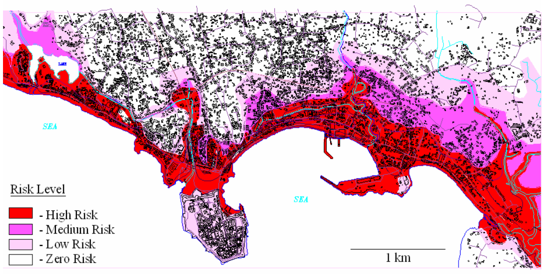
Risk Assessment and Mitigation within a Tsunami Forecasting and Early Warning Framework
Case Study-Port City of Galle



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Enhancing Tsunami Risk Assessment and Management, Strengthening Policy Support and Developing Guidelines for Tsunami Exercises in Indian Ocean Countries (TRATE)

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Enhancing Tsunami Risk Assessment and Management, Strengthening Policy Support and Developing Guidelines for Tsunami Exercises in Indian Ocean Countries (TRATE)

1. Introduction

1.1 Coast at risk

The coastal zone comprising coastal communities, the built environment and eco-systems are exposed to a wide range of hazards arising from natural phenomena and human induced activities. Cities within these zones are centers of economic development and are under severe pressure resulting from planned and unplanned development, population growth and human induced vulnerability, coastal hazards with increasing frequency and magnitude and impacts of global climate change. These unprecedented changes are placing communities at increasing risk from coastal hazards such as severe storms, storm surges and tsunamis leading to coastal erosion, flooding and environmental degradation. Over the last decade, the world has witnessed major coastal disasters, including the Indian Ocean Tsunami of 2004, storm surges resulting from hurricane Katrina in 2005, , cyclone Nargis in 2008, the Great Japanese Tsunami of 2011, Typhoon and storm surge Haiyan of the Philiipines on 2013. The events exposed a lack of knowledge of hazards, vulnerability and deficiencies in preparedness and response. In this respect the assessment and management of risk for coastal hazards plays a vital role for safety of human lives, conservation of ecosystems and protection of the built environment.

Among the tools available, risk assessment is one of the fundamental first steps towards planning, improving and implementing effective disaster risk reduction policies and programmes. One has to know and identify risks if they are to be effectively reduced and contained. There is a need to develop simplified approaches to risk assessment to convince a wider stakeholder base that investing in risk assessments pay. Such approaches bring together so many members of civil society leading the efforts to make disaster risk reduction everyone’s business. One of the important risk management measures is the presence of early warning and public warning systems. Responding positively to such systems play a vital role in saving lives and therefore there exists a strong link between risk assessment and early warning.

Planning and implementation of post tsunami rehabilitation and conservation of coastlines should ideally be undertaken within a multi hazard coastal risk assessment framework giving due consideration to all the coastal hazards. Even when risk assessments are undertaken only for the tsunami hazard it is important to conduct such studies on a platform which can accommodate other coastal hazards.

1.2 Indian Ocean Tsunami Warning System (IOTWS) and Risk Assessment initiatives

In the aftermath of the Indian Ocean Tsunami, the Indian Ocean States decided to establish a tsunami warning system under UNESCO/IOC. Activities in this direction were initiated in March 2005 in Paris. The member states decided that the Indian Ocean Tsunami Warning System (IOTWS) will be a coordinated network of country systems in which each country has the responsibility of identifying the hazard, assessing the risk and issuing the warning to its population. In this respect they will be assisted by Regional Tsunami Service Providers (RTSP) to be established in some of the Indian Ocean countries. Indian, Indonesia and Australia have established the centers for this purpose and from 2013 the IOTWS has become fully operational. Since member states can obtain the warnings from any of the RTSPs it is necessary for RTSPs to operate within a common framework and also ensure that warnings do not vary significantly for a given hazard event. The success of the IOTWS is heavily dependent on system integration of the different elements of the IOTWS and preparedness of member states to work in close coordination with the RTSPs. The performance of RTSPs for a given event will be monitored and compared and attention focused on any limitations.

In order to assist the establishment of the IOTWS by December 2006, six working groups were formed, namely,

1. Seismic Measurement, Data Collection and Exchange
2. Sea Level Data Collection and Exchange
3. Risk Assessment
4. Modelling, Forecasting and Scenario Development
5. A System for Interoperable Advisory and Warning Centres
6. Awareness, Preparedness and Response- ‘the last mile’

In 2010 having assessed the progress the Working Groups were restructured to form three, namely

1. Tsunami Risk Assessment and Reduction
2. Tsunami Detection Warning and Dissemination
3. Tsunami Awareness and Response

This approach also enabled IOTWS to streamline itself with other tsunami warning systems, in particular the Pacific Ocean Tsunami Warning System.

In late 2005, the Working Group on Risk Assessment (WG-RA) conducted a survey of the needs of its membership and following thrust areas were identified to be included in the Terms of Reference of the WG-RA

1. Initiate investigative studies on tsunami hazard sources and data collection
2. Prepare an Integrated Regional Tsunami Hazard Map /Risk Model to enhance understanding of the tsunami hazard for the Indian Ocean basin
3. Develop uniform guidelines for tsunami risk assessment based on the wide experience available among the member countries
4. Provide guidance on tsunami risk management including hazard mitigation
5. Strengthen the capabilities of Indian Ocean states in the field of tsunami risk assessment and management.

The WG-RA adopted a four pronged approach to achieve its tasks

1) Conduct consultative workshops among professionals and stakeholders to prepare the Indian Ocean Tsunami Hazard Map and the Guideline on Risk Assessment and Mitigation.
2) Preparation of the Indian Ocean Tsunami Hazard Map to obtain a better understanding of the hazard sources. This was undertaken by Geo Science Australia based on probabilistic tsunami hazard modeling, with funding from Aus-AID, leading to the publication, Probabilistic Tsunami Hazard Assessment of the Indian Ocean Nations **(Burbidge et al, 2009)**

3) Preparation of the guideline on tsunami risk assessment for the benefit of the member states. The guideline, Tsunami Risk Assessment and Mitigation for the Indian Ocean **(UNESCO, 2009 b)** was prepared and published as a UNESCO Manual and Guideline No.52. This guideline was prepared with the assistance of IOTWS, WAPMERR, Dubai, UNDP, Asia Pacific Regional Centre (APRC), Bangkok.

4) Conduct Seminars and Workshops for training both at national and regional level to assist member states to use the guidelines or develop their own guidelines

In addition to the two documents mentioned above, UNESCO/IOC also published a broad guideline on coastal hazards titled, Hazard Awareness and Risk Mitigation in Integrated Coastal Area Management-ICAM **(UNESCO, 2009 a)** to which the Working Group contributed.

The guidelines provide useful information in implementing tsunami risk assessment and mitigation studies within the broader framework of integrated coastal area management. They provide sufficient flexibility in implementing such studies giving priority to critical variables as applicable to the region/city under consideration.

At the first global meeting of the Tsunami Warning Systems held at UNESCO/IOC Paris in March 2009, the Working Group on Risk Assessment of IOTWS proposed that Case Studies on Tsunami Risk Assessment be conducted on cities and regions covered by the Tsunami Warning Systems. In this respect the Working Group strongly promoted such Case Studies on Risk Assessment in the Indian Ocean States and other ocean basins.

1.3 Enhancing the capability in conducting Tsunami Risk Assessment within a tsunami forecasting and early warning framework.

A tsunami warning system must alert all persons on every vulnerable coast of imminent danger, covered by the system. The response of such a system must be rapid (as soon as possible), accurate (minimize false warning), reliable (continuous operation), effective (to save lives). UN-ISDR Framework for effective Early Warning Systems encompass four critical linked elements,

- Detection, Monitoring and Warning Service (Technical Monitoring and Warning Service)
- Risk Knowledge (Awareness of the Risk)
- Dissemination and Communication (Dissemination of meaningful warnings to Persons and Communities at Risk)
- Response Capability (Public Awareness and Preparedness to Respond)

With the establishment of the IOTWS it is necessary to focus on risk assessment within a tsunami forecasting and early warning framework. It is possible to establish within such a framework a capability that serve, real time operational needs, hazard /risk assessment needs and research/development opportunities through the use of a standard tsunami forecast system that includes tsunami characterization, measurements and forecast models. The importance of this concept has been identified by Dr.Eddie Bernard, formerly of Pacific Marine Environmental Laboratory (PMEL), NOAA, Seattle, USA.

In summary, operating within a Tsunami Forecasting Framework and through the use of a standardized tsunami forecast system including

- tsunami source characterization,
- tsunami measurements, and
- tsunami forecast models

a capability will be developed to serve

- Real-time operational needs (event based)
- Hazard/Risk Assessment needs (strategic risk)
- Research and Development opportunities

.

The tsunami forecast system would have **two** immediate applications:

1. Real-time operational forecasts of tsunami arrival time, tsunami amplitude over time for 12 hours, maximum wave height, and inundation areas
2. Long term assessments of hypothetical tsunamis based on plausible tsunami sources for a particular area. Such assessment could be used for Risk Assessment and for the production of tools such as disaster management maps.

The said capability was developed for the Port City of Galle on the south western coast of Sri Lanka as a Case Study on Tsunami Risk Assessment within a Tsunami Forecasting Framework. In addition to the important steps relating to conducting tsunami risk assessment, the case study illustrates the use of scenario modeling for long term forecasting and strategic risk assessment within the framework of coastal forecasting zones adopted by the Regional Tsunami Service Providers (RTSPs) of the Indian Ocean Tsunami Warning System. It also focuses on critical issues relating to the interpretation of the technical warning issued by the RSTPs and its transformation to a public warning for the benefit of the coastal population.

1.4 Objectives of the Report

The primary objective of this report is to present the results of a case study on tsunami risk assessment and management for a coastal city, on this occasion for the port city of Galle in the southern province of Sri Lanka. Preliminary studies were implemented by **Hettiarachchi et.al (2009)**. Thereafter detailed studies were undertaken at regular intervals on a number of critical areas to examine post tsunami rehabilitation and risk assessment and management which is presented in this report. The report is presented in a manner that it provides the important steps relating to tsunami risk assessment and management in the generic context and thereafter at the end of each chapter the outcome of the applications to the port city of Galle is presented in text boxes.

Components of risk and its assessment, assessment of impacts of hazards, vulnerability, community resilience, risk and risk management methods are discussed in detail in Chapters 2 to 7. A total of eleven text boxes are presented on the applications to the port city of Galle.

Of specific importance is Chapter 8 on Tsunami Risk Assessment within a Tsunami Forecasting and Early Warning Framework, whereby an integrated approach for the analysis of results from early warning systems and inundation modelling for risk assessment is presented for improved tsunami wave height forecasting on the shoreline. This identifies the need to refine the tsunami wave forecasting provided by the Regional Tsunami Service Providers (RTSPs) for cities having complex geometrical shoreline features and bathymetrical features. The basic concept of this approach is presented in Chapter 8 whereas a dedicated case study on improved tsunami wave height forecasting is presented as a separate report (refer Chapter 8 for details). If this case study was included in the main text it would have caused an imbalance in the report due to the very technical nature of the subject matter covered. Here again, the case study is presented initially in the generic form followed by the application to the port city of Galle.

Chapter 9 is dedicated to Resilient Cities, focusing on the UN-ISDR initiative which is fully supported by the Working Group on Risk Assessment and Reduction of the IOTWS.

2. Risk- Components of risk and its assessment

2.1 Components of risk

Risk is primarily a function of hazard and vulnerability. It is usually expressed by the notation

Risk = Hazard x Vulnerability (eq.1)

In this expression hazard and its exposure is included under the broader hazard term. Risk represents the probability of harmful consequences or expected losses (in terms of deaths, injuries, property, livelihoods, economic activity disrupted or environment affected) arising from interactions between natural or human hazards and vulnerable conditions. Therefore in this form risk can be quantified with hazard being associated with the probability of occurrence and vulnerability with potential damage.

Another popular expression for risk incorporates capacity and expressed by the notation

Risk = (Hazard x Vulnerability)/ Capacity (eq.2)

Capacity represents the means by which the community utilizes available resources, abilities and their knowledge base to confront adverse conditions that could lead to a disaster. In this respect community preparedness is considered the pivotal factor. The strengthening of coping capacities usually builds resilience to withstand the impacts of hazards both natural and human-induced. Capacities thus focus on group measures that are in place to help the community to cope with the event.

Prior to the Indian Ocean Tsunami (IOT), many countries in the ocean basin had not adopted a planned approach towards preparedness and response in relation to mega disasters in the coastal zone, an aspect which is considered vital in saving lives. Hence it seemed more appropriate to focus on the importance of preparedness in relation to capacity. In this notation risk is expressed as,

Risk = Hazard x Vulnerability x Deficiencies in Preparedness (eq.3)

The additional term represents certain measures and tasks described as deficiencies, if absent could reduce the loss of human lives and property in the specific interval of time during which the event is taking place. This term is also commonly identified as the inverse of capacity.

2.2 Assessment of risk

For detailed assessment of risk it is necessary to quantify the three main components of risk which is a challenging task. As mentioned before when risk is expressed in the form, **Risk = Hazard x Vulnerability** it is possible to quantify risk in terms of loss. However with the introduction of capacity or preparedness it is difficult to adopted direct quantification methods.

There is no standard technique for such assessment of risk and a number of methods have been used by researchers including quantitative and qualitative methods. Quantification based on qualitative description (ranking methods) and quantification based on detailed analysis of respective parameters hase been successfully adopted. Although studies relating to risk will be able to capture the significance off all the three components there are limitation in the assessment process. However, it is important that risk assessment studies are conducted within the framework defined by the above formulae. This aspect has to be kept in mind when reviewing the outputs from studies on risk assessment.

While risk can be described using plain text and data on risks usually presented in a tabular form, experts have found advantages in representing hazard, vulnerability and risk in the format of maps.

Hazard maps represent the type of hazard, spatial extent of processes, denoting areas possibly affected by an extreme event. The maps provide an overview of the hazardous situation and enables land use management and planning measures to be adopted efficiently. By regular upgrading of the maps it is possible to monitor the hazard profile in specific regions.

Vulnerability maps represent different aspects of vulnerability (geographical location of places which congregate vulnerable groups such as children, elderly and women; physical infrastructure including critical infrastructure susceptible to damage; the location of processes equally susceptible to damage such as those conducting commercial activities in public markets, access to public transportation in bus stands and train stations; health care, education. etc). These maps serve as a tool to identify measures to be implemented in reducing the vulnerability of communities exposed and improving early warning efforts.

It is important to recognize that there are numerous approaches in developing hazard and vulnerability maps depending on the definitions and criteria adopted to classify the levels of hazard and vulnerability. The superposition of the hazard and vulnerability maps lead to risk maps and here again the final outcome will depend on the assumptions made in establishing criteria for the superposition of hazard and vulnerability levels leading to risk levels. Reference will be made to these maps under the sections on hazard, vulnerability and risk.

3. Assessment of impact of hazards

3.1 Classification of coastal hazards

Hazards are potentially damaging physical events, phenomena or human activities that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation. They represent the possibility of occurrence of a natural/human induced event of a probable magnitude or intensity that includes a specific area of exposure. Within this geographical area, human life, ecosystems and infrastructure can be potentially affected by the hazard. Hazards are characterized by their source of origin, path of propagation, intensity, duration, frequency of occurrence and associated probability. Their impacts are assessed with respect to magnitude, space and time.

Hazards can be classified according to the source of origin, natural/human induced and the manner in which it manifest itself, episodic (rapid or near rapid onset) / chronic (gradual onset).

Natural hazards include those arising from meteorological, oceanic and geologic phenomena and long term climate change. Human induced hazards such as oil spills in the vicinity of coastlines have serious impacts on the coastal zones.

Episodic hazards include severe storms, earthquakes, tsunamis and oil spills all of which have limited predictability and may result in major disasters. They are also identified as hazards having a rapid or near rapid onset, although some of them can be monitored for several days prior to their impact on community and society at large. Chronic conditions include shoreline erosion, flooding, sedimentation, sea level rise and coastal environmental and resource degradation. These conditions which may result or increase from disasters arising from episodic hazards, relate to processes which could be measured and monitored over months, years and decades. Unplanned or poorly designed physical interventions in the coastal zone also contribute to the increase of chronic conditions. Some hazards have a slow onset but if neglected can cause major disasters when critical threshold values relating to the magnitude are exceeded.

The communities should be made aware of the types of hazards their characteristics and should be educated on the importance of preparedness in responding to potential disasters in particular when faced with the rapid onset of extreme events.

3.2 Approaches to the analysis of tsunami hazard and its impacts

Tsunami hazard analysis focuses on three areas namely,

- tsunami hazard sources,
- exposure in relation to the said sources and
- potential impact on land.

It is important to initially understand the principal phases of the tsunami wave from generation, propagation to inland dissipation. In this respect it is necessary to be fully aware of the physics of the phenomenon associated with each stage.

- Generation
  - -Geo disturbance
  - -Tsunami source
  - -Initial dissipation
- Deep-water propagation
- Interaction with the continental shelf
- Near-shore transformations
  - -Submarine features
  - -Reduced depth
  - -Combined influence of coastal processes
  - -Shoreline geometry
- Shoreline entry
- Inland dissipation

Tools and methods available to study the hazard include, instrument measurements which captured the event (if any such data is available), field investigations, image analysis and mathematical modelling. The latter includes both deterministic and probabilistic tsunami hazard modelling.

With respect to tsunami hazard sources attention is focused on previous events (their location, magnitude and sequence), seismic gaps and the identification of potential ‘credible scenarios’.

Mathematical modeling is widely used to simulate tsunami wave propagation. Deep water modeling is used until the interaction with the continental shelf and thereafter near-shore and inundation modeling are used. The latter is challenging in view of data requirements and simulation of rather complex phenomena.

When examining its exposure at a specific location on the coastline, for a given hazard source, due attention must be focused on submarine geological features, regional location which will identify the influence of key wave transformation processes, location with respect to continental shelf and shoreline geometry. Depending on these aspects the amplitude of the tsunami wave may be enhanced. Wave reflection from coral atolls and concentration of wave energy within bays and headlands are typical examples of this category.

Investigating the impact of tsunami on land after an event can be studied by measurements from field instruments (if any which has captured the event), post event field observations and satellite images.

Prediction of possible impacts of tsunamis can be achieved by investigating historical records, paleo-tsunami research work and mathematical modeling. The need for reliable, calibrated models with quality data on near-shore bathymetry and onshore topography is considered important for modeling.

3.3 Measurements from field instruments

Measurements of instruments, if any provide useful information on building the hazard profile. Usually tsunamis are monitored by tide gauges. However by the time it is recorded by a given gauge the tsunami has reached the shoreline and the said measurements cannot be used for early warning for that stretch of coastline. However, it can be utilized by other regions and nations to be affected by the propagating wave.

In the case of Sri Lanka, a S4 Wave Current meter utilized to monitor the nearshore climate off the Port of Colombo on the west coast of Sri Lanka, captured the tsunami well. The measurements clearly illustrate the wind waves superimposed on long period tsunami waves and how over time the impacts subside. Of greater importance were the measurements of currents at the seabed at 14 m depth. The currents increased from 25 cm/s to more than 70 cm/s as the tsunami waves propagated into shallow waters in Colombo. On the basis of these measurements, one could imagine the high currents which would have been present on the east coast directly exposed to the tsunami waves.

3.4 Post tsunami field investigations

Post tsunami field investigations comprising interviews with persons who witnessed the event and field measurements provide crucial information on the inundation and damage profile, mechanics of tsunami flow, human security, safety of infrastructure and issues relating to sustainable livelihood.

Interviews with persons provide very detailed information relating to flow characteristics, failure patterns of infrastructure and human response to disaster situations. The inundation profile primarily comprises depth, run up and the spatial distribution. This information should be collected in a planned manner within well defined framework to harness the full potential of the exercise. It is best that interviews are conducted not immediately after the event but providing reasonable time for mature reflection of the event. Soon after the event emotions are very high and the descriptions provided may not be fully accurate.

On one hand field investigations provide an excellent overview and understanding of important aspects relating tsunami wave mechanics and impacts of the hazard. On the other hand they provide detailed evidence on critical aspects of flow behaviour, interaction of waves with humans and structures and ground truth verification in support of scientific explanations of impacts of the hazard.

3.5 Satellite image analysis

Satellite images obtained during and post tsunami period and comparison with pre tsunami period provided extensive information on the hydraulics of tsunami wave propagation and its impacts. Consecutive images were able to trace the full tsunami cycle impacting the southern coast of Sri Lanka and tsunami propagation into water bodies and overtopping of dunes. These images were most helpful in understanding tsunami wave impacts and role of natural protection such as dune systems.

Case Study for the Port City of Galle

Box 1- Mechanics of tsunami wave impact and overall impact on the city

Many coastal cities of Sri Lanka particularly in the east and the south of the island were severely affected by the Indian Ocean Tsunami due to the exposure to the hazard. One of the principal coastal cities devastated was the historic port city of Galle located in the southern province of Sri Lanka. Incidentally the first recorded tsunami to have affected Sri Lanka was on 27th August 1883, arising from the eruption of the volcanic island of Krakatoa. On this occasion too, unusually high water levels followed by the receding beach were observed in Galle around 1.30 pm. The water level fluctuations were not severe and there was no inundation. The said time corresponds well with the tsunami travel time for tsunami waves which would have been generated by the largest eruption of the volcano earlier in the morning. However, on 26th December 2004, Galle was subjected to the severe impact of tsunami waves, their magnitude having increased due to near-shore transformation processes. Persons killed, disappeared, injured and affected were of the order of 500, 90, 1000 and 8120 respectively. Houses and other buildings damaged were of the order of 1600 and 1300. Galle is one of the many coastal cities around the world, which remains heavily exposed to the tsunami hazard. Presence of poorly constructed buildings and inadequate drainage would have contributed towards increased vulnerability.

