Sciences, 3(5), 321–332. https://doi.org/10.5194/nhess-3-321-2003.

Cronin S. (2022). Why the volcanic eruption in Tonga was so violent, and what to expect next. The conversation https://theconversation.com/why-thevolcanic-eruption-in-tonga-was-so-violent-and-what-to-expect-next175035.

Davies, G., Wilson, K., Hague, B. et al. (2024). Australian atmospheric pressure and sea level data during the 2022 Hunga-Tonga Hunga-Ha'apai volcano tsunami. Sci Data 11, 114. https://doi.org/10.1038/s41597-024-02949-2.

Devlin, Adam & Jay, David & Talke, S.A. & Pan, Jiayi. (2022). The 2022 Tonga Volcanic Tsunami: Lessons from a Global Event. 10.5194/egusphere-2022-925.

Egbert, G. D., & Erofeeva, S. Y. (2002). Efficient inverse modeling of barotropic ocean tides. Journal of Atmospheric and Oceanic Technology, 19(2), 183–204. https://doi.org/10.1175/1520-0426(2002)019<0183:EIMOBO>2.0.CO;2.

Garrett, C. (1970). A theory of the Krakatoa tide gauge disturbances. Tellus, 22(1), 43–52. https://doi.org/10.1111/j.2153-3490.1970.tb01935.x

Harrison, G. (2022). Pressure anomalies from the January 2022 Hunga Tonga-Hunga Ha'apai eruption. Weather 77, 87–90.

Kanamori H, Mori J, Harkrider DG. (1994). Excitation of atmospheric oscillations by volcanic eruptions. J Geophys Res 99:21947–21961.

Ličer, M., Mourre, B., Troupin, C., Krietemeyer, A., Jansá, A., & Tintoré, J. (2017). Numerical study of Balearic meteotsunami generation and propagation under synthetic gravity wave forcing. Ocean Modelling, 111, 38–45. https://doi.org/10.1016/j.ocemod.2017.02.001.

Omira, R. et al. (2022). Global Tonga tsunami explained by a fast-moving atmospheric source. Nature 609, 734–740.

Pattiaratchi CB & Wijeratne EMS. 2015. Are meteotsunamis an underrated hazard? Philosophical Transactions of the Royal Society A, 373(2053)

Press, F. & Harkrider, D. G. (1888). J. geophys. Res., 67, 3889. Symons, G. (ed.), Trubner, London.

Proudman, J. (1953). Dynamical Oceanography. Methuen, London.

Renault, L., Vizoso, G., Jansá, A., Wilkin, J., & Tintoré, J. (2011). Toward the predictability of meteotsunamis in the Balearic Sea using regional nested atmosphere and ocean models. Geophysical Research Letters, 38(10), L10601. https://doi.org/10.1029/2011GL047361.

USGS, (2022). U.S. Geological survey M 5.8 volcanic eruption - 68 km NNW of Nuku'alofa Tonga https://earthquake.usgs.gov/earthquakes/eventpage/pt22015050/executive (2022).

Warton, W. J. L. & Evans, F. J. (1888). On the seismic sea waves caused by the eruption at Krakatoa, August 26^{th} and 27^{th}, 1883. Part III. In: Symons, G. L. (ed.) The Eruption of Krakatoa and Subsequent Phenomena. Report of the Krakatoa Commission of the Royal Society of London, 89– 151.

Wijeratne, S., Pattiaratchi, C. (2023). Meteorological and volcanic tsunami signals generated by the Hunga Tonga-hunga Ha'apai eruption, XXVIII General Assembly of the International Union of Geodesy and Geophysics (IUGG) (Berlin 2023). https://doi.org/10.57757/IUGG23-0830.

Wijeratne, E. M. S., & Pattiaratchi, C. B. (2024). Meteotsunamis generated by thunderstorms. Journal of Geophysical Research: Oceans, 129, e2023JC020662. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2023JC020662.

Wright, C.J., Hindley, N.P., Alexander, M.J. et al. (2022) Surface-to-space atmospheric waves from Hunga Tonga–Hunga Ha'apai eruption. Nature 609, 741–746. https://doi.org/10.1038/s41586-022-05012-5.

Yamada M, Ho T-C, Mori J, Nishikawa Y, Yamamoto MY. (2022). Tsunami triggered by the Lamb wave from the 2022 Tonga volcanic eruption and transition in the offshore Japan region. Geophys Res Lett 49:e2022GL098752. https://doi.org/10.1029/2022GL098752.

Yokoyama, I. (1981). A geophysical interpretation of the 1883 Krakatoa eruption, J. Volcanol. Geotherm. Res., 9, 359–378.

Yuen. D.A, Scruggs. M.A, Spera. F.J, Zheng. Y, Hu. H, McNutt. S.R, Thompson. G, Mandli. K, Keller. B.R, Wei. S.S, Peng. Z, Zhou. Z, Mulargia. F, Tanioka. Y. (2022). Under the surface: pressure-induced planetary-scale waves, volcanic lightning, and gaseous clouds caused by the submarine eruption of Hunga Tonga-Hunga Ha'apai volcano, Earthquake Research Advances, 2 (3) (2022), Article 100134, 10.1016/j.eqrea.2022.100134.

Climate Induced Coastal Hazards and Tourism Built Environment: An Assessment on Adaptive Capacity of Hotels along Southern Coastal Belt of Sri Lanka

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ABSTRACT

Climate induced natural hazards (CINH) occurring in coastal environments with fast growing population has increased the level of exposure of systems faster than the vulnerability level decreased (Center, 2015). Especially in the Sri Lankan context with having majority of the hotels along southern coastal belt with 75% of graded hotels in coastal areas, face substantial challenges due to CINH. The local tourism practices and policies have further indicated the limited consideration given on building attributes in mitigating hazards, highlighted the importance of the study to assess the Adaptive Capacity in the tourism built environment.

The assessment method of the study composed of developing a theoretical design framework and a score card method on evaluating building adaptive capacity of selected 5 case studies in coastal built environment. The score card consists of 36 design strategies with an assessment criterion. The presence level of each criterion is recorded in scale of 100%, 50%, 25% and 25%>. Depend on the presence of each criteria, allocation of a score for each was given accordingly. Therefore the final stage of the analysis was assessed through a quantitative metric, considering the qualitative data collected by on-site observations and field search.

The final results have explicitly informed the level of building adaptive capacity of the case studies within moderate to low scale. The overall score was recorded as 47.40% indicating a significant deficiency in building adaptive capacity. In some cases it was identified there are some other external factors effect from other facets of Adaptive capacity on decision making. Further it was concluded the overall cases are structured in mitigation and less on providing flexibility for future adaptation to climate induced natural hazards. Thus the developed appraisal on assessing built attributes in a quantitative metric have given a significant possibility to use it as a "tool" on identifying adaptive capacity level of coastal built environment. Additionally, possible remedies are discussed at the end have given flexibility for future researches on developing and modifying the framework and the score card system for advance methods.

Key words: Adaptive capacity, Coastal tourism, Built environment, Climate induced natural hazards

1. INTRODUCTION

Climate change happened to be one of the leading global crisis upbringing unpredictable hazards, long-term irreversible environmental impacts on all the socio-economic and environmental domains. Along with, we are trapped in a continuous cycle of disaster > respond > recover and repeat (UNDRR, 2021). One of the major impacts of climate change is endured by the coastal environments due to its dynamic nature.

Despite the vulnerability, the coastal context is also happened to be focal points of trade, fishing and tourism which are vital to countries' economy as they highly depend on coastal resources (Amaratunga, 2022). Especially countries within tropical region, particularly in small islands and

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developing countries often experience intense weather conditions which challenge on their livelihood and economic activities (Dhar and Khirfan, 2016; Lane et al., 2015; Khirfan and El-Shayeb, 2019; Intergovernmental Panel on Climate Change (IPCC), 2023).

As per the Ministry of Mahaweli Development and Environment, Sri Lankan tourism industry is also recognized as one of the most vulnerable sectors to climate change impacts (Tam, 2019). Especially coastal tourism being the largest market segment in Sri Lanka, high level of exposure to sea level rise, erosion, adverse weather, and storms would still leave the industry with negative impacts (Tam, 2019).

Examining on literature, a significant gap was identified on how climate change would have a considerable impact on tourism field in Sri Lanka, South Asian regions and tropical context. Thus, the study question upon "whether the Sri Lankan coastal tourism built environment prepared for Climate change?" Therefore, as in architectural point of view it is vital to examine the adaptability and resilience of the coastal tourism built environment to CINH.

Focusing further on the coastal built environment, about 75 percent of the graded hotels in Sri Lanka and 80 percent of the hotel rooms in the country are located in coastal areas (Wijesiri, n.d.).Moreover 1000 miles of coastal area has been extensively utilized for tourism developments (Wijesiri, n.d.) where the main tourism areas are developed along the Colombo city, southwest coast and the east coast (World Bank, 2017)

Despite the developments taken over in western and southwestern coastal line, it is the most vulnerable geographical location to flood and sea level rise (World Bank, 2017). Further taking 2004 tsunami incident as a lesson learnt with damages to the tourism built environments, the adaptive capacity of newly constructed built areas after the incident are still questionable. Therefore the study was developed on a framework base on the adaptive, resilience theories and referring effective practices from developed countries/ similar contextual countries that can assess the factor of adaptive capacity in coastal tourism built environment of Sri Lanka to CINH.

1.1. Climate Induced Natural Hazards in Coastal Environments

Over the time there are several theoretical concepts recognized in order to understand and addressing climate induced natural hazards (CINH) occurring due to global climate change. The establishment of United Nations Framework Convention on Climate Change (UNFCCC) in 1992 aimed to prevent "Dangerous anthropogenic interference with the climate system" by both adaptation and mitigation as responses although the early stages in 1900s and 2000s were mostly considered on mitigation. However climate adaptation was recognized as a necessary policy response during the Bonn Agreement as mitigation alone would limit the progress managing the climatic impacts. In the first IPCC Climate change assessment report in 1990 has outlined three approaches as; Protect, Accommodate, Retreat which later developed into five approaches as response illustrated in Figure 1.

Further, in the PARA framework (Doberstein et al., 2019) which consist of 04 main basic stages of "protect/accommodate/retreat/avoid"

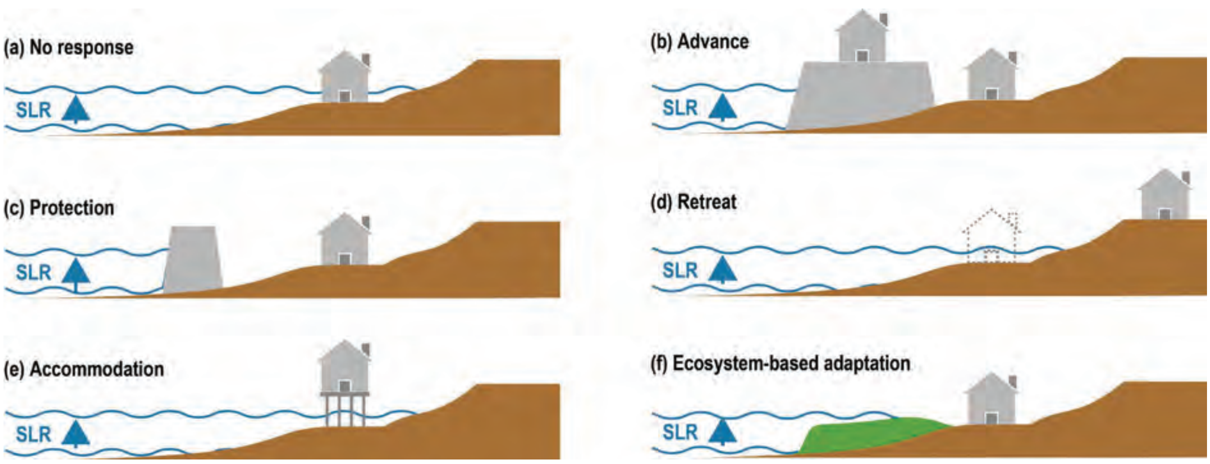


Figure 1. Building approaches to mitigate coastal inundation, Source: Intergovernmental Panel on Climate Change (2022)

where the both resilience and adaptation measures are implemented in different stages. In Sri Lanka, it is evident that "protection" and "retreat" strategies have been prioritized, while the "accommodate" and "avoid" strategies lack significant implementation or supporting evidence. Therefore the study take a direction on exploring on theoretical concepts and strategies related to both adaptable and resilience theories to assess the current coastal built environment.

1.2. Conceptualization of CINH

According to the literature of IPCC (2023) defines "vulnerability" as the predisposition of a system to be adversely affected or being unable to cope with the effects of climate change (Calvin et al., 2023).In mitigation, "resilience" in critical infrastructure taken into consideration, the main properties of such system to be included are resistance, reliability, redundancy and response/recovery in the face of vulnerability (UK cabinet office). Thus, higher the level of resilience in a building component, lesser the level of its vulnerability. Although resilience has been recognized as a concept on mitigating, over the change of context, nature of the event and occurrence, the level of resilience may be limited to a certain time frame and set of conditions. Therefore it is vital to recognize the dynamic face of resilience by adaptation.

The concept of Adaptation defines as the process of adjustment in ecological, social, or economic systems to actual or expected climatic effect, in order to moderate harm or exploit beneficial opportunities (Calvin et al., 2023) Reviewing on adaptive literature on built environment identify adaptability as a "fluid concept" which is a continuous flux than a static object evolve with the changing events, context and to the need of people and its purpose (Schmidt & Austin, 2016). It is further explained buildings are not being a static object but a series of layers which could change at different rates providing flexibility within the structure for change. According to the Framecycle meta-model developed by Robert Schmidt III and Simon Austin (2016) have identified 6 key characteristics in a building system shown in Figure 2. The model is centered on their theoretical definition of adaptability with 6 different characteristics with moving clockwise from relatively high frequency changes to occurrence of changes over the decades (Schmidt & Austin, 2016).

By identifying both resilience and adaptation concepts as basic definitions, adaptation refers

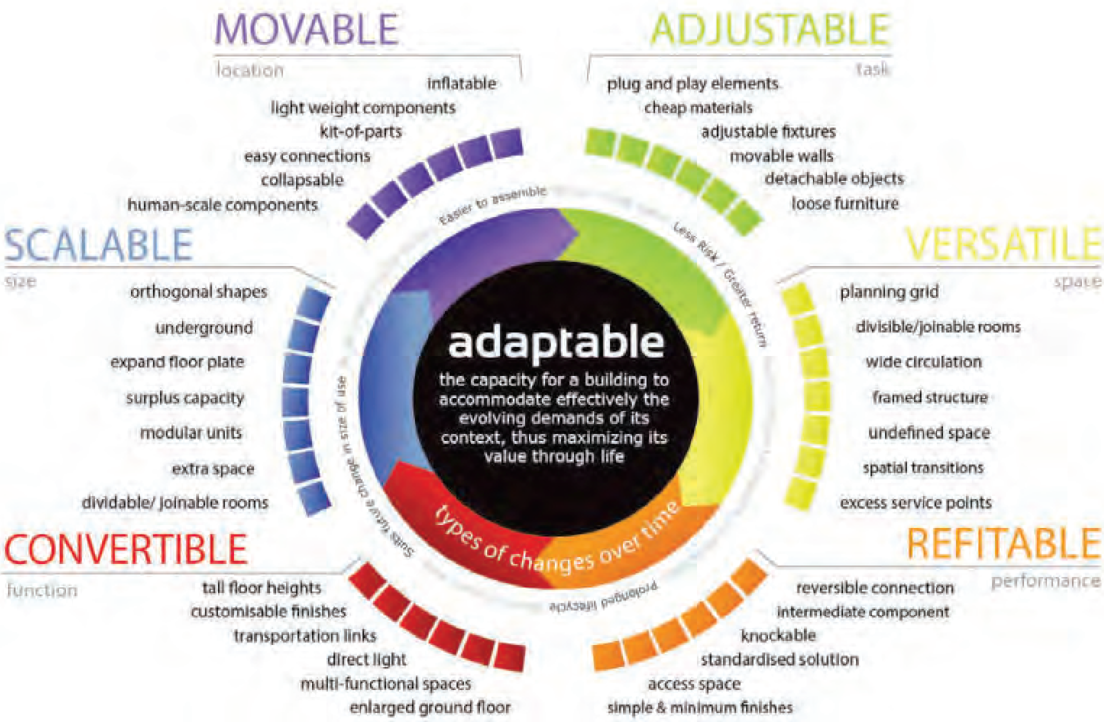


Figure 2. Characteristics of adaptable architecture, Source: Schmidt & Austin (2016)

to the adjustment done in a system for the betterment of life and survival in the changing new environments where resilience describe as the capacity of a system to cope and recover from external shocks in the changing environment. However in some literature, adaptation is seen as being part of the resilience concept described as a combination of "shock absorbing and coping" secondly "evolving and adapting" and "transforming" as stages. This shows the mitigation as the first thought ideal solution in face of risks Nonetheless when a society or a system exceeds the capability to cope they should be able to adapt to the changing context (Mehryar, 2022).

1.3. Adaptive capacity

According to the IPCC assessment report (2023) the concept of adaptive capacity defines it as, "a potential or ability of a system, region, or community to adapt to the effects or impacts of climate change. Enhancement of adaptive capacity represents a practical means of coping with changes and uncertainties in climate, including variability and extremes." (Calvin et al., 2023)It could be further identified in four main domains of adaptive capacity enablers as being technical enablers, social enablers, economical enablers and infrastructure enablers (Antje Lang, 2018; Catherine Campbell, 2022; Cinner et al., 2018; Uyttewaal et al., 2023).As the study based on the aspects of built environment, the main focus is given on the infrastructure enablers to assess the building adaptive capacity. Considering all the factors it is proven there is a common thread among adaptive capacity, resilience and vulnerability concepts and resilience alone is not the ideal desirable state but a combination with transformability or in other words adaptability. Collectively low adaptive capacity would increase vulnerability yet resilience together with adaptive qualities would increase adaptive capacity. In such scenario vulnerability level of a system would decrease.

1.4. Review on design strategies and practices

As per the research conducted by Tam (2019,pg.41) the policy instruments relevant to both Climate change and tourism domains in Sri Lanka was reviewed and it was identified although considerable social enabling approaches and technical approaches were taken into consideration, majority of policy documents haven't elaborated on specific building infrastructural strategies on mitigating. Therefore reviewing on globally developed frameworks like the Sendai Framework, United Nations Office for Disaster Risk Reduction (UNDRR) strategic frameworks and United Nations Development Programme (UNDP) Adaptation Policy Framework (APF) have closely related to the concept of adaptive capacity. Especially the APF framework has addressed the way of enhancing adaptive capacity in both social and physical systems to cope with climate change (Brooks & Adger, n.d.). Therefore as an extension to the APF framework, it was utilized in developing a framework to assess the level of adaptive capacity of coastal built environment in this study.

Additionally Brand's (1994) theory of "shearing layers" which was originally coined by architect Frank Duffy was utilized in reviewing in this study as a classification to identify different design strategies as per building layers which would also state the level of flexibility and resistant within the buildings by using the design strategies.

Reviewing on effective design strategies practiced in the global scale, the paper examined each strategies under 7 layers of the theory of shearing layers. The "Layer 01-stuff" represents the furniture and material usage in a building. As per the review on effective practices the usage of either fixed or movable furniture gives resilience or flexibility to secure the object before a disastrous situation. (City of Melbourne & City of Port Phillip, 2021).Waterproofing/salt resistant material usage and applying as coatings to protect and maintain the objects is another important consideration. (Environment, 2021)

The layer 02 –space plan or the spatial layer of a design gives either a level of flexibility or restrictions depending on the spatial planning of the building. In a good practice, a flood design oriented building could provide either internal/ external flood transitional spatial arrangement or by repurposing the floors as strategies to withstand. (Coastal Flood Resilience Design Guidelines, 2019) .The Service system within a building as a layer is another determiner that increase or decrease the level of capacity a building have in a disaster. Having on-site energy generating capacity, water sources and backup systems with well-planned floor drainage systems in internal/external spaces ensure a system to be self-maintained and efficiently face for an emergency in face of CINH (Coastal Flood Resilience Design Guidelines, 2019). Skin of a building is one of the layers that front in line to face any hazardous force as a cover to the building. As per the literature for an example integrating wet/dry flood proofing would either allow water seepage to the building or restrict it (Coastal Flood Resilience Design Guidelines, 2019). The structural layer in a building is another main component supporting in mitigation or adaptation through different construction methods like, design for deconstruction, amphibious structures, and floating structures in face of CINH. (Environment, 2021)

Apart from the building entities, the site and the surrounding of the building are considered as the last two types of the layering system. Actions taken within the site boundary such as boundary walls, vegetative buffers, building forms generated from site conditions becomes a protective layer for the building in case of a hazardous event. Further elements beyond the site boundary such as natural setting, vegetation would enhance the level of resilience and adaptation (Coastal Flood Resilience Design Guidelines, 2019).

Base on the reviewed design strategies and categorizing as per the building layers, a 'Nexus' was generated with 36 design strategies with its relation to adaptive and resilience shown in the Figure 3. This has further supported in developing the theoretical framework as an assessment tool.

2. FORMULATION OF THE FRAMEWORK

Depend on the literature review and the developed nexus diagram, a unified theoretical framework has been created on enhancing the adaptive capacity of coastal hotel built environment to CINH which illustrates in Figure 5. It contains the phases of improving adaptive capacity from identification of the vulnerability group to engaging stakeholders in the process of maintaining adaptation. The framework is developed with different adaptive capacity enablers where one could further explore on the technical, social and economic aspects of the adaptive capacity on enhancing it. The main aim of this study is to acknowledge the infrastructure aspect within framework and develop a set of evaluating criteria or as a set of design guideline in face of CINH to mitigate or adapt to the risk factor. Figure 4 explains the data extraction process for the framework development which was done under 4 stages.

The research analysis thereafter was carried out using a "score card system" That was produced through the theoretical framework with a set of design strategies in the nexus further examined on field visits by a set of "evaluation criteria" according to the presence for each strategy. After the photographic study, each criterion was marked according to the presence level in percentage.

2.1. Method of study

Figure 6 explains the research methodology which consists of 4 phases. A qualitative data analysis methodology is used in the first two stages using all the general literature surveys, research gap analysis and cross evaluations. The third stage of developing an integrated design framework is also based on qualitative information derived from the literature collected in first two stages. The framework is primarily based on the APF (Adaptation Policy Framework) process on enhancing adaptive capacity stages and derived design strategies in nexus of adaptive and resilience theories. The fourth stage of the methodology involves in applying the design framework to assessment. As per the first 2 phases of the APF identifying the vulnerable system and base on the macro analysis assessment of its vulnerability, derive the selection of case studies within the critical zone. In the appraisal stage, the observed data is analyzed in a quantitative approach by a score card to derive into conclusion of acknowledging the research question.