The tsunami waves, which reached the offshore waters of Galle were primarily diffracted waves, diffraction taking place around the southern coast of Sri Lanka. In the context of tsunamis the location of Galle is extremely exposed. It lies besides a wide bay and a natural headland on which is located the historic Galle Fort with very reflective vertical non-porous walls on all sides. Furthermore, there exists the Dutch Canal west of the headland, conveying water through the city centre. The waves in the vicinity of Galle, which were increasing in height due to reduced water depths, were further subjected to a series of near-shore processes which increased their heights even further. The canal was a facilitator in conveying the massive wave and associated flow towards the city centre.

In the vicinity of the headland on which the Galle Fort is located, the wave energy concentrates due to refraction. These waves then reflected from the vertical solid walls of the Fort and moved around the headland. Such walls reflect almost all the incident wave energy with very high wave heights at the wall itself. There is hardly any dissipation. On the west of the headland the waves moved ferociously into the Dutch Canal. On the east it moved along the bay. The wide bay in Galle further contributed to the increase in wave height by modifying the shoaling process via reduced wave crest width to accommodate the bay shape. The combined effect of this phenomenon and the wave coming around the eastern side of the Fort caused a massive wave of destruction along the Marine Drive located around the bay (**see Figure 1**). It is certainly not surprising that many survivors referred to a moving large black wall similar to that of the Galle Fort.

The city of Galle is therefore not only exposed to tsunami waves which will diffract around the southern part of Sri Lanka it is even more exposed in the context of near-shore coastal processes which will further increase wave heights. This aspect is identified as increased exposure within the risk assessment framework.

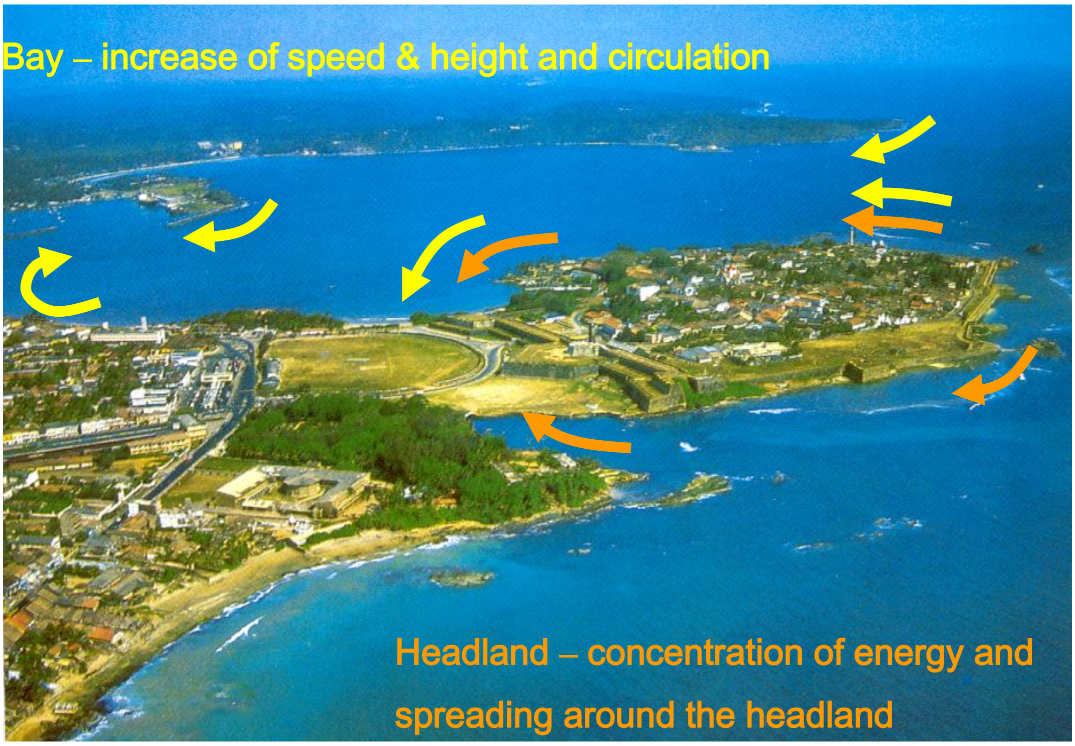


Figure 1: *Galle Bay and Headland*

Case Study for the Port City of Galle
Box 2- Post Tsunami Field investigations for Hazard Analysis

A two pronged approach was undertaken to assess the impact of tsunami on the Galle City by the University of Ruhuna and Moratuwa. These studies primarily related to the assessment of inundation, flow directions and damage to buildings and infrastructure.

In the first approach the assessment of inundation was carried out in an organized manner by dividing the area under study into 250m x 250m grids. At least one location was selected for each grid and a total of 138 points used. People living within the respective areas were interviewed for all grids. Information on inundation depth and flow direction was obtained together with other associated parameters of the hydraulic regime. The collected data were used to identify the

- Inundation profile comprising depth, length, run up and spatial distribution
- Inundation contours with wave direction and information that may help to estimate the flow speed
- Distance from sea along the tsunami flow path

The said data generated a tsunami hazard map for the City of Galle based on the field measurement arising from the Indian Ocean Tsunami.

In the second approach studies were undertaken to study the damage to buildings and infrastructure and specific flow regimes which were generated due to the location and spacing among buildings. Those who survived the tsunami were able to describe devastating impact of flow regimes such as that of jetting effects which occurred along streets separating rows of buildings. These studies were more relevant to study the vulnerability of infrastructure.

Both studies focused attention on human vulnerability and in particular the impact of strong currents at a given depth, which were very much more than the currents witnessed at similar depths due to flooding by rainfall and spillover from rivers and canals.

It was evident that the results of the study will also useful in identifying for the Indian Ocean Tsunami scenario the following,

- Evacuation routes and refuge areas
- Safe areas and safe buildings
- Proposed locations for fixing sign boards on evacuation routes

Figure 2 illustrates the data collection points and **Figure 3** illustrates the inundation depth and the direction of incoming wave. Wave directions and inundation heights were established after the interviews with the people. **Figure 4** illustrates the inundation contours established from field investigations. This represents one form of a tsunami hazard map for the impact of the Indian Ocean Tsunami on the City of Galle based on extensive field measurements conducted after the event.

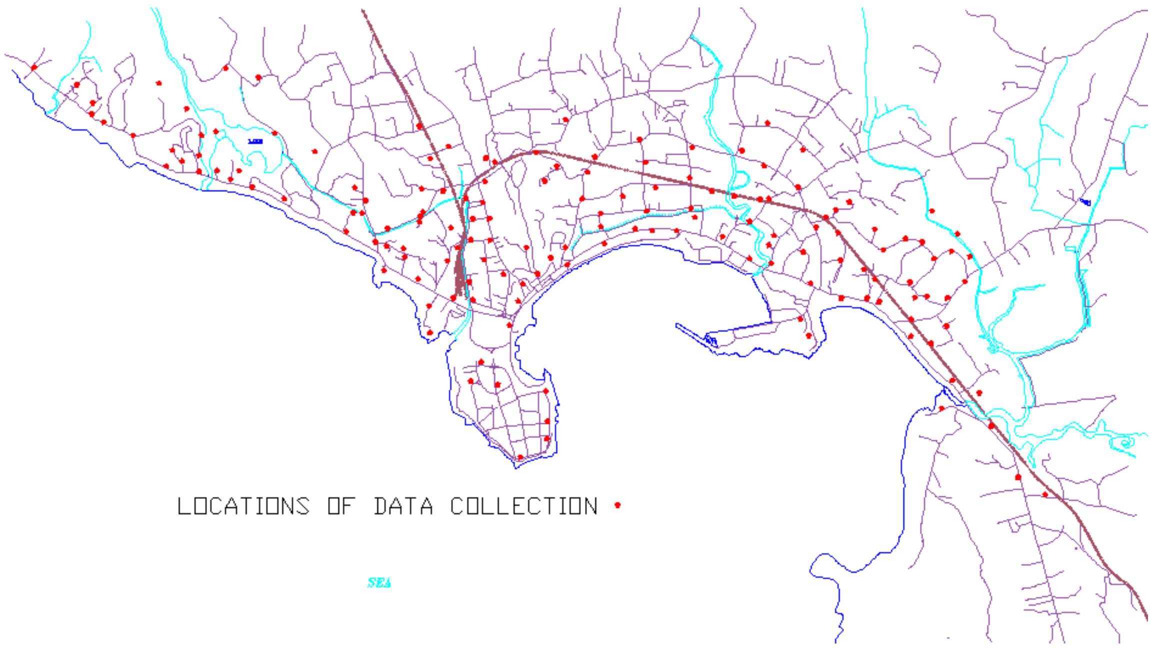


Figure 2: *Data collection locations*

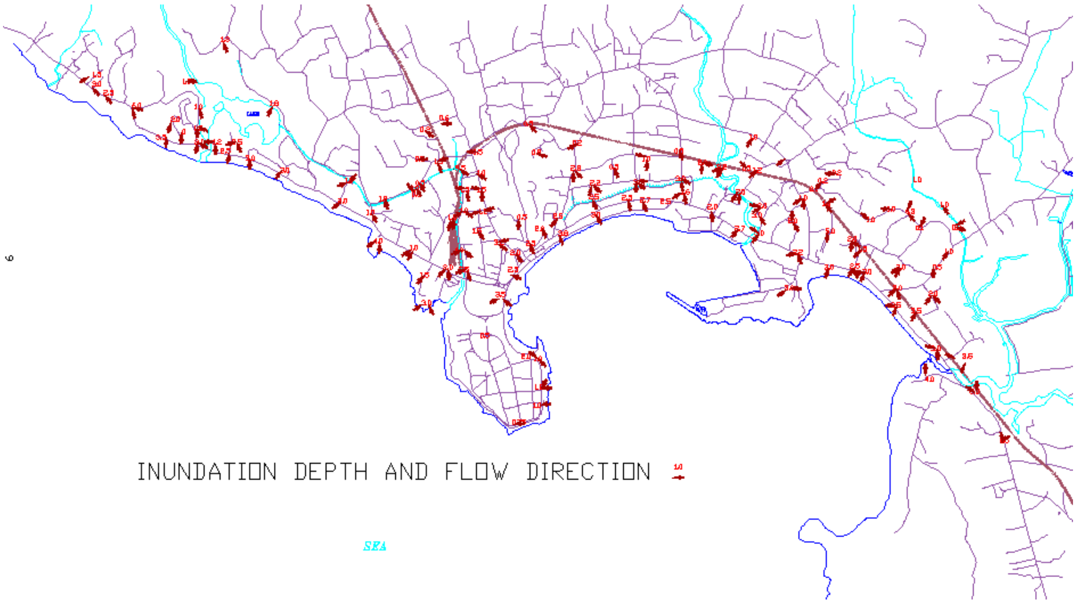


Figure 3: *Inundation depths and wave directions*

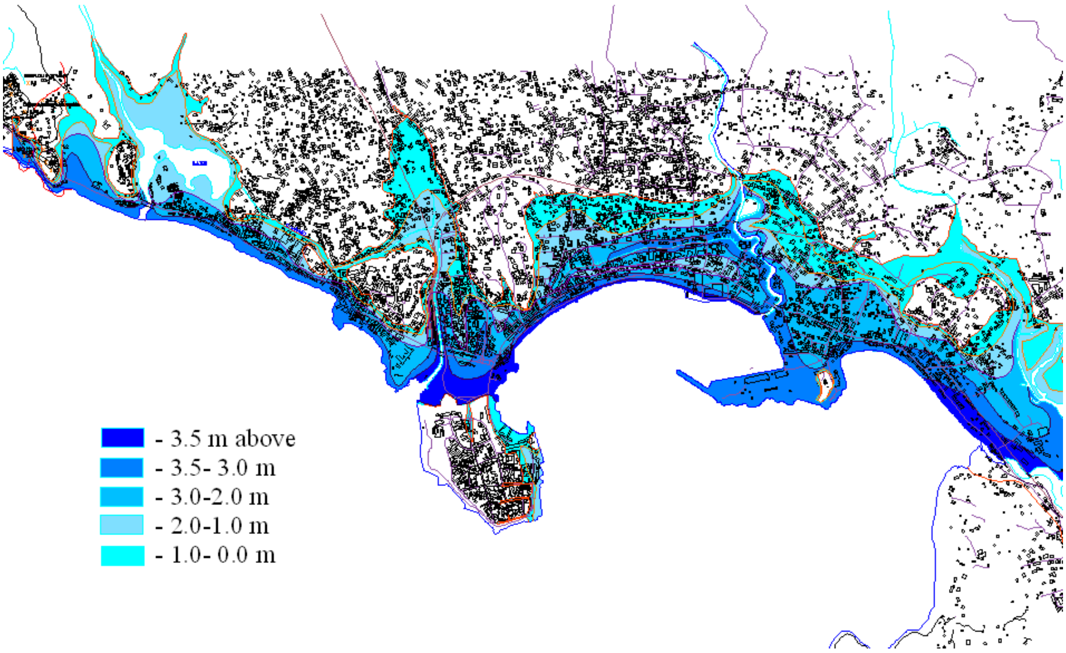


Figure 4: *Inundation Contours*

3.6 Deterministic Tsunami Hazard Modelling

Deterministic tsunami hazard modelling comprising, deep water, near-shore and inundation modelling is primarily carried out with three objectives

- Study overall exposure of the country/island, region or city to a given hazard source
- Simulate tsunamis which have occurred and compare them with field measurements on height, inundation length and run up
- Simulate potential tsunamis based on 'credible scenarios' from geologic and seismic studies

Results from modelling of tsunamis which have taken place and 'different credible scenarios', provide a data base of the key parameters relating to inundation and the flow regime. Inundation height, length and its distribution, run up and velocity are some of those parameters. These parameters can then be used for the development of critical hazard scenario by relating to threshold values for security of people and infrastructure.

Modeling studies generate a valuable data base which can be used for scenario based risk assessment.

Case Study for the Port City of Galle
Box 3- Deterministic Tsunami Hazard Modelling

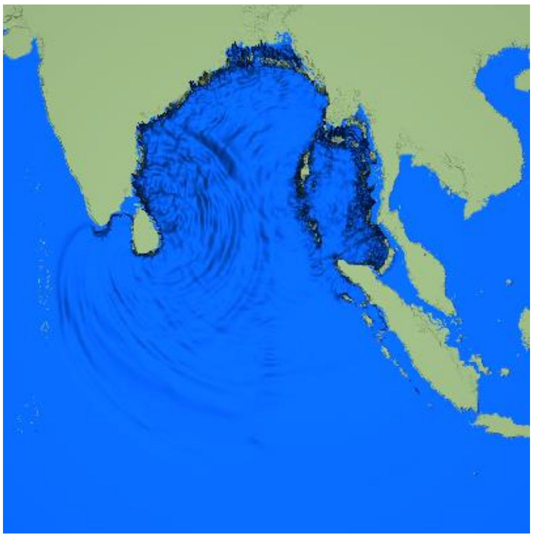
Numerical modeling of tsunami phenomena was carried out to obtain information on the coastal region of Sri Lanka that could be affected by potential tsunamis. General course grid modeling was carried out for the coastal region in the southern parts of the island and detailed fine grid modelling, including tsunami run-up and inundation was carried out for the City of Galle. The results of this exercise were used for the preparation of hazard maps for the City of Galle for different scenarios based on mathematical modelling. It was evident that the Indian Ocean Tsunami represented the worst case scenario. The numerical modelling procedure is described below for a few scenarios.

Generation and deepwater propagation of the tsunami waves were modeled using the AVI-NAMI model. The module for co-seismic tsunami generation of AVI-NAMI uses the method developed by **Okada (1985)** and the module for tsunami propagation solves Nonlinear Shallow Water Equations. ANUGA fluid dynamics model based on a finite-volume method for solving Shallow Water Wave Equations was used for the inundation modeling. In the ANUGA model the study area is represented by a mesh of triangular cells having the flexibility to change the resolution of the mesh according to the area of importance. A major capability of the model is that it can simulate the process of wetting and drying as water enters and leaves an area and therefore suitable for simulating water flow onto a beach or dry land and around structures such as buildings. Bathymetric and Topographic data were obtained from two studies. High resolution near shore bathymetric data were obtained from the Galle Port Development Project in 2007 and high resolution topographic data were obtained from the LIDAR surveys for nearshore coastal areas implemented with Italian assistance after the 2004 Tsunami.

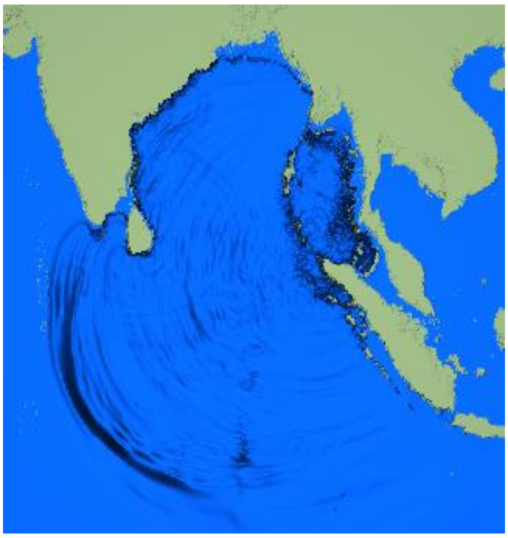
Broad scale deep water propagation modelling was carried out for a number of source scenarios selected from the Sunda/Java Trench. The results of four selected scenarios are presented here. Fault length of 500 km, a width of 150 km, dip angle of 8^0, a slip angle of 110^0 and a displacement of 40 m was used for the study. **Table 1** gives the source details and the maximum and minimum wave amplitudes from the propagation modeling. **Figure 5** provides snap shots of tsunami propagation for these four scenarios, 180minutes after the earthquake. **Figure 6** illustrates the distribution of computed maximum tsunami heights over the Indian Ocean.

	Longitude	Latitude	Strike Angle	Max. Amplitude (m)	Min. Amplitude (m)
Scenario 1	92.00' E	8.52' N	350'	2.015	-1.501
Scenario 2	94.26' E	3.09' N	329'	3.477	-2.391
Scenario 3	97.01' E	2.07' N	329'	1.419	-1.33
Scenario 4	97.60' E	-0.60' N	329'	2.608	-2.081

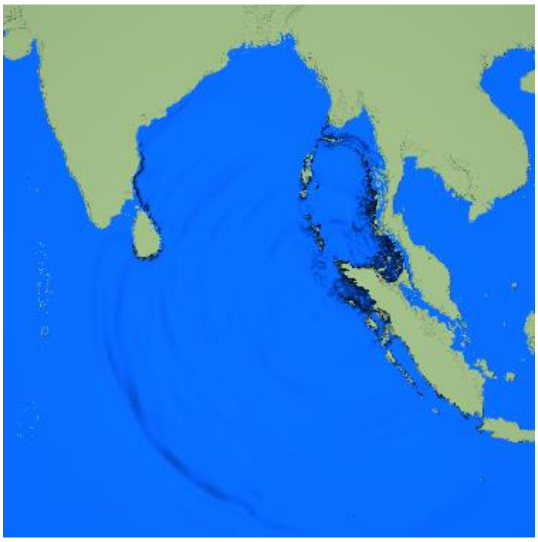
Table 1: *Source details and the maximum and minimum wave amplitudes from the propagation modeling*



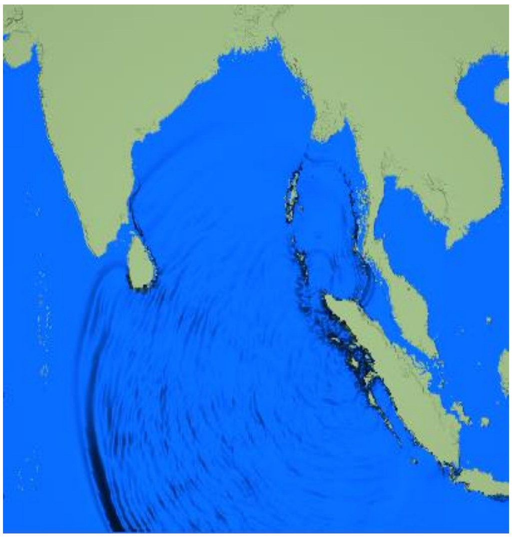
(a) Scenario 1



(b) Scenario 2

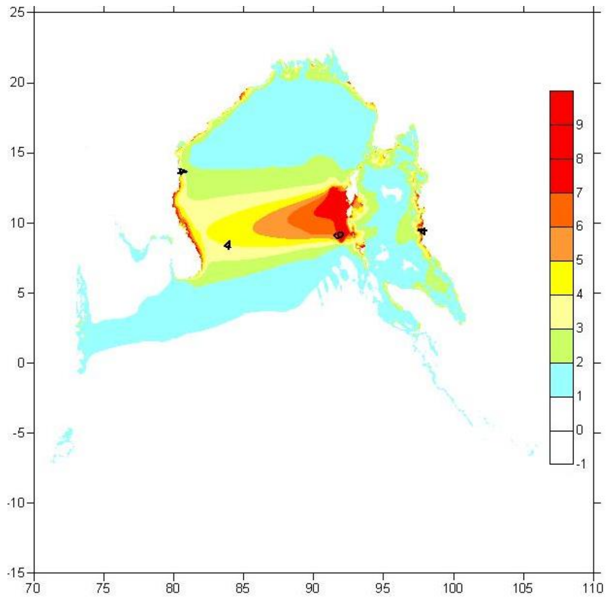


(c) Scenario 3

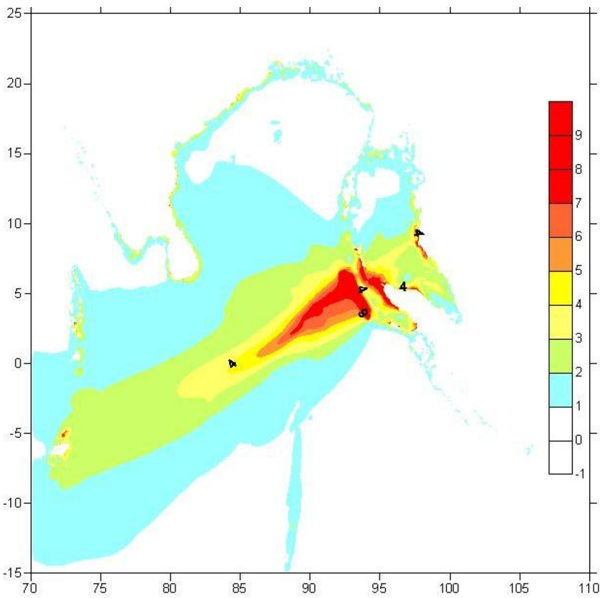


(d) Scenario 4

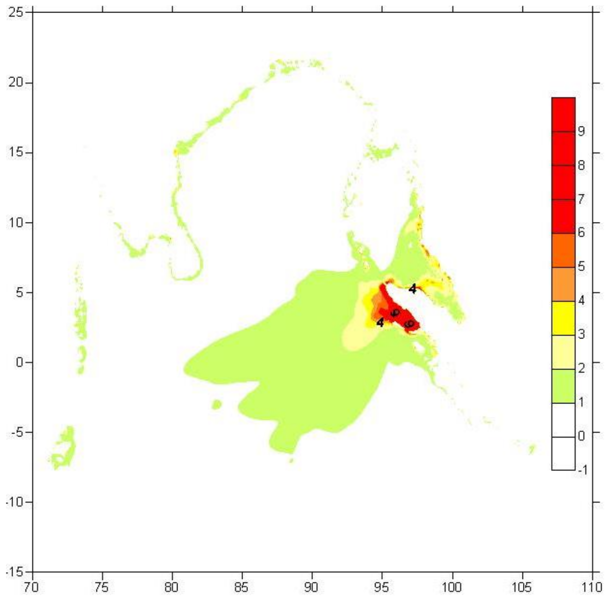
Figure 5: *Snap shots of tsunami propagation for four scenarios, 180minutes after the earthquake*



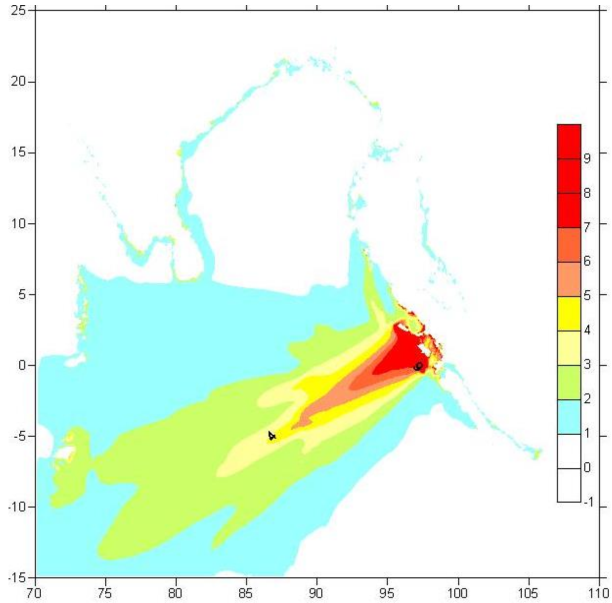
(a) Scenario 1



(b) Scenario 2



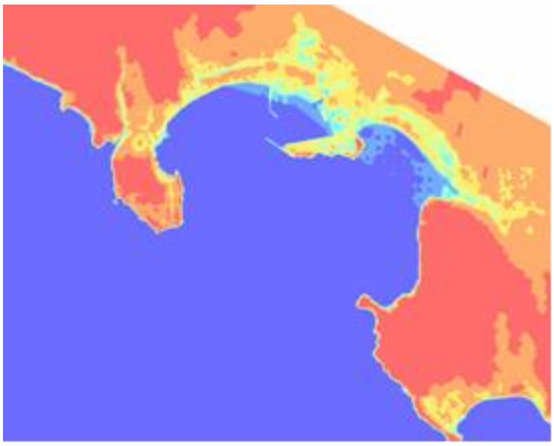
(c) Scenario 3



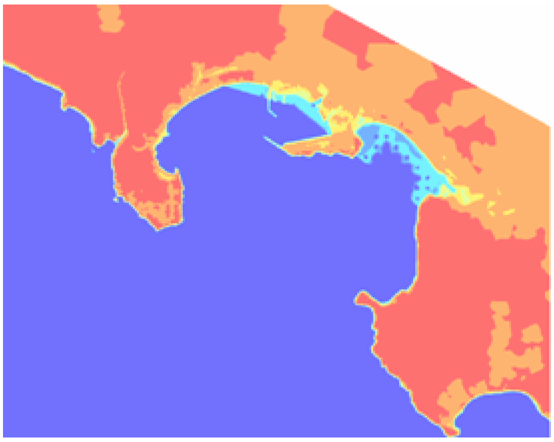
(d) Scenario 4

Figure 6: *Distribution of computed maximum tsunami heights over the Indian Ocean*

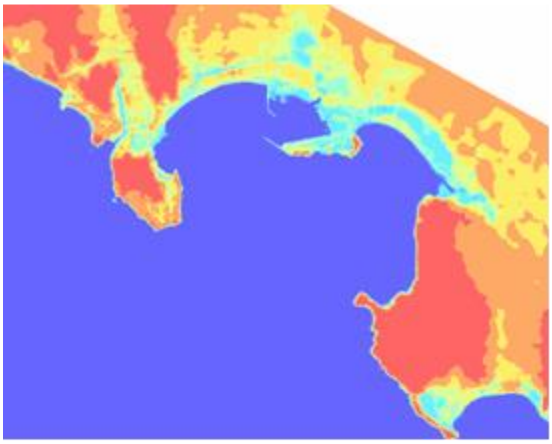
Based on the results of the deep water model, inundation modeling was carried out using the ANUGA model. Modelling results give valuable information of the coastline of Galle that could be affected by potential tsunamis. The model results are very useful for the preparation of Hazard maps. **Figure 7** gives the inundation modeling results for 4 scenarios.



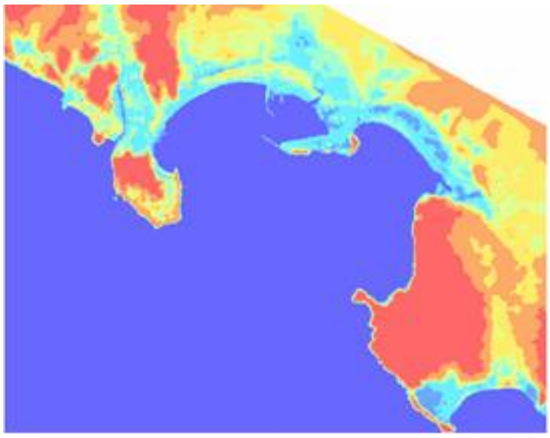
(a) 2m_20min tsunami wave



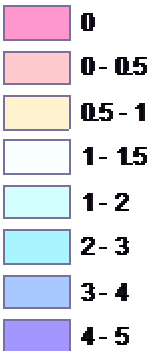
(b) 3m_20min tsunami wave



(c) 4m_20min tsunami wave



(d) 5m_20min tsunami wave



All inundation depths are in meters

Figure 7: *Deepwater Propagation and Inundation Modelling for Port City of Galle*

3.7 Probabilstic Tsunami Hazard Modelling

Probabilistic tsunami hazard modelling seeks to assess the probabilities of certain wave heights being exceeded due to the arrival of a tsunami at locations under investigations. These probabilities are expressed in terms of expected return periods. A Probabilistic Tsunami Hazard Assessment of Indian Ocean Nations was carried out under the leadership of Geoscience Australia **(Burbidge et al 2009).**

Two views quickly emerged in discussions among the panel of developers. On one hand, the hazard assessment should avoid over-estimating the hazard by considering only those sources for which there is solid evidence for generation of large tsunami. On the other hand, the assessment should be careful not to miss source zones that may generate large tsunami even if they have not done so historically – as was the case for the 2004 Indian Ocean Tsunami (IOT). The panel decided that these two important views could best be accommodated by developing two assessments, referred to here as low-hazard and high hazard end member assessments. This affords a clear expression of uncertainty in the hazard as the difference between the two end members, while it was hoped that any additional confusion created in application of the two assessments to mitigation would be manageable. The geographical pattern of the low-hazard assessment is broadly reflective of the impact of the IOT. The high hazard assessment, on the other hand highlights areas potentially threatened by local tsunami, such as the western Makran and southern Java coasts, which are at the same time the areas of highest uncertainty in the hazard assessment. For the high-hazard case, the earthquakes considered can rupture along each subduction zone to a length determined by the lesser of either the length of the subduction zone, or the rupture length associated with a magnitude 9.5 earthquake which is the maximum used in the study and is equal to that of the largest earthquake ever recorded (the 1960 Chilean earthquake).

These studies lead to the development of a range of maps which provide useful information as described below.

<u>Hazard Curves</u>- the relationship between the return period and the maximum tsunami amplitude for a particular model output point

<u>Maximum Amplitude Maps</u>- the maximum tsunami amplitude that will be exceeded at a given return period for every model output point in a region

<u>Probability of Exceedance Maps</u>- for a given amplitude, the annual probability of that amplitude being exceeded at each model output point in a region

<u>Deaggregated Hazard Maps</u>- relative contribution of different source zones to the hazard at a single location

<u>National Weighted Deaggregated Hazard Maps</u>- indication of the source of the hazard to a nation or region as a whole

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Case Study for the Port City of Galle
Box 4- Probabilistic Tsunami Hazard Modelling

The important observation from the outcome of probabilistic tsunami hazard modelling is that for Sri Lanka the low hazard and high hazard maps are very similar in character with maximum hazard along the east coast and the high hazard case being greater than the low hazard case by about 30%. Both low and high hazard cases for Sri Lanka are dominated by the events in North Sumatra and Nicobar Islands. Probably this seems that the Indian Ocean Tsunami was the worst case scenario for Sri Lanka.

The offshore tsunami hazard for Sri Lanka and the deaggregated hazard maps are illustrated **in Figures 8 and 9**. The deaggregated hazard displays the relative contribution of different sources to the tsunami hazard at a particular location.

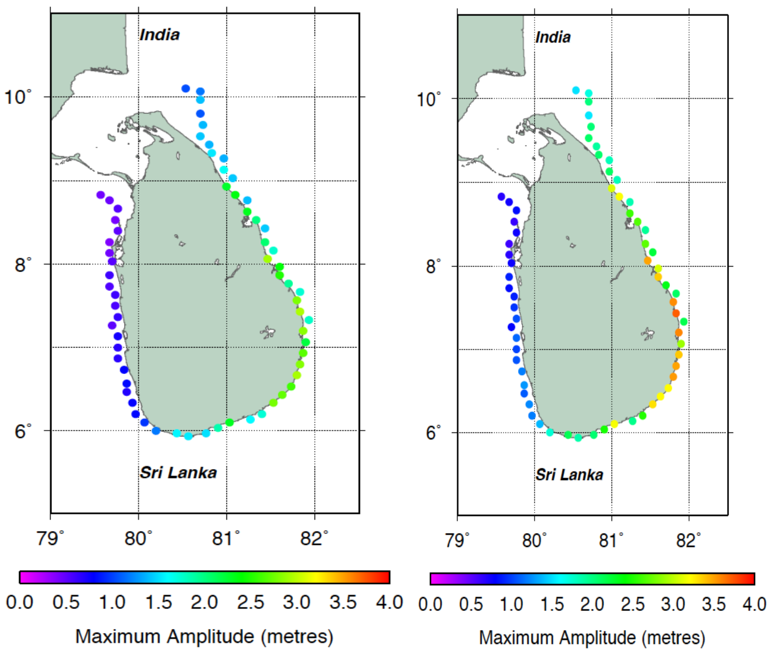

Figure 8: Offshore tsunami hazard for Sri Lanka- low and high hazard end members

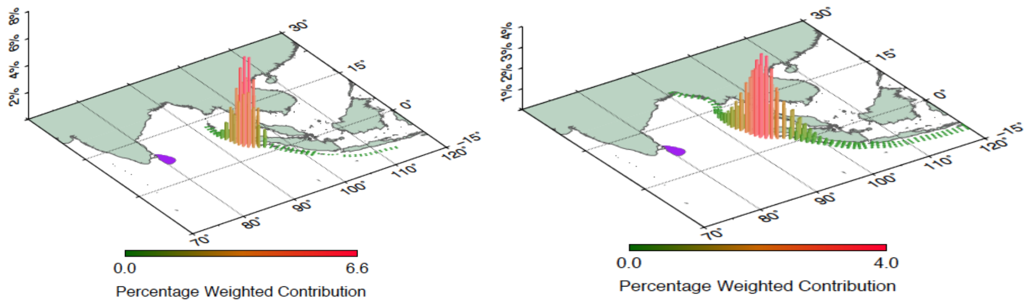

Figure 9: The deaggregated hazard displays for Sri Lanka low and high hazard end members

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3.8 Tsunami Hazard Analysis for Risk Assessment

Tsunami hazard analysis for risk assessment could be achieved either via a multiple scenario based or an event based approach. For risk assessment against the tsunami hazard it is important to assess scientifically and establish the basis and criteria on which such an exercise is undertaken. In developing hazard maps for risk assessment it is necessary to develop hazard levels and many approaches are available for defining such levels.

For a multiple scenario based approach, the superimposition of the impact of scenarios will clearly indicate areas which have high a greatly likelihood of being affected. The probability itself of say inundation and its magnitude can be assessed by several methods which will consider the probability of occurrence of each event leading to an integrated hazard map. **Strunz et al (2011)** adopted this approach for tsunami risk assessment in Indonesia and relevant information is presented.

For the event based approach attention is focused on individual events, say for example, worst case scenario or scenarios with specific frequencies of occurrences and impacts. After a mega tsunami such as the Indian Ocean Tsunami (IOT) it is customary to focus attention on the impacts of such events for strategic planning, say for example, location of hospitals, critical facilities such as power stations, water treatment plants. This approach is relevant to countries which are located at a considerable distance from the fault lines and therefore usually impacted by tsunamis arising from very large earthquakes. Even if planning is based on observations arising from a single extreme event it is important to analyse impacts of credible scenarios and operate within a framework of a scenario based approach. This provides a justification for the use of event based approach for selected scenarios.

Tsunami hazard maps comprise several hazard levels, say for example, the use of four levels of hazard, high, medium, low and very low (near zero) which are usually based on both inundation depths and flow speeds. The latter will consider both human security and infrastructure protection. Once the criteria for hazard levels are established the hazard maps can be developed from results obtained for inundation and flow speeds from both field investigations and mathematical modeling.

Case Study for the Port City of Galle
Box 5- Hazard Map (event based for Indian Ocean Tsunami)

For the City of Galle it was decided to develop an initial risk assessment based on the Indian Ocean Tsunami which represents the worst case of the hazard scenarios. For this event, results from both field investigations and deterministic tsunami hazard modelling were available and a good comparison existed between the two. These results could be used for long term strategic planning and location of important buildings and for the identification of evacuation routes and safe places/buildings, preparation of evacuation plans and placement of signposts for the benefit of the community at risk.

For the city of Galle, hazard levels were developed based on inundation and flow speeds. The four hazard levels were classified as given below.
High- Inundation level above 0.5m with high flow/current speeds (>1.5 m/sec)
Medium- Inundation level between 1m to 2m with low flow speeds
Low- Inundation level less than 1m and low flow speeds
Very low (Zero) - Very small or no inundation to have any impact on humans

Results from investigation conducted by Ports and Airports Research Institute, Japan on resilience of humans against tsunami currents, for both males and females were also referred to in developing these hazard levels, because hardly any studies exist on the impact of tsunami wave currents on persons

Figure 10 represents the Hazard Map developed from this analysis

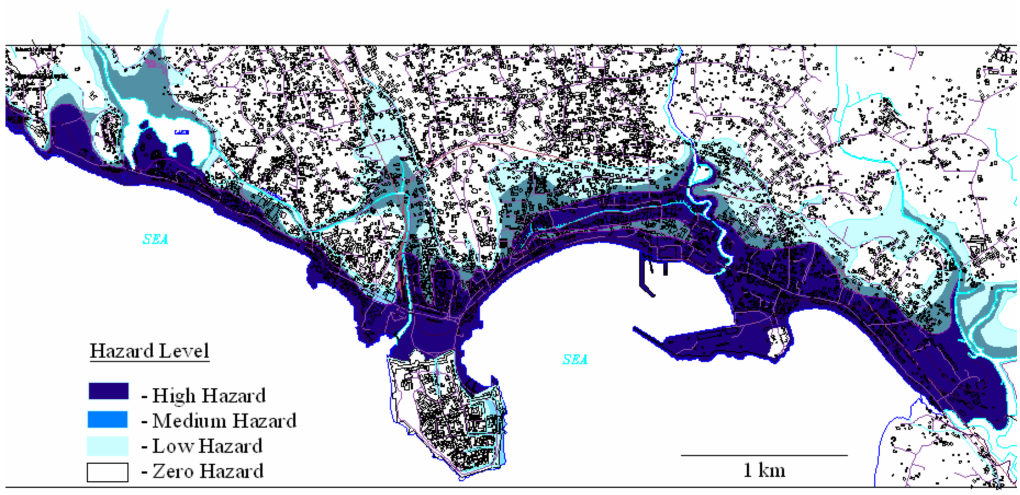

Figure 10: *Hazard Map*

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4. Assessment of vulnerability

Vulnerability represents characteristics and circumstances of a community, a system or an asset that make it susceptible to the damaging effects of a hazard such as tsunami, an earthquake, a flood, etc. It arises as a consequence of conditions determined by physical, social, economic, political, institutional and environmental factors that characterize the framework of development employed in every society. The basic components of vulnerability can be broadly classified as human, physical, socio-economic, environmental, functional and administrative **(Villagran 2006)** and is therefore dependent on several factors related to the said components. These include, among others, population characteristics and density, degree of poverty, livelihoods, building types their strength (structural vulnerability), and a variety of other factors.

Detailed assessment of vulnerability remains a complex area in view of the widely varying parameters which have to be analysed and in view of the difficulties in defining and quantifying certain parameters. Assessment of vulnerability can therefore be implemented at different levels using varied approaches from simplified to highly sophisticated, commencing from very basic data bases to highly sophisticated data bases both referral and relational. Description of approaches and models on vulnerability analysis is presented in detail by **Birkman (2006)** and a summary is available in **UNESCO 2009a.**

4.1 Single dimension of susceptibility approach to vulnerability

A simplified approach for vulnerability assessment would focus on critical parameters of interest from the broader components of human, physical, socio-economic, environmental, functional and administrative and this should be identified in consultation with all stakeholders. Typically they cover population (characteristics, distribution, location and livelihood), status of infrastructure, exposure and preparedness for effective safe evacuation in response to warning. This approach is primarily a one dimensional approach of susceptibility. Reviews of recent post tsunami vulnerability studies indicate that the greater focus have been on potential loss of life and damage to houses and dwellings. Only a few studies have considered other aspects in detail.

4.2 Sector approach to vulnerability

A framework to breakdown vulnerability assessment into components by analyzing how disasters can impact the different sectors which comprise society was proposed by **Villagran (2008)** thereby moving from single dimension of susceptibility to three dimensional sector approach**.** The sector approach identifies dimensions of vulnerability in three dimensions, namely dimensions of susceptibility, sectors and scale of consideration. In effect dimensions of sectors and scale are added to the existing dimension of susceptibility. Typical sectors identified are, housing, communications, education, health, energy, government, industry, commerce, finance, transportation, public infrastructure, environment, tourism etc**. Figure 11** illustrates this concept graphically. The framework proposes the differentiation within each sector in terms of five areas related to susceptibility, namely, human, physical, socio-economic, environment functional and administrative. These areas can easily be linked to factors identified by UN-ISDR as increasing the susceptibility of communities to the impact of a hazard. Third dimension targets the scale of consideration from a household to national level, via city, district and provincial levels. The advantage of this approach, in particular from a policy point of view, is that it promotes the effective assignation of responsibilities relating to the reduction of vulnerabilities.