2.2. Research Analysis

The research analysis is done by using the "score card system" That was produced through the theoretical framework with set of design strategies to be assessed with a criterion in the existing coastal hotel built context. According to the presence level of assessment criteria, each criterion obtained a certain score index out of 100 to quantify the presence of design strategy as a percentage. In this process the qualitative data gathered through a photographic study and the score card method analyzed in a quantitative approach to get the outcome result in a measureable entity of Building Adaptive Capacity (BAC). Therefore the assessment criteria

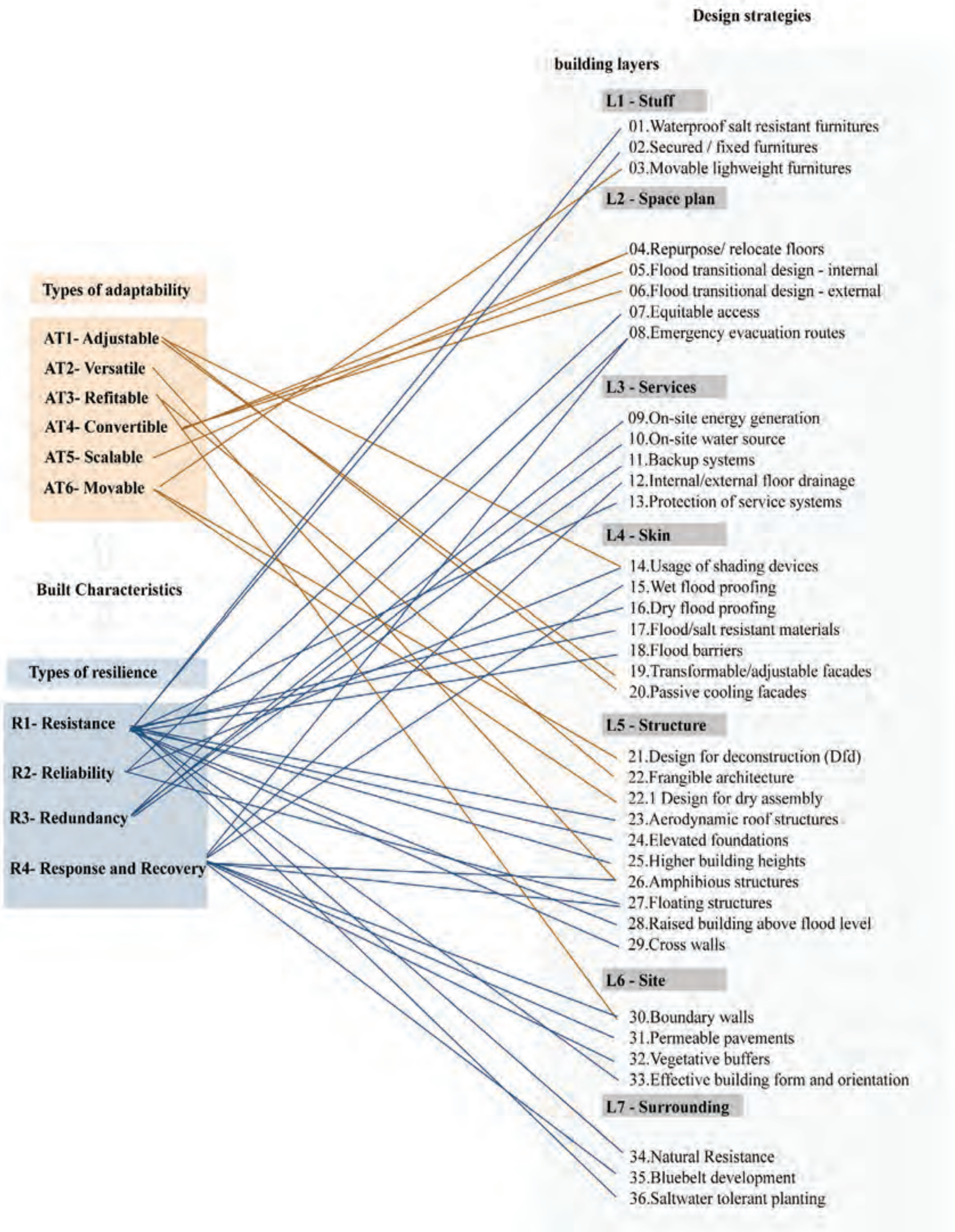


Figure 3. Nexus diagram

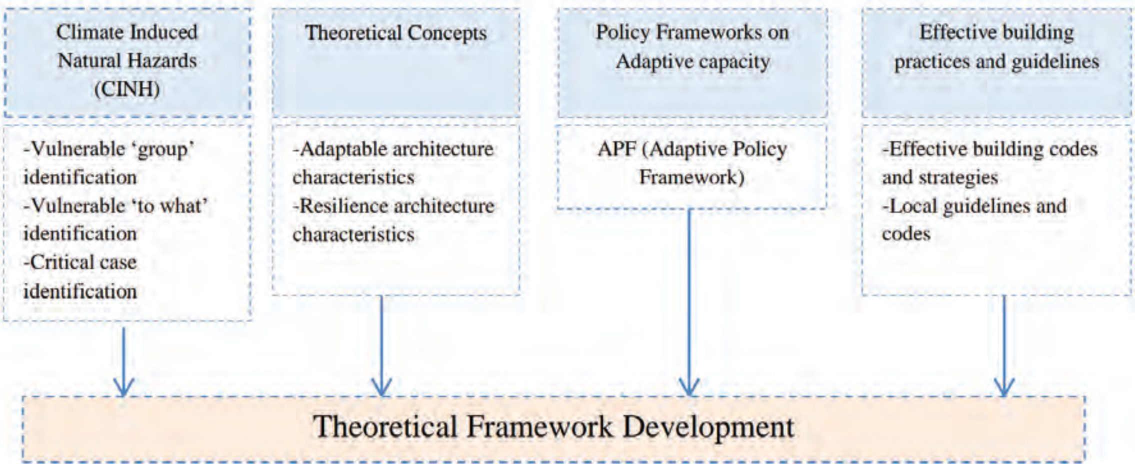


Figure 4. Data extraction

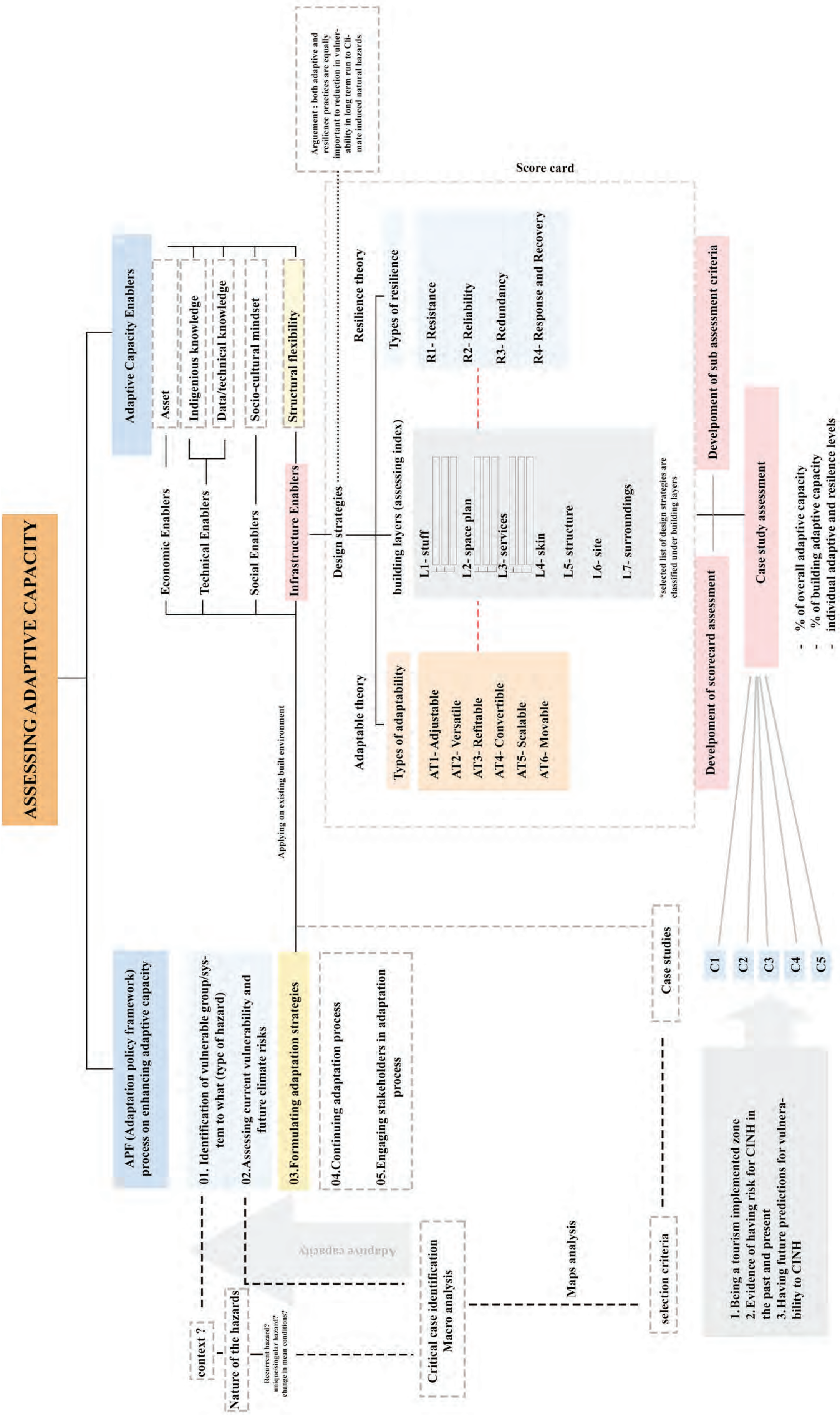


Figure 5. Theoretical framework

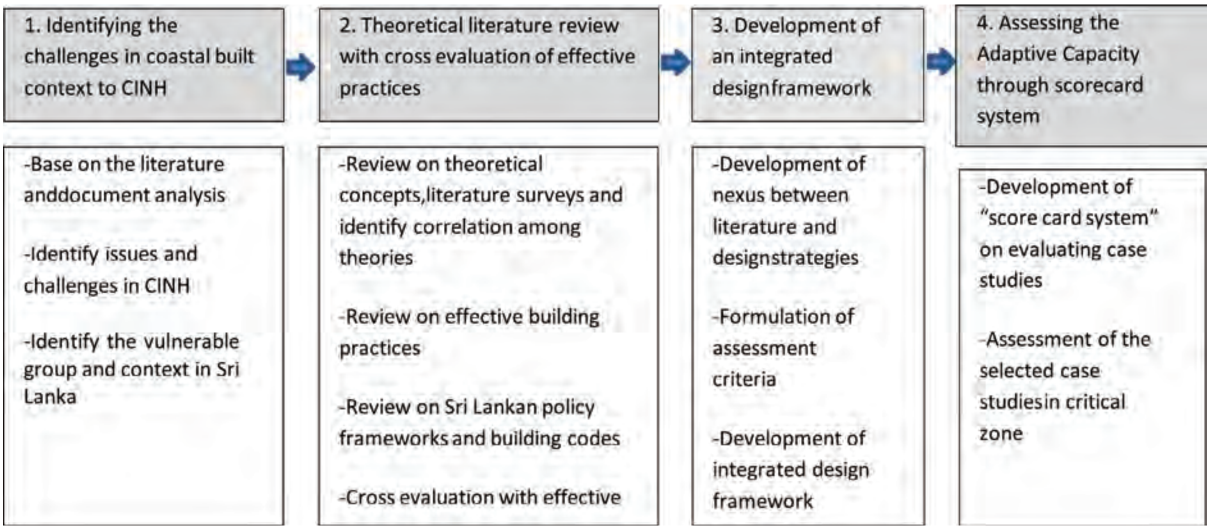


Figure 6. Research methodology

were given a score index for each according to this basis of a hierarchy in this research study.

- Depending on the **level of essentiality** the hierarchy of given marks would be high compared to other criterias
- Depending on the **level of general usage of specific strategies** in local context, the given marking would be decreased for other criterias where the usage is minimum/ not in usage/ not familiar in local context.

In adaptation for any other research study on evaluating specific case studies on BAC, the score index method could be variable as a flexible entity as well as a provision has given for addition/ vary the design characteristics and its assessment criteria. Within this research study have adapted the below mentioned quantifying methods in Figure 7 for the analysis of BAC.

The Final outcome result of building adaptive capacity of each case study was rated in similar

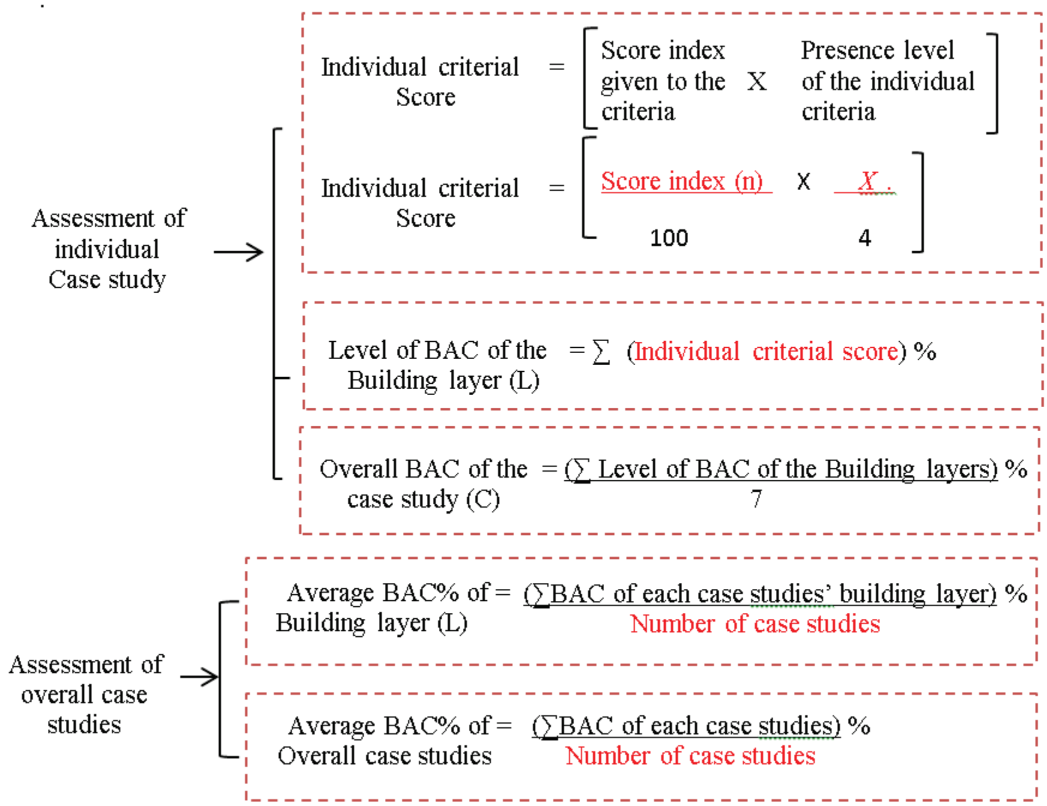


Figure 7. Quantification methods

scale of 100%, <75%,<50%, <25% and 25%> in accordance with the general idea of "very high", "High", "Moderate", "low" and as "very low".

3. CASE STUDY SELECTION

Selection of an appropriate and vulnerable coastline for the application and assessment of the evaluation methodology described earlier was based on consideration of 03 main criteria.

1. Being a tourism implemented zone
2. Evidence of having risk for CINH in the past and present
3. Having future predictions for vulnerability to CINH

Unawatuna Rumassala area which is located in the southern coastal belt of Sri Lanka is one of the most attracted coastal destinations in Sri Lanka and it has been recognized as one of the best location with both natural beauty and historical value. Currently the tourism industry within the area happens to be the major host of anthropogenic activities in the selected critical case study area which illustrated in Figure 8 (Thennakoon & Wasana, 2018).

Due to that reason, many unauthorized constructions have been developed within the beachfront area and has been expanded in the land use (Thennakoon & Wasana, 2018). Apart from the causes of anthropogenic activities, coastal erosion and climate induced natural hazards within the area happen to be one of the major geographical and environmental issues faced by the built environment and people. Therefore the Unawatuna Coastal area has been selected as a critical case study in the research. Hence it was identified as a potential case study location and the macro level impact assessment with simulation maps have further shown the Vulnerability within the beach front built environment and to human asset.

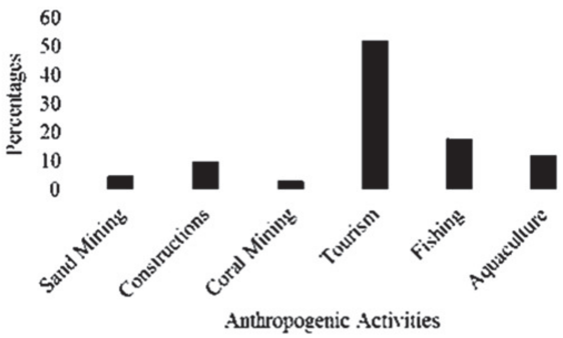


Figure 8. Anthropogenic activities in Unawatuna coastal area, Source: Thennakoon & Wasana (2018)

As the research conduct on analyzing hotel built environment as it is vital to examine on their preparedness to CINH, the selection of case studies in the critical zone is extracted by this selection criteria.

1. Hotel buildings within 30m buffer zone.
2. Selection of only beach front hotels.
3. Hotels which are only fall under the category within vulnerable areas.

According to the Google survey on selecting beachfront hotels, a number of hotels were resulted (Figure 10). In comparison with the simulated map of predicting coastal inundation in the most recent year 2030 shown in Figure 9, it is visible 2 specific zones which fall under the vulnerability zones.

Zone 01: Rocky coastline- high water levels and aggressive waves income during seasonal tides. Occurrence of Storms with high wind conditions. Due to the impacts of such hazards, high level of turbulences near shoreline with wave crashing vibrations and high wind velocity could be experienced.(Owner of a hotel located in Zone 01, personal communication, December 14, 2023)

Figure 9. Predicted sea level by year 2030 simulation, Source: Climate Central, Inc (2023)

Figure 10. Selected critical zones in Unawatuna case study area, Source: Google maps (2023)

Zone 02: Sandy coastline- Long term occurrence of coastal erosion within the area. Loss of considerable land extent due to the erosion. Impacts from seasonal tides with storm surges, flooding and high wind levels. (Owner of a hotel located in Zone 02, personal communication, December 14, 2023)

The data collection process was conducted through direct observations of the case studies by obtaining data as primary data collection. The data collection was done in 3 methods by interviewing the hotel stakeholders within the premises, by collecting photographs of each individual case study for further photographic study and using the scorecard checklist illustrated in Table 1 as the primary tool for examine on the presence of design strategies within the building and its surrounding. The conducted interviews with the participants were ensured their willingness and consent for audio recording and permission for taking photographs within the premises.

4. RESULTS AND DISCUSSION

The selected case studies were evaluated under 3 stages as individual photographic studies, in a score card assessment and overall analysis of each case study with a cross evaluation by a final appraisal index.

As per the final outcome of the analysis, the findings were discussed under 03 stages as cross evaluations of different parameters, case studies and according to building layers. All the data derived within the findings are calculated as per the assessment criteria explained.

Based on the results from the scoring system it is innately visible, the level of Building adaptive capacity of the selected case studies in the beachfront locations in Unawatuna coastal area are more within the scale of moderate to low scale of building adaptive capacity indicated in Table 2. On the scale of ranking, case study 01 and Case study 05 are in accordance of 1st and 2nd place in comparison to other 03 case studies. With a low level of 40.44% capacity level, case study 02 rank the 5th place and with mere addition of 0.36% case study 04 ranks in the 4th place.

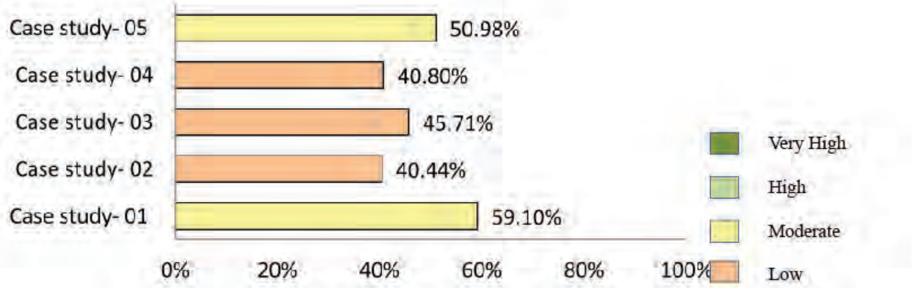
As per the comparison among each case study according to the capacity percentages in each layer compared in Table 3, some significant scenarios could be identified. One of the significant incident could recognize is the very low level of percentage with 0.35% support for the case study -04 capacity level while high level of percentage support with 7.68% and 7.32% in case study 01 and case study 05 to be recognized. The cause for such difference could be the capacity level of backup systems within the buildings and secured level of such systems in face of CINH. On the other hand, it can

Table 1. Assessment score card of L1 and L2 of Case study 01(score cards were individually generated throughout the research for all 07 layers)

Layer	No.	Design characteristics	Assessment criteria	Presence level 100%	75%	50%	25%	25%>	General comment
L1 - Stuff	01	Waterproof salt resistant materials and coating	1.1 Waterproof/ intentionally weathered flooring (outdoor/indoor)	X					Successfully applied.
			1.2 Waterproof/ intentionally weathered doors/windows	X					
			1.3 Waterproof/ intentionally weathered furniture(outdoor/indoor)	X					
			1.4 Waterproof salt resistant fittings			X			
	02	Secured / fixed furniture	2.1 Screwed or in-built furniture				X		Slightly applied.
	03	Movable furniture	3.1 Lightweight furniture/material usage		X				Successfully applied.
L2 – Space plan	04	Repurpose/ relocate floors	4.1 Provisions for Vertical/horizontal expansions			X			Slightly applied.
			4.2 Accessibility to relocate equipment above flood level (AFL)				X		
			4.3 Multifunctional spatial arrangement				X		
			4.4 Accommodating temporary activities in hazard prone areas			X			
	05	Flood transitional design - internal	5.1 Gradual elevation from the flood direction			X			Moderately applied.
			5.2 Human scale incremental tiers		X				
	06	Flood transitional design - external	6.1 Gradual elevation from the flood direction	X					Successfully applied.
			6.2 Human scale incremental tiers	X					
	07	Equitable access	7.1 External accessibility					X	Moderate but external accessibility not considered.
			7.2 Internal accessibility		X				
	08	Emergency evacuation routes	8.1 Alternatives for access/exit points					X	Not applied.
			8.2 Evacuation direction signage					X	

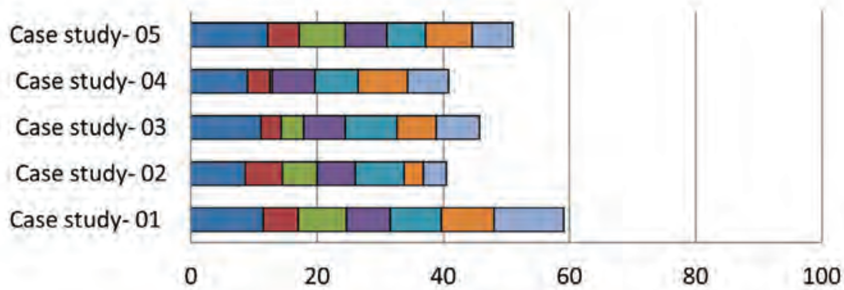
100%- Excellent; 75%- Good; 50%- Moderate; 25%- poor; 25%> - Not relevant; Resilience; Adaptive; Resilience +Adaptive

Table 2. Resultant on level of Building Adaptive Capacity in case studies



	Case study- 01	Case study- 02	Case study- 03	Case study- 04	Case study- 05
Adaptive capacity %	59.10%	40.44%	45.71%	40.80%	50.98%

Table 3. Resultant on BAC level of case studies in building layers



	Case study- 01	Case study- 02	Case study- 03	Case study- 04	Case study- 05
L1-stuff	11.43	8.57	11.07	8.93	12.14
L2-space plan	5.53	5.88	3.21	3.57	5
L3-service	7.68	5.54	3.57	0.35	7.32
L4-skin	6.96	6.07	6.61	6.78	6.61
L5-structure	8.04	7.77	8.21	6.88	6.16
L6-site	8.39	3.04	6.25	7.86	7.32
L7-surrounding	11.07	3.57	6.79	6.43	6.43

be also assumed that differences in the financial strength possessed by each case study might have caused for such difference in their capacity levels.

Another incident could identify is that, the higher structural capacity owned by the C1, C2 and C3 in comparison to other 2 cases. While the C1, C2 and C3 accommodate within the zone 01 where rocky landscape is, C4 and C5 are located within the sandy coastal front in zone 2. Even there is a significant attempt taken by the zone 1 hotel buildings in structurally to face CINH, there wasn't much effort to be seen in the zone 2 case studies in mitigating natural hazardous events. As per the interviews with the hotel stakeholders in C4 (zone 2), it was stated that there is a significant social and political external impacts to be considered than making effort for unpredictable natural incident in future.(Owner of Case Study 4, personal communication, December 14, 2023) which shows in one way why the level of capacity in structural system is low due to other external factors in social context.

When considering on overall capacity levels on each layer, the highest is recorded by the layer 01-Stuff and the lowest by the layer 02-space plan. According to the literature, layer 01-stuff has been identified as the most brittle layer causing it to have constant attention and maintenance over the course of time.(Abdelsabour & Farouk, 2019) Therefore it can be concluded as a result the Layer 01-stuff in the case studies has shown a higher capacity level compared to other layers due to maintenance. The reason for Layer 02-space plan to be obtained a low capacity level is that the negligence of building codes by not accommodating equitable access and emergency evacuation routes within the hotels. As a significant result it is identified that all the case studies have not considered on planning evacuation routes or aware the visitors. Even though considerable provisions were given for the disable access in few case studies, the overall level of provision is low.

When review on the resultant in Table 4, the highest level of resilience and adaptability is recorded by the Case study 01 and the lowest resilience by case study 04 and lowest adaptability by case study 05 in comparison to other case studies. The reason for such low record on the usage of adaptive strategies is that, low level/not usage of concepts like amphibious structures, floating architecture, frangible architecture, design for deconstruction etc in the local context. Thus, it is visible the overall cases are structured in mitigation and less on providing flexibility for future adaptation.

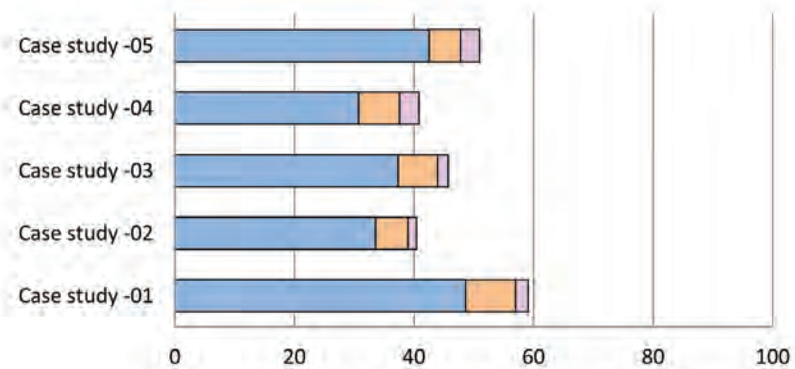
Coming back to the research question inquired in the beginning of the research, all the resultants from the research analysis could conclude to the fact that the selected case studies within the critical area obtain a lower level of overall adaptive capacity of 47.40%. Base on the hypothesis, it is proven the majority of the selected case studies are not well prepared for Climate induced natural hazards in future and have not taken required level of actions on mitigation and adaption.

Further during the field visits and interviews it was understood for the assessment of building adaptive capacity there are external factors have been affected on the decision making process during construction as well as in maintaining process. Therefore it was identified there is an effect from other facets of Adaptive capacity as; social enablers, economic enablers and technical enablers on building adaptive capacity. As this study primarily focuses on assessing Building adaptive capacity of the building infrastructure, it also encompasses a potential to be developed with incorporating other research fields from social, economic and technology backgrounds to address the whole spectrum of adaptive capacity within a system to CINH.

5. CONCLUSION

The research topic concentrated on is clearly focused on the "infrastructure aspect of the Adaptive capacity" of coastal front hotel built context and their level of capacity to CINH.The proposed design framework is a new "index" or a "tool" for assessing adaptive capacity in coastal built environment. It is a guided tool to the procedure of evaluating contexts as well as helpful as a design guideline for developing resilient and adaptive buildings to face risks. As a result, the suggested framework could be used as a benchmark, an evaluation index, or as an assessment tool for projects that have been completed. Additionally it could be used as a checklist for design teams in coastal front projects that are still in pre-design stages. Future research

Table 4. Resultant on levels of resilience and adaptability



	Case study - 01	Case study - 02	Case study - 03	Case study - 04	Case study - 05
Resilience	48.66	33.57	37.32	30.71	42.5
Adaptability	8.3	5.44	6.61	6.88	5.26
Resilience+adptability	2.14	1.43	1.78	3.21	3.22

studies could be guided by the suggested 36 design strategies and their 87 assessment criteria and Future researches on developing and modifying the framework and the score card system have the potential flexibility on adapting as a versatile tool.

The development of the scorecard could involve incorporating or modifying strategies to align with specific building layers, as well as refining the assessment criteria and scoring index to fit the unique context of each project. The scorecard is designed to be flexible, enabling its adaptation to different project categories while maintaining consistent evaluation standards based on the outlined criteria

Simultaneously, the framework is structured for application in various critical coastal locations, guiding the enhancement of adaptive capacity by identifying vulnerable groups and their exposure to specific natural hazards. Furthermore, the framework can be expanded to encompass other enablers, such as social, economic, and technical factors, to provide a comprehensive understanding of "adaptive capacity." This would involve gathering data through questionnaires, technical reports, and surveys.

6. REFERENCES

III, R. S., & Austin, S. (2016). Adaptable Architecture: Theory and practice. Routledge

Abdelsabour, I., & Farouk, H. (2019). (DFD) DESIGN FOR DISASSEMBLY FRAMEWORK AN APPROACH TO ENHANCE THE DESIGN CONSTRUCTION PROCESS. JES. Journal of Engineering Sciences, 47. https://doi.org/10.21608/jesaun.2019.115751

Amaratunga, D. (2022). How does climate change affect coastal regions? Retrieved from rics.org: https://ww3.rics.org/uk/en/journals/land-journal/how-does-climate-change-affect-coastal-regions-.html

Antje Lang. (2018). Adaptive Capacity: An Introduction. WeADAPT. https://www.weadapt.org/knowledge-base/vulnerability/adaptive-capacity-an-introduction

Brooks, N., & Adger, W. N. (n.d.). Assessing and Enhancing Adaptive Capacity.

Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W. W. L., Connors, S., Denton, F., Diongue Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., … Péan, C. (2023). IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland. (First). Intergovernmental Panel on Climate Change (IPCC). https://doi.org/10.59327/IPCC/AR6-9789291691647

Catherine Campbell. (2022). Presidents Medals: Developed / veloping; Embracing the Rising Tide. https://www.presidentsmedals.com/Entry-18130

Center, A. D. R. (2015). Sendai framework for disaster risk reduction 2015–2030. United Nations Office for Disaster Risk Reduction: Geneva, Switzerland. https://www.apec epwg.org/media/2584/e1a8e2e1c1125430bcf585c521ca6bcb.pdf

Cinner, J., Adger, W., Allison, E., Barnes, M., Brown, K., Cohen, P., Gelcich, S., Hicks, C., Hughes, T., Lau, J., Marshall, N., & Morrison, T. (2018). Building adaptive capacity to climate change in tropical coastal communities. Nature Climate Change, 8. https://doi.org/10.1038/s41558-017-0065-x

Coastal Flood Resilience Design Guidelines. (2019). Boston Planning & Development Agency. http://www.bostonplans.org/getattachment/d1114318-1b95-487c-bc36-682f8594e8b2

Environment, U. N. (2021, July 5). A Practical Guide to Climate-resilient Buildings & Communities. UNEP - UN Environment Programme. http://www.unep.org/resources/practical-guide-climate-resilient-buildings

Intergovernmental Panel on Climate Change (IPCC). (2022). The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change (1st ed.). Cambridge University Press. https://doi.org/10.1017/9781009157964

Mccarthy, J., Canziani, O., Leary, N., Dokken, D., & White, K. (2001). Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 19.

Mohamed, M., Chen, T., Su, W., & Jin, T. (2019). Proactive Resilience of Power Systems Against Natural Disasters: A Literature Review. IEEE Access, PP, 1–1. https://doi.org/10.1109/ACCESS.2019.2952362

Owner of case study 04 hotel. (2023, December 14). [Personal communication].

Owner of case study 03 hotel. (2023, December 14). [Personal communication].

Sara Mehryar. (2022, December 9). What is the difference between climate change adaptation and resilience? Grantham Research Institute on Climate Change and the Environment. https://www.lse.ac.uk/granthaminstitute/explainers/what-is-the-difference between-climate-change-adaptation-and-resilience/

Smit, B., & Wandel, J. (2006). Adaptation, adaptive capacity and vulnerability. Global Environmental Change, 16(3), 282–292. https://doi.org/10.1016/j.gloenvcha.2006.03.008

Tam, S. (2019). Sounding the alarm: Is the Sri Lankan tourism sector prepared for climate change? University of Waterloo. http://hdl.handle.net/10012/14643

Thennakoon, T. M. S. P. K., & Wasana, S. (2018). *Impact of Anthropogenic Activities on Coastal Landscape Changes in Unawatuna Coastal Zone, Sri Lanka*. https://api.semanticscholar.org/CorpusID:216685201

UNDRR. (2021). UNDRR STRATEGIC FRAMEWORK - 2022 -2025. United Nations Office for Disaster Risk Reduction. https://www.undrr.org/publication/undrr-strategic-framework-2022-2025

Uyttewaal, K., Prat-Guitart, N., Ludwig, F., Kroeze, C., & Langer, E. (2023). Territories in Transition: How social contexts influence wildland fire adaptive capacity in rural Northwestern European Mediterranean areas. Fire Ecology, 19, 13. https://doi.org/10.1186/s42408-023-00168-5

Wijesiri, L. (n.d.). Potential of coastal and marine tourism. Daily News. Retrieved November 10, 2023, from https://archives1.dailynews.lk/2018/12/11/features/170903/potential-coastal and-marine-tourism

World Bank. (2017). Sri Lanka: Managing Coastal Natural Wealth. The World Bank Group

Reframing 'Build Back Better' Framework for Post-Tsunami Resettlement: A Field Study in Galle, Sri Lanka

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ABSTRACT

The tsunami aftermath in Sri Lanka led to a coastal buffer zone policy, displacing survivors to distant donor- built settlements. Despite advocating for holistic recovery, the "building back better" (BBB) approach encounters challenges aligning with community needs. Thus, it underscores the need to consider physical, social, economic, environmental, and psychological factors in post-disaster resettlement, emphasizing a reframing of BBB to meet survivors' specific needs. It aims to redefine "Build Back Better" for post-disaster communities by aligning with community needs and integrating theories like Scudder's stress settlement process, Cernea's Impoverishment Risks model, and Bohle's vulnerability and livelihood concepts. It proposes Sustainable Community Development (SCD) to tackle poverty and basic needs, with organized indicators, including psychological aspects. Two relocation settlements in Galle's Akmeemana were examined: Katupolwatta, constructed by a local contractor, which deteriorated due to various issues, and Green Village, designed by German architects and praised for its quality and planning, reflecting differing outcomes in post-disaster resettlement. A mixed-method approach is used to collect extensive data through a thorough questionnaire, incorporating both qualitative and quantitative techniques. The scorecard system developed and applied during the case study evaluation. The study found that "building back better" is unfamiliar to housing recipients, and stakeholders often fail to align donated houses with relocated communities' desired lifestyle. Over 20 years, analysis showed professional architects may lack understanding of traditional living and community needs. Consequently, communities modified or abandoned their houses, with many returning to previous risky locations. This indicates BBB may not be practical. Implementers should adopt a community-based approach to ensure homes, addressing long-term dissatisfaction. This highlights the need for reframing BBB and its role in post-disaster recovery.

Key words: Forced relocation, Social, Environment, Physical, Psychological, Sustain

1. INTRODUCTION

In addressing the urgent challenges faced by communities forced into relocation after natural disasters, it proposes a redefined "Build Back Better" (BBB) approach for post-disaster recovery that incorporates Sustainable Community Development (SCD) principles. The research offers a unique perspective by integrating SCD with BBB to create a recovery model that is more adaptable and human-centered, focusing not only on physical reconstruction but also on long-term social and cultural resilience. This is especially pertinent in the context of increasing climate-induced displacements, for which existing frameworks are insufficient to fully protect and support environmentally displaced individuals (Bradley, 2010).

While resettlement is often necessary following large-scale disasters, it brings extensive economic, physical, and social impacts (Wei Liu, 2020). Although the BBB approach has become a cornerstone in post-disaster reconstruction for promoting transformative change, significant gaps remain in its application, particularly in addressing the holistic needs of displaced populations (Glenn Fernandez, 2019). Previous

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studies have noted BBB's shortcomings in ensuring housing suitability, social cohesion, and livelihood sustainability in resettled communities. However, few have systematically explored how SCD and theoretical frameworks like Thayer Scudder's stress and settlement process, Michael Cernea's Impoverishment Risks, and Bohle's vulnerability model can enhance BBB's effectiveness for displaced communities.

Focusing on two tsunami-relocated communities in Galle, Sri Lanka—Katupolwatta (Salzburg) and Green Village—the research uniquely evaluates BBB's adaptability over time. By examining these communities across two distinct periods (2006-2015 and 2015-2024), the research assesses the extent to which BBB principles have addressed the evolving needs of resettled populations and identifies where gaps in BBB attributes persist. This comparative analysis not only highlights the limitations in BBB's current form but also demonstrates how a reframed approach can offer a more resilient and responsive model for future recovery efforts.

Through comparative analysis, this research offers fresh insights into the effectiveness and adaptability of BBB in meeting the long-term physical and psychological needs of resettlers. By exploring these impacts, it also proposes practical policy recommendations aimed at improving the BBB framework for future applications in post-disaster recovery. In doing so, the research seeks to validate its reframed BBB-SCD approach as a model for sustainable, human-centered recovery in vulnerable communities.

1.1. An Overview of Climate-Induced Disasters and Post-Tsunami Resettlement Challenges in Sri Lanka

In the Global South, climate-induced disasters lead to extensive displacement and infrastructure damage, with both slow-onset and rapid-onset disasters exacerbating these crises (Reduction, 2021). The December 26, 2004, tsunami in Sri Lanka is a notable example, causing approximately 30,000 deaths, displacing around one million people, and leading to an economic loss of $700 million USD (Manuel Garcin, 2008; Sooriyaarachchi Piumika, 2018). In response, the Sri Lankan government implemented a coastal buffer zone policy, displacing many residents to donor-built settlements often far from their original homes (Muggah, 2008). Effective post-disaster recovery in such contexts requires addressing complex challenges in housing, infrastructure, and community resettlement (Ahmed, 2011).

While the "Build Back Better" (BBB) approach promotes sustainable rehabilitation, practical challenges—including land ownership issues, site selection difficulties, costs, and environmental concerns—hinder its effective implementation (Monica Mazza, 2014). Furthermore, there is often a limited understanding of BBB among architects and practitioners, which can result in insufficient consideration of survivors' needs. Thus, it aims to address these gaps by proposing actionable policy recommendations to support more effective and sustainable resettlement strategies.

Additionally, this research incorporates qualitative perspectives from the displaced communities in Galle, grounding the analysis in the lived experiences of affected individuals. Through interviews and firsthand accounts, the study will capture and validate the needs and challenges faced by these communities, providing a nuanced, human-centered view on post-tsunami resettlement challenges in Sri Lanka.

1.2. Overview of Reframing the "Build Back Better" Approach: The Importance of Including Diverse Theoretical Frameworks

Reframing the "Build Back Better" (BBB) approach by integrating diverse theoretical frameworks is essential for addressing the limitations in current disaster recovery strategies. Originally developed after the 2004 Indian Ocean Tsunami and later embedded in the Sendai Framework, BBB aims to transform disaster response into opportunities for resilience and comprehensive improvement, beyond mere repair (Dube, 2019; Benge and Neef, 2020). However, while the BBB framework strives to enhance physical, social, environmental, and economic resilience, its practical implementation often overlooks community-specific needs and cultural contexts (Clinton, 2006; Ophiyandri et al., 2013).

Incorporating Sustainable Community Development (SCD) principles into BBB addresses this gap by emphasizing long-term community well-being and ensuring that reconstruction aligns with both social and environmental needs (Ophiyandri et al., 2013). This integration supports post-disaster recovery efforts that are culturally appropriate, technically sound, and responsive to the aspirations of displaced communities. Khasalamwa (2009) highlights that BBB should balance various community needs, including those related to mental health and social stability, to foster holistic resilience. Delays in housing reconstruction, for instance, not only exacerbate psychological stress but also deepen displacement issues.

To enhance the BBB framework's capacity to support displaced communities effectively, this approach employs multiple theoretical frameworks, each addressing distinct limitations within BBB:

Scudder's Stress and Settlement Process: This model will illuminate the psychological and social stressors experienced by resettlers over time, often neglected in physically focused BBB assessments. By analyzing these aspects, Scudder's model guides the BBB framework toward a deeper understanding of how prolonged displacement impacts mental well-being (Scudder, 2005).

Cernea's Impoverishment Risks and Reconstruction Model: Cernea's framework is instrumental in identifying economic and social risks associated with forced relocation, including loss of livelihoods and social networks. This model will guide policy recommendations aimed at reducing these risks, improving the planning and implementation of relocation efforts to safeguard the welfare of displaced individuals (Cernea, 1997).

Bohle's Double Structure of Vulnerability and Sustainable Livelihood Frameworks: Bohle's model emphasizes both external factors (e.g., environmental hazards) and internal coping mechanisms, which are critical for adapting BBB to foster resilience. Together with Sustainable Livelihood frameworks, which focus on livelihood security and development, these theories will guide BBB adaptations that build resilience by addressing the full spectrum of vulnerabilities in displaced communities (Bohle, 2000; Ellis, 2000).

Community Productivity Indicators from SCD Theory: This framework underscores the need for equitable and culturally sensitive approaches in recovery efforts, ensuring that the BBB model remains community-centric and supports cultural preservation (Morse and McNamara, 2013).

In summary, integrating these frameworks allows for a more comprehensive and resilient BBB approach that addresses psychological, social, economic, and environmental dimensions of recovery, aligning more closely with the needs and aspirations of displaced communities (Neeraj, 2020).

1.3. Significance of research

This research is pivotal in addressing critical shortcomings within the "Build Back Better" (BBB) framework, particularly regarding forced relocation due to climate-induced disasters. The extensive displacement following the 2004 tsunami in Galle, Sri Lanka, where communities were relocated 10–13 kilometers from their original homes, underscores significant flaws in BBB's land selection and planning processes. These forced relocations disrupted traditional livelihoods and social networks, and despite improvements in housing, many residents express a desire to return to their original locations (Karl Kim, 2015). The significance lies in its focus on bridging the gap between the BBB framework and the actual needs of displaced communities. By identifying cultural, social, and economic deficiencies in current practices, this research emphasizes the importance of community engagement and the consideration of long-term impacts, areas that have been largely overlooked (Glenn, 2019). Thus, it seeks to develop a "reframed framework" that integrates community feedback and traditional lifestyle patterns, enhancing resilience by aligning recovery efforts with the real needs and aspirations of affected populations.

Moreover, this research addresses a broader gap in empirical evidence on the effectiveness of forced relocation measures and their community impact. It explores the political dimensions of forced relocation, recognizing that such processes are inherently political and involve complex power dynamics (Silva, 2017). Thus it also examines the practical challenges in implementing BBB (Siri Hettige, 2004), contributing to a deeper understanding of how post-disaster recovery efforts can be improved to better support displaced individuals and communities, ensuring recovery strategies that are sensitive to long-term community well-being.

2. METHOD OF STUDY

In order to understand the complexities of post-disaster recovery and the practical application of the 'Build Back Better' (BBB) framework, this research adopts a predominantly qualitative methodology. To comprehensively capture insights, a multi-method data collection approach was adopted, incorporating questionnaire surveys, direct observations, document reviews, and interviews. The primary data collection included a questionnaire survey administered to 30 households in each of the two selected tsunami housing schemes, supported by field surveys and interviews conducted with 35 selected households from each community. Sampling Approach: A snowball sampling technique was utilized to identify and engage key respondents, particularly when accessing a wide range of stakeholders in the affected communities. This process began with an initial survey targeting an identified sample. Surveyed participants were then asked to refer additional individuals who might provide valuable insights. This iterative sampling continued until reaching either the desired sample size or a saturation point, where new participants frequently identified previously surveyed respondents, indicating a comprehensive sample. Stakeholder Categorization: Stakeholders were organized into two main groups to compare the effectiveness and reception of various housing interventions:

1. **Housing Scheme Developers:** This group includes professionals involved in creating housing schemes for displaced communities. It encompasses architects, local authorities, NGOs, and local contractors, providing diverse perspectives on post-disaster housing development.
2. **Residents of Housing Schemes:** This group focuses on comparing residents based on the type of housing intervention. It includes:
    - People residing in architect-led housing schemes.
    - Residents in housing schemes involving both architects and the community in the design process.
    - Individuals in housing schemes developed by NGOs and local contractors without architect involvement.
3. This methodological approach ensures a comprehensive understanding of the effectiveness of different housing interventions and allows for the assessment of extent to which the BBB framework has been successfully realized in each context.

2.1. Methodology Stages

Figure 1 shows the methodology types used in this study.

2.2. Questionnaire Content

The structured questionnaire captures the multifaceted experiences of displaced communities across different stages of resettlement. Each part is designed to gather insights that reflect evolving community needs, pre- and post-tsunami conditions, and the effectiveness of resettlement strategies.

- **Part 1:** Gathers demographic and background information from individuals relocated due to the tsunami, now living in resettlement areas. It includes age, gender, marital status, occupation, income, education, duration of residence, and dwelling characteristics to contextualize the varied backgrounds of affected individuals.
- **Part 2:** Examines life conditions in the pre-tsunami era (before 2004) by documenting sociocultural, economic, and physical factors. It explores livelihood patterns, housing conditions, community structures, and general lifestyle before the tsunami, setting a baseline for comparing post-resettlement living standards.
- **Part 3:** Analyzes the 2005–2014 resettlement phase, comparing two resettlement approaches - community-driven/professional and donor-driven/non-professional. This section assesses community vulnerability, housing quality, livelihood support, neighborhood challenges, and the overall suitability of resettlement housing.
- **Part 4:** Covers the post-tsunami phase from 2015 to 2024, examining long-term conditions in housing, psychological impacts, livelihoods, and application of the BBB framework. Metrics include physical, social, environmental, economic, and community productivity across dimensions of social

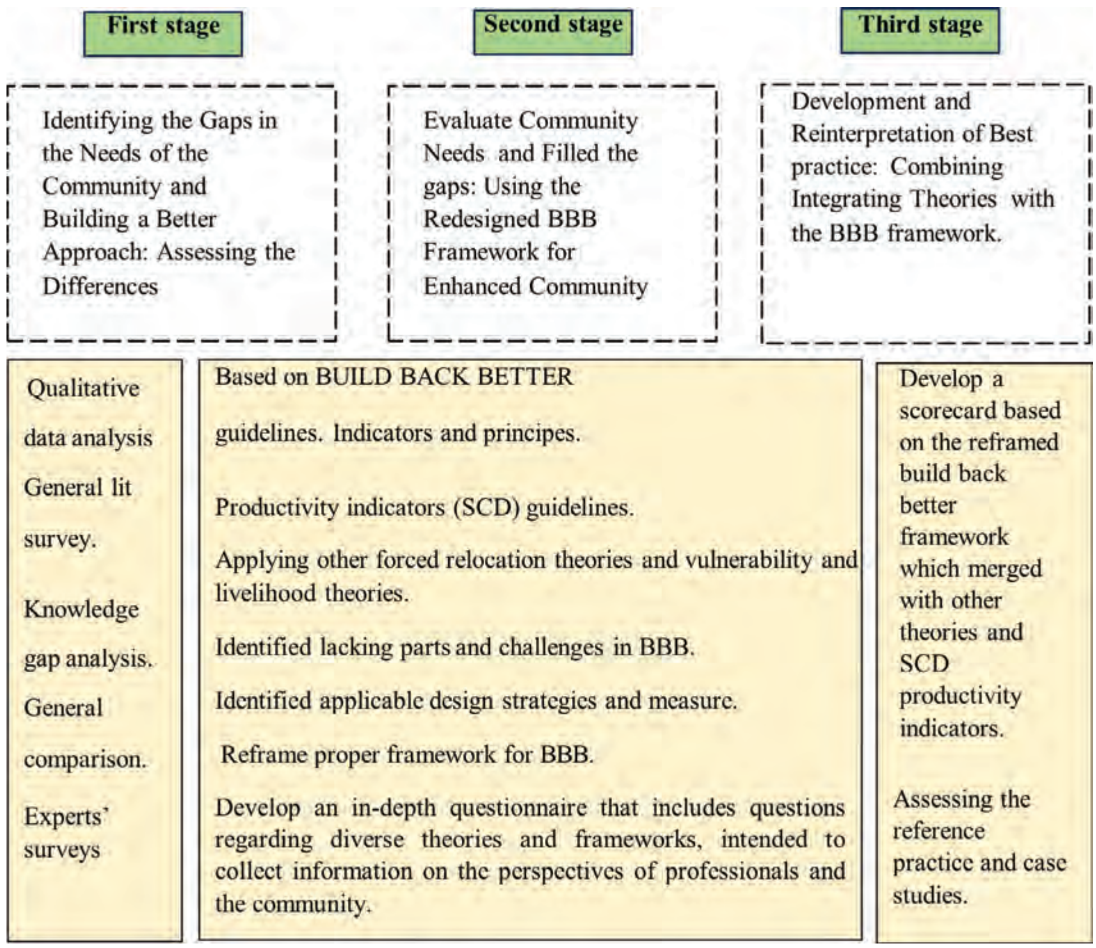

Figure 1. Methodology types; Source; Author

cohesion, economic resilience, environmental sustainability, and community engagement.

3. DEVELOPING A RECONSTRUCTED BUILD BACK BETTER FRAMEWORK

This section outlines the expanded BBB framework, integrating Sustainable Community Development (SCD) to create a holistic, human-centered approach for post-disaster recovery.

- **Scope and Limitations of Theoretical Framework:** The reconstructed BBB framework prioritizes principles of Sustainable Community Development (SCD) to address sociocultural, psychological, and economic resilience in post-disaster recovery. SCD's productivity indicators cover social, environmental, and economic aspects essential for long-term sustainability. This integration makes BBB more responsive to the diverse needs of resettled communities, aligning with the Sendai Framework's goal to create resilient societies that are "better prepared and empowered to deal with future disasters."

THEORETICAL FOUNDATIONS AND FRAMEWORKS:

- **Build Back Better:** This research employs BBB principles, focusing on six core indicators to assess recovery effectiveness.
- **Sustainable Community Development (SCD):** SCD indicators evaluate social, cultural, environmental, and economic productivity, aiming to create cohesive, resilient communities.
- **Thayer Scudder's Stress and Settlement Process:** Recognizes the stress continuum in forced relocation, emphasizing the need for stable transitions and long-term well-being.
- **Bohle's Conceptual Model on Double Structure of Vulnerability:** Analyzes vulnerability as a twofold structure that affects both livelihood and psychological resilience.

- **Sustainable Livelihood Frameworks:** Provides tools to assess livelihood sustainability and resource management in resettled communities.
- **Michael Cernea's Impoverishment Risks and Risk Management:** Highlights impoverishment risks in forced relocation, addressing risks like social disarticulation and loss of livelihood.

Figure 2 shows the Scope and limitation of the theoretical reframed framework.

Figure 3 shows the framework application.

4. CASE STUDY EVALUATION

The primary goal of this research is to evaluate community needs and deficiencies using best practices derived from the Build Back Better (BBB) framework and Sustainable Community Development (SCD) attributes. For this study, I selected two case studies of post-disaster resettlements following the 2004 tsunami in the Galle Municipal Area. Figure 4 shows the Divisional Secretariats and Grama Niladhari

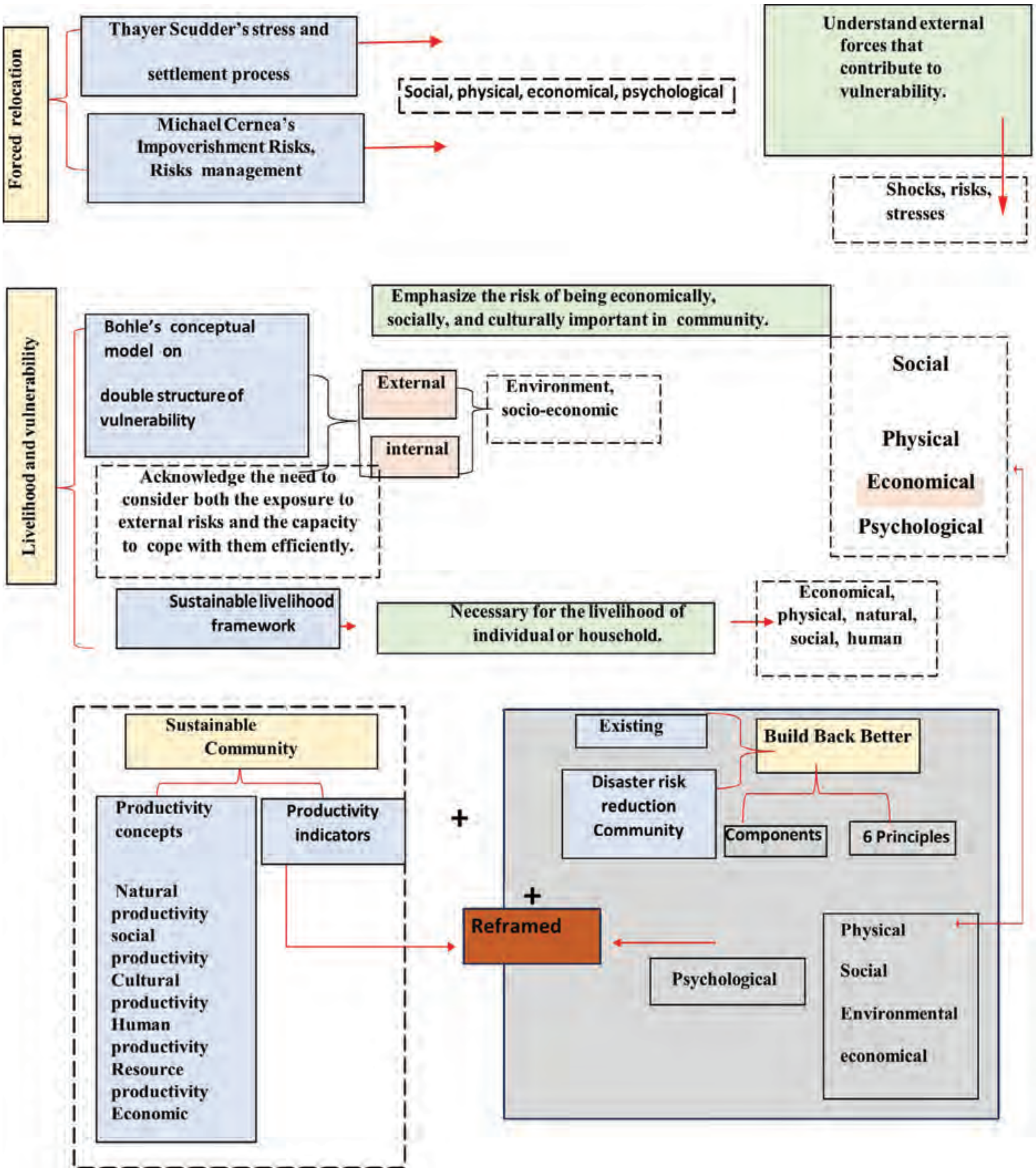

Figure 2. Scope and limitation of the theoretical reframed framework; Source: Author