A detailed sector approach for vulnerability was also applied in a benchmark project for the City of Galle, Sri Lanka by **Villagran (2008)** and its advantages were clearly observed. In particular it is easy to understand the factors which maintain existing levels, reduce and increase vulnerability. The application of this method requires vast amount of data and consumes time. However, one of the important strengths of the study was that it provided guidance in identifying the critical parameters which could be adopted for a simplified approach on vulnerability. Arising from this study it is possible to adopt a simplified approach with reduced but critical parameters and compare the output of both studies.

A simplified approach based on critical parameters determined via a process of consultation is presented in **Box 7** for the City of Galle. It was evident that simplified approaches based on relevant critical parameters provide effective vulnerability analysis on which risk assessment can be undertaken with confidence.

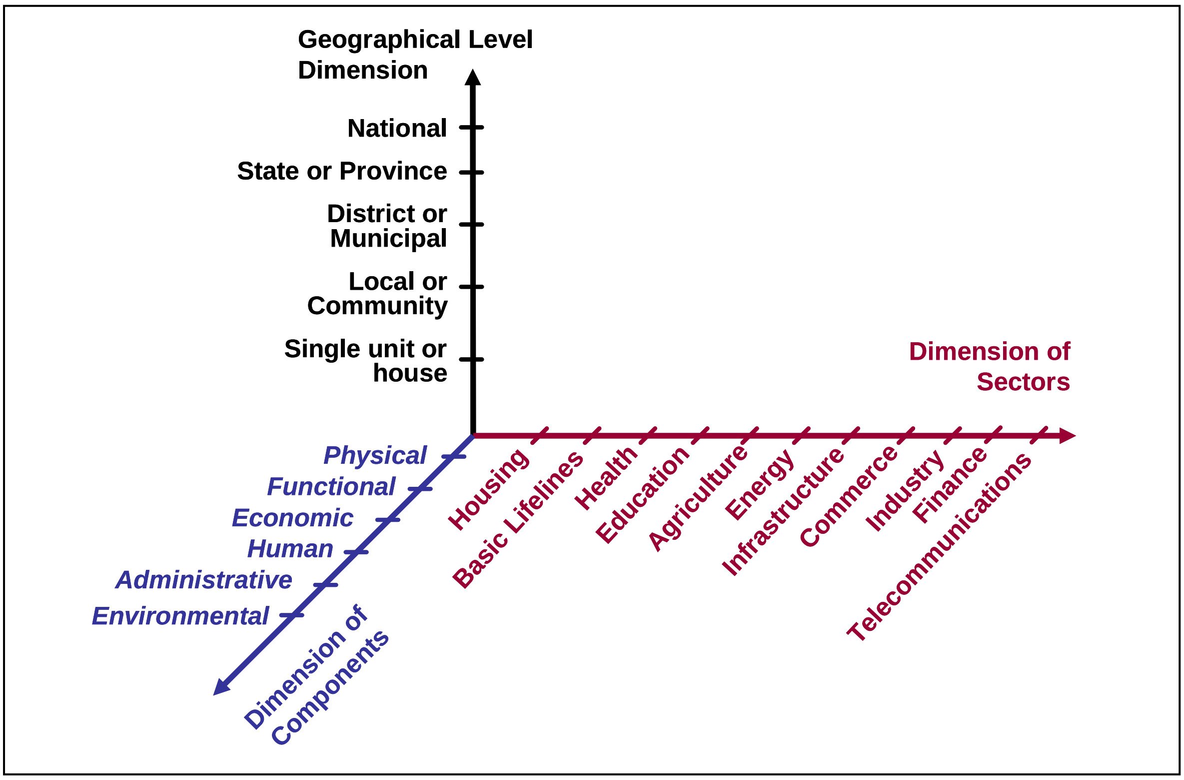


Figure 11: *The Sector Approach and Dimensions of Vulnerability*

4.3 Capacity and Preparedness

While vulnerability represents the proneness of society and its full structure to be affected by the hazard, capacities focus on group measures that are in place to help the community to cope with the event and preparedness represents the presence of measures and tasks which could reduce the loss of human lives and property slightly before or during disaster. In this respect communities must be made aware of the hazards, their exposure, vulnerabilities and the importance of capacity building and preparedness leading to hazard resilient communities. The strengthening of coping capacities usually builds resilience to withstand the impacts of hazards, an aspect discussed in detail in **Section 5.** The key areas of interest which require attention in this field are awareness, education, preparedness, early warning, response, evacuation, safe places and evacuation structures and hazard resilient infrastructure.

Case Study for the Port City of Galle

Box 6- Structural Vulnerability and Damage Assessment

Classification damage and driving forces

Understanding the type and extent of damage and the underlying reasons for the damage are the important elements for damage interpretation. Rather diverse damage profiles arising from complicated mechanisms were observed along the Sri Lankan coastline. The reasons for damage varied from the impacts of forceful tsunami waves to destructive inundation spreading with high velocities over several hundred meters inside the coastal zone.

When analyzing the field observation data it was found that four main levels of damages were noticeable in south and southwest coast of Sri Lanka including the city of Galle.

1. inundation without damage to property (no damage/ minimum damage)
2. inundation with partial damage to property (partial damage)
3. severe inundation with major damage to property (fully damaged)
4. sever inundation with complete destruction of property (fully damaged or destroyed)

Non damaged buildings fall into the category of those that were not affected or experienced only mild flooding. Buildings with minimum and partial damage can be used after cleaning, repair and rehabilitation. Buildings which were fully damaged or destroyed have to be rebuilt.

For understanding damage there are two important aspects to be investigated, namely

1. Strength of the hazard at given location- which can be classified by tsunami height and speed.
2. Vulnerability of buildings and infrastructure- which can be classified under structural conditions, namely, weak, moderate, strong based on materials used, type of construction and overall robustness.

From the field studies on damage investigation it was possible to identify important zones with respect to hazard impacts. Based on the vulnerability of buildings and infrastructure, lower and higher damage levels were observed.

Zone 1- Areas subjected to hardly any inundation due to geographic location, Areas of high elevation and those at a considerable distance from shoreline belong to this zone.

Zone 2- Areas subjected to low inundation with minimum damage. Most of these areas were not directly exposed to the tsunami hazard but experienced the secondary effects of the propagating tsunami wave. This was due to a number of reasons including sheltering from neighboring areas. Inundation heights of the order of 1-2 m were observed in these zones with low velocity profiles. Buildings and infrastructure that are structurally weak were affected.

Zone 3- Areas subjected to medium inundation with moderate to more serious damage. Most of these areas experienced tsunami inundation heights of the order of 1-4 m, with damage of moderate scale. Most of the houses, roads, and bridges were found to be damaged. The damage would have been limited due to the presence of coast protection and shielding from buildings more exposed to the hazard. Inundation distances were found to be several hundred meters and inundation height was several meters. Buildings and infrastructure that are structurally weak and moderate were affected.

Zone 4- Areas subjected to high inundation with serious damage. In addition to direct exposure, the influence of the amplification of tsunami waves due to nearshore and offshore bathymetries and topography may have contributed to high tsunami waves. These areas are also influenced by the local effects such as headlands, large inland water bodies connected with sea (lagoons) with less obstructions and resistance to incoming waves. The areas where there were no proper coastal protection works, minimum amount of healthy sandy beaches with dunes and vegetation were considered under this category. Inundation heights of the order of 4-7 and inundation distance than 1.0 km were observed. Buildings and infrastructure that are structurally weak, moderate and even strong were affected.

Damage in the city of Galle

Figures 12 and 13 provides an overall profile of damage buildings in the city of Galle and its neighbourhood.

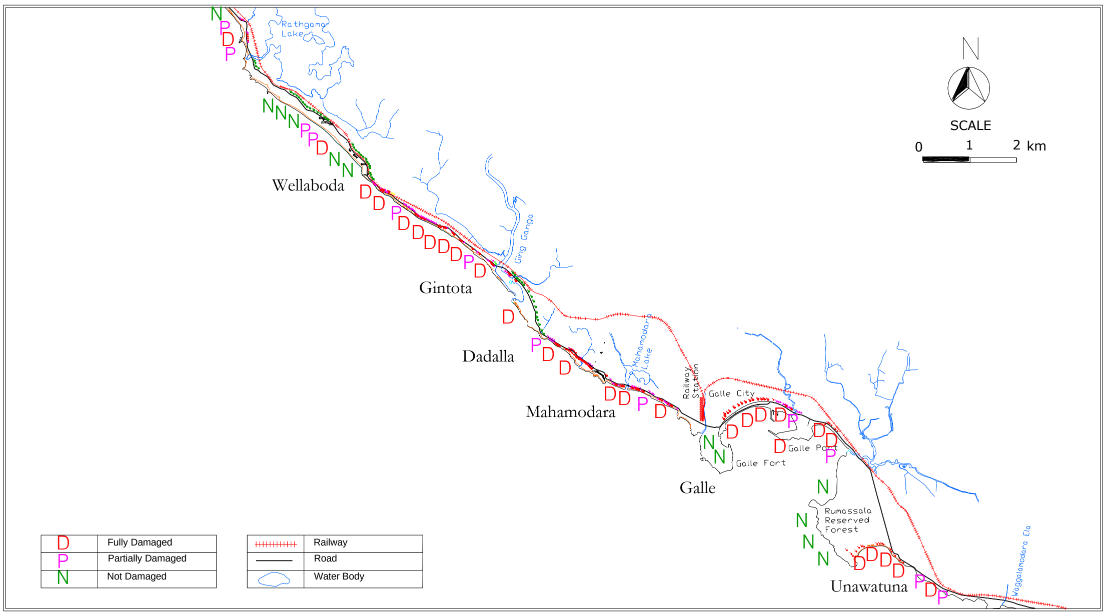


Figure 12: Pattern of damages to houses (Unawatuna to south of Hikkaduwa)

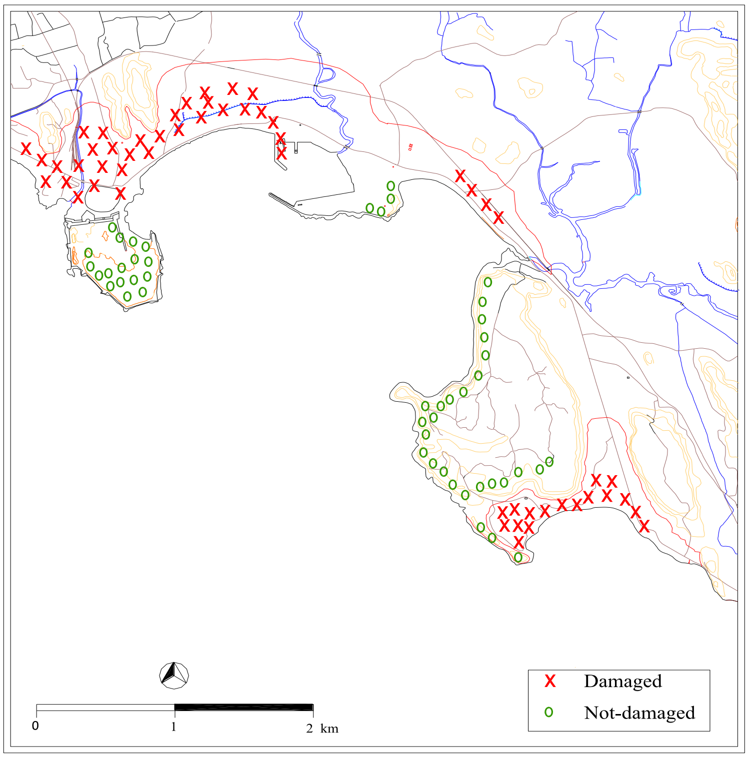


Figure 13: *Damages to Galle*

Galle can be considered as a unique location in terms of its exposure to tsunami hazard. There were two main areas of damage, one behind the Galle Harbour and the other behind the Unawatuna bay (to the left and right of the Figure 13). During the field observations it was learnt that both the areas received significantly high waves. Heavy erosion and high damages behind the Galle Fort shows that, severe wave action propagated through the canal adjacent to the Fort. However the effect of the main breakwater of the Galle port was moderate in protecting the area behind the port. The area between the port and the Unawatuna experienced severe damages due to the similar mechanism as explained earlier.

In the south of Galle, Unawatuna area, damages were intensified due to the low-line topography around the Unawatuna bay. The elevation of inland areas and the narrow area surrounded by the cliffs were just above the mean sea level. Inundation heights of 1.5 m were observed more than 200 m inside from the coast. Hence the effect of the coastline geometry and local topography were found to be significant.

Analysis in greater detail of data relating to the failure patterns around the Sri Lankan coastline revealed that at relatively low inundation depths of up to around 2 m, it was mainly the boundary walls of 1–2 m height that succumbed. As depths increased, single-storey masonry structures, used for most of the housing stock along the coastline, were significantly damaged; and at inundation depths of around 4 m, they were completely swept off their foundations. The vulnerability curves in **Figure 14**, based on post tsunami surveys **(Department of Census and Statistics, 2007)**, give the percentage of complete damage that can be expected for various wave heights. These percentages increase rapidly in the range between 2 and 4 m. Areas that had more than 50% of houses with permanent materials (Per Mat > 50%) had lower percentages of complete damage than areas with less than 50% of houses with permanent materials (Per Mat < 50%). Higher inundation depths of 3–5 m were accompanied by significant scouring, and a few two-storey structures failed through undermining of foundations. It should be noted that the main threats from a tsunami wave on a structure are overturning, sliding and scouring **(Dias et al, 2006)**. Multi-storey buildings with reinforced concrete frames such as tourist hotels, government buildings and school buildings remained essentially intact.

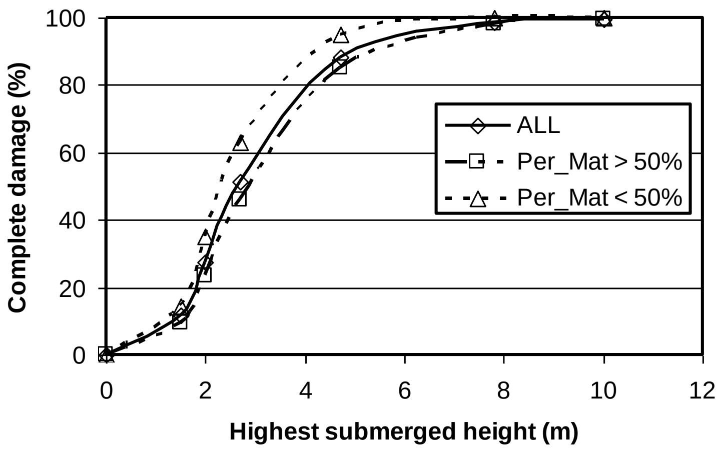


Figure 14 - Vulnerability curves for various categories **(Dias et al, 2009)**

Damage analysis also highlighted the existing differences in social vulnerabilities. For example, it was the housing of the very poor that was most affected, both because of inferior quality and also because it was located virtually on the coast where land is not regulated **(Khazai et al, 2006).**

Case Study for the Port City of Galle
Box 7- Assessment of vulnerability

Having reviewed all relevant information including the detailed study of **Villagran (2008)** it was decided to adopt a simplified approach giving attention to the identification of relevant parameters via stakeholder consultation.

During the consultation it was important to present a strategic approach, commencing from the exposure of vulnerable systems, their sensitivity and resilience where applicable.

Systems exposed, primarily include the population (human), buildings and infrastructure (physical), socio economic fabric of society (socio economic), ecosystems/ natural environment (environment). Services and infrastructure essential for the functioning (functional) and administering (administrative) of society are the other two important aspects.

A community which is well informed of the hazards and prepared are less vulnerable because they are able to move away from prior to the hazard sets in or in a better position to respond intelligently to emergency situations.

The important parameters considered under each category are listed below

Population (human)
Population exposure, its geographical distribution, mobility, variation with time
Sensitive age groups (below 10 years and over 65 years)
Disabled persons
Literacy
Access to dwellings and isolation where applicable
Employment
Income levels, in particular those under extreme poverty levels
Places at which persons congregate (places of religious worship, markets, bus, railway stations)

Buildings and Infrastructure (physical)
Houses, Buildings, Infrastructure and their classification with respect to materials, construction, space and elevation (number of floors)
Human dwellings- Houses, Housing complexes
Critical Buildings- Schools, Hospitals, Homes for the elderly, Hotels and Emergency Services
Roads and Bridges and other public facilities
Airports
Marine facilities of commercial ports and fishery harbours
Infrastructure for industries, trade and commerce
Critical installations (eg. nuclear) and Storage of dangerous and hazardous materials
Critical Services for society to function- Power Stations, Fuels Stations, Water Supply and Purification Schemes, Waste Treatment
Information for Administration - Government and Public Record Offices, Banks

Socio economic activities
Types of socio economic activities engaged by the community and detailed profile relating to the city (Fishing, Aquaculture, Agriculture, Trade, Industries, Tourism)
Vulnerable elements associated with economic activities (fishing boats)

Environment
Important features of the natural environment including their status
Ecosystems, Agriculture and Aquaculture

Functional
This relates to critical infrastructure and services which should be functional for the benefit of society
Hospitals, Fuel Stations, Power Stations, Water Supply and Purification Schemes, Public Order Institutions, Emergency Services (fire brigade), Sea ports, Airports, Travel and logistics for disaster management

Administrative
This relates to critical information for administration of society
Government and Public record offices, Courts of justice, Banks etc

Capacity and Preparedness

Enhancing Community knowledge- Awareness, education, preparedness, early warning, response, evacuation, safe places and evacuation structures and hazard resilient infrastructure, evacuation drills.

Emergency Operations- All emergency operations should function efficiently in accordance with standard operation procedures and Emergency Professionals must move into action without delay. Availability of Incident Command Systems may prove to be useful.

Based on the review of above parameters, the following broad groups were identified to accommodate the relevant parameters relating to the vulnerability of the City of Galle.

- Population, its profile and geographical distribution
- Socio-economic profile of residents including livelihood
- Buildings, infrastructure and its status,
- Ecosystems and areas of environmental importance.
- Capacity to evacuate, within the broader framework of awareness, preparedness, early warning, response and safe evacuation

In addition attention is focused on profile of the occupants, sources of income and household economic level, conditions of buildings and infrastructure and community knowledge.

It is noted that factors relating to exposure of vulnerable elements to hazards, presence of existing protection, distance from sea and elevation were duly accounted in the hazard analysis.

Critical elements identified for City of Galle included

- Train Station
- Bus Terminal.
- Area of congregation in front of Post Office.
- Houses
- Schools (4)
- Mahamodera Teaching hospital
- School of Nursing
- Sambodhi Children Home
- Main Street – Trade and Commerce.
- Fish market, vegetable and fruit market
- Fuel stations
- District Administartive Building.
- Municipal Council Building.
- Coastline road network , Colombo to Matara
- Commercial Port
- Fishing harbour and boat landing sites (3).

In the final analysis it is important adopt weightage factors for relative importance after reaching agreement in consultation with stakeholders. **Figure 15** illustrates the Vulnerability Map developed on the above analysis.

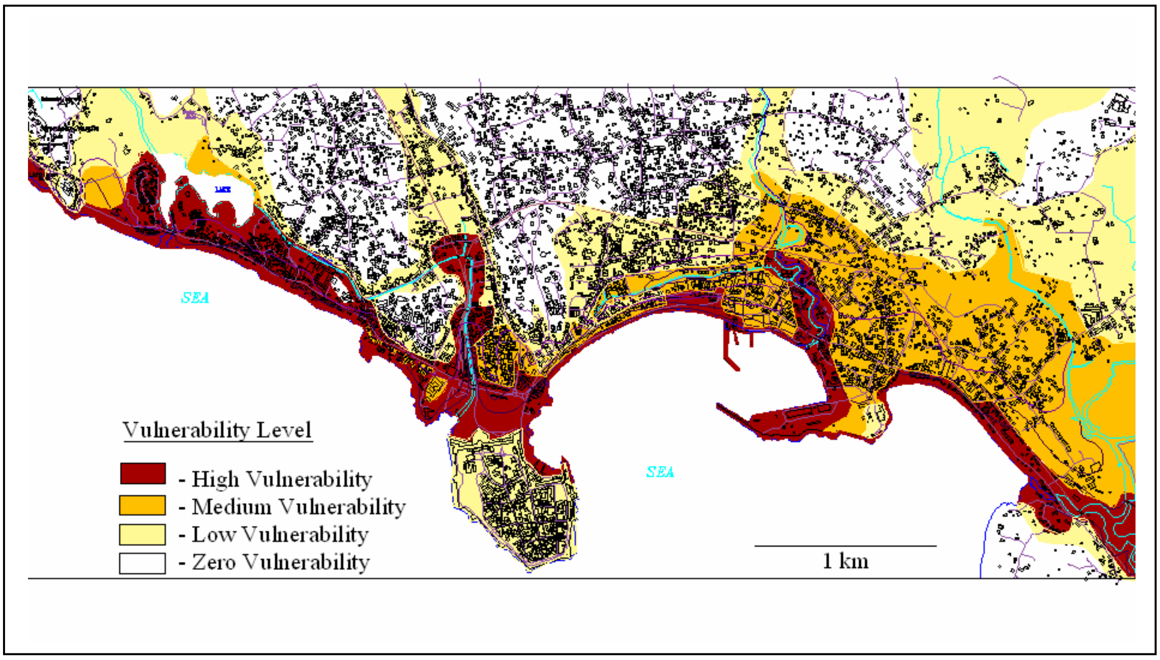


Figure 15: *Vulnerability Map*

5. Improving Community Resilience

5.1 Establishing the resilience of coastal communities

Coastal community resilience is identified as the capacity to absorb and withstand impacts of hazards, to emerge from disaster events and to adapt efficiently to changing conditions. Economic and social development pressure in coastal areas, increasing population density and distribution, human induced vulnerabilities, together with increasing frequency and duration of storms, long term sea level rise and other hazards have created conditions for disasters of high severity occurring more frequently. The period of time between disasters and recovery is becoming smaller and coastal communities have restricted capacity and reduced time to recover and emerge. Some communities are continuously facing disasters, event after event, depriving them of time to plan and achieve long term recovery. In effect they lead a life of continuous response to varying disasters. Such communities have to be identified as high risk areas and studies have to be undertaken on special area risk assessment and management.

Building hazard resilient communities requires a full understanding of hazards both episodic and chronic, the frequency of occurrence, the time scale over which they act and the geographic extent of impact. The community should be aware of the impacts on human life, ecosystems, agriculture and infrastructure. A hazard resilient community can only be developed via an understanding of hazard and vulnerability leading to reductions in the level of risk through proper land-use practices, reduction in the components that make up vulnerability and improved preparedness. Lower levels of risk reflect a resilient community and this can be achieved via a three pronged approach of reducing the impact of hazards, reducing vulnerability and improving preparedness. The community itself can harness the full potential of their indigenous knowledge in developing measures on improving preparedness. Enhanced coastal community resilience enables populations at risk to adapt a wide range of coastal hazards with a greater degree of confidence.

5.2 Coastal Community Resilience- Approach of USAID/ASIA Guideline

Risk knowledge which represents the awareness of the community of potential hazards, vulnerability and the proneness of the community to the impact of the hazards is a critical component of coastal community resilience. In response to the establishment of the Indian Ocean Tsunami Warning System, USAID/ASIA promoted a strategic approach towards Coastal Community Resilience (CCR) to tsunamis and other coastal hazards through the U.S IOTWS Programme implemented in 2007. This approach which had been developed via a consultative process with national stakeholders provided an effective way of assessing coastal community resilience and is recommended for application. It reflects the understanding of the community on critical risk issues and therefore is linked to capacity. The outcome of the approach is presented as a practical guide, titled, 'How resilient is your coastal community' **(U.S. IOTWS Programme 2007)** provides an effective way of assessing the resilience of coastal communities and is recommended for usage. The CCR assessment developed is identified as a very useful rapid assessment undertaken by all stakeholders to identify strengths, weaknesses and opportunities to improve resilience.

The approach primarily deals with eight generic elements of coastal community resilience which is considered of pivotal importance in reducing risk from coastal hazards, efficient recovery and adaptation to change. Resilience has to be built up in each of these areas to ensure a well balanced approach towards community resilience. This in turn will enable the community to 'live with risk', arising from wide a range of coastal hazards, with an equal high degree of confidence.

Eight generic elements of coastal community resilience are considered fundamental to reduce risk from coastal hazards, accelerate recovery, and adapt to change. Building coastal community resilience in each of these elements to maintain an optimal balance is essential and considered an ongoing process. The elements of coastal community resilience and desired outcomes as identified in the said guide **(U.S. IOTWS Programme 2007)** are:

(i) **Governance:** Leadership, legal framework, and institutions provide enabling conditions for resilience through community involvement with government.

(ii) **Society and Economy:** Communities are engaged in diverse and environmentally sustainable livelihoods resistant to hazards.

(iii) **Coastal Resources Management:** Active management of coastal resources sustains environmental services and livelihoods and reduces risks from coastal hazards.

(iv) **Land Use and Structural Design:** Effective land use and structural design that complement environmental, economic and community goals and reduce risks from hazards.

(v) **Risk Knowledge:** Leadership and community members are aware of hazards and risk information is utilized when making decisions.

(vi) **Warning and Evacuation:** Community is capable of receiving notifications and alerts of coastal hazards, warning at-risk populations, and individuals acting on the alert.

(vii) **Emergency Response:** Mechanisms and networks are established and maintained to respond quickly to coastal disasters and address emergency needs at the community level.

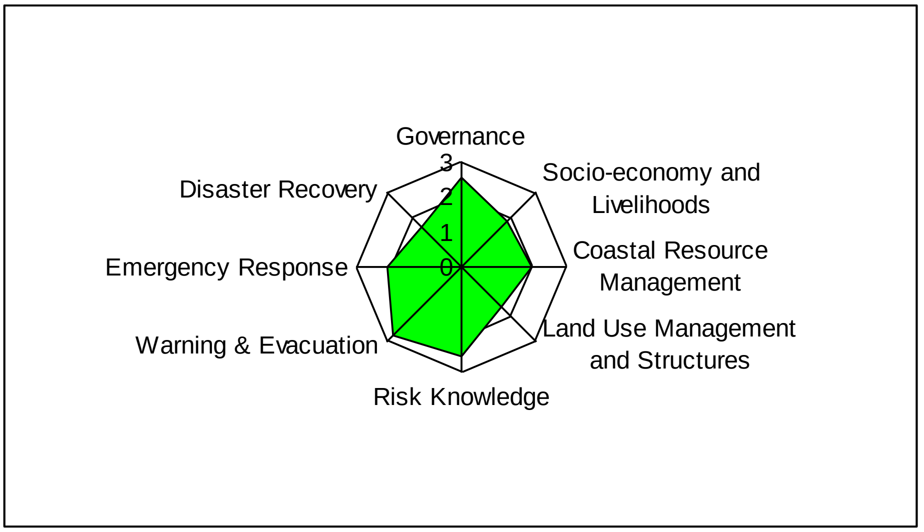
(viii) **Disaster Recovery:** Plans, are in place prior to hazard events that accelerate disaster recovery, engage communities in the recovery process, and minimize negative environmental, social and economic impacts.

Reference is made to **Section 9** which outlines the UN-ISDR campaign to make cities resilient.

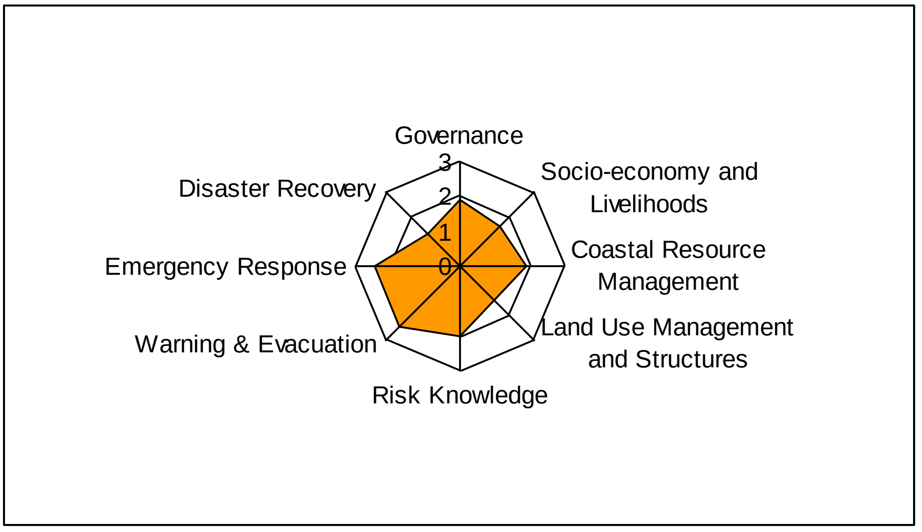
Case Study for the Port City of Galle
Box 8- Coastal Community Resilience

A survey on coastal community resilience was carried out in accordance with the guideline for several sectors of society including middle level managers, villagers in the Galle District..

Figure 16 illustrates the results from the said survey.



(a) Middle Level Managers



(b) Villagers

Figure 16: *Coastal Community Resilience*

The results indicate that both Middle Level Managers and Villagers had a good understanding on Warning and Evacuation because it has been a major thrust area after the Indian Ocean Tsunami. The knowledge on Land Use Management and Disaster Recovery is comparatively low. Based on this analysis appropriate action can be taken to enhance the knowledge base in other areas.

It is recognized that risk knowledge represents one of the key elements on which a hazard resilient community can be build. Without this knowledge the community cannot establish pathways towards resilience. Risk knowledge is strongly linked to all aspects of coastal community resilience and as identified in the guideline **(U.S. IOTWS**

Programme 2007), this knowledge base enables the community, the government agencies and other stakeholders to work in collaboration,

- to incorporate risk related issues to the decision making process
- to identify measures to reduce impacts of hazards on societal, economic and cultural resources
- to manage coastal and environmental resources in an effective manner for sustaining multiple uses, including that for disaster risk reduction
- to adopt safe construction in accordance with hazard resilient design standards and to identify safe locations and construct safe evacuation structures
- to develop effective warning systems, warning dissemination and evacuation plans
- to identify highest risk areas for immediate disaster response
- to develop disaster recovery plans and mitigation methods against potential hazards

One of the principal ways of improving the resilience of coastal communities against hazards is to implement risk assessment studies. This enables them to understand exposure to hazards, issues on vulnerability and planning emergency measures and response, recovery and overall hazard mitigation measures. In effect risk assessment studies provide an opportunity of understanding hazards before they are translated into disasters and the outcome of such studies can be used effectively to adopt measures to improve the reliance of coastal communities. It is emphasized that risk knowledge is the foundation on which all other elements of CCR is developed and community resilience can only be built by giving high priority to risk knowledge.

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6. Assessment of Risk

Risk Assessment is an essential task that is conducted initially to determine the degree of risk that coastal communities face, and subsequently to identify the measures that are needed to reduce such risks through a variety of structural and non structural measures aiming at reduced exposure to such hazards, reduce vulnerability, increased preparedness and increased coping capacities.

As pointed out earlier, while risk can be described using plain text and data on risks presented in a tabular form, it is advantageous in representing hazard, vulnerability and risk in the format of maps.

Risk maps identify areas of comparable risk. Typically these maps can be developed by the superimposition of hazard and vulnerability maps. For superimposing them it is necessary to establish the criteria for defining risk levels and identify the method adopted. It is also necessary to educate the user on the value of information presented and potential limitations in its applications. On most occasions risk maps provide a qualitative classification (similar to hazard and vulnerability maps). For some situations quantitative scales can be adopted (in the form of deaths, damage/economic losses per year).

For example let us consider hazard and vulnerability maps, each comprising four levels of classification, namely, high, medium, low and very low (zero). The relevant criteria adopted for the hazard and vulnerability will be clearly defined in the preparation of the respective maps. For superimposing them it is necessary to establish the criteria for risk levels. On one hand high levels of hazard superimposed on either high, medium, low, and very low levels of vulnerability (or vice versa) may be classified as high level of risk assuming that the high hazard is the dominating parameter. However, one may question whether it is appropriate to define high risk levels for superimposing a high hazard level with low or very low vulnerability levels (or vice versa). On the other hand a high level of hazard superimposed on low or very low levels of vulnerability (or vice versa) may be classified as medium giving due recognition to reduced levels of vulnerability, thereby resolving the issue at stake. The approach to be adopted is the prerogative of those who develop the risk map but it is important to adopt a logical and consistent approach in developing hazard, vulnerability and risk maps as well as to clearly state the methods adopted.

Case Study for the Port City of Galle
Box 9- Risk Assessment

In this study the hazard and vulnerability maps, each comprising four levels of classification, namely, high, medium, low and very low (zero) have been prepared as described in **Boxes 5 and 7**. For superimposing them it is necessary to establish the criteria for risk levels. For this study, a high level of hazard superimposed on either high, medium or low levels of vulnerability (or vice versa) has been classified as high level of risk. Medium level of hazard with medium level of vulnerability too has been rated as a high level risk. Medium level of hazard with low level of vulnerability is rated as medium level of risk (or vice versa). Finally low level of hazard with low level vulnerability has been rated as low level of risk. If either the hazard or vulnerability is near zero then risk is considered as zero.

Figure 17 illustrates the risk matrix adopted for superposition of hazard and vulnerability for the risk assessment case study.

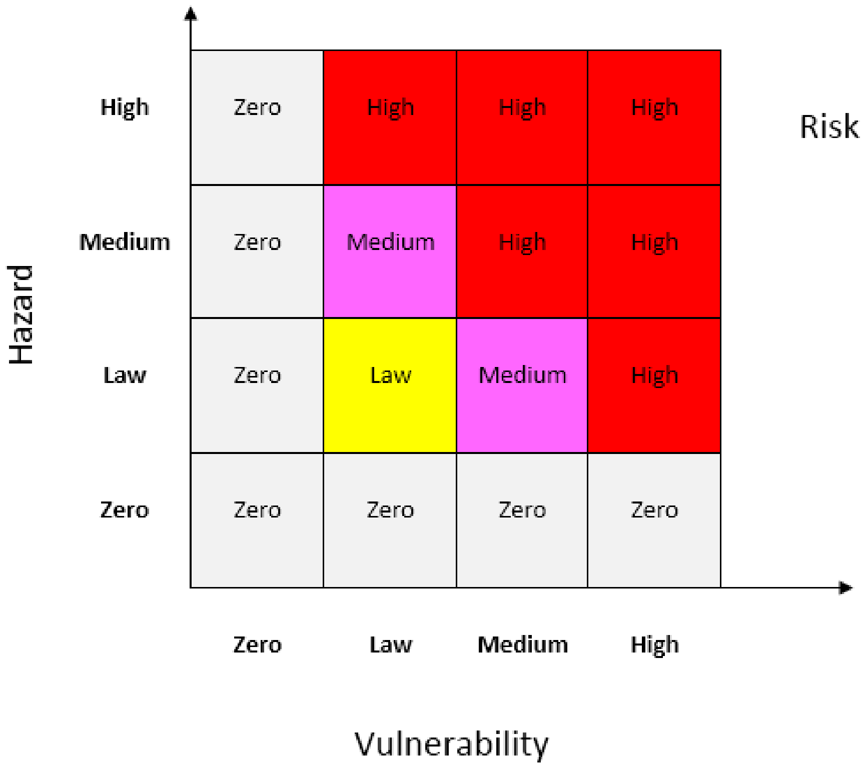

Figure 17: Risk Matrix

Figure 18 illustrates the Risk Map developed by superimposing hazard and vulnerability maps using the above criteria. According to this approach, a level of high risk will be present for large populations, in particular comprising a high percentage of elderly and children, residing at low elevations, within short distances from the seafront, in an environment of easily damageable infrastructure, with easy disruption to livelihood and not having the capacity to evacuate quickly and not protected by coastal flood protection schemes, thus having direct exposure to the sea.

It is emphasised that other criteria can be used for this type of analysis and this aspect was discussed in **Section 6.** Even if slightly different criteria are used in defining risk levels, the final changes in the risk maps are not significant. This mainly because of the approach adopted for the preparation of hazard and vulnerability maps and the assumptions made for their superposition leading to risk maps. There is an inherent averaging process in the method.

It is also noted that sufficient information is available from this study to conduct a scenario based hazard analysis and levels of risk could have been developed on such an analysis. This study focused on event based hazard analysis which can be used for strategic planning buildings and infrastructure and preparedness for safe evacuation. The Indian Ocean Tsunami certainly represents the worst case scenario but other scenario can be used to identify the potential impacts from more likely events having a high frequency of occurrence. However in the case of Sri Lanka which is at considerable distance from the fault lines, other credible scenarios have had very little impact. As mentioned earlier the previous recorded tsunami for the City of Galle was on 27th August 1883, arising from the eruption of the volcanic island of Krakatoa.

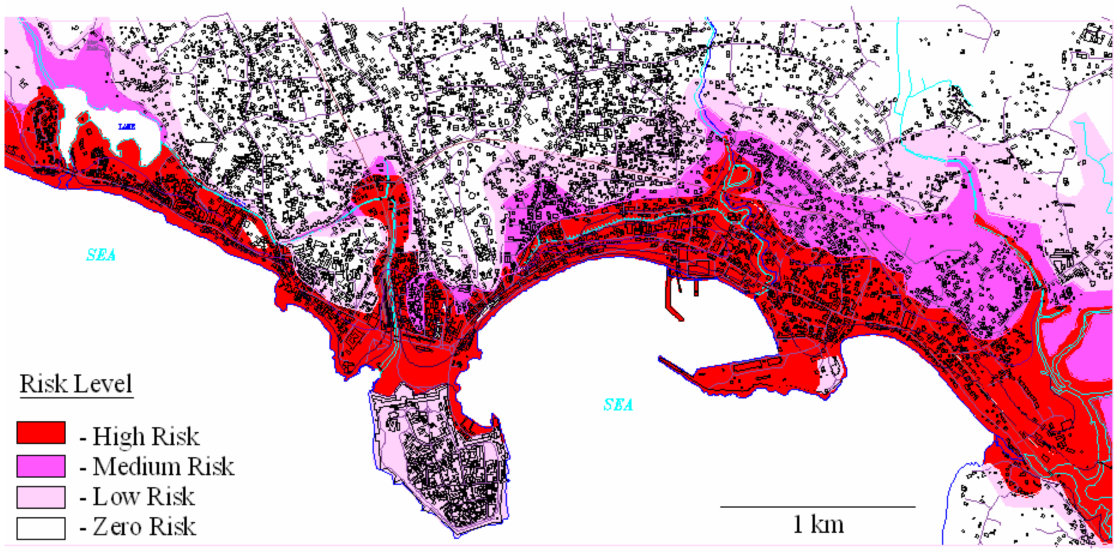

Figure 18: *Risk Map*

7.0 Managing Risk- Classification and Planning Risk Management Measures

7.1 Classification of Risk Management Measures

There are many measures that could be adopted for risk management in coastal zone management when planning for a tsunami and other coastal hazards that accompany high waves and high inundation. These include physical interventions such as protection structures, utilizing the full potential of coastal ecosystems, regulatory interventions in the form of extending existing setback defense line and early warning systems for community preparedness. These have to be supplemented with public awareness on disaster preparedness, efficient evacuation procedures, incorporating planned evacuation routes, safe places and evacuation structures that effectively integrate with the overall planning process.

Measures for risk management can be broadly classified into four categories, namely, those which mitigate the impact of the hazard, mitigate exposure and vulnerability to the hazard, improve preparedness and response and risk transfer via insurance.

7.1.1 Measures that mitigate the impact of hazard (Physical Interventions)

1. The implementation of artificial measures for protection including offshore breakwaters, dikes and revetments
2. The effective use of natural coastal ecosystems including coral reefs, sand dunes and coastal vegetation

7.1.2 Measures that mitigate the exposure and vulnerability to the hazard

1. Land use planning
2. Regulatory interventions such as set back of defense line, in particular for critical infrastructure for sustaining society and those infrastructure to be used by highly vulnerable groups
3. Adaptation of building codes to incorporate guidelines related to coastal hazards for a variety of infrastructure and enforcement regarding the adoption of such building codes leading to hazard resilient buildings and infrastructure.
4. Other regulatory interventions to reduce the level of vulnerability to acceptable levels.

7.1.3 Measures that improve preparedness and response

1. Early warning systems (local and regional)
2. Public warning systems
3. Evacuation routes and structures
4. Community education, using a variety of aids including maps

7.1.4 Risk Transfer via insurance

1. Development of appropriate mechanisms for risk transfer for different hazards, insurance, catastrophe bonds or funds

It is emphasised that Hazard, Vulnerability and Risk Maps play a vital role in Risk Management. In fact it is important to upgrade these maps regularly considering the beneficial aspects of risk management measures adopted. These maps lead to the production of Disaster Preparedness/Management Maps.

7.2 Planning Risk Management Measures

In many countries, prevailing policies target disaster response efforts to a larger degree than risk management efforts. Hence a first priority is to incorporate or strengthen policies targeting risk management and to incorporate accountability regarding risk management activities as a way to complement the accountability that already exists in the case of disaster response.

Subsequently, it is important that risk and disaster management should be undertaken within a framework of multiple hazards. It is recognized that Risk Management for a city/region which should be an important part of an Integrated Coastal Area Management Plan, has to be based on options relating to Policy and Management. These options reflect the strategic approach for achieving long term stability in particular for sustaining multiple uses of the coastal zone giving due consideration to the threats and risks of hazards. They must be formulated on a sound scientific basis preferably to function within the prevailing legal and institutional frameworks. However, if the need arises institutional improvements should be affected and new laws should be imposed. In this process high priority should be given to stakeholder participation.

Policy and Management options must be formulated on a sound scientific basis preferably to function within the prevailing legal and institutional frameworks. However, if the need arises institutional improvements should be affected and new laws should be imposed. In this process high priority should be given to stakeholder participation. Extreme care has to be exercised when obtaining the active participation of stakeholders who have witnessed and suffered heavily in terms of life, property and economic avenues from severe natural disasters. Most of them need a long time to completely recover from their traumatic experiences.

Policy Options identify possible courses of action on shoreline, as,

(1) Maintain existing defense line
(2) Setback defense line
(3) Retreat
(4) Advance

In order to implement the Policy Options various Management Options are considered provided they are appropriate for the coastal classification. They are summarized as,

(1) Do nothing
(2) Reinstate to previous state
(3) Modify the existing design
(4) Develop new design

Once the Risk Assessment study is completed mitigation options have to be developed within the framework of Policy and Management Options with due consideration given to stakeholder consultations.

Over the last two decades the Intergovernmental Panel for Climate Change has presented a three pronged adaptive response strategy to combat sea level rise, namely,

1. Retreat
2. Accommodate
3. Protect

Many responses to sea level rise, which have to be adopted in the long term, are very similar to those required to address existing coastal area problems. Hence an integrated approach is strongly recommended when planning and responding to multiple coastal hazards. If considered in isolation, the effectiveness of such responses would be reduced mainly due to incompatible policies and/or actions taken by other coastal sectors.