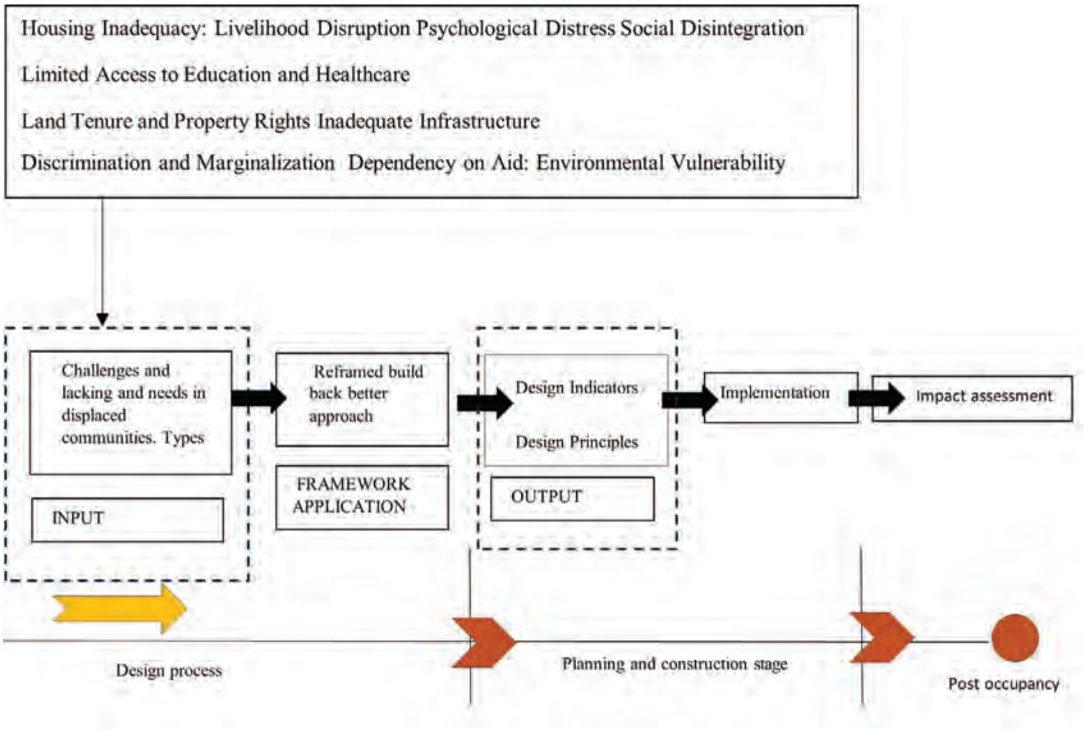

Figure 3. Framework application; Source: Author

(GN) divisions in the study areas. The first case, an early housing project initially deemed the best in the region, has since declined due to poor maintenance, conflicts between host and resettled communities, its distance from the main city, subpar housing quality, and a lack of common facilities from 2006 to 2015. This project was executed by a local contractor with Austrian funding. The second case is highly regarded for its quality and long-term planning, developed by a professional architect from Germany with support from a German funding agency from 2006 to 2015. The study focuses on Galle due to the significant impact of forced relocation,

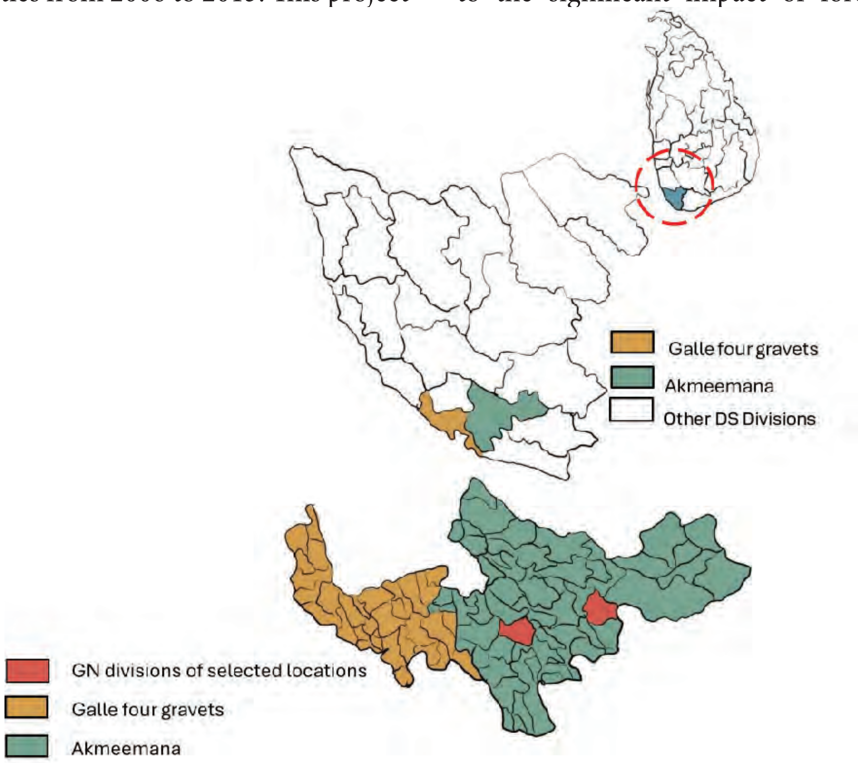

Figure 4. Divisional Secretariats and GN divisions of study locations; Source: Author

particularly in the Akmeemana Division, which covers over 6,437 hectares and includes 116 villages with a population of approximately 75,298 people. The selection was narrowed to two of the twelve available relocated communities in Akmeemana, where challenges, especially related to livelihoods, are most pronounced. The research involved analyzing photographs, research papers, and expert resources, exploring the period before the tsunami, the 2004 tsunami impact, post-disaster temporary housing in Galle, and the progression of permanent resettlements from 2006 to 2024.

The Green Village (Karanketiya) is a post-tsunami settlement situated 13 kilometers from Galle city, consisting of 90 housing units funded by Diakonie Catastrophenhilfe, Germany. Each unit includes two bedrooms, a living room, a kitchen, and a bathroom, set on a 10-perch plot. Access requires a 1-hour bus ride followed by a 2-kilometer walk. In contrast, the Katupolwatta settlement, also a post-tsunami project, is located 8.5 kilometers from Galle city on an eight-hectare plot and was established with funds from Salzburg citizens. It features 78 housing units with similar amenities but faces significant social and economic issues, including alcohol abuse, crime, and violence, largely due to employment conditions and challenges in community integration. The selected housing schemes are shown in Figure 5 and 6.

Figure 5. Katupolwatta settlement, Source: Author

4.1. Case Study Framework

Figure 7 *shows the case study framework.*

4.2. Score card evaluation- Katupolwatta

The assessment of Katupolwatta highlights deficiencies in infrastructure, environmental management, and economic support. The original construction inadequacies, such as undersized kitchens and poorly designed living spaces, have led to frequent modifications by residents. Community infrastructure was minimal, lacking essential services like advisory support, recreational areas, and skill development programs. Furthermore, the absence of waste management and inadequate drainage systems have resulted in environmental degradation, demonstrating gaps in applying BBB and SCD principles. Although access to educational institutions is relatively satisfactory, the lack of government support for promoting local industries and services such as counseling reveals the pressing need for comprehensive redevelopment. This case underlines the importance of integrating BBB with SCD, especially for infrastructure planning, environmental restoration, and community engagement.

4.3. Score card evaluation-Green Village

The Green Village settlement evaluation indicates moderate success in implementing sustainable practices such as water storage,

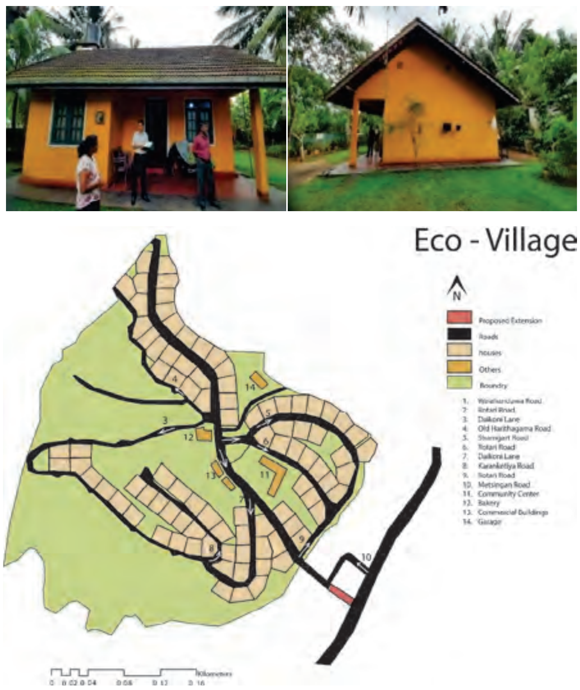

Figure 6. Green Village (Karanketiya), Source: Author

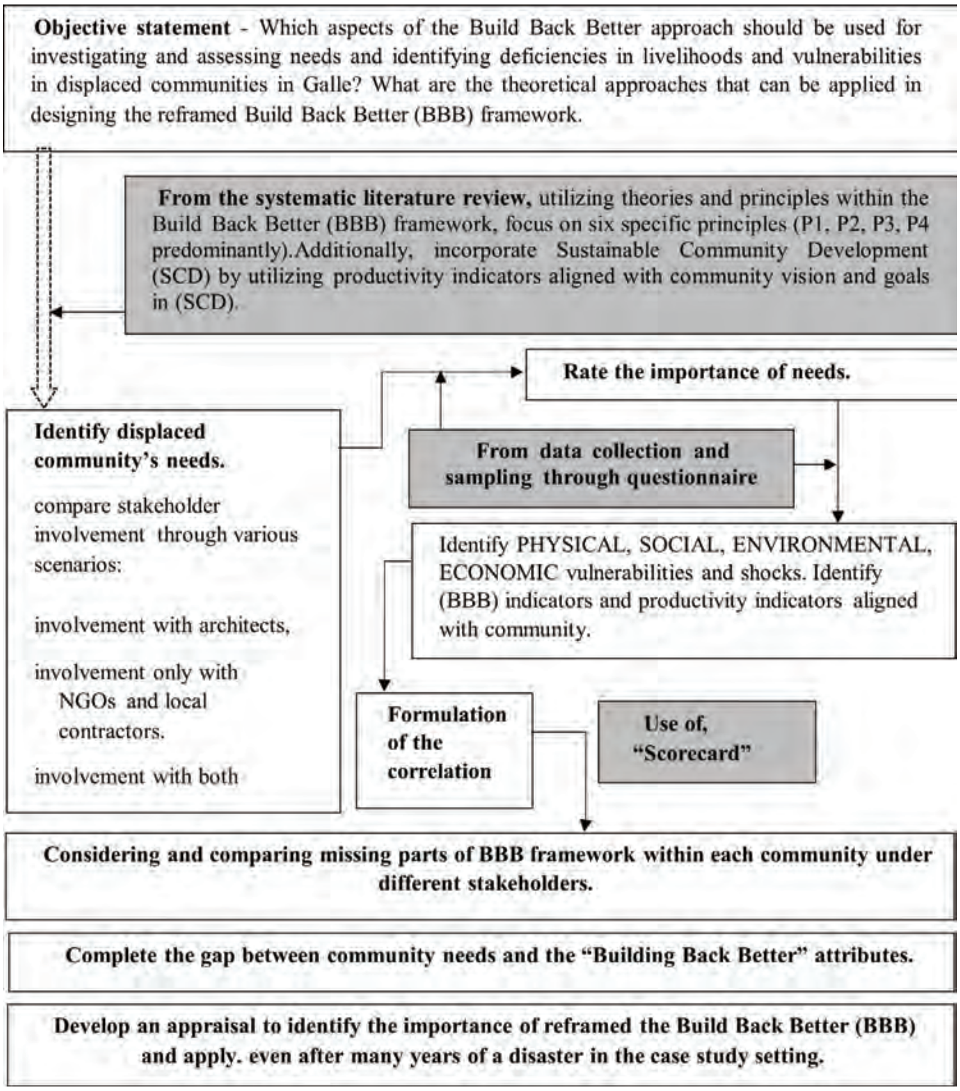

Figure 7. Case study framework; Source: Author

rainwater harvesting, and composting. While some physical planning aspects like road capacity and material durability were well executed, critical functional needs—such as adequately sized kitchens, living spaces, and community hubs—remain unaddressed. Environmental aspects are partly effective, but wastewater management and adaptive structures for climate resilience are underdeveloped. Though green spaces and community gardens are present, they are poorly maintained, reflecting a lack of long-term support. Social infrastructure like community hubs and workshops was either minimally functional or nonexistent, and economic opportunities, such as skill development programs, were not effectively integrated. This assessment suggests that while Green Village has strengths in physical and environmental aspects, it requires greater investment in economic and social infrastructures to align with BBB's comprehensive goals.

4.4. Comparison Between Katupolwatta and Green Village (Haritha Gama)

Katupolwatta Settlement:

Katupolwatta faces numerous challenges in planning and design, particularly in the quality of core areas like kitchens, toilets, and living spaces. These inadequacies lead many residents to modify their homes to address functional needs. Environmental infrastructure is also lacking, with issues such as poor waste management and drainage systems. Community infrastructure is minimal, with few facilities or social services available, such as advisory services, recreational spaces, economic support mechanisms, or skill development programs. Additionally, deteriorating community spaces and insufficient environmental management underscore the need for a comprehensive redevelopment approach that considers both physical and social needs.

Green Village (Haritha Gama):

Compared to Katupolwatta, Green Village reflects moderate improvements in planning, design, and environmental management. It incorporates some functional and environmental elements, like water storage and rainwater harvesting, yet falls short in areas like wastewater management and the development of structures adaptable to climate-related hazards. While some community spaces and green areas exist, they are poorly maintained, and the settlement lacks robust economic and social support mechanisms, receiving limited government assistance. Environmental efforts include native vegetation and community gardens, but challenges in waste management and sustainable agriculture remain. Overall, Green Village demonstrates some progress in planning, environmental management, and community infrastructure, yet both settlements face substantial challenges.

4.5. Discussion

4.5.1. Strengths and Weaknesses

The initial assessment framework highlights the discrepancies between community needs and existing practices in post-disaster housing, underscoring the importance of community-driven approaches. The modified Build Back Better (BBB) framework used in this study illustrates that psychological impacts from disasters and relocation are critical considerations that often go unaddressed. Incorporating a "psychological" indicator alongside gradual integration of essential design components helps bridge this gap. The research's structured format facilitated clear comparisons, making distinctions between current practices and community needs more evident and promoting effective decision-making.

Despite the usefulness of the BBB principles and sustainable community development framework, challenges remain. Budget constraints and spatial limitations in small community houses hinder full implementation. Data collection exposed difficulties in meeting all scorecard criteria, with community dynamics, such as conflicts, affecting the use of shared facilities. The diverse aspirations of community members reinforce the need for adaptive strategies rather than a uniform approach, ensuring responsiveness to unique needs and perspectives.

4.5.2. Practical implementation and direction for future study.

Thus, the vital role of human agency in post-disaster housing reconstruction is emphasized, recognizing the broader socio-cultural and psychological effects of relocation It calls on designers, architects, and planners to move beyond simply replacing physical structures and to actively engage with vulnerable communities during the design process. Such engagement is crucial, as communities possess intimate knowledge of their needs and aspirations, contributing to solutions that foster resilience and sustainability.

Thus, adapting the Build Back Better (BBB) framework to contemporary requirements should consider physical, psychological, social, environmental, and economic factors, ensuring alignment with each community's specific characteristics. This approach, rooted in BBB and Sustainable Community Development (SCD) principles, meets communities where they are and supports them in building forward in meaningful ways.

4.6. Key Policy Recommendations with Architectural Considerations:

Address Long-Term Psychological Needs and Social Integration

- Policy Recommendation: Develop mental health support programs and community-building initiatives to assist resettlers in adapting to new environments. Establish regular support groups and counseling services to address trauma and social integration challenges.
- Architectural Component: Design private and semi-private spaces, such as quiet rooms and community counseling centers, within housing schemes to provide safe spaces for mental health support. Utilize natural lighting, calming color schemes, and views of green spaces to create therapeutic environments that promote psychological well-being.
- Justification: BBB acknowledges the psychological impacts of relocation, while SCD emphasizes community cohesion and emotional well-being as essential for long-term resilience.

Foster Community Ownership and Engagement

- Policy Recommendation: Encourage resettlers' active participation in the design and planning of their new communities, respecting local knowledge and preferences. Establish feedback mechanisms for ongoing community involvement in decision-making.
- Architectural Component: Integrate flexible architectural designs that allow residents to personalize their spaces, reflecting cultural preferences. Use participatory design workshops that involve residents in planning shared spaces and architectural features to ensure a sense of ownership and satisfaction with the built environment.
- Justification: Community engagement fosters resilience and satisfaction, aligning with SCD's participatory principles and enhancing BBB's adaptability to community-specific needs.

Enhance Economic Opportunities and Skill Development

- Policy Recommendation: Implement vocational training programs, financial assistance, and access to microfinance for residents, with NGO partnerships to offer skills aligned with job market needs.
- Architectural Component: Design multipurpose spaces that can serve as community hubs for training, workshops, and entrepreneurial activities. These spaces should be flexible and able to accommodate various vocational and skill-building programs, promoting economic self-sufficiency within the community.
- Justification: SCD prioritizes poverty alleviation and economic empowerment, while BBB promotes livelihood enhancement to prevent impoverishment, consistent with Cernea's Impoverishment Risks Model.

Improve Environmental and Infrastructure Resilience

- Policy Recommendation: Integrate sustainable practices like rainwater harvesting, waste management systems, and resilient infrastructure. Include green spaces to promote environmental and social benefits.
- Architectural Component: Use resilient architectural materials and building methods that withstand local environmental challenges. Incorporate passive design strategies for natural ventilation and cooling and integrate green roofs and walls to mitigate heat and enhance biodiversity. Design green spaces and pathways that connect residential units, fostering an environmentally integrated and resilient community.
- Justification: SCD's ecological focus, coupled with BBB's emphasis on creating safe, sustainable environments, reduces vulnerabilities and improves community adaptability.

Promote Social Cohesion through Cultural and Recreational Spaces

- Policy Recommendation: Design shared cultural and recreational facilities, such as parks and community centers, to foster connections and a shared identity.
- Architectural Component: Develop open, inviting community centers, parks, and shared recreational spaces that respect cultural preferences and facilitate social gatherings. These spaces should include shaded areas, seating, and natural elements that create a welcoming atmosphere for both formal and informal gatherings.
- Justification: This approach aligns with SCD's social development goals and BBB's commitment to rebuilding a sense of community, reducing stress and social isolation.

Regular Monitoring and Adaptive Policy Frameworks

- Policy Recommendation: Establish a monitoring system to track and respond to evolving community needs over time, with flexible policies for emerging challenges based on community feedback and environmental assessments.
- Architectural Component: Design adaptable structures that can accommodate future modifications based on changing community needs. Use modular construction techniques to allow for adjustments in layout and function, supporting the community's

evolving needs without requiring significant overhauls.

- Justification: Adaptable policies reflect BBB's iterative approach and SCD's emphasis on adaptive management to evolve with community needs.

Ensure Access to Healthcare and Essential Services

- Policy Recommendation: Provide consistent healthcare services, including emergency facilities, and support basic needs through mobile health units and community health workshops.
- Architectural Component: Integrate accessible healthcare spaces within the housing scheme, designed for easy navigation, with designated areas for mobile health units and community workshops. Include shaded waiting areas, ramps, and clear signage for all facilities to accommodate diverse users.
- Justification: SCD emphasizes basic service access for quality of life, while BBB prioritizes health and safety in resilience, helping resettlers adapt effectively.

Emphasize Continuous Education on Disaster Preparedness and Management

- Policy Recommendation: Conduct regular disaster preparedness workshops to empower residents with knowledge on risk mitigation, sustainable livelihoods, and first-response activities.
- Architectural Component: Design disaster-resilient buildings with clear emergency routes, designated safe zones, and signage for easy evacuation. Community centers should include areas equipped for disaster preparedness training, with accessible storage for emergency supplies.
- Justification: Disaster resilience education fulfills a core BBB objective and aligns with SCD's focus on informed and resilient communities.

5. CONCLUSION

The research aims to redefine the concept of "Build Back Better" to foster sustainable communities' post-disaster. "Build Back Better" should not simply involve providing new housing; rather, it should create spaces where individuals feel a lasting sense of belonging that surpasses pre-disaster conditions. Since its introduction in 2005, BBB has guided post-tsunami housing projects under the Sendai Framework. Originally, it served as a quality standard and morale booster, assuring survivors that the new houses were worth living in. However, the study found that many housing recipients are unfamiliar with the term and often modify or sell the houses provided under this initiative. Donor agencies and authorities frequently fail to align housing designs with the residents' desired way of life, despite having time to understand these needs during community establishment.

The study underscores the importance of addressing the emotional and psychological needs of impacted populations, not just focusing on physical structures. Community satisfaction is key to creating a real sense of "home" and encouraging active involvement in socioeconomic recovery. Confusion over multiple BBB guidelines complicates effective implementation, showing that a community-based approach is essential for delivering true homes, not just houses. Reframing BBB to align with community needs—considering physical, psychological, social, environmental, and economic factors—is crucial for long-term satisfaction and sustainability.

The study incorporates theoretical models such as Thayer Scudder's stress and settlement process, Michael Cernea's Impoverishment Risks Model, Bohle's vulnerability model, and the Sustainable Livelihood Framework to better understand and address the challenges faced by displaced communities. Sustainable community development (SCD) principles are recommended to alleviate poverty and meet basic needs, creating an evaluation framework with five core indicators plus a "psychological" factor assessed through a scorecard. Case studies of two settlements—one designed by a professional architect and the other by a local contractor—demonstrate that the architect-designed community achieved higher ratings for quality and planning, whereas the contractor-led settlement faced issues with maintenance and lack of facilities. This emphasizes that both professional and non-professional housing schemes need to understand and reflect community needs for effective resettlement.

Furthermore, the key policy recommendations provide an architectural dimension that supports BBB and SCD principles.

It suggests incorporating mental health support spaces, adaptable structures, and participatory designs that empower residents and foster a sense of ownership. Multipurpose spaces for vocational training, green areas for environmental resilience, disaster-resilient designs, and culturally meaningful gathering places further enhance the built environment. These elements collectively address the physical and psychological needs of resettlers, supporting resilience and adaptability while cultivating a genuine sense of community.

In conclusion, post-disaster housing solutions require more than physical rebuilding; they must address psychological and social needs to ensure the creation of sustainable, livable communities where residents can thrive long-term.

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7. REFERENCES

Ahmed, I. (2011/07/19). An overview of post-disaster permanent housing reconstruction in developing countries. *International Journal of Disaster Resilience in the Built Environment*, 164.

Arlikatti, S. (2017). Should I Stay or Should I Go? Mitigation Strategies for Flash Flooding in the Himalayan Communities of India. *International Journal of Disaster Risk Reduction*.

Bradley, R. C. (2010). Disasters and Displacement: Gaps in Protection. *Journal of International Humanitarian Legal Studies*, 35.

Dias, N. K. (August 2016). Long-term satisfaction of post disaster resettled communities: The case of post tsunami – Sri Lanka. *Disaster Prevention and Management An International Journal*, 594.

Dube, E. (2019). The build-back-better concept as a disaster risk reduction strategy for positive reconstruction and sustainable development in Zimbabwe: A literature study. *International Journal of Disaster Risk Reduction*.

Fernando, N. (May 2010). *Graduate Research Series vol. 6: Forced Relocation after the Indian Ocean Tsunami 2004-Case study of vulnerable populations in three relocation settlements in Galle, Sri Lanka.* Bonn, Ger many: UNU-EHS Hermann-Ehlers.

Fernando, N. (May 2010). *Graduate Research Series vol. 6: Forced Relocation after the Indian Ocean Tsunami 2004-Case study of vulnerable populations in three relocation settlements in Galle, Sri Lanka.* Bonn, Ger many: UNU-EHS Hermann-Ehlers-Str. 10.

Fernando, U. (2006). Everyday Practices of Humanitarian Aid: Tsunami Response in Sri Lanka. *Development in Practice 16*.

Garcin, M. J.-F. (2008). Coastal risks in Sri-Lanka - GIS, scenario and modelling approaches. *Nouvelles approches sur les risques côtiers : Aléas, vulnérabilité, changement climatique, variations du trait de côte*.

Hettige, S. N. (2004/01/01). *Improving Livelihoods of the Urban Poor – A Study of Resettlements Schemes in Colombo, Sri Lanka.*

Kim, K. (2015). The Theory and Practice of Building Back Better. *Journal of the American Planning Association*, 292.

Lacsamana, L. F. (2017). *Build Back Better: Making Inclusion Work in Disaster Recovery in the Aftermath of Typhoon Haiyan.*

Liu, W. J. (2020). Effects of disaster-related resettlement on the livelihood resilience of rural households in China. *International Journal of Disaster Risk Reduction*.

Mannakkara, S. S. (2014). Re-conceptualising "Building Back Better" to improve post-disaster recovery. *International Journal of Managing Projects in Business*.

Muggah, R. (2008). *Relocation Failures: A Short History of Internal Displacement in Sri Lanka.*

Roseland, M. (2000). Sustainable Community Development: Integrating Environmental, Economic, and Social Objectives. *Progress in Planning*, 132.

Silva, M. (2018). Involuntary disaster relocation and its impact on children: a case study in Galle, Sri Lanka. *Procedia Engineering*, 197.

Silva, M. N. (2023). Climate Crisis, Global Migration, and Disaster Research Social Work as a Bridging Agent. .

Sisira Jayasuriya, P. S. (January 2006). Post-Tsunami Recovery:. *ADB Institute*.

Societies, International. (2010/01/01). *World Disasters Report* .

Sooriyaarachchi, P. (2018). Coastal community resilience level of Tsunami prone area : a case study in Sri Lanka. *Procedia Engineering*, 690.

Zayas, J. (2017). *Build Back Better: Making Inclusion Work in Disaster Recovery in the Aftermath of Typhoon Haiyan.*

The Long-term Impact of Forced Relocation 20 Years After the 2004 Indian Ocean Tsunami: A Case Study of Selected Relocation Settlements in Galle and Batticaloa, Sri Lanka

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ABSTRACT

The 2004 Indian Ocean Tsunami devastated the coastal regions of Sri Lanka taking the lives of thousands and destroying billions worth of movable and immovable properties. In the aftermath, the government of Sri Lanka initiated a large-scale programme to relocate the families lived in the 100 meter buffer zone in the South and 200 meters in the East and North affected by the Tsunami to safer areas. However, a plethora of studies on these relocated settlements has raised questions regarding the effectiveness and appropriateness of the relocation measures pointing to many shortcomings in the relocation process. In the context of fast approaching 20th anniversary of the 2004 Indian Ocean Tsunami, this study explores the long-term impact of the relocation programme on the socio-economic conditions of the households in resettlements in the Akmeemana Divisional Secretariat in Galle and the Batticaloa Municipal Council area. The key objectives of this research are 1.) examining the long-term impacts of forced relocation on relocated communities including children, the elderly, host communities, new settlers, and families who migrated back to the buffer zone 2.) understanding coping and adaptation strategies communities had utilised to counter these impacts and 3.) to identify the measures that need to be integrated to improve the effectiveness of future relocations. Accordingly, the study employed four structured interview schedules to collect primary data from the host community, resettlers, relocatees who had moved back to the buffer zone and new settlers with an overall sample of 650 respondents and 30 in-depth interviews with key informants. Findings of the study highlighted the long-term impacts experienced by relocated communities. Notably, the livelihoods of the relocated communities have been disrupted, primarily due to the considerable distance to the city centre and transportation difficulties. The faulty infrastructure at the settlements and the lack of financial and administrative support from the government, has impacted the community's financial stability and overall quality of life. Children and the elderly have suffered significantly due to the relocation. Children have experienced disruptions to education causing them to drop out of schools while social environment of the elderly were severely affected by relocation. Moreover, the study uncovered a significant strain that relocation had exerted on the social relations within the communities and with host communities due to faulty of infrastructure as well as conflicts. In response to many challenges brought forth by relocation, these communities have adopted a range of coping and enhancement strategies such as changing livelihood activities, engaging in self-employment, increasing spending on children's education, and returning to the buffer zone by selling, renting, or leasing their respective housing units. In conclusion, based on the findings the authors propose certain measures to be implemented to improve effectiveness of future relocations efforts. These measures include advocating for participation and consultation of relocated communities, incorporating an understanding of the social structure and cultural characteristics into relocation decision-making, increasing the emphasis on livelihood restoration and recovery, exerting adequate time, resources, and effort to constructively deal with relocation-induced risks in the long-term, accounting for pre-existing vulnerabilities of relocatees when designing relocation programs, and implementing long-term monitoring and evaluation of relocated communities.