It is important that post disaster planning should be undertaken in the context of overall coastal hazards one of which remains tsunamis. Although the chances of an extreme event such as that of the 26th December taking place is remote, the impacts of extreme events sets the agenda for strategic planning and location of key infrastructure. It is recognized that a Coastal Hazard Protection Plan for a city which is an integral part of an overall Coastal Zone Management Plan has to be based upon Policy and Management Options. These options reflect the strategic approach for achieving long term stability in particular for sustaining multiple uses of the coastal zone giving due consideration to the threats and risks of hazards.

7.3 Classification of Physical Interventions (Artificial and Natural)

In the light of the discussion in **Sections 7.1 and 7.2**, mitigation by physical interventions is classified into three types, depending on their location and function in protecting the coast. These interventions may be achieved by both artificial methods via coastal engineering design and also by harnessing the full potential of natural coastal ecosystems. The types of interventions and typical examples for each category are listed below.

(i) Reduce the impacts of tsunami waves prior to reaching the shoreline.
(eg. Tsunami Breakwaters, Coral Reefs)

(ii) Protect the coastal zone by preventing the inland movement of tsunami waves.
(*eg. Tsunami Dike, Sand Dunes*)

(iii) Mitigate the severe impacts of tsunami waves on entry to the shoreline.
(*eg. Tsunami Dikes, Revetment, Mangrove and Coastal Forests*)

On many occasions both methods can be adopted in parallel to develop well-integrated hybrid solutions satisfying environmental concerns.

7.4 Development of Guidelines for tsunami resistant buildings

The coast is an area of high economic activity and it is not possible to transfer all activities to areas that are completely free from potential tsunami hazards. For some areas of the coast, safe evacuation areas may be too far away for citizens to reach on foot thus necessitating vertical evacuation structures. Therefore there is a need to develop Design Guidelines and Construction Manuals for tsunami resistant housing and infrastructure for the benefit of the public and wider usage.

Given the background of discussion in the previous sections, two types of guidelines are required.

1) Overall Design Guidelines providing advice on location, layout, orientation, structural configuration, geo-technical considerations and other considerations relating to good design practice.

2) Detailed Design Guidelines leading to hydraulic and structural loads, geo-technical issues and detailed design information.

The Overall Design Guidelines could be developed from the experience gained from damage assessment from different parts of the country and such assessment should be analyzed in the context of the hydraulic regime which would have been generated by the tsunami at that location. In particular local effects which can enhance the impact of tsunamis have to be taken into consideration. Relevant information from other countries that have been affected by tsunamis is also be very useful for this exercise. It is important that damage assessment should cover infrastructure that was (i) destroyed (ii) damaged (iii) survived (least affected). Reference is made to Box 6 which was presented earlier.

Case Study for the Port City of Galle

Box 10- Risk Management- Hazard Mitigation and its integration with development projects

In 2000, Japanese Port Consultants (JPC) developed a Master Plan for the development of the Port of Galle. In view of critical environmental issues relating to the Galle Bay, including the presence of the historic Galle Fort (west side), buried archaeological sites (exceeding twenty) within the bay and the famous coral reef system (on the east side) it was recognized that the development should be restricted to a two berth medium size harbour. In order to maintain healthy exchange of tidal flow for the well being of the coral reef system, JPC in consultation with the environmental specialists incorporated an offshore detached breakwater, which coincidentally has all the characteristics of an effective tsunami breakwater (**see Figure 19**). It must be admitted tsunamis were not part of the agenda of the engineering and environmental terms at that stage, long before the Indian Ocean Tsunami impacted Sri Lanka.

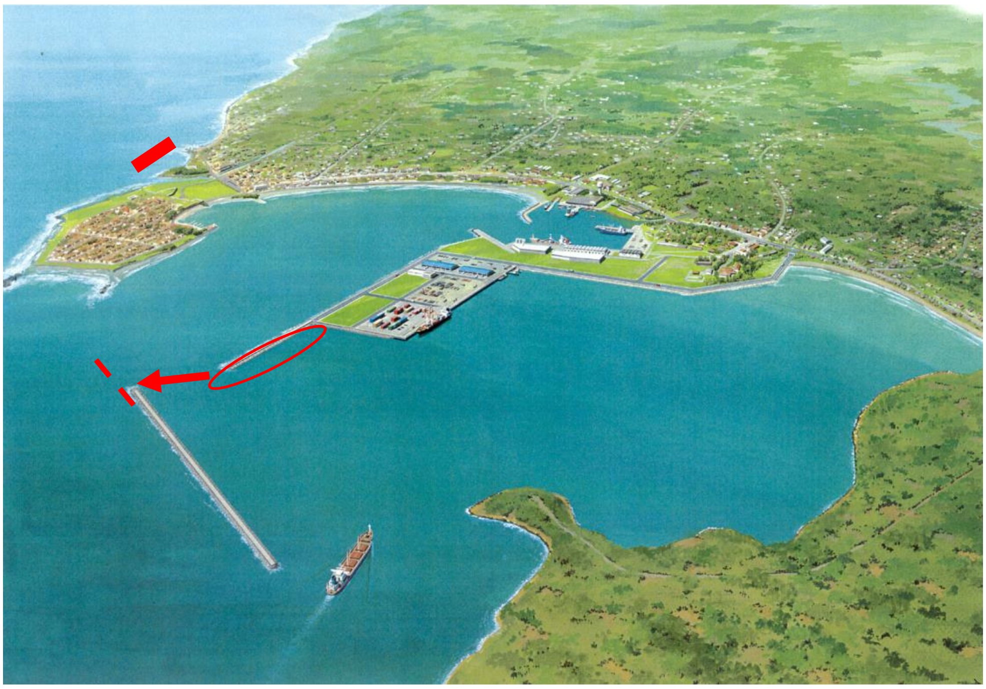

Figure 19: *Master Plan for the development of the Port of Galle*

On analyzing the damage aftermath of the Indian Ocean Tsunami, the proposed development of the Galle harbour and the use of the offshore breakwater were revisited. Through numerical modelling it was determined that by implementing this project with a slightly extended offshore breakwater in the direction of the Galle Fort, the City of Galle will have the benefit of a Tsunami Breakwater as part of a port development project. Considerable reduction of the inundation area could be achieved. Once this extension is designed it may be possible to reduce the length of the revetment protruding near the berth. The construction of a small offshore breakwater in front of the channel located west of the headland would provide additional protection.

Table 2 illustrates the breakdown in reduction in inundation area which can be achieved by the construction of the offshore breakwater for the Indian Ocean Tsunami scenario, as determined by modelling. Although the reduction in the inundation area is around 13%, considerable energy is dissipated as wave travel over the offshore breakwater thereby the destructive wave velocities are considerably reduced thus limiting potential damage. Inundation with lower velocities of flow will cause considerably less damage.

Rank of Inundation Depth	Simulated Inundation Area	
	Present Condition	After Galle New Port
0.0 - 1 m	259.3 ha	225.0 ha
1.0- 2 m	177.1 ha	196.7 ha
2.0 - 3 m	90.0 ha	67.6 ha
3.0 - 3.5 m	14.7 ha	10.4 ha
3.5 m above	14.0 ha	9.6 ha
Sub-total	555.3 ha	509.4 ha
Deduction (Reclamation of Galle New Port)		28.3 ha
Total	**(A) 555.3 ha**	**(B) 481.1 ha**
Change of Inundation Area		**74.2 ha** 13 % of (A)

Table 2 Reduction in inundation are achieved by the construction of the offshore breakwater for the Indian Ocean Tsunami scenario.

A protection wall (tsunami dyke) of modest proportions, along the coastline, can supplement the tsunami breakwater. The design details and the structural configurations can only be determined after carrying out mathematical modeling and physical modeling to assess the performance of the proposed configuration. A hybrid approach using both artificial and natural methods seems very appropriate for this situation. These are some of the physical mitigation measures which can be successfully adopted as feasible options for the protection of the city of Galle. These measures will also be effective against potential coastal hazards that have a greater probability of occurrence than an extreme tsunami wave event **(see Figure 20)**

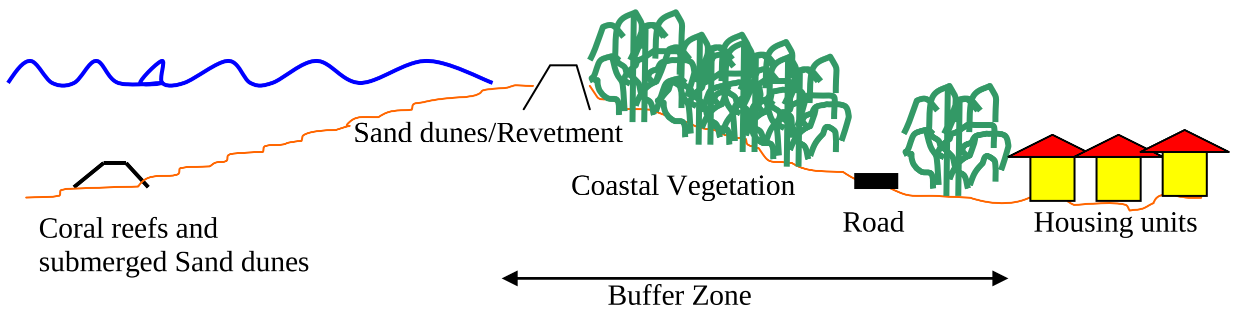

Figure 20: *Hybrid approach using both artificial and natural methods*

Case Study for the Port City of Galle
Box 11- Preparation of Disaster Management Maps

Based on the investigations described in **Boxes 5,7 and 9** and public consultations via meetings with officials of the government and non-government organisations, affected people and questionnaire surveys, Hazard, Vulnerability and Risk Assessment Maps were prepared. This was followed by the preparation of Disaster Management Maps. In this respect two maps were prepared, namely, Maps of safe places and buildings and Maps of Evacuation Routes and Sign Posts. These maps will be refined with further investigative studies and modeling work if necessary. The said maps are presented below in **Figures 21 and 22 (a), (b) and (c)**. The latter illustrates the implementation of sign posts which is considered very important in particular if there are people who are visiting or going through the city during a hazard event for which a warning has been issued.

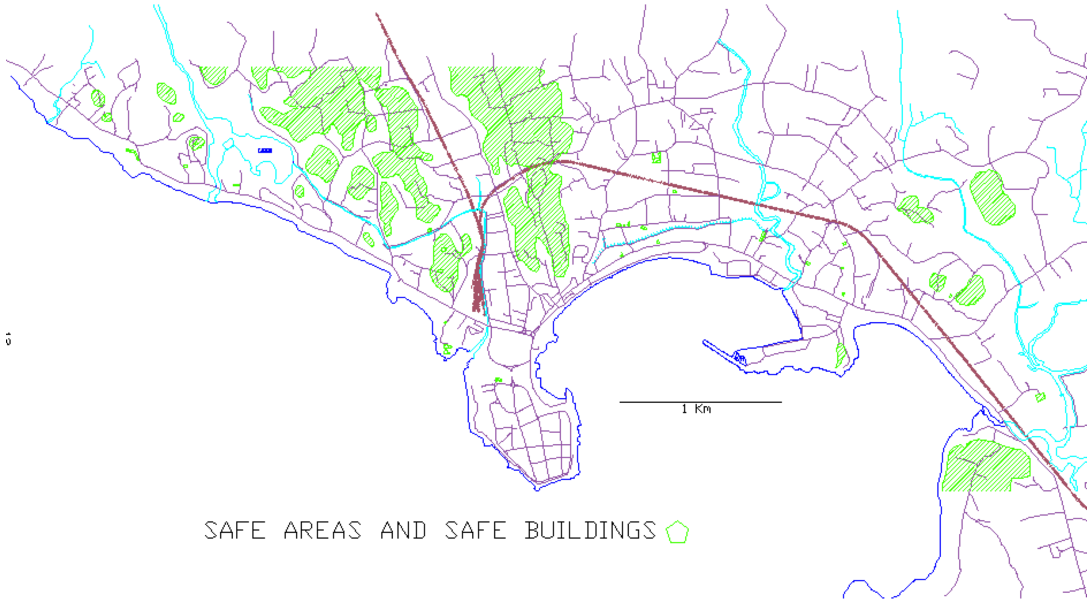

Figure 21: *Safe areas and safe buildings*

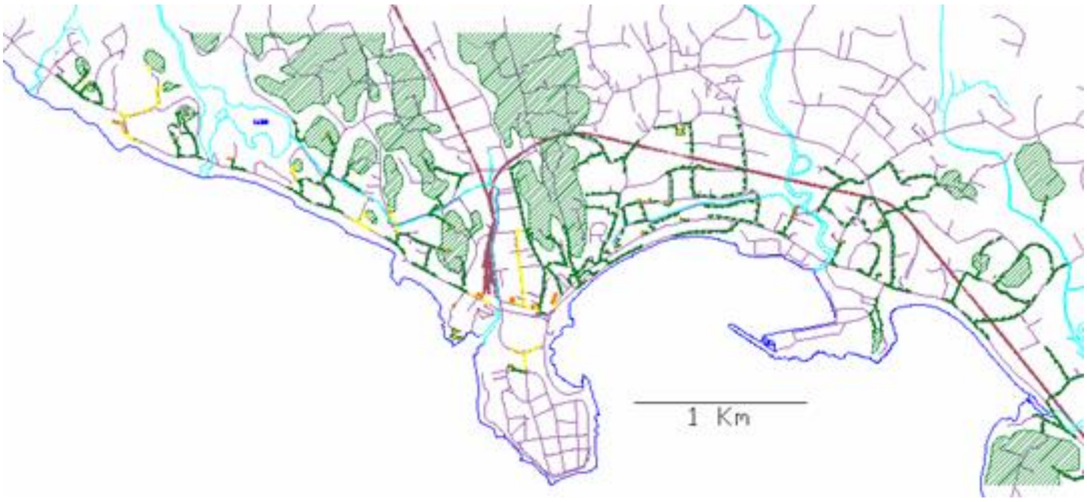

Figure 22(a): *Evacuation Places and Routes*

Figure 22(b): *Evacuation Places and Routes*

Figure 22(c): *Evacuation Places and Routes*

8. Tsunami Risk Assessment within a tsunami forecasting and early warning framework

8.1 Tsunami Warning Systems and their classification

A Tsunami Warning System must alert all persons on every vulnerable coast of imminent danger, covered by the system. The response of such a system must be rapid (as soon as possible), accurate (minimize false warning), reliable (continuous operation), effective (to save lives). UN-ISDR Framework for effective Early Warning Systems encompasses four critical linked elements **(Figure 23).**

- Detection, Monitoring and Warning Service (Technical Monitoring and Warning Service)
- Risk Knowledge (Awareness of the Risk)
- Dissemination and Communication (Dissemination of meaningful warnings to Persons and Communities at Risk)
- Response Capability (Public Awareness and Preparedness to Respond)

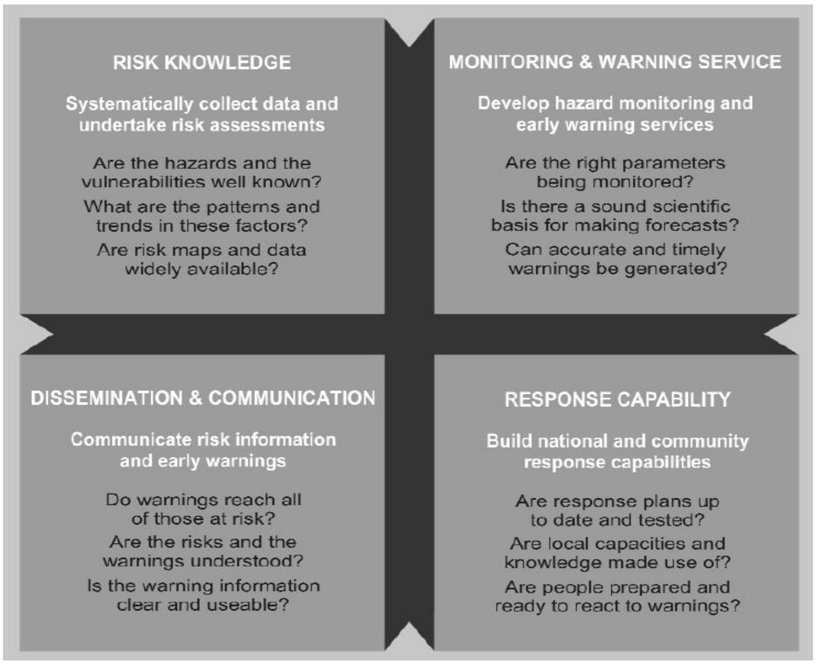

Figure 23: UN-ISDR Framework for effective Early Warning Systems

The detection of hazard in a tsunami early warning system can be broadly classified into three categories, namely, Minimal, Standard and Advanced. In the Minimal System warning is based on earthquake detection only. Standard System includes tsunami detection followed by earthquake detection using ocean based equipment. In an Advanced System, earthquake detection and tsunami detection are followed by tsunami forecasting. The latter has been successfully adopted by the Pacific Tsunami Warning System. NOAA has researched this subject in great detail. The advanced system requires the computation and storage of large amount of scenarios of tsunami hazard sources and the corresponding inundation of exposed areas on land served by the warning center. This information should be accessed easily when an earthquake having the potential of generating a tsunami takes place. On the strength and location of the earthquake the relevant potential scenarios are identified and then compared with sea level data from buoys and tide gauges as soon as such information is available from the sea level monitoring instrument network. Through a process of inversion, the tsunami source is refined thus acquiring a clear understanding of the actual tsunami generated.

8.2 Forecasting from the Indian Ocean Tsunami Warning System

The Indian Ocean Tsunami Warning System (IOTWS) is a coordinated network of country systems in which each country will be responsible for identifying the hazard, assessing its risk and issuing the warning to its population. In this respect the member states will be assisted by Regional Tsunami Service Providers (RTSPs) who will be monitoring the ocean basin wide hazard through seismic and sea level monitoring networks, extract information from the database of tsunami scenarios, run forecasting models and provide advisories to the National Tsunami Warning Centers (NTWCs) of member states. The information is presented on a predetermined format known to the NTWCs of the member states. India, Indonesia and Australia serve as RTSPs and the member states can receive information from theses three providers. Obviously the three service providers issue advisories on the same format using the same template and format. Details of the Indian Ocean Tsunami Warning System are described by **Ryan (2014).**

When a tsunami occurs the damaging waves are not uniformly distributed around the coasts of the Indian Ocean or even across a single country. There is a wide variation in the tsunami wave heights even over short distances of the order of 5-10 km. Some locations will experience destructive waves while others will see very small sea-level anomalies or none at all. For purpose of hazard assessment and provision of advisories the Indian Ocean coastline is classified into zones, namely, Coastal Forecasting Zones (CFZs). This classification is based on the division of all of the coasts around and in the Indian Ocean into zones which average about 100 km long and extend 50 km seaward from the coast. Accordingly, each coastal forecast zone is represented by a rectangular box extending 100 km in length (along the coast) and 50 km in width (across the coast). The box starts from the 30 m bathymetry line to ensure that there are sufficient numbers of undersea grid-points in the model simulations of different RTSPs. The results of the model simulations within the 100 x 50 km boxes are then extrapolated to the adjacent coasts to provide tsunami wave forecasts. **Figures 24 and 25** provide a clear outline of a Coastal Forecast Zone (CFZ) used by the RTSPs.

A recent development in the IOTWS has been to refine the coastal zones to match administrative boundaries as an aid to local warning formulation. These CFZs are used by all of the RTSPs to describe the geographical extent of a tsunami hazard.

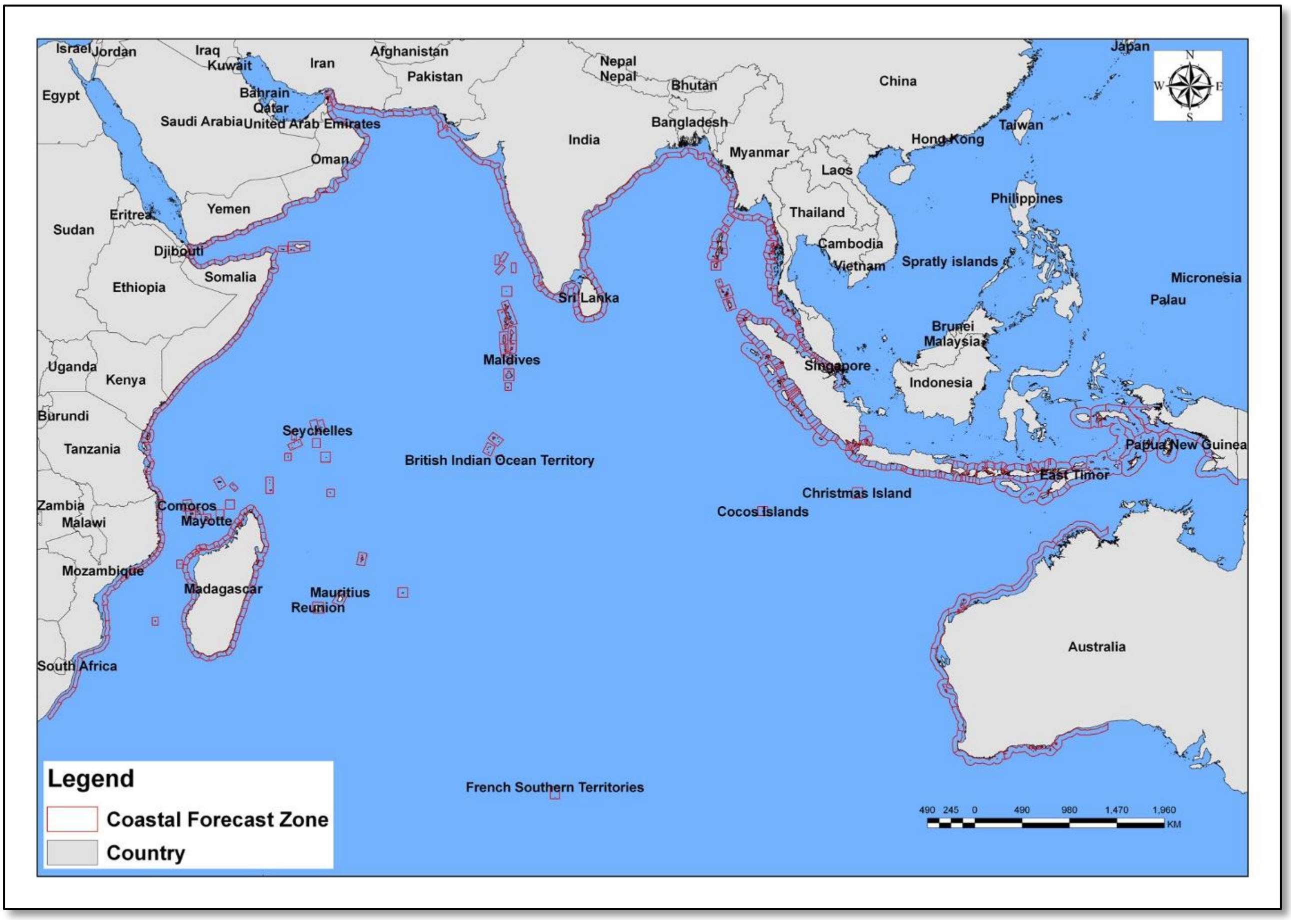

Figure 24: Coastal Forecast Zone Map

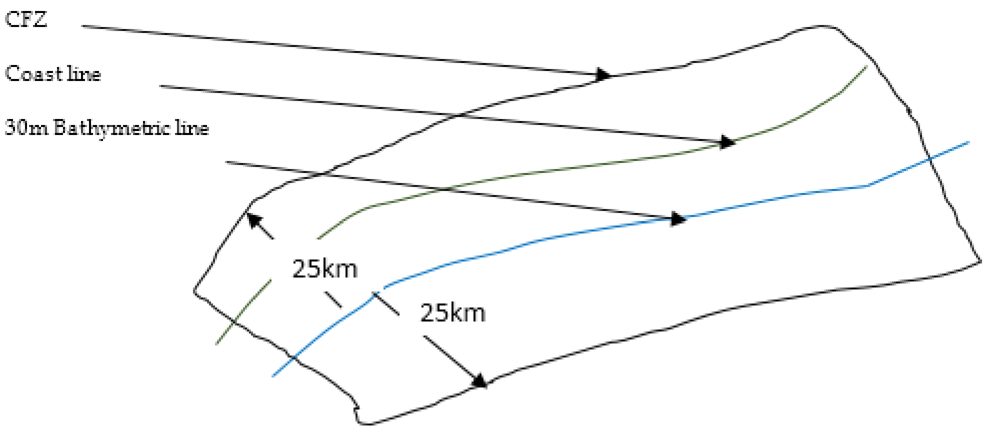

Figure 25: A Coastal Forecast Zone

The RTSPs employ similar tsunami forecasting methodologies, but there are differences in the details of the models, analysis and overall processes used. The common core of the forecasting approach is to pre-calculate ocean-wide tsunami characteristics in deep water (20-30 metre depth or greater) for a large number of earthquake scenarios, using an oceanographic model based on hydrodynamics and bathymetric data. From the model's grid of forecast tsunami parameters, RTSP will provide representative values, such as tsunami arrival time and maximum tsunami amplitude. In the case of the IOTWS, for each Coastal Forecast Zone (CFZ) the RTSPs will provide this information for single point at a depth of 30m. The single value represents a conservative value based on the results computed for a number of forecasting points within the given CFZ.

Within the bounds of the common methodology just described, the RTSPs differ in many technical details of their forecasting process, such as:

- the location and spacing of earthquake scenarios on which the data bases of model forecasts are based
- the assumptions about earthquake rupture geometry and energy transfer to the ocean
- the method of selecting representative values for each forecast zone.

The data bases of earthquake scenarios used by the RTSPs are composed of many model runs based at a large number of likely earthquake locations. At each location it is necessary to carry out several model runs, each at a different earthquake magnitude, so that when a real earthquake occurs a scenario which closely matches the observed location and magnitude can be selected.

When a significant earthquake occurs, based on the initial assessment of seismic data, each RTSP selects from the data base of pre-calculated scenarios, a number of possible scenarios which may match the real earthquake.

Having done this the initial selection RTSPs can adopt the following methods.

1) Seismic information presented in the latest update together with the expertise of specialized personnel are utilized to select the most likely scenario and uses the forecast data from that run of the model scenario in its advice to the (NTWCs). Sea-level monitoring networks are then used to confirm that a tsunami was generated and to assess the accuracy of the model predictions.

2) Sea-level observation network are utilized to compare the wave amplitudes with their model predictions and refine the tsunami hazard source. The models are designed for deep water (greater than 20 to 30 metres depth), so tsunameters located well away from coastal shallow waters provide the most reliable comparisons with the model predictions. Thereafter it is possible to "invert" the tsunami model, using observed wave amplitudes to calculate the magnitude of the generating earthquake. This method could be used to correct the magnitude determined by seismic measurements, but is not currently used operationally by the RTSPs. However, a quick, simplified method of comparing tsunameter observations with model predictions and adjusting earthquake magnitude is employed in some of the RTSPs. Using this method, deep-water sea-level measurements can result in real-time adjustment of the coastal zones forecast to be under threat.

Thereafter the RTSPs determine the threat on the coast by extrapolating from the deep water model predictions (at 30 m) to 1 meter depth at the shoreline, assuming a uniform slope from 30 m depth to the shoreline and by using Green's law. This predicted wave height at 1 m depth is referred to as the 'RTSP estimate' of the wave height at 1 m depth. A threat is deemed to exist in any zone if tsunami waves of 50 cm or more positive amplitude are forecast to occur at the beach (1 meter water depth).

The extrapolation of wave amplitude from deep to shallow water is an approximation based on simplifying assumptions on the slope of the sea floor and the orientation of the coast. All centers use the Green's Law approximation for this crucial step, and National Tsunami Warning Centers NTWCs should be aware of the inaccuracies which are likely to result and appropriate measures adopted to correct for any underestimation of wave height at the coastline.

A more refined and accurate approach would be to make use of a database of inundation scenarios for a wide range of tsunami wave heights and select the appropriate scenario for the hazard situation under consideration. Coastal inundation models can be coupled to the broad scale deep-water models to produce detailed coastal wave forecasts. In this approach, the inundation scenario corresponding to the actual tsunami is identified from the database and is then used for public warning. For this purpose, large data bases on inundation modeling have to be prepared, archived and accessed during a hazard event.

Implementing detailed inundation modelling along a full length of coastline is a difficult task requiring high resolution bathymetry, topography and considerable computing power. The preparation of data bases is time consuming. Due to the time required for detailed inundation modeling the use of pre-computed data-bases becomes essential for this approach to be adopted. During early warning for a hazard event there is no time available to run inundation models to provide accurate forecasting on the shoreline.

It is best that such data bases be developed for high risk cities and regions as identified from risk assessment studies. Detailed inundation modeling is a prerequisite for risk assessment and therefore this approach provides an opportunity to integrate early warning with risk assessment. The availability of reliable inundation data (hazard data) along with the tsunami information will certainly save lives and is of vital importance for human safety.

Generally this is not practical at the present stage of development for the RTSPs. However, it is expected that in the future through collaboaration with national warning centers this can become part of the RTSP real-time service.

8.3 Tsunami risk assessment within a tsunami forecasting and early warning framework.

With the establishment of the IOTWS it is relevant to focus on risk assessment within a tsunami forecasting and early warning framework. It is possible to establish within such a framework a capability that serves, real time operational needs, hazard /risk assessment needs and research/ development opportunities through the use of a standard tsunami forecast system that includes tsunami characterization, measurements and forecast models illustrated in **Figure 26**. This concept was identified by Dr.Eddie Bernard, formerly of the PMEL, NOAA, Seattle, USA.

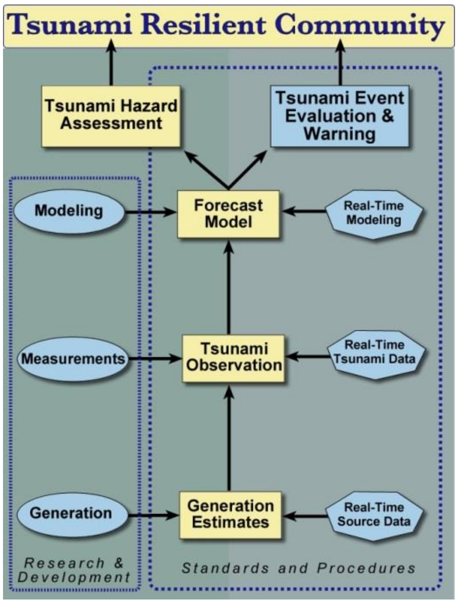

Figure 26: Risk assessment within a tsunami forecasting and early warning framework (after Eddie Bernard, NOAA)

In summary, a capability can be developed to serve

- Real-time operational needs (event based)
- Hazard/Risk Assessment needs (strategic risk)
- Research and Development opportunities

while operating within a Tsunami Forecasting Framework and through the use of a standardized tsunami forecast system including

- tsunami source characterization,
- tsunami measurements, and
- tsunami forecast models

The tsunami forecast system would have **two** immediate applications:

1. Real-time operational forecasts of tsunami arrival time, tsunami amplitude over time for 12 hours, maximum wave height, and inundation areas
2. Long term assessments of hypothetical tsunamis based on plausible tsunami sources for a particular area. Such assessment could be used for Risk Assessment and for the production of tools such as disaster management maps.

While shallow water wave amplitude is being forecast by extrapolation from deep-water modeling, the effect of small coastal features such as headlands, bays and sand-bars cannot be quantified in RTSP products. These features can introduce significant variations in the observed tsunami wave amplitude and run-up within a single coastal forecast zone. There is considerable scope for national agencies to add value to the RTSP service by carrying out high-resolution inundation modeling for risk analyses for critical or vulnerable coastal zones.

All RTSPs have developed data bases for the source scenarios which are accessed during an event by the RTSPs and operated within the common template of the CFZs for tsunami forecasting. For tsunami risk assessment of region or city, it is customary to model different scenarios from deep water to inundation. For establishing a strong link between short term forecasting (early warning for events) and long term forecasting (strategic risk assessment) it would be advantageous to conduct risk assessment within the template of CFZs adopted by RTSPs. This will enable both short term and long term forecasting to be expedited and implemented very efficiently, in particular, to provide reliable early warning, strategic risk management and increased preparedness. This approach provides a platform for the integration of short and long term forecasting.

Consider for example, a CFZ of 100 km divided into 10 sub units each of 10 km length for convenience **(Figure 27)**. A typical risk assessment study for a city would cover a coastline varying from 10-50 km and therefore falls within a single CFZ (of 100 km).

Let us assume that a city of high vulnerability having a coastal front of 10 km is located anywhere within the CFZ (any of the 10 km stretches in **Figure 27**). Tsunami early warning for the entire CFZ is given by the transfer of the single wave height value at 30 m to 1m depth assuming uniform slope and wave shoaling. However, in reality there may not be a uniform slope and the city may be located within a bay (inset A), a headland (inset B), on the banks of an estuary (inset C) or behind a harbour (inset D). It can be expected that the tsunami wave heights for the first three cases would be increased due to enhanced exposure and for the latter decreased due to the protection afforded by the breakwaters of the harbour. On the other hand tsunami wave heights may be less due to near shore frictional and other damping effects such as reefs. Such dissipation is even more affective if the tsunami strikes during low tide, as observed offshore of the Kenyan coastline for the Indian Ocean Tsunami in 2004. If the city concerned is of high risk then it is necessary to have a refined wave height at 1m depth for the coastal front of the city. This could only be done by conducting detailed modelling taking into account near shore bathymetry and geometric variations at the coast. The refined wave height obtained can be used for mathematical modelling for inundation. By comparing the wave heights at 1m depth obtained from the 'RTSP estimate' and from refined modelling, it is possible to assess whether there is a significant difference which would matter in the event of hazardous event.

It is expected that if the city is heavily exposed and of high vulnerability, conducting risk assessment within tsunami forecasting and early warning framework will enable those who are engaged in disaster risk reduction to make assessment in a very efficient manner and responding very positively to hazardous events. This will strengthen the cooperation between the national warning centres and those engaged in risk assessment.

In summary it is very advantageous to have risk assessment and early warning carried out on a common template and the CFZ concept of RTSPs offer this platform. On either side of the 30 m depth deepwater modelling and near shore modeling would be undertaken. Both early warning and risk assessment require data bases of hazard scenarios and they also require wave height prediction on the coast which is done as an ‘estimate’ by RTSPs for early warning and via ‘more refined techniques’ for risk assessment. Wave height forecasting on the shoreline adopted by the RTSPs refer to a simplified approach of transfer of wave height based on uniform slope, where as for risk assessment detailed modelling is done. Both can be done on the CFZ concept thereby complementing each other. This approach provides an excellent cross reference and above all strong awareness of approaches adopted RTSP thus educating a wider stakeholder base on the said approach. In effect, the seismic hazard data bases of the RTSPs can be used to determine deep water wave height at 20-30 m depth for both early warning and risk assessment. For cities and regions found to be at a high risk, it is advisable to maintain data bases of inundation modeling and during a hazardous event the scenario corresponding to the actual tsunami is identified from the said data bases and used for public warning.

The relevant details of this process can be examined via a case study illustrated below for a coastal city in which tsunami risk assessment is undertaken within a tsunami forecasting framework.

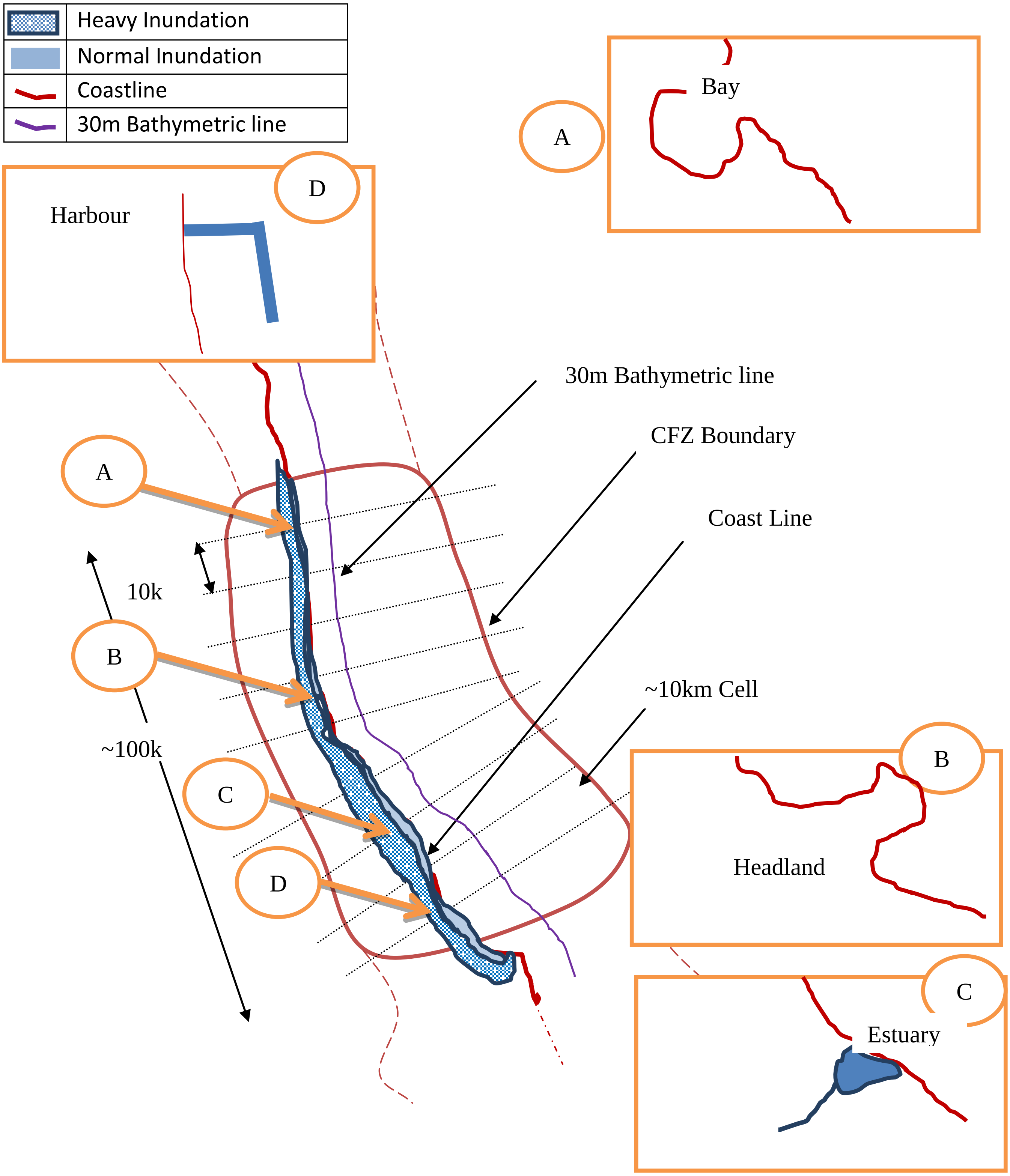

Figure 27: Coastal forecasting zone with typical shoreline features

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Case Study for the Port City of Galle

Box 12- Improved Tsunami Wave Height forecasting-An integrated approach for the analysis of results from early warning systems and inundation modeling for risk assessment

A case study on the above subject was carried out for the Port City of Galle and the outcome is presented in a detailed report (**Hettiarachchi, Samarasekera and Ratnasooriya 2015)**. A summary of the case study is presented below and it illustrates,

- the use of scenario modeling for long term forecasting and strategic risk assessment within the framework of coastal forecasting zones adopted by the Regional Tsunami Service Providers (RTSPs) of the Indian Ocean Tsunami Warning System
- the differences between forecasting from RTSPs and detailed modeling for risk assessment and
- some of the critical issues relating to the interpretation of the technical early warning issued by the RTSPs and its transformation to a public warning for the benefit of the coastal population

Galle CFZ consists of six coastal forecast points as illustrated in following **Figure 28**. The latitude and longitude of these points are given in **Table 3**. As an example, the maximum wave height forecasted by INCOIS for the Indian Ocean Tsunami at 30m bathymetric line for the said CFZ was 3.1m which is also shown in **Figure 28** along with the wave heights at other forecasting points. An image of the Galle Bay is given in **Figure 29.**

CFP_ID	Latitude	Longitude	Region
1	6.050185	79.959702	HIKKADUWA
2	6.311199	79.966026	KOSGODA
3	6.172561	80.004524	TELWATTA GANGA
4	6.224144	80.008614	AMBALANGODA
5	5.984229	80.202583	GALLE
6	5.976019	80.245842	UNAWATUNA BEACH GALLE