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1. INTRODUCTION

Considering the number of deaths, missing and displaced people reported from the 2004 Boxing Day tsunami disaster in Sri Lanka, the then-government decided to strictly re-impose the buffer zone regulation. As a result, 100 meters from the permanent vegetation line of the beach in the south and 200 meters in the north and east were declared 'no construction zones' for residential purposes. Those who stayed in the buffer zone areas before the tsunami were forbidden from returning to their previous residence to reconstruct their completely or partially damaged houses. Instead, they were forcibly relocated into donor-built relocated settlements. The government decided to implement the buffer zone regulation to, on one hand, protect people from future tsunamis and other coastal hazards and, on the other, improve their living conditions outside the buffer zone. In this context, the government had introduced relocation as a disaster risk reduction strategy. The central problem of this strategy is the uprooting of the people and the destruction of communities while pledging to protect lives from future tsunamis and other coastal hazards.

It is against this background that this paper tries to examine the impact of forced relocation on vulnerable groups including children, and the elderly while exploring the challenges that emerged from the relocation process two decades after the tsunami and understanding coping and adaptation strategies employed relocated communities to face these challenges. This paper also examines issues faced by new settlers (those who have settled down in selected settlements as renters and those who have purchased original resettlers' land), host communities, and even those who migrated back to the buffer zone by closing, renting, or selling their houses.

2. DISPLACEMENT, FORCED RELOCATION, AND RESETTLEMENT

Forced relocation is primarily a political phenomenon as various government organizations use various acts to relocate people. According to Turton, forced relocation occurs when "Persons are forced to leave their homes or homelands for whatever reason and have been allocated specific areas for them to settle down in their own country with at least minimum resources and services to re-establish their lives" (Turton, 2006:13-14). Therefore, forced resettlement changes people's socio-spatial settings. Its impact on people is determined by their health, gender and economic position (de Wet, 2009). In this context, the social reconstruction of resettled communities in a new socio-spatial setting is a challenge. Although there are some relocation cases with successful outcomes, the complexities of the situations lead to a lack of guarantee of successful outcomes. Further to Turton, like refugees, forced resettlers belong to the poorest, most politically marginalised members of society who are at risk of ending up alienated from their government (Turton, 2006). In line with Turton's definition, forced relocation is identified in the context of the present study as, "those persons who lived 100 metres from the permanent vegetation line of the beach in the western and southern coastal areas and 200 meters in the eastern and northern areas, who were forced to leave their completely or partially damaged homes to live in new places due to the political decisions taken by the government to fully implement the buffer zone regulation (i.e. no construction zone) under the Coastal Conservation Act No. 57 of 1981, amendment, No. 64 of 1988.

According to Michael Cernea's Impoverishment Risks and Reconstruction Model for Resettling Displaced Populations (IRR model), Displaced people face a risk of economic, social, and cultural impoverishment when they settle in new locations. Eight important possible risks such as landlessness, joblessness, homelessness, marginalisation, food insecurity, increased morbidity and mortality, loss of access to common property resources, and social disarticulation which influence one another are discussed in this model (Cernea, 2000). He further suggested using this model as a planning and monitoring tool for implementers to avoid or minimise such risks before relocation and if not, then populations are likely to face economic, cultural, and social impoverishment after relocation. He argued that there is a high probability that these risks will produce serious consequences in badly planned or unplanned relocation. Therefore, planners and implementers must consider these risks and minimise their negative impact on the plan relocation process.

Anthony Oliver-Smith (2009) studies various types of relocations/resettlements and tries to answer why relocation/resettlement goes wrong on most occasions. According to him, this is due to a range of factors such as shortcomings in planning, financing, implementing, and administering resettlement projects. As a result, these settlements generally end up as development disasters. Chris de Wet (2009) further states that the inadequacy of input-related factors such as national legal framework and policies, political will, funding, pre-displacement research, careful implementation and monitoring are contributing to relocation failures. Inherent complexities related to cultural, social, environmental, political, institutional, and economic factors, which are interrelated to each other, also contribute to relocation failures. Therefore, the resettlement process comes out of the complex interaction of all these factors leading to unpredictability in the linear rational planning approach. In this context, the challenge is to develop a policy to ensure the genuine participation of all stakeholders in resettlement planning and decision-making to ensure socially, economically, and environmentally responsible relocation projects. According to Koenig (2009), planning needs to consider the three main rights of relocated people – the rights to livelihoods, housing, and improved living conditions. However, most relocations are defined only in terms of housing, neglecting economic and social reconstruction.

3. RESEARCH METHODS AND SAMPLING

People who lived in the buffer zone area of the Galle Municipal Council before the tsunami were relocated into new large settlements (50 or more housing units) constructed in the Akmeemana Pradeshiya Sabha (Rural Council) area. Therefore, we purposively selected three resettlements, namely, China Charity, Salsburg, and Kadiragamar settlements situated in the Akmeemana area to conduct the field survey. All these three settlements were situated 10 to 15 km away from the Galle city area. We also purposively selected a Swiss resettlement village situated in the Batticaloa Municipal Council area of the Eastern Province as another location to conduct fieldwork. People who stayed in the buffer zone areas of Dutch Bar, Navaladi, and Kallady were relocated into the new settlement situated in the same Municipal Council area, but 7 km away from the old settlements.

A random sample of re-settlers (95 from Batticaloa and 188 from Galle), new settlers (47 from Batticaloa and 75 from Galle), host community members (47 from Batticaloa and 60 from Galle) and those who had returned to the buffer zone (53 from Batticaloa and 50 from Galle) at the time of the research were selected to conduct interviews. Separate interview schedules were prepared for each group. Both qualitative and quantitative data were collected for the study. Data collection spanned nearly nine months and another three months were spent on data entry and analysis. The findings of the study were first presented to local-level officials in two separate meetings in Akmeemana and Manmunai North Divisional Secretariats, conducted on the 26th of February and the 11th of June, 2024, respectively. Key informant interviews were conducted with government officials at the Divisional Secretary level. In-depth interviews were conducted with youth and the elderly as well. Collected survey data were entered into the Statistical Package of Social Sciences (SPSS) and were used to conduct relevant univariate, bivariate, and multivariate analyses.

4. SALIENT SOCIO-DEMOGRAPHIC CHARACTERISTICS OF RESETTLERS IN GALLE AND BATTICALOA

When examining interview samples from resettlers in both Galle and Batticaloa, 58% of household heads were interviewed from Batticaloa settlements compared to 40% in Galle settlements. A significant proportion of females (81%) were interviewed from Galle compared to Batticaloa (59%). Age-wise, the majority of resettlers (51%) in Batticaloa belong to the age cohort of 31-50 compared to Galle (44%).

A slightly higher proportion of Batticaloa resettlers (56%) compared to Galle resettlers (50%) had lived in their previous place for 21 to 40 years, before the tsunami. This shows how hard it is for resettlers to move into new settlements as they must economically and socially adapt to the new environment which takes considerable time. Most families who stayed in the buffer zone area in the city of Galle were relocated into new settlements constructed in the Akmeemana Village Council area situated 10 to 15 km away from Galle city. In this context, Galle urban settlers became rural resettlers because of the relocation. However, Batticaloa resettlers were settled in the same urban council area in a new resettlement constructed 7 km away from their previous place

It is vital to state here, that 90% of the interviewed resettlers in Galle have been living in the new settlement for the last sixteen years or more, compared to 79% of respondents in Batticaloa. Therefore, it can be concluded that a significant proportion of resettlers have gained various experiences living in the new settlements for the last sixteen years or more.

5. RESEARCH LOCATIONS AND THE RELOCATION PROCESS

Galle is a coastal city consisting of multi-ethnic, multi-religious, and multi-caste groups. Resettled people mainly depend on the city for various income-earning activities and services before relocation. The city dwellers, who lived in the buffer zone area were relocated to new settlements situated in the Akmeemana area, which is dominated by Buddhists and the Goyigama caste group. Key officials state difficulty in finding State land from the Galle city area and the high cost of purchasing private land as the main reasons for why the government relocated people into new settlements in Akmeemana area instead. State land was found mostly in the Akmeemana area, hence relocation settlements were constructed in this area even though some of the land was not in a good enough condition to build new settlements.

Most of the lands selected to construct new settlements for donors were either abandoned paddy fields, tea plantations, or hilly forest land and some were situated in flood-prone areas. People, who were displaced due to their houses being partially or completely destroyed and did not have any other place to permanently stay, were unable to return to their previous place of residence due to the buffer zone regulations. As a result, they had no choice but to settle down in new settlements situated far from their previous place, even though they were aware of the potential distance-related issues. Even if they did not like to settle down in the new Akmeemana settlements, they were unable to stay in either temporary or transitory shelters, due to the lack of water, space, and electricity around the clock.

Those who lived in the Dutch Bar, Navaladi and Kallady areas in the Batticaloa city area before the tsunami were exposed to thirty years of ethnic war between the Sri Lankan Army and Liberation Tigers of Tamil Eelam (LTTE). There was a ceasefire in 2002 between the LTTE and the Sri Lankan government which was later breached by both parties. As a result, the ceasefire was over by the time the tsunami hit. The discussions held between the two groups to continue the ceasefire after the tsunami were unsuccessful. While the reconstruction of tsunami-destroyed houses and infrastructure took place during the war, Eastern Province came under the complete control of the Sri Lankan government by the end of 2007. It is important to note that the communities studied in Batticaloa were displaced several times due to prolonged exposure to the Sri Lankan Civil War from 1983 to 2007 and the tsunami. Therefore, while the challenge of recovery was complex for Batticaloa resettlers as they faced continued violence and armed incidents, displacement was not a new experience for them, who also had prior experience living in temporary camps (Thurnheer, 2014). However, displacement and resettlements were new experiences for Galle Resettlers.

The main responsible party in the institutional arrangement for resettlement was the task force appointed by the president for rebuilding the nation (TAFREN). The Tsunami Housing Reconstruction Unit (THRU) was set up as part of TAFREN under the Urban Development Authority, to work closely with the District and Divisional Secretaries in the reconstruction of permanent housing. TAFREN also worked to restore livelihoods, health, and education infrastructure as well.

Officials did not actively involve the buffer zone communities affected by the Tsunami in the relocation process, although some settlers have visited a few relocation sites to see the construction of housing. Most of the affected household members wanted to resettle somewhere close to the previous settlement, outside of the buffer zone, which was not possible due to most of the large settlements being situated 10 to 15 km away from the city in Galle and 7 km away from the city in Batticaloa. Nevertheless, affected people did not have any other option other than settling in given settlements.

The relevant DS-level officials did not properly monitor the construction of houses. Re-settlers complained that, as a result, the resettlements lacked quality housing in general and common infrastructure facilities such as community centres, streetlights, good access roads etc. It is important to note that local councils were not actively involved in the relocation process. For instance, when people relocated from their ancestral houses situated in the Galle MC area into donor-built relocation settlements situated in the Akmeemana rural council area, the rural council Chairman remarked that they were neither consulted nor actively involved in any resettlement construction or monitoring activity, that took place within the rural council, although 1000 or more new families were resettled into the area. Further, according to the chairman, it is important to increase human and other resources in the rural council before the resettlers are moved into the area so that the rural council can better facilitate these relocated communities. However, it took nearly 5 to 10 years to receive more staff, funds, and other relevant machinery and equipment (tractors for garbage collection, gully bowsers, etc.) from various donors and government agencies. Until then the local councils lacked the capacity to handle the needs of the resettled communities and, as a result, the new settlers suffered due to the lack of facilities. It is evident from this statement that the local government responsible for providing services to resettlers did not have the budget or even the training to cope with new responsibilities efficiently.

6. AWARENESS OF RELOCATION-RELATED SOCIO-ECONOMIC RISKS BEFORE RELOCATION

A significant proportion of Batticaloa (95%) and Galle (88%) resettlers were aware of the various risks they were likely to face in the new settlements, such as distance to the main city, finding employment in new settlements, access to the sea and access to services, to name a few. In other words, families forced to resettle did not have any other option than settling down in the new settlements, despite knowing the risks, because they were unable to reside in temporary or transitory shelters. It is important to note that some resettlers had to face unpredicted risks after relocation. For instance, resettlers from Galle reported tensions and physical conflicts between host and resettled communities, which were not anticipated challenges. Batticaloa resettlers had to grapple with floods and air pollution due to the construction of an incinerator by the Ministry of Health to burn hospital waste next to the resettlement.

7. ECONOMIC STATUS OF HOUSEHOLDS AFTER RELOCATION

Nearly 48% of Galle resettlers, compared to only 15% in Batticaloa, stated that they had to change or quit income-earning activities soon after relocating to the new settlements, mainly due to the distance to the city and transport difficulties. When exploring resettlers' household economic situation after relocation and staying sixteen years or more in resettlements, only one-third of respondents both in Galle and Batticaloa stated that their household economic situation got better. Two-thirds stated that the situation got worse due to multiple reasons such as increased expenses, decreased income, and lack of employment opportunities. When further questioned about their outlook on their household economic situation in the future, a significant proportion of resettlers in Batticaloa (80%) were pessimistic compared to resettlers in Galle (52%). This could be mainly due to the economic situation of the country, the high cost of living and the lack of employment opportunities in the area.

This pattern was further confirmed when a significant proportion of respondents answered negatively (73% in Batticaloa and 86% in Galle) when inquired from resettled families whether their household income is generally sufficient to meet household expenses. As a result, they have employed various strategies to cope with the situation such as borrowing money from friends and relatives, cutting down expenses, and withdrawing savings. It is evident from these findings that a significant proportion of the sample employs available social capital for their survival. On the other hand, one-third of respondents from both locations employ vulnerable strategies such as pawning valuables, depending on money lenders, and buying essential goods on credit, which show dependency on external sources for their survival. This in turn will force them to stay in a vicious cycle of poverty.

8. POVERTY AMONG RESETTLERS

Interviewed resettlers were requested to identify whether their households belonged to ‘very poor’, ‘poor’, or ‘non-poor’ categories, considering the socio-economic condition of their households at the time of the interview. Results show that 58% of Batticaloa resettlers belong to very poor (16%) or poor (42%) households while 66% of Galle resettlers belong to very poor (11%) or poor (55%) households. 42% of Batticaloa resettlers and 35% of Galle resettlers identify their households as non-poor households. A prominent characteristic of poor and very poor households, in both Galle and Batticaloa is the fact that they do not have a permanent income source in the household. However, at least one household member is casually employed, and some members are looking for employment. This income is insufficient for household survival and they suffer from a lack of savings. Some household members are engaged in vulnerable lifestyles as drug addicts and alcoholics and have even fallen into debt traps. There are also chronically ill household members. Most of the households are beneficiaries of the Samurdhi social security program and receive other government assistance for the elderly or the disabled. On the other hand, non-poor households have at least one or two permanent sources of income in the government or private sector or are engaged in businesses as trawler boat owners, normal boat owners, or even running a grocery shop. Some of these households have at least one member working in the Middle East or South Korea.

However, unemployment is prevalent in both locations. 72% of all respondents interviewed stated that there was at least one member without employment and in search of employment at the time of the interview. Regarding the difference between research locations, a slightly higher proportion of households with unemployment was reported from Batticaloa (nearly 73%) compared to Galle resettlements (71%). Households with unemployed members were higher in very poor and poor categories both in Batticaloa (60% and 77% respectively) and Galle (65% and 73% respectively) resettlements. The study further examined the gender variation of unemployed household members. There were more unemployed females (84%) compared to their male counterparts (16%). Unemployment was also prevalent among those with education only up to post-primary level (26%) or Ordinary Level (44%). It became evident from the interviews conducted with the main respondents that it is difficult to find employment in the new settlement areas. Therefore, unemployed women aspired to get training from the government or any other institution to build skills in cookery or sewing to be able to engage in self-employment or work in a garment facility. These could fulfil a crucial need of the relocated communities by assisting them to earn an additional income source for the family which in turn assists families in the very poor and poor categories, to move out of the poverty cycle in the long run.

When exploring the perception of the poor and very poor households in Batticaloa regarding the present and future financial and social standing of their household after relocation, the study found that there is an association between these two variables (Cramer’s V .370, Statistically significant .005). For instance, 87% of the very poor households and 73% of the poor households (overall 62%) are of the view that their financial and social standing has become worse after relocation. 80% of the total Batticaloa Households (including 93.3% of the very poor and 90% of the poor) are of the perception that the worsened situation will continue even in the future due to the present economic situation of the country and the lack of employment opportunities in the area (Cramer’s V, .363 Statistically significant .005).

As for Galle, the interviewed resettlers perceived the present social and financial status of their households as follows; 90% of respondents of the very poor and nearly 76% of poor category households (overall 67%) are of the view that their financial and social standing have become worse after relocation (Cramer’s V .373). Nearly 52% (overall percentage) is of the perception that the worsened situation will continue even in the future (that is 70% of the very poor and 54% of the poor) (Cramer’s V .134, Statistically not significant). This is also due to the high cost of living caused by the present economic situation of the country and the lack of employment opportunities in the area. It is also important to note that a reasonable proportion of Galle resettlers, 48%, belonging to the poor and the very poor are of the view that their economic situation will get better in the future compared to only 20% of Batticaloa resettlers. In other words, the Galle resettlers are of the view that the present economic situation will get better in the future which in turn will reduce the cost of living and create more employment opportunities for them to engage in. They also think that their children will be able to obtain decent employment with a good level of education in the future. Some even aspire for foreign employment in the Middle East or Korea. All these micro and macro factors will assist them to move out of the cycle of poverty in the future.

9. CHILDREN AND THE ELDERLY

The study also explored issues and problems school children, and the elderly had to face after relocation. Overall, nearly 16% of resettled households reported that their children dropped out of school after relocation (21% in Batticaloa and 14% in Galle). This is mainly due to the loss of income of the household head, increased distance to the previous school, and increased expenditure on transportation. This has disproportionately affected the very poor households with 50% in Batticaloa and 36% in Galle reporting school dropouts. At present, most of these children have grown into adults and are engaged in casual employment or household activities. Nearly 38% of households, 30% in Batticaloa and 56% in Galle resettlements, have changed their children to schools closer to the new settlements to cope with increased transportation expenditure although they are concerned about the quality of education, which the children received from popular schools in the city before relocation. There is a small proportion of parents in Galle who still send their children to popular schools in the city irrespective of distance and increased transport expenditure.

Nearly 48% of respondents in Galle stated that at least one household member suffers from chronic disease/s while Batticaloa households reported only 18%. It is evident from the interviews conducted with elderly people in both relocated settlements who are suffering from chronic illnesses that they have difficulties accessing services in the city due to transport difficulties. The elderly in general also raised their concern about being away from the social environment that they had before. They were attached to their previous place for two or three generations. Relocation has uprooted them from previous places, and as a result, they have lost neighbours, friends, and relatives who lived with them before relocation, and they do not have the time to reconstruct such a friendly social environment in the new settlements. Hence, they feel isolated more than ever before. This could be the reason why most elderly people are completely opposed to relocation. For instance, one elderly person said,

> "We have only a few more years to live. I wanted to die and be buried in my village where my ancestors were born, lived, and died. After moving to this settlement, I still feel new to this area. Considering the distance to the previous place, I cannot meet my old friends as frequently as before as it is difficult for me to travel by bus. Earlier we used to talk with them daily as they stayed within walking distance to my house. Resettlement has scattered friends, relatives and earlier neighbours into different places. I do not think my children can cremate or bury my body in my family burial ground in Galle."
>
> (Male Resettler in Galle, age 85, 2023)

This also shows that it is not an easy task to reconstruct a better social environment for the elderly. Even after sixteen years or more after relocation, there was no such program for the elderly in place initiated by government or non-government organisations.

10. RELATIONSHIP WITH NEIGHBOURS AND HOST COMMUNITY

Creating a community in a resettlement is a process. It is a huge challenge as members in the resettled community need to overcome trauma, adjust to the new environment, build new social networks, and collaborate with external organizations for support in rebuilding their lives without becoming dependent (Alaniz, 2017). The success of creating a community can be measured by the way people treat each other and the way they think about their neighbours, host community, and their own community.

According to 99% of Batticaloa respondents, their neighbourhoods and resettlements are peaceful. The percentage is much less in Galle, where nearly 77% of respondents consider their neighbourhoods and settlements mostly peaceful, with some reporting quarrels and tensions caused by alcoholics, personal jealousies, land disputes, and extramarital relationships. In both locations interviewed respondents know their neighbours and have reciprocal relationships such as helping each other in difficult situations either by giving money, advice, or labour. It is important to note that 98% of Batticaloa respondents know at least one or two of their present neighbours from the previous settlement. This percentage is slightly low in Galle (95%). Similar to this, both respondents in Galle and Batticaloa have at least one known friend from the previous settlement residing in the present settlement. Known friends assist each other in difficult situations by giving money, advice, and labour.

As to the question of whether any relatives of respondents live in the present settlement, nearly 88% of Batticaloa respondents stated that at least one related family lives in the new settlement compared to 69% in Galle. In both settlements, they help each other in difficult situations by exchanging money and food and looking after children. On the other hand, only 69% of Galle respondents stated that at least one related family lives in the new settlement.

There are also newcomers to the Batticaloa and Galle resettlements who have moved in as renters or as new settlers who purchased housing units from the original settlers. Most of these new settler families in Batticaloa (58%) had moved into the settlement mainly 10 years after relocation, while most of the new settler families in Galle (50%) settled within the first five years of relocation. Resettlers, who have sold or rented their housing units, have either moved back to the previous place close to the buffer zone or a new place close to the city.

In Batticaloa, the host community also faced transportation difficulties before and after relocation settlements were built. Yet nearly 94% of the host community members in Batticaloa, where most have a peaceful relationship with fellow community members and resettlers, do not intend to leave their settlements. The host community in Galle also faced difficulties due to a lack of common infrastructure and transportation difficulties due to a lack of good access roads, both before and after relocation settlements were built. Host community members in Galle have mostly peaceful relationships with fellow community members and resettlers, with some quarrels and tensions and 98% of them do not intend to leave their settlements. However, host community members were of the view that necessary common infrastructure should be built and in place before allowing resettlers to settle down in new settlements.

11. PLACE, HOUSING, AND OTHER COMMON NEEDS

61% of respondents from Batticaloa stated that their present housing unit and place are better than the previous one. This is mainly due to reasons such as the quality of housing, homeownership, and housing units with more space. However, 74% of Galle respondents are of the view that their previous housing unit is better than the present one, with only 20% stating the opposite. This is mainly due to reasons such as distance from the city, lack of services in the new place, and poor-quality housing. As stated before, most of the resettlers who lived in the city of Galle before the tsunami aspire to move into new settlements constructed in the city or closer to the city. This is because relocating to the Akmeemana area, after the buffer zone regulation was re-imposed following the tsunami, disrupting their income-earning activities and social relationships. However, this was not possible as only very few resettlements were constructed in Galle city due to land scarcity. Most large resettlements were constructed in the Akmeemana area about 10 to 15 km away from the city of Galle. In this context, Galle city dwellers converted into rural dwellers, as a result of relocation, which reduced access to various common quality services and other employment opportunities available to city dwellers.

Since then, various politicians and officials in the Akmeemana area have pledged to develop Akmeemana city as a regional city, especially after the construction of the Southern Highway in General and the Pinnaduwa exit point close to the Akmeemana area. However, it is evident from the responses of resettlers in the Akmeemana area that they still depend on the city of Galle to obtain various services even after residing in the new settlements for sixteen or more years. They also believed that their previous place and housing unit were better than the present one. Comparatively, Batticaloa resettlers were resettled in places well within the city area after displacement.

Resettlers from both locations requested the development of proper solid waste management and wastewater disposal systems in the settlements as a way to improve their living conditions. They also requested to build factories in the vicinity of the settlements to create employment opportunities for casually employed or unemployed youth in the area.

12. MIGRATING BACK TO THE CITY/ BUFFER ZONE

A significant proportion of the interviewed resettlers (nearly 90%) from Batticaloa intended to live in the settlement, while only 10% wanted to leave. Those who wanted to leave would like to move back to their previous place or somewhere closer to the city, mainly by selling their housing unit. A significant proportion of the interviewed resettlers from Galle (nearly 80%) intended to live in the settlement, while only 20% wanted to leave. Those who wanted to leave stated that they would like to move back to their previous place or somewhere close to the city, mainly by selling their housing unit. Only a small portion of interviewed resettlers wanted to leave their respective resettlements at the time of the interview,

Yet data from the Divisional Secretariat show that more than half of resettlers in the settlements chosen for the previous study had gone back to their previous place before the tsunami by selling, renting, or closing their housing units due to multiple reasons including distance to the city, lack of employment opportunities in new settlement areas, poor quality housing as well as the reduction of buffer zone regulation (40 or 45 meters in Galle and 80 meters in Batticaloa). The researchers also explore the views of the people who have moved into the buffer zone regarding whether they will be safe from future tsunamis and other coastal hazards. Most people are of the view they now know what a tsunami is, unlike in 2004, and where to run to protect their lives when they get the evacuation call. When asked they also stated further that they did not know what would happen to their movable and immovable properties. Government officials are of the view that they may have to expect more casualties and damages in future tsunamis especially in the Galle area as now there are more families and various businesses that operate in the buffer zone area. Coast Conservation Department officials have the authority to demolish new constructions in the buffer zone area, constructed without their permission, although according to officials, they refrain from doing so mainly due to political pressure.

Resettlers who have sold their lands have done so by signing a transfer letter in front of a lawyer as they did not receive the original deed at that time. However, according to the land officer at DS Division, this practice has not been accepted as legally valid. As a result, land deeds were only handed over to original settler families and not new settler families. As such, a new issue has already emerged for people who had purchased the land from original resettlers who sold their houses before obtaining the deed. As original deeds were not given to those who purchased lands from original resettlers, new settlers are now unable to obtain the deed for their name until they pay the government-valued amount for the property. One new settler stated the following,

> "We purchased this land and house for one million Sri Lankan rupees from the first owner. Both parties signed a letter in front of a lawyer transferring the ownership to the new owner once the original deed was received. However, we came to know from the land officer that they gave a deed to the original settler, and it cannot be transferred to the new owner until ten years have passed. If we want to obtain this land for our name, then we must pay another one million Sri Lankan rupees to the government. This is the value assessed by the government valuation department for the new land"
>
> (Galle, new settler, 2023)

It is evident from this statement that now this new settler must pay another one million rupees to the government to obtain legal ownership of the land. There are new settlers who have purchased lands from the second or third owner of the house and they do not know the first settler. There are no other options given by the government for new settlers to obtain ownership of the purchased land other than paying the amount mandated by the government. This is a new issue emerging among new settlers.

When inquired about the buffer zone regulation from resettlers who lived sixteen or more years in the new settlements, nearly 92% of respondents from Batticaloa stated that the buffer zone regulation positively impacted the livelihoods of relocated people. According to them, it was the correct decision as they now live in their own house, in a tsunami-free location with most of their relatives and friends and with access to good quality water for household use. 84% of respondents from Galle stated that the buffer zone regulation positively impacted the livelihoods of the relocated people mainly as they now live in their own houses in lands that they own and close to their relatives. However, the lack of employment opportunities and distance to the city are perceived as issues among respondents in Galle.

13. NEW SETTLERS (PURCHASED OR RENTED)

47 respondents from Batticaloa who have either rented (29) or purchased (17) houses were interviewed. Most people who have purchased housing units have done so by paying Rs.500,000 to Rs.1,000,000 and those who have sold their housing units illegally have done so by signing an agreement in front of a lawyer (88%). Those who have rented the house have done so by obtaining a monthly rental of Rs. 5000 or below. Many renters and new settlers who have purchased or rented housing units have done so mainly due to the low price. However, most of them have identified the distance to the city as one of the main disadvantages. New settlers have a very peaceful relationship with both host and resettled communities. They actively engaged in organizing religious activities and other community activities like New Year celebrations with host and resettled communities. Nearly 94% of new settlers intend to stay in this settlement.

In Galle, 74 respondents who have either purchased (63) or rented (11) houses in resettlements were interviewed. People who have purchased housing units have done so by paying Rs.500,000 to Rs.1,500,000 and those who have sold their housing units illegally have done so by signing an agreement in front of a lawyer (85%). Those who have rented the house have done so by obtaining a monthly rental between Rs.5000 and Rs.10,000. Most renters and new settlers who have purchased or rented housing units have done so mainly due to the low price and also because of the close proximity to relatives, who are either in the settlement or the neighbouring village. Most new settlers have identified an unfavourable social environment (conflicts, drug addiction, alcoholism, and being labelled as tsunami resettlers) as one of the main disadvantages. New settlers have mostly a peaceful relationship with both host and resettled communities with some quarrels and tensions. New settlers actively engaged in organizing religious activities and other community activities like New Year celebrations with host and resettled communities. Nearly 67% intend to stay in this settlement.

14. CONCLUSION

This study was conducted with the aim of 1.) examining the long-term impacts of forced relocation on relocated communities including children, the elderly, host communities, new settlers, and families that had migrated back to the buffer zone, 2.) understanding coping and adaptation strategies communities had utilised to counter these impacts, and 3.) to identify the measures that need to be integrated to improve the effectiveness of future relocations.

Based on the findings of the study we argue that the selected relocated communities in Galle and Batticaloa are suffering from a plethora of long-term impacts caused by the relocation process. The long-term socio-economic impact of relocation has significantly reduced the quality of life of relocated communities with specific impediments to their livelihoods and social relations. These livelihood impacts are a result of failure in the relocation process to identify the genuine wants and needs of the relocated communities, the lack of effective and long-term support to revitalize existing livelihood strategies and initiate new means of income generation, and failure in infrastructure facilities.

Vulnerable groups such as children and the elderly have suffered significantly because of the relocation. Education of children had been disrupted by factors such as increased distance to the schools, transportation difficulties, and having to change schools. These challenges have caused a significant number of children to drop out of school after relocation. The elderly too have suffered significantly due to being uprooted from their familiar places, which has negatively impacted their social relations due to having inadequate time to build new relationships.

Moreover, the relocation process has also worsened the impact on host communities of the settlements by putting a strain on shared infrastructure facilities. This is because the relocation programmes have rarely taken measures to improve common infrastructure facilities to accommodate the increased population either prior to or after relocation. In addition, findings also explored the experience of new settlers who have moved in by either renting or purchasing households from the relocatees. They have been attracted to the settlement due to the low prices. Nevertheless, they too are susceptible to the infrastructure failures and transportation challenges experienced by resettled communities. Further, the new settlers have experienced difficulties in obtaining the legal ownership of households due to government regulations, pushing them to reconsider the decision to move into the settlement in the first place.

Overall relocated communities have employed multiple coping strategies to overcome the impacts generated by the relocation process. These include changing livelihoods, more than one household member engaging in income-earning activities, borrowing money using formal or informal means, changing schools of children to reduce travel time and expenditure, and more. Nevertheless, it is difficult to assume that these coping strategies have been significantly effective as a large majority of the relocated communities identify themselves as belonging to low-income categories and barely managing to make ends meet. As a result, individuals with sufficient social and financial capital have moved back to the buffer zone by selling, renting, or closing their houses in relocation settlements. They are aware of the risks of being susceptible to a natural disaster such as a tsunami but are willing to take the risk to overcome the multifaced impacts of relocation.

In conclusion, the findings of the study point to the need to treat relocation as a long-term process which can cause long-term impacts, requiring flexible and innovative solutions. Further, findings point to the existence of additional groups of influence in the relocation process including the host community, new settlers, and relocatees that migrated back to the buffer zone. These groups are also susceptible to the long-term impacts of relocation and require close attention from the implementing organizations.

15. RECOMMENDATIONS

One of the key objectives of the study is to identify the measures that need to be integrated to improve the effectiveness of future relocations. This section presents a concise group of recommendations authors have developed based on the findings of the study, that can facilitate the effectiveness of future relocation activities.

1. Advocating for participation and consultation

   The risks of planned relocation can be mitigated if inputs from beneficiaries are seriously taken into consideration in key aspects of decision-making.

2. Incorporating an understanding of the social structure and cultural characteristics into relocation decision-making

   The social structure and the cultural characteristics of both the relocated community and the original community should be considered when arriving at critical decisions in relocation projects.

3. Increased emphasis on livelihood restoration and recovery

   Livelihood recovery and restoration may call for measures such as relocating vulnerable groups to settlements that are closer to their original settlements, provision of self-employment opportunities, etc.

4. Administering planned relocation as a long-term process

   Project authorities should exert adequate time, resources, and effort to constructively deal with relocation-induced risks in the long term.

5. Account for pre-existing vulnerabilities of relocatees when designing relocation programs

   Aspects of program design, including the program structure, the amount of funds provided, and the way the funds are provided, should be ideally decided based on the socio-economic characteristics of the target beneficiaries.

6. Long-term monitoring and evaluation

   Long-term monitoring and evaluation of resettlers in general, and vulnerable families in particular, is vital. This in turn will assist planners and implementers in introducing various interventions at different stages of relocation.

16. REFERENCES

Alaniz, R. (2017). *From Strangers to Neighbours: Post-disaster resettlement and community building in Honduras.* Texas: Texas University Press.

Cernea, M. (2000). Risks, safeguards and reconstruction. A model for population displacement and resettlement. In M. Cernea and C. McDowell (eds), *Risks and Reconstruction. Experiences of Resettlers and Refugees*, Washington, D.C.: The World Bank.

Coast Conservation Department (1997). Coast Conservation Management Plan (Revised) 1997. Colombo: Coast Conservation Department.

Coast Conservation Department (2005). Developers Guide and Procedures for Coastal Development. Colombo: Coast Conservation Department. Available from https://www.coastal.gov.lk/images/pdf/Permit_Guidline.pdf

Coast Conservation Department (2006). Relevant Regulations and Permit Process for any Development Activities in the Coast Conservation Zone. Colombo: Coastal Conservation Department

De Wet, C (2009). Does Development Displace Ethics? The Challenge of Forced Resettlement. In A. Oliver-Smith (ed.), *Development and Dispossession: The crisis of forced displacement and resettlement*, 77, 96. New Mexico: School of Advanced Research Press.

Koenig, D. (2009). Urban Relocation and Resettlement: Distinctive Problems and Distinctive Opportunities. In A. Oliver-Smith (ed.), *Development and Dispossession: The crisis of forced displacement and resettlement,* 119-139. New Mexico: School of Advanced Research Press.

Oliver-Smith, A. (2009) Introduction: Development-Forced Displacement and Resettlement: A global human rights crisis. *Development and Dispossession – the crisis of forced displacement and resettlement,* 3-23. New Mexico: School of Advanced Research Press.

Thurnheer, K (2014) *Life Beyond Survival: Social Forms of Coping after the Tsunami in war-affected Eastern Sri Lanka*. Wetzlar: Medienproduktion.

Turton, D. (2006). Who is a forced migrant? In *Development-Induced Displacement: Problems, Policies and People.* C. J. De Wet, (ed.), 13-27. Oxford: Berghahn Books.

Revisit the Tsunami Resettlements: Women in Designed Living Environment

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ABSTRACT

Great Indian Ocean tsunami devastated the life of coastal communities adding new life experiences. Lessons learnt will beneficial in preparing communities for future disasters. Present study investigates the plight of women in designed living environment of tsunami resettlements and specific concerns were on site selection, location, design and suitability of the physical area. Five tsunami resettlements of South coast of Sri Lanka considered to explore the status of women through case study approach. Site observations, transect walks, in-depth interviews with key informants of the resettlements, focus group discussions and storytelling were data collection tools. Of the sample, all resettlements were established in new locations, away from original location, especially from the coast and distance vary from 2 -15 km. Women who were in decision making level of the family and displaced were considered mainly to collect the views on living environment. Design intensions of donors and policy makers and residents feedback on their lived experience of two decades were mismatch with economic and socio-cultural needs of the women and families. Special needs of the women were ignored in site selection, housing design, provision of civic infrastructure, access to services, especially education and health care and restoration of livelihood alternatives. Most of the families adopted to maintain permanent house in resettlement and temporary or semi-permanent house in original location creating socio-cultural issues. Sites, designed living environment, housing design did not cater the familial responsibilities, mainly care of children, and the elderly, schooling, and search for food. Home-based income generating activities that contribute to household income and supporting shore-based fishery activities damaged badly. Design, house and living environment must be sensitive to functional requirements of the home and domestic needs.

Key words: Housing design, Living environment, Resettlement, Tsunami, Women

1. INTRODUCTION

The right to housing was recognized in the 1948 Universal Declaration of Human Rights and in the 1966 International Covenant on Economic, Social and Cultural Rights. Other international human rights treaties have since recognized or referred to the right to adequate housing or some elements of it, such as the protection of one's home and privacy. Housing deprivation is at the heart of poverty and social exclusion and closely linked with unemployment (Perera et al., 2015) and exaggerated by the disasters (De Silva et al., 2023). Natural disasters, especially great Indian ocean tsunami devastated the lives of thousands of fishing communities pushing women and children into deep crisis. Inadequate housing conditions negatively affect not only people's health, wellbeing, and quality of life, but also their access to employment and to other economic and social services (Perera and Karunathilake, 2023; Perera et al., 2015). Women, especially women living in poverty and added disaster burden, are more reliant on social housing than men, often due to being the primary carer for children. Further, women share deprived housing conditions equally, the consequences are particularly severe for women, and perpetuate their exclusion from

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education and employment. Women in poor health or with disabilities were found more likely than men to face difficulties with inadequate resources and housing (De Silva et al., 2023). Elderly, face a much higher risk of needing to move to a hospitals and health care facilities. Therefore, convenience access is essential for the resettlements and its residents.

The consequences of compatible housing are far-reaching for internally displaced communities: the quality of housing impacts on its residents' health and safety, their ability to function as productive members of society, and their sense of well-being in their community. Good housing contributes to good health outcomes, provides protection from the elements and supports a family's needs throughout its life cycle. These factors have a particular impact on women. In many low-income fishery households across coastal belt, whether in rural areas or in the cities, the home is still the woman's domain. The quality of the living environment impacts partn her day-to-day experiences and capacities to meet the needs of all who depend upon her. With reference to all women are especially keen on home improvements and often the drivers of such initiatives within their households.

Increasingly, and especially women in high-unemployment contexts, like fishery, the income-earning potential of housing is also need to recognized in design resettlements (Manatunga and Abeysinghe, 2017; Perera and Karunathilake, 2023; Perera et al., 2015). Many women identify entrepreneurial opportunities through their housing, using their homes as their business premises (Spencer et al., 2023); fish processing, dry fish retailing, running a shop on site, or working remotely. Some are contributing to household income through pre and postharvest activities of fishery, especially fish processing and retailing brings considerable income to the household (Seenapatabendige and De Silva, 2022).

A home and its surroundings also affect a woman's identity and self-respect (Fernando et al., 2020; Perera et al, 2015). This social dimension, while less tangible, is nevertheless hugely significant in coastal fishing communities (Seenapatabendige and De Silva, 2022). A home offers long- and short-term security for women as household members, especially those that are wives and daughters of fishermen who work in commercial fishery. Secure housing provides safe shelter and protection from internal displacement or other challenging circumstances (Pournima et al., 2017; Fernando et al., 2020; Perera and Karunathilake, 2023).

Further, a secure home enables more choices and more individual freedom to engage in economic options and child education (Ool, 2028). Tsunami resettlements provided permanent housing, a safe place for living which is essential for the greatest recovery needs (Seenapatabendige and De Silva, 2022). Without a permanent home and essential infrastructure, it is difficult for people to rebuild their lives and livelihoods. Further, new houses provided ownership of asset to the families who lost all assets. Another impact of home ownership is access to collateral, which enables women to access financial services and accelerate their earning potential. Moreover, permanent home brought more opportunities to households, especially for women and their economic activities. Women are therefore a very important part of the housing solution, and should be understood as such, by policy makers, project implementers, and service providers. Present study investigates the plight of women in designed living environment of tsunami resettlements and specific concerns were on site selection, location, design and suitability of the physical area.

Proper, reasonable, affordable and safe housing will empower women's role, welfare as well as unique opportunity, gender inclusivity, equity and improve the lives. Houses for internally displaced people, especially for women and girls in low-income environments is challenging. Poor quality housing impacts negatively on health and well-being, increases risk of violence and assault, and diminishes the ability to care for children (Perera et al., 2015; Sridarrana, 2017; Perera and Karunathilake, 2023).

Especially, households of coastal fishing communities, comprised of basic facilities and poor in quality prior to the Tsunami in 2004. Women and girls are often responsible for meal preparation, water collection, taking care of children and elderly, common daily task detrimental to family wellbeing (Figure 1). Indian ocean tsunami devastated coastal fishing communities leaving thousands homeless two decades ago.

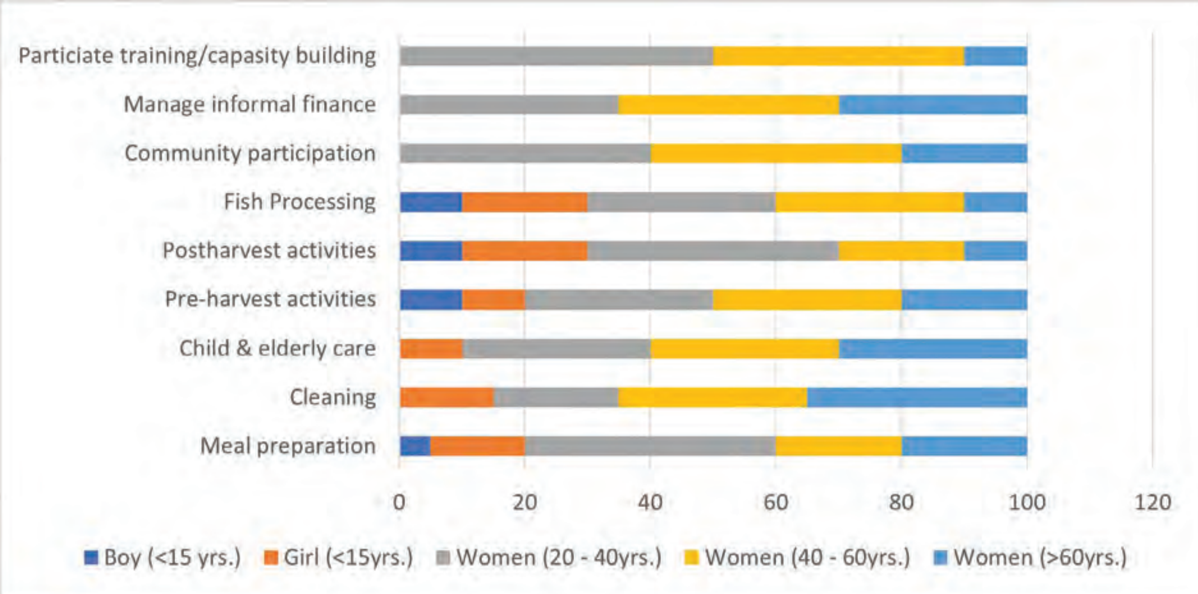


Figure 1. Contribution of women in household activities

Post tsunami resettlements offered good quality, affordable housing with services including clean water, sanitation and energy equips women and girls. Most of the resettlements were established away from their original lands, and moved from coast to inland areas. Structure of the resettlement villages and housing designs of houses were imported from foreign countries, and mismatch with the local culture (Seenapatabendige & De Silva, 2023). Funding organizations and foreign donors were facilitated the resettlements along with housing designs which rarely discussed with affected local communities or poor community participation in decision making (Seenapatabendige & De Silva, 2023). But most of the resettlement villages and housing designs were delivered with better health and an enhanced sense of privacy, comfort and space. This in turn expected towards liberates women, girls and marginalized groups to engage in educational attainment, income generation and recreation, improving quality of life and opportunities substantially.

Post tsunami resettlements delivered basic facilities, essential for living, such as in-home water supply, electricity, sanitation etc. liberates women and girls from the burden of daily household chaos while freeing up time to engage in employment opportunities and education, reducing the risk of violence and assault, and providing a private space for homework. Further, resettlement arrangements ensured that all housing was equipped with functioning services including water and sanitation, electricity, energy, waste collection and access to infrastructure.

2. CONCEPTUALIZATION

Role of women in household decision making and nature of home provided are central to developing coping strategies to mitigate the impact of disaster and building resilience among communities. Post-tsunami rehabilitation and resettlement aimed to relocate affected communities from temporary shelters to permanent housing, especially developed resettlement villages. Further, most of the resettlements were established away from their own lands or original locations expecting fast recovery from traumatic conditions developed from losses and damages in one hand. On the other hand, government impost low on 100 m coastal buffer zone. Relocation and resettlement plans were targeted to develop facilities within short period time and allow communities to settled down in new places with brand new houses. Community participation or user perspectives on location selection, housing design, arrangement of infrastructure facilities was ignored due to time factor or many other unknown reasons (Seenapatabendige and De Silva, 2022). Most of the housing designs were perilously used in other countries in similar resettlement projects while countable number of resettlements used the user views and designed to match with local cultural requirements.

Main focus of the study was to find out the plight of women in designed living environment of selected tsunami resettlements schemes of South coast of Sri Lanka and the specific concerns were to find out the users' perceptions and long-term satisfaction on resettlement houses and to explore the status of household resilience through long term adaptability to resettlements. Results of the quantitative literature review (Table 1) highlighted the research gap, impact of the build environment of the Tsunami resettlements on the life women in fishing communities who are playing multiple roles. The investigation provides effective evidence, especially how resettlement housing, may be used to prioritized disaster prone zones. Moreover, due to limited availability of theoretical applications on assessing disaster resilience (Imani et al., 2022) through quality housing, it is mainly characterized by the state of various dimensions of well-being of households (physical, social, economic, institutional and natural aspects). Figure 2 highlighted connection between key dimensions of the resettlement houses and resilience building process. Physical capability is integral part of community resilience architecture (Imani et al., 2022), residents need to be able to access food, water, sanitation as well as engage in economic activity to aid in recovery (Teo et al., 2013). Design, structure and materials used for houses directly linked with the performance of household, especially women. Social and economic resilience of relocated coastal communities are vital tools to gauge the impact and effectiveness of facilities delivered to

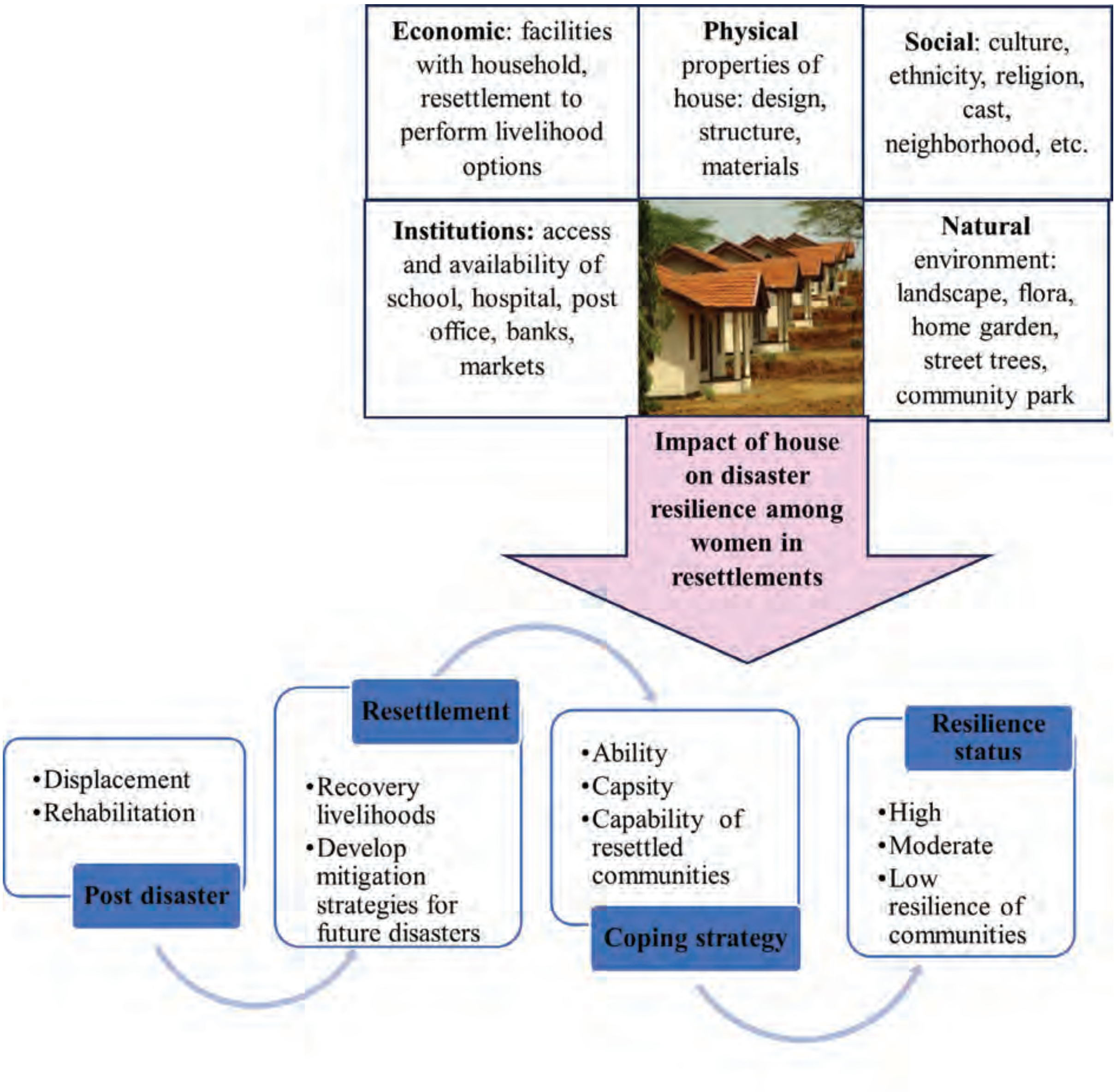


Figure 2. Assessing community resilience (women) status of the tsunami resettlements

Table 1. Results of the content analysis of the published research on post disaster resettlements

Author/s	Published year	Country	Objectives	Conclusion
T.G.U.P. Perera, Indu Weerasoori & H.M.L.P. Karunarathne	2015	Sri Lanka	To explore the factors that contributed to the success and failures of the resettlement housing programs	Resettlers are satisfied with development efforts and plans should be sustainable overtime. Success and higher rate of satisfaction of resettlement depended on autonomy and perception on provided facilities. Site selection naturally becomes a factor which unfolds dissatisfied for resettlers owing to the socio-cultural relationship that the resettles had with their previous location.
Niroshan Perera and K Karunathilake	2023	Sri Lanka	To find out the sociological perspectives on resettlement housing, with reference to popular resettlement model.	The importance of having a good neighborhood, financial strength, and social status to enjoy inner peace of mind and overall emotional and psychological well-being of a woman. Most resettlers had gained better social recognition gained the advantage of relocation and developed their business and work
Pournima Sridarrana, Kaushal Keraminiyage, Dilanthi Amaratungaa	2017	Sri Lanka	To explore the long-term adaptability issues, face by the communities who live in resettlements	Inadaptable built-environment was identified as a reason for resettlement failures. This includes understanding the factors affecting acceptance and rejection of the new environment. House ownership, climate adaptability and cultural appropriateness of the houses, livelihood, availability and affordability of social and physical infrastructure are determining the adaptability to the new environment.
Bee Lan Oo1, Riza Sunindijo, and Fatma Lestari	2018	Indonesia	To explore the users' long-term satisfaction with the provided housing, and explores how their satisfaction level relates to their demographic characteristics and level of participation in the reconstruction processes.	Households have varying perceptions of the present housing, its location and neighborhood. Overall satisfaction level is statistically positively associated with household income, but not their level of participation and other demographic characteristics including age, education, family size, number of children and elderly in the family, and number of years of living in the present housing.
Jagath Manatunge Udaya Abeysinghe	2017	Sri Lanka	To study the level of satisfaction of affected persons in the long term after receiving houses in new settlements with 'better' socio-economic and physical facilities.	Despite the availability of abundant funding, the opportunities to plan, design and implement sustainable community-responsive resettlement program for tsunami affected households were essentially missed. Design and construction of houses, which is the key focus of any resettlement program, the outcome has been disappointing. Overall, it can be noted that the occupants in the resettled communities included in the present study are not satisfied in the long-term due to many physical, environmental and socio-economic factors.
Marife M. Ballesteros	2013	Philippines	Assessing the benefits and costs of resettlement projects that are implemented by the national government.	Resettlement policy and compliance with the policy needs to be strengthened. This study also highlights the need for an inclusive urbanization process, so that negative externalities can be minimized and the marginalized people are not made to suffer the impacts of development. There is also much to learn from a social impact assessment of resettlement projects, specifically how households, and/or the community and the government, can undertake the reconstruction process

Author/s	Published year	Country	Objectives	Conclusion
K. B. Seenapatabendige and Achini M. De Silva	2022	Sri Lanka	Aimed to perform an architectural analysis on the resettlements to investigate the perspectives of the displaced communities.	Houses of fishing villages were located in huge open and common space where village structure is away from individualism. These shared open spaces help to build strong bonds among neighborhood that share and care the daily life of each other. Especially, fishers are away for fishing, fisher women, elderly, and children were cared and protected by neighborhoods. Moreover, fisher women engaged with various shore-based cottage industries such as fish drying, making coir ropes, and dress making. Housing designs were in line with the livelihood. Verandah was a common space which families use for engaged with cottage industries, small business, family gathering, placed of study for the kids, rest and relaxes place, and net mending. Most of the resettlement housing designs were ignored the verandah in the housing designs.
Barsha Shrestha, S. Uprety and J.R. Raj Pokharel	2023	Nepal	To identify households' perceived importance of housing satisfaction factors and their significance in post-disaster resettlement housing programs.	Results revealed that thermal comfort and social-cultural factors played crucial roles in overall housing satisfaction, influencing outcomes such as partial occupation or resettlement housing abandonment.
Fatma KÜRÜM VAROLGÜNEŞ	2021	Turkey	To determine long-term satisfaction indicators for permanent housing use in resettlement areas.	Physical planning for resettlements essentially needs to analyze the user, housing and environment, climate, geological structure, social and cultural characteristics of the region.
N. Fernando, A.C. Senanayake, D. Amarathunga, R. Haigh, C. Malalgoda and R.R.J.C. Jayakody	2020	Sri Lanka	To investigates the impact of the disaster induced relocation process on displaced communities, to investigate the various needs of victims in different stages of displacement and how relocation has altered the social, cultural, and livelihood dimensions of the victims.	Post disaster relocation need to understanding the social and economic details of various displaced groups, policy planners have tended to neglect the necessity of conducting a needs analysis with the main reason being the lack of perception of relocation as a long-term process
S. Madushani, J. Upeshika & E.M.K.S. Ekanayaka	2019	Sri Lanka	To provide guidance and government financial assistance to complete the "core-house" for the beneficiaries, to ensure a disaster resilient core house, to evaluate the success and failure factors of the government resettlement sites, to suggest the necessary requirements to be considered in future resettlement plans	Consider the livelihood of vulnerable communities in site selection for resettlement is essential. Diversification of economic activities, increased institutional support for providing infrastructure facilities, application of planning aspects to improve the community relationship.

Author/s	Published year	Country	Objectives	Conclusion
B. M. R. L. Basnayake, D. A. M. De Silva, and S. K. Gunatilake	2023	Sri Lanka	to examine the approaches and challenges faced by traditional agricultural communities in re-building landslide-depredated mountain landscape	Unplanned post disaster resettlement natively affected on livelihood and resettlers have changed their employability as daily wage workers, migrants, or non-agricultural-based jobs. It badly affected their income level as well as social well-being. Trauma, social negligence, heavy dependency on government support, and abandoned generations-old agricultural livelihood made communities violate away from resilience-building programs.
Jenny Spencer, Badra Yusuf, Elvirah Riungu, Sophia Alden, Gabrielle Hubert, Untethered Impact, Raagsan	2023	Somalia	To understand the context of internally displaced women and developing durable solutions that enable the women and children at the center of the current displacement crisis in Somalia to better support themselves requires a deeper understanding of their lives, livelihoods, and market and rural networks, and preferably includes their involvement	Rural origins, displacement experiences, identity, personal connections to the rural areas, livelihood options and income, market linkages, financial inclusion, etc. were identified as significant factors which lead to establish sustainable resettlements for internally displaced women.
N. Fernando, A. Senanayake, D. Amaratunga, R. Haigh, C. Malalgoda and R.R.J.C Jayakody	2020	Sri Lanka	To explore various needs of victims in different stages of relocation, to examine how relocation has altered the social, cultural and livelihood dimensions of the said needs of the victims, to understand the role of the built environment in the relocation process	Post disaster relocation needs long way to go in adopting the existing frameworks of relocation in accepting the overall physiological, psychological, and social impacts. Careful community-centered planning, execution, and monitoring is vital to ensure that relocation will not end up in a novel phase of a disaster.
Masud Ur Rashid	2017	Bangladesh	To investigate the process and background of the transformation of settlements	Significant changes in the construction materials of rural settlements, especially eco-friendly or green solutions to provide comfort to residents. Housing, the stability of settlement increases with the durability, and houses need to match with family size and economic activity.
Seam Hak	2018	Cambodia	To study the project impact on income, education, and livelihoods of households in the resettlement site using a gender lens, to understand how men and women cope with the impacts, and their main constraints in developing coping strategies and to provide recommendations for better gender equality in resettlement	Before eviction of the people to the resettlement site, essential need to prepare all basic infrastructures, design house compatible with social, economic and environmental aspects of the location.

(Rashid, The Continuous Process and Purposes of the, 2017) (Ekanayaka, 2019) (Hak, 2018) (B. M. R. L. Basnayake, 2023) (Ballesteros, 2013) (N. Fernando, 2019) (Barsha Shrestha, 2023) (Jagath Manatunge, 2017) (Mahmud, 2003) (TGUP Perera, 2011) (Karunathilake, 2023) (Saira Abid, 2023) (VAROLGÜNEŞ, 2021) (Lueyeevang, 2018) (Rashid, Transformation of Housing in aLow-income Settlement:A Study of Domestic Spaces in Ershad NagarResettlement Camp, 2019) resettlements. Social and economic resilience in coastal regions refers to a community's ability to live on scarce natural resources when it is generally highly reliant on such resources (Dasgupta and Shaw, 2015). Economic resilience is an inventory between loss and damaged property and renewed post disaster property. Women and girls contributed significantly on economic pillar; such as household activities, shore based pre and post-harvest activities prior to tsunami. Study attempts to identify the impact of resettlement housing on economic inclusion of women. Further, social pillar is influenced by communication, networking, participation, composition of the communities and resource status (Rose, 2006). Social component is significantly influenced by the involvement of women in cultural, religious and community work, managing social and marketing networks and inclusiveness. Resettled in new location, sometimes unfamiliar community setup, such as from costal location to inland place, issue on cultural mismatch, or exclusion in some cases. Institutional dimension is important facilitator in resilience building (Weichselgartner and Pigeon, 2015). Access to institutions and availability of services. Natural dimension in resilience building among relocated and resettled communities is less explored. Since tsunami affected communities resettled in inland locations, away from coast make them less vulnerable to natural hazards, such as cyclones, coastal erosion, heavy rains, floods, etc. But communities lost the generation's old livelihood options, ecosystem services, natural land use which tightly link with community life.

Wellbeing dimensions comprised of collection of parameters (Imani et al., 2022), and each contains variety of variables. Conceptualization (Figure 2) of the resilience building among resettled communities, and impact of housing on it can be evaluate through wellbeing indicators.

A comprehensive literature search was performed via Scopus, Web of Science and Google and peer reviewed papers were selected for the review process. During the record screening, inclusion and exclusions criteria were applied and empirical studies, peer-reviewed academic journal articles, abstracts, extended abstracts were included and reports were excluded (Table 1). The timeline from 2010-2023 was selected. Tsunami resettlements, resilience building, built environment and women were considered as key word search. Limited number of studies conducted on architectural analysis of Tsunami resettlements and especially impact of housing on resettled women.

3. METHODOLOGY

South coast of Sri Lanka is one of the most vulnerable regions, frequently affected by natural disasters. Cyclones, floods, coastal erosion, heavy rains and 2004 great Indian ocean tsunami are the most prevalent natural disasters. Five tsunami resettlement villages of South of Sri Lanka were chosen as target research location because house designs of resettlements varied and established away from the coast (Figure 3). Further, one of our previous studies focused on architectural analysis of resettlement houses, and present study aimed to investigate the same resettlements after two decades and identify the impact of housing design on women and their livelihoods, most influential member of household decision making. South coast, one of the most socially and economically important landmasses which cater both fisheries and tourism industries. Further, disaster induced coastal zone management policies significantly affected on resettled communities.

Five case studies purposely selected from 3 adjacent divisional secretariats of Galle district of Sri Lanka were investigated. Case study selection based on characteristics of the resettlements; type of housing design (single story, two story, duets), distance to coast/fish landing sites and type of landscape. Composition of the resettlements were; Polwaththa, Ambalangoda (59 homes), Galaboda, Ambalangoda (139), Peraliya (32), Wathuregama (36) and UNESCO village (57) The primary method of data collecting (Table 2) in this study was through field observations (site visits, walkthrough), in-depth interviews with key informants, focus group discussions (5) with residents of each resettlement, a questionnaire survey, with two distinct sets of questions prepared to find out the users' perceptions, long term satisfaction on resettlement houses. To begin, a questionnaire survey was distributed to female residents of selected resettlements for the purpose of explore the status of household resilience through long term adaptability to resettlements. Evaluate user's perspectives, especially women, on resettlement housing designs of 5 case studies using five-point rating scale and ratings varied from 5 – strongly agree to 1 - strongly disagree. Filed observations lead to identify the present status of

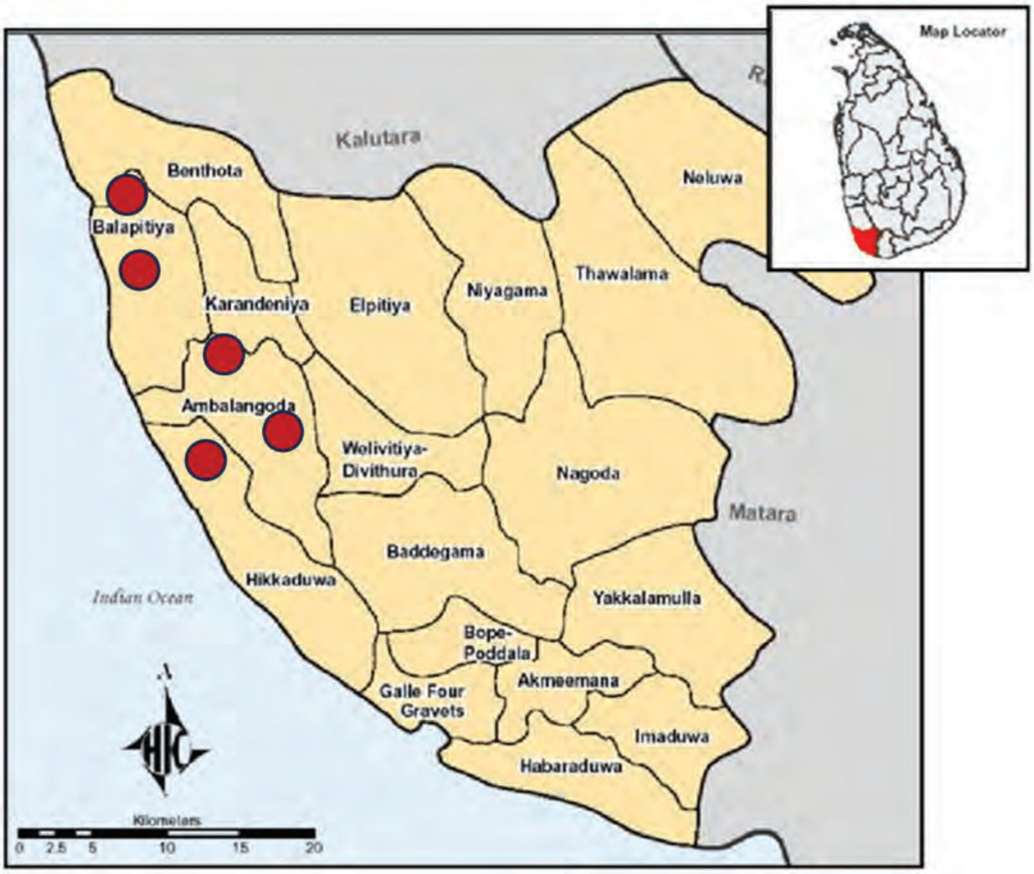


Figure 3. Map of the research locations: 2 resettlements from Balapitiya DS Division, 2 resettlements from Ambalangoda DS Division and 1 resettlement from Hikkaduwa DS Division of Galle district, Sri Lanka

the resettlements, two decades after establishment and modifications made to houses. Further, we have visited both resettlements and previous lands of them, especially to observe the rebuilt housing facilities to accommodate their fishing operations and fish processing business. Second step was to conduct focus group discussions with the participation of community members where female members were selected randomly. Discussions were audio recorded and flip charts were used to collect the thoughts of participants. First, researchers were explaining the context, aim of the research and allow for questions. Secondly, discuss the questions on housing design, structure, materials used, landscape, access and availability of services, institutions, etc. and modifications made to facilitate their daily routines. Third step of data collection was on questionnaire survey, where structured questionnaire was used to measure the effectiveness of housing design on performance of households, especially women and the role of house design in resilience building among affected communities.

Table 2. Summary of data collection tools

Objective	Approach	Method	Analysis	Output
To find out the users' perceptions, long term satisfaction on resettlement houses.	Qualitative	Site visits, Walkthrough, In-depth interviews Focus Group Discussions	Photograph analysis Building analysis Descriptive statistics	User (family and women especially) perception on house and built environment and status of the long-term satisfaction of the resettlement
To explore the status of household resilience through long term adaptability measures	Mixed	Site visits In-depth interviews Storytelling Focus Group Discussions	Photograph analysis Building analysis	Inventory of local knowledge applied in adaptation and resilience building

4. RESULTS AND DISCUSSION

Present research eyed to find out the users' (women and family) perceptions and long-term satisfaction on resettlement houses, especially on house design, structure, materials used and built environment. Further, study explore the household resilience through long-term adaptability measures of tsunami resettlements on life of internally displaced people, especially on women and their lives. Gender in displacement settings, especially how both men and women adopt to new environment, long term satisfaction on housing facilities and continue their livelihood options, and the role of housing on their performance showed varied results.

First approach was to identify the role of women in fishery and none fishery households to understand the infrastructure requirements to perform the tasks natural, socially and culturally assigned to women; wives, mothers, grandmothers, daughters, sisters. Prior to the tsunami, fishing communities were nestled in coastal belt and convenience access allow to participate many shore-based activities, both pre-harvest and post-harvest while performing household tasks. Figure 4 explain the role of women in small scale fishery households (about 80%), commercial fishery households (about 15%), women in none fishing households (3%) and women in tourism ventures (2%). Women in fishery households are responsible to manage day to day household tasks and their interventions are essential for fishery households compared to none fishing households. Male members (farther, grand farther and sons) are keen on fishing and fishery related business and limited time devoted for household chaos. Small scale fishermen spent considerable amount of their time daily for fishing and related work and fishermen of commercial fishery spent months (av. 2 months or 60 plus days) away from home for fishing. Women in fishery households holds huge responsibility in manage household functions, especially decision making on daily operations. Therefore, quality housing, infrastructure facilities and convenience access is essential for women members to perform the tasks.

Housing solutions provided to internally displaced women who were vulnerable to disasters and accompanied issues explored to find out the relationship between housing quality and

Role of women	Women in small scale fishery households	Women in commercial fishery households (offshore/deep sea)	Women in none fishing households	Women tourism ventures
Household level	Mother/wife/sister/daughter Caretaker of children, elderly and sick members of the family Food shopping & meal preparation Support children's education Manage household finance	Mother/wife/sister/daughter Caretaker of children, elderly and sick members of the family Food shopping & meal preparation Support children's education Manage household finance	Mother/wife/sister/daughter Caretaker of children, elderly and sick members of the family Food shopping & meal preparation Support children's education Manage household finance	Mother/wife/sister/daughter Caretaker of children, elderly and sick members of the family Food shopping & meal preparation Support children's education Manage household finance
Fishery: Preharvest activities	Support net mending and preparation			
Fishery: Postharvest activities or other livelihood activities	Fish sorting, grading, fresh fish retailing: fresh fish and processed fish Fish processing: buying, cleaning, drying, slating, smoking Manage market networks	Fish sorting, grading, fresh fish retailing: fresh fish and processed fish (dry and salted), dried fish from multiday boats – Bottu karawala Fish processing: drying, slating, smoking Manage market networks	Dry fish retailing and manage market networks Catering business, sweetmeat preparation, manage grocery store	Manage small scale guest houses, catering, manage clothing retails (Batiks, hand crafts, etc.)
Community participation	Fisheries coop activities Community level societies: gatherings, meetings, volunteer work, religious activities Political work: meetings	Fisheries coop activities Community level societies: gatherings, meetings, volunteer work, religious activities Political work: meetings	Community level societies: gatherings, meetings, volunteer work, religious activities Political work: meetings	Community level societies: gatherings, meetings, volunteer work, religious activities Political work: meetings
Financial engagement	Manage household level finance, organize and participate informal financing, manage formal financial work: banks	Manage household level finance, organize and participate informal financing, manage formal financial work: banks	Manage household level finance, organize and participate informal financing, manage formal financial work: banks	Manage household level finance, organize and participate informal financing, manage formal financial work: banks
Training & capacity building	Participate workshops, training programs, etc. on various alternative livelihood	Participate workshops, training programs, etc. on various alternative livelihood	Participate workshops, training programs, etc. on various alternative livelihood	Participate workshops, training programs, etc. on various alternative livelihood

Figure 4. *Role of women in coastal fishing communities*

their performance. Figure 5 brings the results of user perspectives on safety and security in housing design, allow for convenience, efficient use of space, easy access to services, incorporate home like features, access to natural green spaces, provide and bring comfort to residents, accompanied by support services and spaces for community buildings. Results revealed that resettlements established considerably away from coast highlighted as less satisfied in terms of convenience and incompatible with neighborhood communities and access to support services. Even though, some resettlements (Galaboda, Ambalangoda and UNESCO village, Kosgoda) established far away from the coast, 15-20 Km away from original land, and resettlements were designed with all necessary infrastructure facilities for living. Unfortunately, convenience and access to resources were considered as main hurdle to perform the functions naturally and socially assigned to women. Further, most of the women in fisher families used to engaged in shore-based activities; both pre and postharvest work and distance to resettlement make them away from usual activities. Poor household earnings, especially earnings of women were restricted by inability to join with shore-based activities. Further, resettlements were designed with limited back yard space and improper waste disposal arrangements. These restrictions hinder women's engagement in fish processing in one hand. On the other hand, neighborhood mismatch limits their engagement in livelihood options.

Few solutions were adopted to overcome the hurdle, such as returned to original place or own land on coast and bult temporary home or micro type house to engage in usual activities. Since shore-based activities; fish processing, retailing, net mending, etc. were identified as considerable income generating work to the families. Fish processing (drying, salting, and other value adding) ensure economic wellbeing of women while catering to day-to-day household needs; such as children's education, health care, contribute to religious and community work.

Plans of the resettlements considered for the study were developed to understand the present status and figures 6 -10 brings the village maps of selected case studies. Field observations and focus group discussions revealed that few categories of resettlement houses; abandon with or without modifications, fishers house, none fisheries house and sold-out house. Figures highlighted the village plan, housing arrangements along with other infrastructure available in each resettlement. Of the sample, resettlement 1 and 5 represent the single-story separate houses while rest of the resettlements comprised with two story detached houses. In general, most of the houses currently in use, except few (55%), were modified to facilitate the lifestyle of residents. Of the sample most of the houses were modified with verandah. Veranda as a missing component from some resettlements but one of most essential section of fishermen's household. Of the sample Veranda like space found in only one resettlement village of single-story duplex house. Extra living room of re-settlement houses occupied the space of veranda to accommodate the extended family (Seenapatabendige, 2023). Verandah, a multifunctional space of the most tropical houses which identified as most frequent used section of the house. Further, kitchenet or outside small kitchen space was added to the design to facilitate local firewood hearth and type of cooking which cannot be accommodated within the small

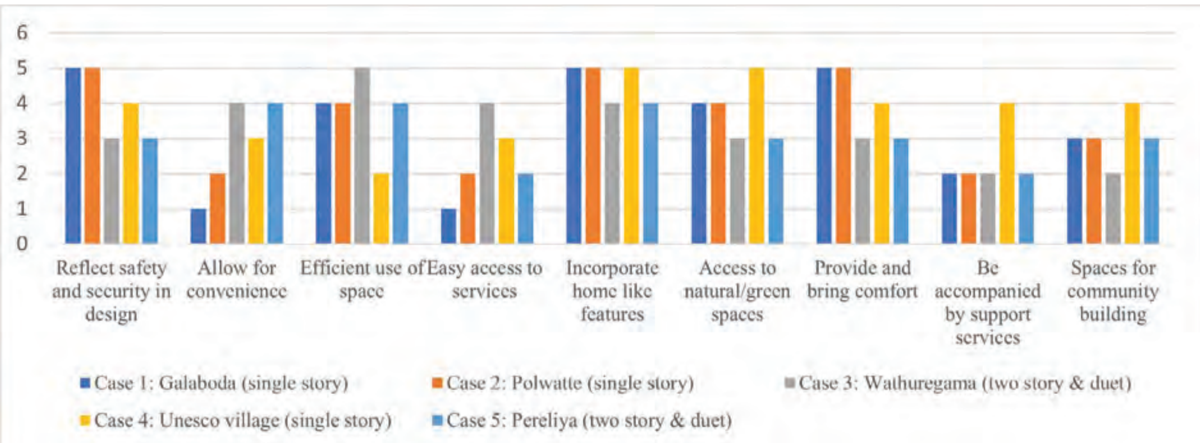


Figure 5. Women's perspectives on houses of the tsunami resettlement villages after two decades of disaster

internal kitchen. Of the sample, houses were comprised with small living room space and some residents modified the space to cater the demands of extended family. Moreover, all household maintain small home garden within the very narrow space provided. Road side green spaces, trees and home gardens converted the resettlement villages into a livable place. All resettlements considered having abandon, sold out houses and most of the fishing family's mange two houses; resettlement house and micro/temporary home at their coastal land. The option of maintaining two houses added extra burden on women's role, especially on security issues, children's education and most importantly alcoholism and drug abuse of male members of the family.

Figure 6. Resettlement 1- Polwaththa

Figure 7. Resettlement 2 – Galaboda

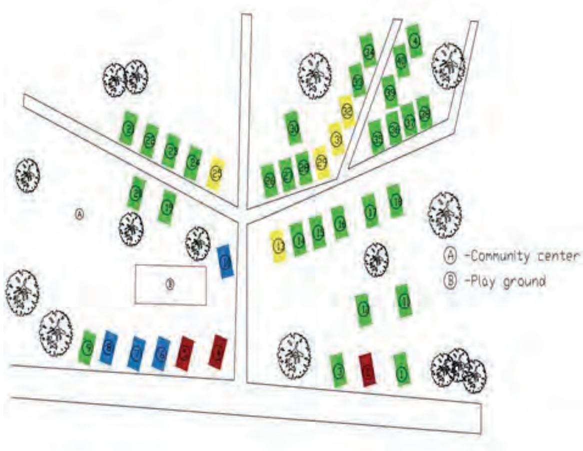


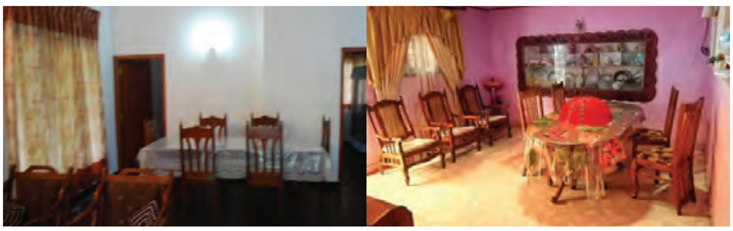
Figure 8. Resettlement 3 – Pareliya

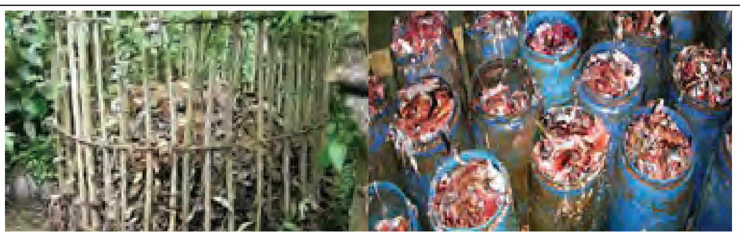
Figure 9. Resettlement 4: UNESCO village

Figure 10. Resettlement 5 – Wathuregama, Ahungalla

Table 3 brings the some of the modified features of the resettlement houses along with the reasons behind the design modification.

Table 3. An account on design modifications to the resettlement houses and reasons for modifications

Modification	Reasons for modification	Modified house
Verandah	Most of the houses added verandah to the design. Traditional tropical houses possess certain special spaces, Verandah to create a sustainable house (Zin et al., 2012) and appropriate to the local climate, provides an effective thermal comfort condition (Seenapatabendige, 2023)	
Kitchen	Fire wood hearth is common to many households and economical. But most of the resettlement houses design with kitchenet type which hardly facilitate to maintain local food preparation style. Therefore, residents added outside kitchen to the design and some places expanded the available kitchenet	
Living room	Small living room was found in original housing design along with separate dining space. Quite large living room which accommodate living, dining, watching television, learning space for children, common working space related to livelihood option, store valuable equipment like sawing machine, etc. Therefore, some residents redesign their living space which can accommodate the functions of extended family	

Modification	Reasons for modification	Modified house
Boundary walls	Not available in original design. Most of the houses added boundary walls and entrance gates aiming to maintain security and privacy. Especially, boundary walls or fences are common addition to duet houses	
Home/ kitchen garden, backyard	All most every household maintain backyard which has string link with local food culture. Home gardens bring bundle of benefits to residents. Common structure comprised with fruit trees (banana, mango, papaya), coconut, vegetables, spices and herbs, and flowers. Living fences accommodate for flowers, herbs, medicinal plants, leafy vegetables, etc.	
Garbage pit	Not available in original landscape and local governments were not provided expected service. Therefore, most of the households maintain the garbage pit	
Parking/fish drying space	Not available to the original design and tiny foot/motor cycle shed built outside the home	

Modification	Reasons for modification	Modified house
Other extensions	Modification and extension were made to facilitate their day to day social cultural life: Buddhist shrine, extra bed room, store room, shop space, etc.	

5. CONCLUSIONS

Present study investigated the plight of women in designed living environment of tsunami resettlements and specific concerns were on site selection, location, design and suitability of the physical area. Housing for internally displaced goes beyond a shelter or physical structure; it is regarded as a psychological reality that ensures a safe and secure haven, promoting physical comfort and mental well-being while upholding a sense of peace and dignity. Resettlements provided safe, comfortable housing for internally displaced people initially and residents were highly satisfied with received assets. But long-term satisfaction varied with the occupation of the residents. Convenience and access difficulties identified a most frequently considered factors on housing satisfaction. Social, cultural and economic factors influencing on long term housing satisfaction and search for alternative options. Most dissatisfied housing option was single- and two-story duet houses. Resettlement planning, especially houses designed without participation of disaster affected communities, donors and institutions produced socially and economically vulnerable shelters. Alternative options, such as maintaining two houses brought unnecessary social issues into the household.

6. REFERENCES

Akbarnejad, A., Godard, L., FitzGerald, A. (2023). Women-Centered Housing Design Toolkit: Principles, strategies, and actions to design long-term housing for women and children with experiences of violence. BC Society of Transitions Houses. Accessed 9th August 2024. https://wcdtoolkit.bcsth.ca/wp-content/uploads/2023/04/Women-Centred-Housing-Design-Toolkit-April-17.pdf

B. M. R. L. Basnayake, D. A. (2023). Challenges of Resilience Building AmongTraditional Agricultural CommunitiesDisplaced by the Landslides. *Springer Nature* .

Ballesteros, M. M. (2013). Evaluating the Benefits and Costsof Resettlement Projects - A CaseStudy in the Philippines. *Evaluation for Agenda 2030: Providing Evidence on Progress and Sustainability.* Philippines: Ballesteros and Egana (2013).

Barsha Shrestha, S. U. (2023). Factors Influencing HousingSatisfactioninPost-DisasterResettlement: A Case of Nepal. *Sustainability 2023.*

Ekanayaka, S. M. (2019). An Evaluation of Success and Failures in Disaster InducedResettlement Program: A Case Study of Resettlement Sites inGalle. *Equitable Resilience.* Sri Lanka: National Building Research Organisation.

Hak, S. (2018). Resettlement Impacton Poor Households. In C. Vaddhanaphuti, *Resettlement*

Impacton Poor Households. Cambodia: Regional Center for Social Science andSustainable Development (RCSD).

Jagath Manatunge, U. A. (2017). Factors Affecting the Satisfaction of Post-DisasterResettlers in the Long Term: A Case Study on theResettlement Sites of Tsunami-Affected Communitiesin Sri Lanka. *Journal of Asian Development*.

Karunathilake, N. P. (2023). Psychological Impact of Poverty Alleviation through ResettlementProgrammes: Special Reference to Young Adult Women Resettlersin Sri Lanka.

Lueyeevang, S. (2018). *Exploring the Impact of Resettlement on Women:A Case Study of the Nam Mang 3 Hydropower Dam in Central Laos.* New Zealand: School of Geography, Environment, and Earth SciencesVictoria University of Wellington.

Mahmud, S. (2003). Women and the transformation ofdomestic spaces for incomegeneration in Dhaka bustees. *Journal of Urban Policy and Planning.*

N. Fernando, A. S. (2019). Disaster, displacement and relocation: an analysis of the needs andpolicy implications on a displaced community in sri lanka. *10th International Conference on Structural Engineering and Construction Management (ICSECM).* Sri Lanka : (ICSECM).

Rashid, M. U. (2017). The Continuous Process and Purposes of the. *International Journal of Architecture, Engineering and Construction*.

Rashid, M. U. (2019). Transformation of Housing in aLow-income Settlement:A Study of Domestic Spaces in Ershad NagarResettlement Camp. *Journal of Environmental Design and Planning*.

Saira Abid, G. S. (2023). Fostering Well-Being in Resettled Communities: CultivatingCultural Resilience and Sustainable Development inResettlement Caused by Ghazi Barotha HydropowerProject, Pakistan. *Water 2023*.

TGUP Perera, I. W. (2011). An Evaluation of Success and Failures in Hambantota,Siribopura Resettlement Housing Program: Lessons Learned. *Sri Lankan Journal of Real Estate*.

VAROLGÜNEŞ, F. K. (2021). Success factors for post-disaster permanent housing:example of turkish earthquakes. *Journal of Design, Art and Communication*.

Saira Abid, G. S. (2023). Fostering Well-Being in Resettled Communities: CultivatingCultural Resilience and Sustainable Development inResettlement Caused by Ghazi Barotha HydropowerProject, Pakistan. *Water 2023*.

TGUP Perera, I. W. (2011). An Evaluation of Success and Failures in Hambantota,Siribopura Resettlement Housing Program: Lessons Learned. *Sri Lankan Journal of Real Estate*.

Teo, M.; Goonetilleke, A.; Ziyath, A. (2013). TeAn integrated framework for assessing community resilience in disaster management. In Proceedings of the 9th Annual International Conference of the International Institute for Infrastructure Renewal and Reconstruction, Brisbane, Australia, 7–10 July 2013; pp. 309–314.

Varolgunes, F. K. (2021). Success fcators for post-disaster permanent housing : example of Turkish earthquakes. *Journal of Design, Art and Communication*

Zin, M. H. M., Ibrahim, N. L. N., Zain, M. F. M., and Jamil, M. (2012). The Social and Environmental Roles of Verandah in Tropical Houses, World Academy of Science, Engineering and Technology 68

Tsunami Disaster Management by Amature Radio 2004/05 - A Case Study

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ABSTRACT

Relief for Tsunami Disasters An account of the Tsunami Disaster Relief Amateur Radio Emergency Communication Network Operational activities carried out by the Radio Society of Sri Lanka (RSSL) and its members in the aftermath of the Tsunami disaster in December 2004 is provided firsthand in Amateur Radio Emergency Communication Network and Related Activities – 2004/05.Data collection was done by members of RSSL who took part in the communication campaigns for disaster relief were asked to share their stories. The emergency communication network was set up under the direction of the Prime Minister's office, the Government Information Communication and Technology Agency (ICTA), and the RSSL. The first communication link was to be established from Hambantota in Southern Sri Lanka to Colombo at the request of the Prime Minister's office. Three volunteers travelled with the team as they departed Colombo on the evening of December 27, 2004, with the goal of arriving in Hambantota early the following morning. An HF transceiver was operational and a 40m wire dipole antenna was installed in thirty minutes. There was no electricity available in the neighbourhood due to disruptions in the supply. To charge the transceiver, the team utilised a car battery that they brought with them. This was the only communication link to the outside world from Hambantota at that time. Final outcome from the study is when Mobile phone system was overloaded and all other communications failed Ham radio stood tall, just plain uncomplicated Short Wave saved lives. In the month of December 26th 2023 RSSL successfully conducted the last Ham radio disaster drill to make sure everything in order and prepare for any calamities.

Key words: RSSL, Tsunami, Ham Radio, Disaster, Sri Lanka

1. INTRODUCTION: TSUNAMI AND DISTRUCTION

One of nature's most destructive forces, tsunamis can result in significant property damage, casualties, and loss of life. The Japanese word "tsunami," which is pronounced "soo-nah-mee," is made up of the letters "tsu" and "nami." The characters "nami" stand for wave, and "tsu" for harbour. A large-scale disruption of a body of water's surface causes a sequence of very huge waves to emerge, known as tsunamis. In addition to near-shore and underwater landslides, near-shore and underwater volcanoes, human-induced explosions on land or underwater, and even space objects impacting ocean bodies, earthquakes are one of the main drivers of tsunamis (Yeh et al., 2022).

These waves can reach 1,000 miles per hour and are frequently less than a metre high in deep, open ocean waters. The leading edge of the waves, however, slows down as they approach shorelines and shallow water, and the wave then starts to "pile up" behind them, increasing in height (Teresa et al., 2020). By the time these waves hit the beach, their crests can reach heights of several metres. On occasion, though, the dip of the wave arrives before the peak. In this instance, exceptionally wide or unprecedented areas of the seabed are exposed by what looks to be an extremely low tide, rather than extremely high water levels,

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which would normally be the first indication of a tsunami. It is crucial to remember that the biggest tsunami waves are frequently not the first ones, and the interval between wave crests can range from a few tens of minutes to over an hour (Koshimura et al., 2020). On December 26, 2004, an Amassive 9.0 earthquake occurred under the Indian Ocean near Sumatra. In an instant, the earthquake caused a tsunami to race towards the coasts of Indonesia, Sri Lanka, India, and other countries at up to 500 mph, killing over 150,000 people and uprooting millions more (Figure 1).

2. HAM RADIO

Among its 3 million practitioners worldwide, amateur radio, or 'ham radio', is a hobby that has led the way in electrical and computer engineering since its inception in 1894, when young Italian inventor Guglielmo Marconi first demonstrated wireless technology at his summer residence in Bologna (Figure 2). Since that momentous discovery, amateur radio has played enormous and significant roles in igniting the worldwide engineering workforce, sparking new technologies, captivating the imagination of inventors, and fostering friendship and goodwill among nations. This three-part series of articles traces the development of amateur radio throughout history and demonstrates the incredible influence that ham radio has had on the world and the engineering community. Two-way radios are used by amateur radio operators

Figure 1. Over 150,000 people were killed by the earthquake-triggered tsunami. The earthquake measured 9.0 on the Richter scale. This is the fourth largest earthquake in the world since 1900 and the largest since the 1964 Prince William Sound, Alaska earthquake. (Map courtesy of the U. S. Geological Survey).

to converse with one another. In contrast to other personal radio services like General Mobile Radio Service (GMRS), Family Radio Service (FRS), or CB radio, amateur radio operators must obtain government certification and pass an exam (Shukla, 2023).

Across the whole radio frequency spectrum, certain frequencies are available to amateur radio operators. Regardless of the season, time of day, or night, choosing the right frequency enables efficient communication within a town, region, nation, continent, or the entire planet. While local and regional communication can be facilitated by the use of VHF and UHF bands, television and high-speed data transfer can be supported by the use of microwave bands. Shortwave frequency bands, or HF bands, can be used for international and interregional communication (Rikitianskaia and Balbi, 2020).

Amateur radio, or "ham radio" as it is popularly called, has been a hobby since the turn of the 20th century. It has fostered a global pool of skilled technical specialists and acted as a global testing ground for wireless communications technologies. In addition, the pastime has given people from all walks of life from ages 5 to 109 a unique social melting pot where they may come together to share their passion for wireless communications and experimenting (Mn et al., 2022).

3. EMERGENCY COMMUNICATION CHARACTERISTICS

Emergency communication services for the public have long been provided via amateur radio. This is especially true in situations where broadcasting services and public telecoms are severely damaged by natural disasters, leaving amateur radio as the main remaining form of communication.

In situations where other communication channels aren't accessible, amateur radio operators possess the knowledge, tools, and expertise to offer prompt assistance. Because most amateur radio equipment is battery-powered, incredibly portable, and able to operate over a wide range of frequencies, it is appropriate for use in emergency situations. Interoperability across frequency bands and quick network deployment both inside and outside of communities are made possible by this. Because they use this ability as a major component of their pastime, operators are also typically well-versed at improvising and restoring communications under substandard conditions (as may be found during disasters). Amateur radio groups have the chance to practise emergency readiness by setting up emergency

Figure 2. The Theodore. S. Rappaport with Guglielmo Marconi's original wireless set as preserved from 1894 at the Marconi museum in Villa Griffone, Balogna, Italy (photo taken in October 2013 at the Marconi Society board meeting and it is the first Ham Radio)

stations utilising temporary antennas and emergency power during an annual international contest event known as 'Field Day' (Potter et al., 2022).

4. ORGANIZATION OF EMERGENCY AMATEUR RADIO SERVICES IN TSUNAMIN IN SRI LANKA

Many operational functions are supported by local and regional amateur radio emergency networks including:

- Voice and data messaging and
- Surveillance and notification

The user agency can transmit messages using voice networks that link many sites both inside and outside the affected area by using voice communication. The messages can be unwritten, allowing staff members of the user agencies to communicate with one another, or pre-written and forwarded using a common format (much like telegrams).

The user agency can send messages over a digital radio network that connects several places both inside and outside the affected area or region by using data communication. These messages are sent to a different destination after being input using a computer keyboard. These communications usually consist of lists of things or facts that are so lengthy and complex that it is not practical to use the voice traffic service.

Using a voice network, surveillance enables the user agency to keep an eye on and manage activity in a certain region. Amateurs utilise handheld radios to conduct surveillance; they can do so alone or in cooperation with user agency personnel. The amateurs usually keep an eye on parking lots, roads, special facilities, and people in order to report any issues that may emerge. When positioned in safe areas, amateurs who have received training can assist in the early warning stages as trained spotters and observers (storm and flood watchers, as well as observers of tsunami waves). Many amateur organisations can improve their operations by installing remote wireless video systems thanks to today's technology, particularly in high-risk areas. Many of the functions found in commercial notification systems, such as paging, can be included into existing infrastructures and tone-alert radio, radio-activated alarms and sirens, hazard detection and monitoring equipment, etc (Raghunath and Raghunath, 2020).

5. SRI LANKAN STOREY ABOUT HAM RADIOS FIRST CALL ON HELP

A doctor named Sarath, 4S7SW, who works close to a hospital in Mathara, Sri Lanka that was badly devastated by the tsunami, made a plea for food, clothing, and medication as relief. C. K. "Ram" Raman, VU3DJQ, claims that Sarath was keeping an eye on frequencies between 15 and 20 metres. On 40 metres, Indian hams had also set up a net.

According to Radio Society of Sri Lanka (RSSL) president Victor Goonetilleke, 4S7VK, "uncomplicated shortwave" radio saved lives. "Ham radio was and will remain a significant factor," he stated in an email forwarded to the ARRL. According to Goonetilleke, before amateur radio operators intervened, not even the prime minister of Sri Lanka had communication with the outside world. He recalled, "Our control centre was inside the prime minister's operational room at his official residence. "This will demonstrate how much they valued our offerings."

According to Goonetilleke, only the amateur radio HF link remained operational, and even satellite phones malfunctioned. One issue was that there were no generators available to recharge the batteries, which were getting low. Between Hambantota and the government offices in the affected area as well as the prime minister's disaster management headquarters in Temple Trees, a ham radio link was kept up. "We closed the link after the police got a communications link up in Hambantota," Goonetilleke stated. We entered because communication was problematic at the district secretary's office, which only had a satellite phone. Asantha Illesinghe, 4S7AK, Dimuthu Wickremesinghe, 4S7DZ, and Kusal Epa, 4S7KE, were in charge of running the Hambantota station.

6. COMMUNICATION NEVER FADED TSUNAMI DISASTER IN SRI LANKA

The messages that were sent from Hambantota to Colombo were mostly sent over the HF communication link. At the time, Hambantota's only means of communication with the outside world was this. The messages came from the government and military personnel in charge of the relief effort. They asked for operational support and detailed the food and medication that needed to be transported from Colombo to other places. Other operational signals transmitted over the communication link included the number of casualties, the actions taken to identify the victims, the provision of hygienic and health services to the areas, and the number of additional personnel needed for relief support.

Additionally, a car equipped with a mobile VHF (Very High Frequency) transceiver equipment was utilised to broadcast information from the surrounding areas to the Hambantota District Secretariat office via a VHF link, and then that information was relayed to Colombo via an HF link. Two days later, Hambantota's other communication infrastructure was progressively restored, starting with the cell phone networks. At the district secretariat of Hambantota, the police also established a communication post. The communication link established by the RSSL was removed once other communication services had been restored (Figure 3 and Figure 4).

7. LINK TO DISASTER - STORY TO TELL

"My friends 4S7KE, 4S7AK, and 4S7DZ drove a four-wheel drive from the interior to the coastal town of Hambantota because the main road along the coast was badly damaged, blocked by debris, and unusable," Goonetilleke said. Thanks to George Jacobs (W3ASK, CQ Propagation Editor Emeritus), I was well aware of my propagation and confident that we could maintain a connection on frequencies of 3 and 7 MHz. Thus, shortwave triumphed when all other methods, even cellular ones, failed. It's very easy; we didn't even need a TS-50 or other little mobile HF set; instead, we used our best radio, the ICOM IC-7400, two 12-volt batteries, dipoles, some food, drink and filled the rest of the vehicle with food for the displaced. I stood by in Colombo at the prime minister's (residence) to run the link in and coordinate."

"I wish I could scream aloud and tell people in some high places that SW (shortwave) is alive when everyone else is dead," Goonetilleke continued. When the electricity goes out, your cell phone dies, and you are unable to even

Figure 3. Disaster relief emergency communication operations at Hambantota District Secretariat. Asantha Illesinghe (4S7AK), Kusal Epa (4S7KE) Dimuthu Wickramasinghe (4S7DZ) and Achini Abeygunawardena

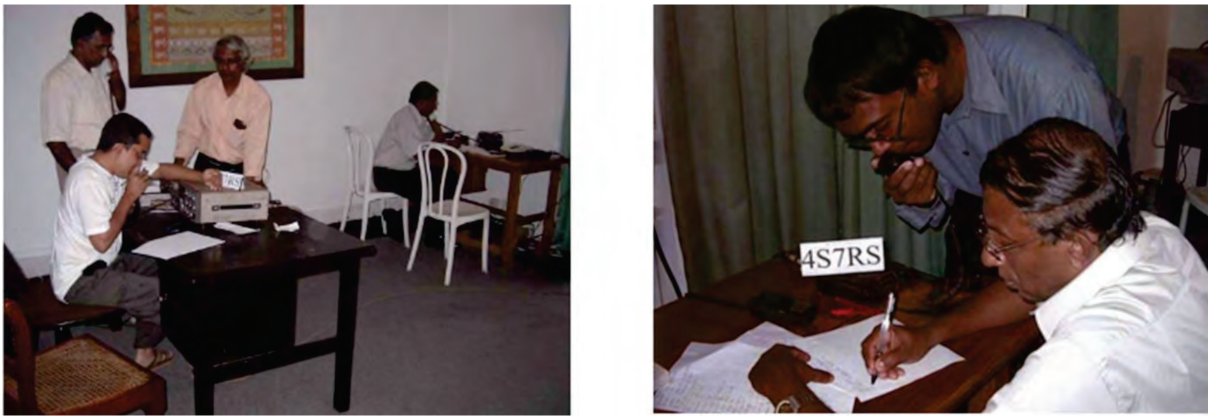

Figure 4. Communication operations room in Colombo at Prime Minister's official residence (Temple trees). Kamal Edirisinghe (4S7AB), JT Wijeratne (4S7VJ), KKG Kulasekera (4S7KG), Bharath Aponso (4S5BA) and Victor Goonetilleke (4S7VK)

charge the batteries in your mobile phone or GTS (Global Telephone System), what should you do? If we needed to run on just one or two watts, we had our Morse key close at hand, but the batteries held. Although the forces reestablished communication 12 hours or more later, it will take some time to restore utilities because most of the district was severely damaged. We went out of the prime minister's disaster room after operating there for 48 hours and are currently in fax contact with them, providing information to the coordinating centre. We are attempting to reunite missing persons, provide information on displaced camps and individuals, and facilitate the movement of food and necessities from our three outposts. Despite having limited resources, we are working to increase our coverage. Sadly, when we asked for a disaster preparedness force, everybody scoffed, even our members.

8. HAMS TRAVEL WITH RELIEF TEAMS

We are aware of multiple amateurs who are visiting the catastrophe area from the United States and Great Britain as of mid-January. Adam Steed (KE7EBX), a recently licenced ham from Lehi, Utah, is travelling to Columbo, Sri Lanka, to serve with the International Red Cross. According to Doug McKay, KD7LRJ, Steed intends to use EchoLink to stay in touch with his family and the Utah ARES group while he is there. Two radio amateurs from Britain attempted to assist in the wake of the tsunami/earthquake tragedy by taking a plane to Sri Lanka. John Baker, GØMTQ, and Malcolm Harwood, MØXAT, brought essential medical supplies and ham radio equipment that were provided by the employees of the British Capitol Movement Service, where Malcolm's wife, Lily, works. Both hams will assist members of the Radio Society of Sri Lanka during a planned one-week stay.

9. TSUNAMI DISASTER PREPAREDNESS DRILL

Drills for tsunami disaster preparedness are essential for coastal towns to practise quick decisions and teamwork in the case of a real

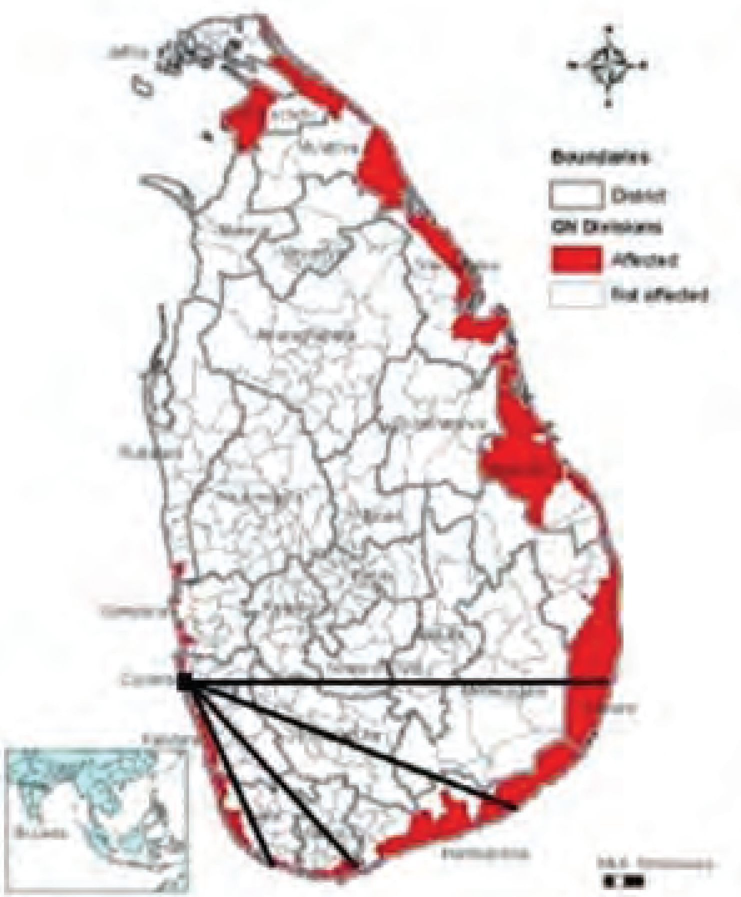

Figure 5. Amateur Radio Communication links provided to aid Disaster relief communication

disaster. Residents benefit from these drills by learning the designated safe zones, evacuation routes, and communication techniques. Through the use of a tsunami simulation, participants can discover areas where their evacuation plans need to be improved, such as locating obstructions on escape routes or making sure everyone is aware of where to assemble. In the event of a real tsunami, this activity promotes readiness and could save lives as well as important time. This exercise, which was completed on December 26, 2023, will be held annually as a chance to improve our capacity for disaster response and resilience (Figure 6).

Always remember that practice and planning are the keys to a successful drill. Communities in Sri Lanka can improve communication and information sharing during a tsunami drill by utilising ham radio successfully, which will improve their readiness for crises in the real world. Figure 7 provides an explanation of it in Sinhala, and it was published in nearly all Sri Lankan newspapers.

10. HAPPY ENDING

We'll take each day as it comes since we have an amazing mission ahead of us. How can one enter the frame of mind of someone like that? questioned 4S7VK Victor Goonetilleke. In a matter of minutes, the people's coastal existence crumbled like a pack of cards. The entire nation is in a stupor, and some individuals are in such a trance that they are unaware of it. However, life must go on, and each day we grow a bit stronger in preparation for the next sunrise. According to Prasad, "news media representatives saw our amateur radio service to the society in the hour of need." Additionally, I appreciate their efforts in educating the public about amateur radio communication. The potential of amateur radio communication in bringing people together is thus established once again."

Figure 6. Disaster Preparedness call from the members.


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Figure 7. Disaster prepardenss drill article was published in the Divina Newspaper on 28.12.2024.

11. CONCLUSION

With the blessings of mother nature on this lovely, tranquil island in the Indian Ocean, the tsunami of December 26, 2004, was undoubtedly beyond the wildest dreams of any Sri Lankan accustomed to a serene, carefree life. As a result, the tsunami stunned the nation, which had never been ready for a disaster of this magnitude. But after the initial shock, the nation accepted the reality of the situation. Unbelievably, the radio amateur community—which was viewed by many as a collection of hobbyists—showed how a small but committed group of civic-minded individuals might use radio communication technology to play a significant role in the aftermath of the disaster.

12. ACKNOWLEDGMENT

This story could not have been told with- out generous input from all of the ama- teur radio operators mentioned in this article.

13. REFERENCES

Koshimura, S., Moya, L., Mas, E. and Bai, Y., 2020. Tsunami damage detection with remote sensing: A review. Geosciences, 10(5), p.177.

Mn, C., Np, C.Y. and Devanathan, M., 2022, January. Establishment of Ground Station for two-way Communication via Geostationary Amateur Radio Satellite. In 2022 IEEE Fourth International Conference on Advances in Electronics, Computers and Communications (ICAECC) (pp. 1-6). IEEE.

Potter, S.J., Clayton, D., Kind-Kovacs, F., Kuitenbrouwer, V., Ribeiro, N., Scales, R. and Stanton, A., 2022. The wireless world: Global histories of international radio broadcasting. Oxford University Press.

Raghunath, P. and Raghunath, P., 2020. A Glocal Public Sphere: Opening up of Radio to Communities in South Asia. Community Radio Policies in South Asia: A Deliberative Policy Ecology Approach, pp.145-192.

Rikitianskaia, M. and Balbi, G., 2020. Radio studies beyond broadcasting: Towards an intermedia and inter-technological radio history. radio journal: international studies in broadcast & audio media, 18(2), pp.159-173.

Shukla, R.K., 2023. Radio for Disaster Management. In International Handbook of Disaster Research (pp. 1517-1526). Singapore: Springer Nature Singapore.

Teresa, A.R.E., Vasanth, G.J. and Vidya, C., 2020. A review on the potential effects of tsunami on built environment. Materials Today: Proceedings, 33, pp.711-715.

Yeh, H., Barbosa, A. and Mason, B.H., 2022. Tsunamis effects in man-made environment. Complexity in Tsunamis, Volcanoes, and their Hazards, pp.187-211.

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