Table 3: Coastal Forecast Points in Galle CFZ

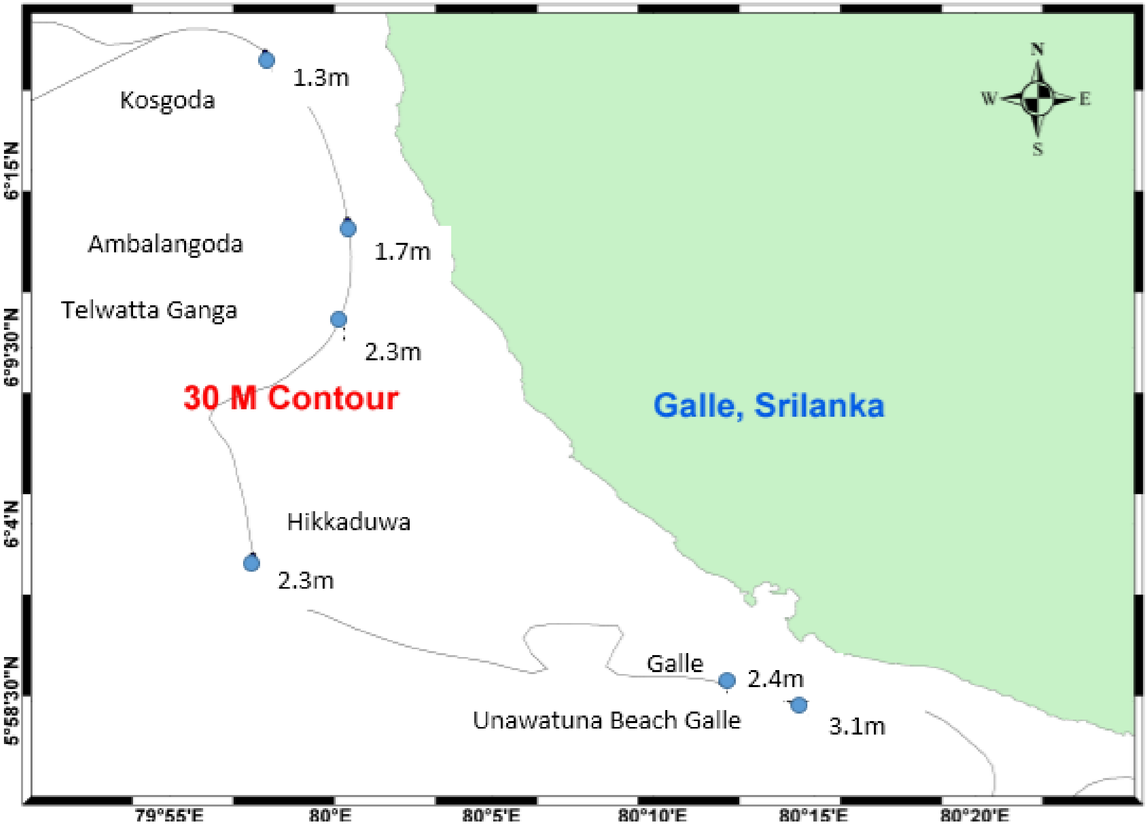


Figure 28: Coastal Forecast Points in Galle CFZ

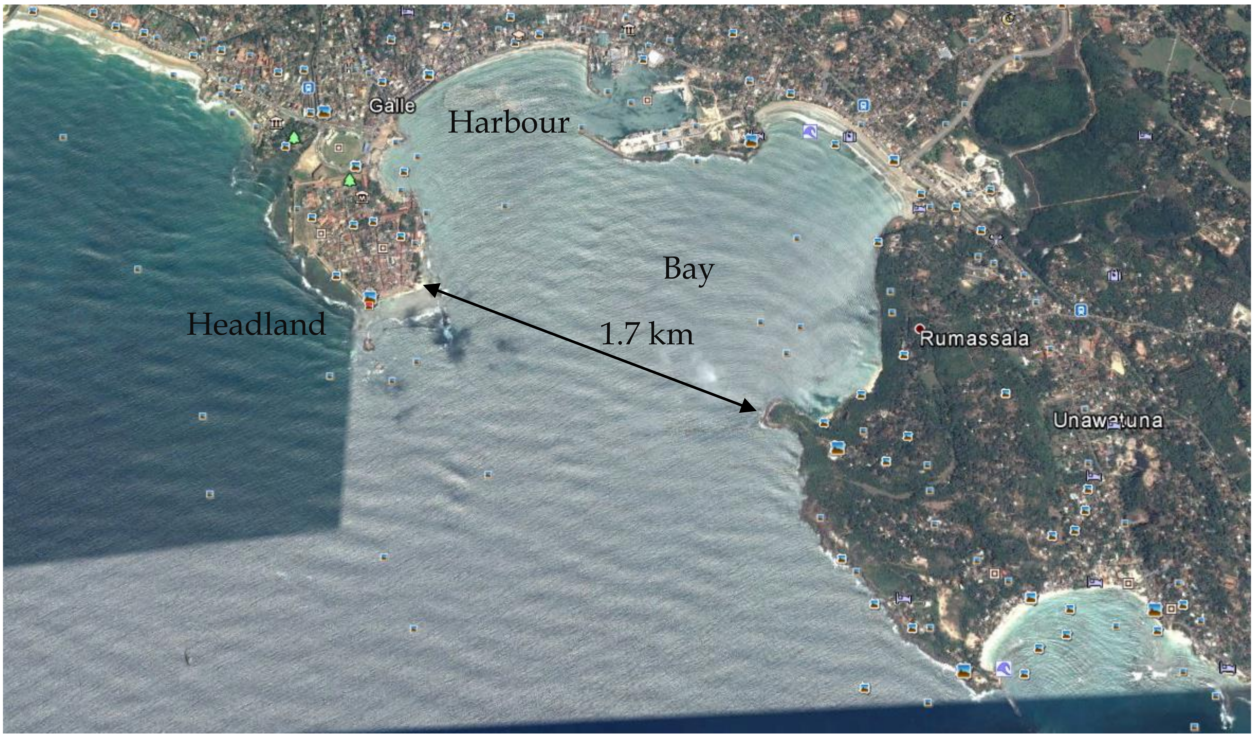
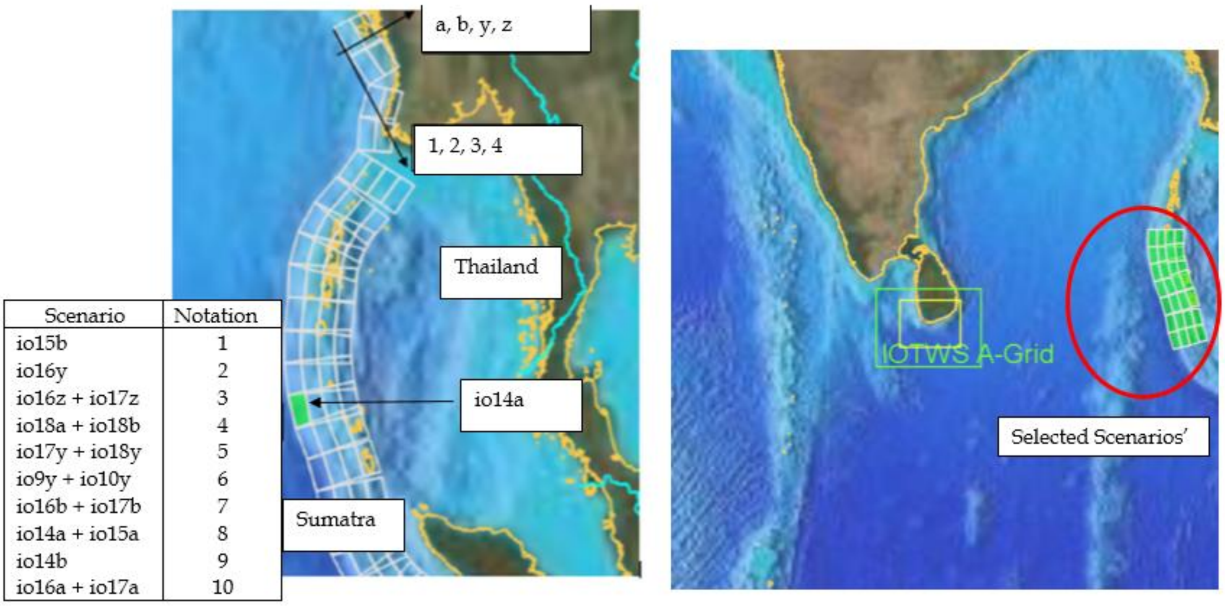


Figure 29: Google Image of the Port City of Galle

It is essential to run an inundation model considering linear momentum flux using very high resolution to obtain accurate wave heights at the beach. The application of the Green's law is inadequate for both tsunami early warning forecasting and risk assessment for cities having complex geometrical boundaries.

The ComMIT numerical model was applied in 1 arc second resolution in finite different method for a 21 scenarios including an earthquake near Indian Ocean Tsunami of 2004 and earthquakes of M_W = 8.2 and 7.8. The scenarios 1 to 10 in the case of earthquakes M_W = 7.8 and 8.2 were selected in accordance to the ComMIT source parameter selection methodology. **Figure 30** illustrates the location of the hazard sources.



Scenario	Notation
io15b	1
io16y	2
io16z + io17z	3
io18a + io18b	4
io17y + io18y	5
io9y + io10y	6
io16b + io17b	7
io14a + io15a	8
io14b	9
io16a + io17a	10

Figure 30: Hazard scenarios for the case study

Table 4 illustrates the results obtained by using the ComMIT model at a depth of 1 m at 5 points, P1, P2, P3, P4 and P5 illustrated in **Figure 31**. A comparison of the results for the different scenarios is given in **Figure 32**. The table also provides a comparison between the prediction by detailed inundation modeling and application of Green's Law assuming uniform slope.

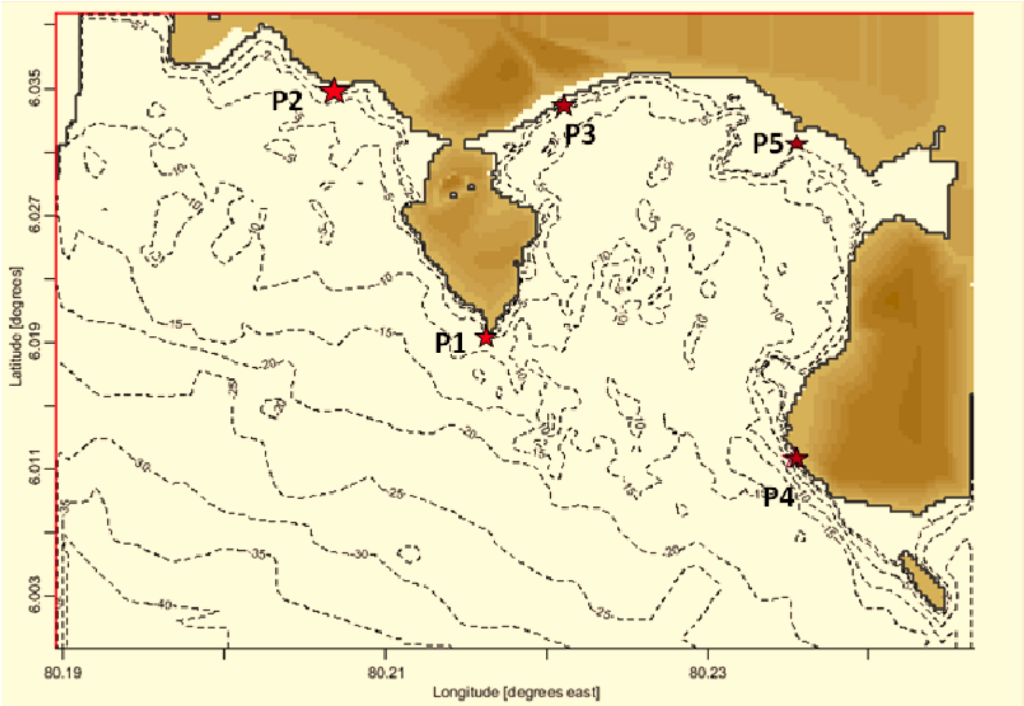


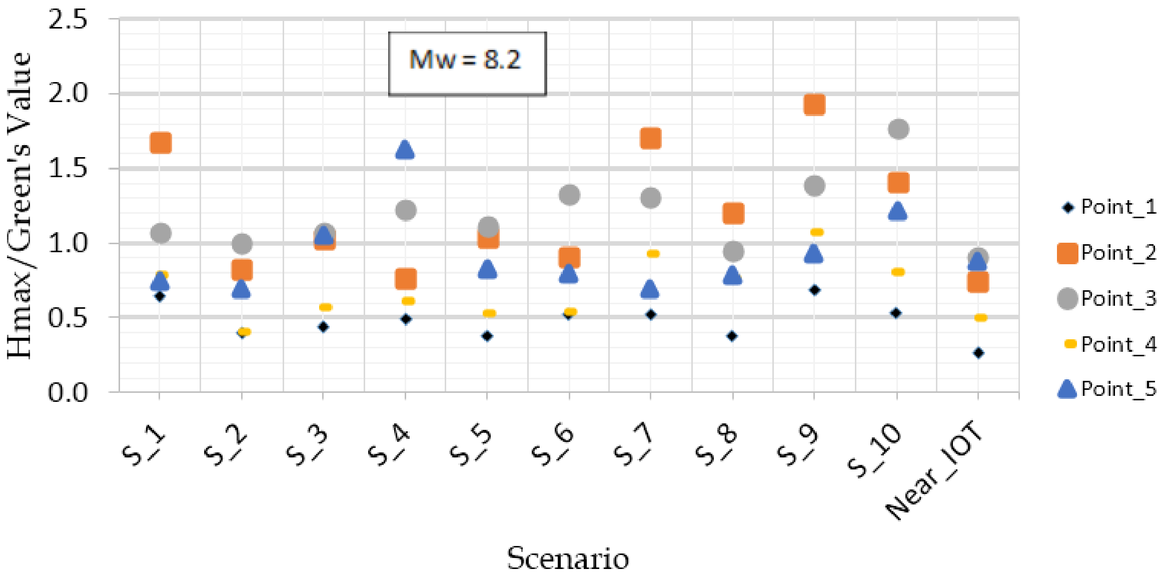
Figure 31: Selected Points in Coast in Galle CFZ

The ratio of prediction 'Hmax (inundation model)/H Green's Law' equals or exceeds 1.5 on nine occasions for point P2, five occasions for point P3 and four occasions for P5. Three points are primarily points within the bays. P2 in particular has displayed high ratios. In the case of points P1 and P4, which correspond to points at the headlands the ratio is less than 1, on all occasions apart from two exceptions at P4. This may be due to energy energy dissipation arising from a combination of the shallow water depths together with rock and coral outcrops present around the headlands. Resistance from such features can reduce the wave heights by energy dissipation and will not permit the usual increase in wave heights associated as tsunami waves enter shallow waters.

To summarise, the results from 21 tsunami hazard scenarios for 5 locations leading to 105 data points on the coast have been presented. Three points were within a bay and two points adjoin headlands. For a perfect agreement, the ratio of prediction should be unity.

		H_30m/cm	H_1m/cm										Green's Value
			P1		P2		P3		P4		P5		
Magnitude	Scenario	Max	Max	Hmax/Green's Value	Max	Hmax/Green's Value	Max	Hmax/Green's Value	Max	Hmax/Green's Value	Max	Hmax/Green's Value	Max
9.2	Near_IOT	200	122	0.3	347	0.7	426	0.9	228	0.5	412	0.9	468
7.8	S_1	11	17	0.7	50	1.9	34	1.3	24	0.9	29	1.1	26
	S_2	10	15	0.7	30	1.3	34	1.5	17	0.7	25	1.1	23
	S_3	8	14	0.8	24	1.3	28	1.6	16	0.9	27	1.5	18
	S_4	5	6	0.5	17	1.5	13	1.2	5	0.5	17	1.6	11
	S_5	9	14	0.6	33	1.5	34	1.6	16	0.7	28	1.3	22
	S_6	1	1	0.6	2	0.8	3	1.4	1	0.6	4	1.6	2
	S_7	9	8	0.4	35	1.7	22	1.1	14	0.7	19	0.9	21
	S_8	12	20	0.7	44	1.5	37	1.3	23	0.8	32	1.1	28
	S_9	6	10	0.7	37	2.5	23	1.6	16	1.1	22	1.5	15
	S_10	11	12	0.5	33	1.3	31	1.3	17	0.7	31	1.3	25
8.2	S_1	42	64	0.6	166	1.7	106	1.1	77	0.8	74	0.7	99
	S_2	51	48	0.4	98	0.8	119	1.0	47	0.4	82	0.7	119
	S_3	41	41	0.4	99	1.0	102	1.1	54	0.6	101	1.1	95
	S_4	16	18	0.5	29	0.8	45	1.2	22	0.6	60	1.6	37
	S_5	46	42	0.4	112	1.0	119	1.1	56	0.5	89	0.8	108
	S_6	4	5	0.5	8	0.9	12	1.3	5	0.5	7	0.8	9
	S_7	26	31	0.5	103	1.7	79	1.3	56	0.9	42	0.7	60
	S_8	52	46	0.4	146	1.2	115	0.9	93	0.8	95	0.8	122
	S_9	22	35	0.7	99	1.9	71	1.4	54	1.1	48	0.9	51
	S_10	34	42	0.5	113	1.4	142	1.8	65	0.8	98	1.2	80

Table 4: Wave height variation - (Linear Momentum Flux vs. Green's Law)



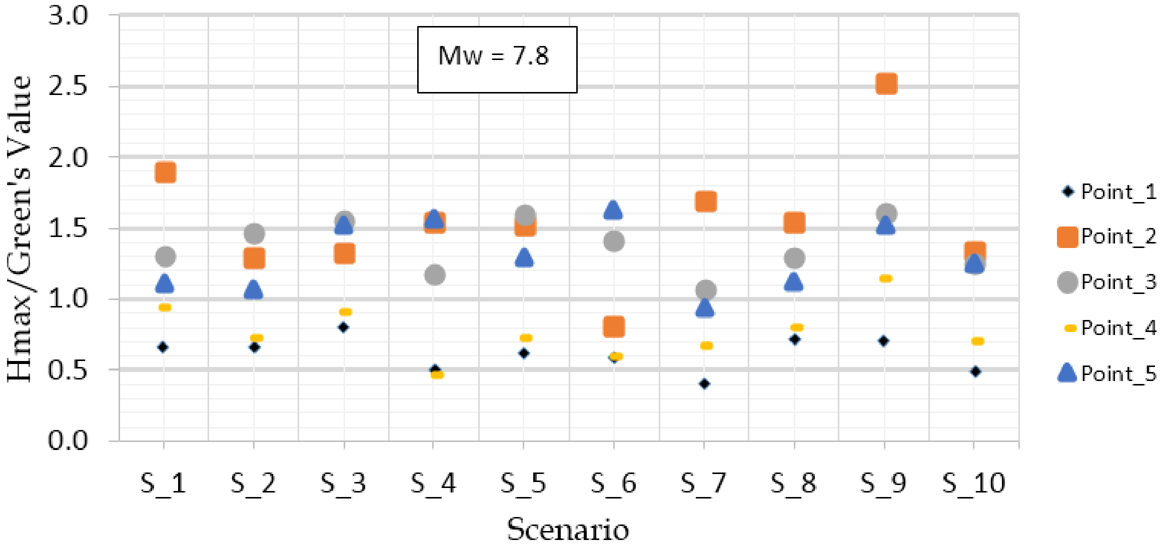


Figure 32: Comparison of results from the application of Green's Law and Linear Momentum Flux

On examining the variation for scenarios for all three moment magnitudes (**Table 4** and **Figure 32**), on 37 occasions (35% of all data points) the variation of the ratio of prediction is within the range plus or minus 20%. On 36 occasions (34% of data all points) the ratio is below 20%. In this category all 31 occasions refer to Points P1 and P4 which are adjoining headlands. Although headlands are expected to focus energy, it seems that in the case of Galle there has been energy dissipation which can be accounted by shallow depths, rock out crops and coral reef systems (particularly with respect to P4). On 30 occasions (29% of all data points) the ratio is above 20%. In this category 24 occasions refer to Points P2 and P3 which are within bays. The highest value of the ratio is 2.5. This study has confirmed that within a bay, tsunami wave heights can increase as much twice to that corresponding to straight and uniform slope shoreline which is assumed under Green's Law. The study has identified the importance of energy focusing along shorelines on varying geometry and the need to engage in inundation modeling and prepare data bases for cities at high risk along such coastlines. Such data bases can be accessed during a tsunami hazard event and leading to a refined forecasting on the shoreline thus ensuring human safety and saving lives.

9. Resilient Cities

9.1 Disaster resilient cities

Cities and urban areas are becoming increasingly vulnerable to disasters due to various reasons. One of the major challenges for cities is the rapid growth of urban population and population density. As a result of rapid urbanisation, the world's population is increasingly concentrated in large cities with poor housing and lack of basic protective infrastructure **(Red Cross, 2010; UN-ISDR, 2010a).** A high population growth is visible in many urban areas which has increased the pressure on land and other essential services such as drainage systems, waste management etc. Due to the high demand for lands in cities, many poor constructions are witnessed in marginal land, floodplains, sloping lands, and reclaimed land which are unsuitable for human settlements. These improper land-use practices have increased the risk of disasters. All these in combination with unplanned development have made cities extremely vulnerable to natural disasters.

Weak urban governance has also placed cities at high risk **(UN-ISDR, 2010b)**. Financial and resource capacities of many local governments are rather poor and would adversely affect disaster response capacities. Most of the local governments are not self-sufficient and has to rely on national government and external agencies during emergencies. On the other hand participation of local stakeholders and community is comparatively low and uncoordinated emergency response services affect the swift response and preparedness **(UN-ISDR, 2012).**

A resilient city is defined as "a city that has developed the systems and capacities to be able to absorb future shocks and stresses over time so as to still maintain essentially the same functions, structure, systems, and identity, while at the same time working to mitigate the present causes of future shocks and stresses" **(RecilientCity.org 2010).** Accordingly, when a disaster occurs in a disaster resilient city, the effects to the physical systems and human communities would be minimal**. UN-ISDR (2010a)** has identified the following parameters of a disaster resilient city.

- Is one where disasters are minimised because the population lives in homes and neighbourhoods with organized services and infrastructure that adhere to sensible building codes; without informal settlements built on flood plains or steep slopes because no other land is available.
- Has an inclusive, competent and accountable local government that is concerned about sustainable urbanization and that commits the necessary resources to develop capacities to manage and organize itself before, during and after a natural hazard event.
- Is one where the local authorities and the population understand their risks and develop a shared, local information base on disaster losses, hazards and risks, including who is exposed and who is vulnerable.
- Is one where people are empowered to participate, decide and plan their city together with local authorities and value local and indigenous knowledge, capacities and resources.
- Has taken steps to anticipate and mitigate the impact of disasters, incorporating monitoring and early warning technologies to protect infrastructure, community

assets and individuals, including their homes and possessions, cultural heritage, environmental and economic capital, and is able to minimize physical and social losses arising from extreme weather events, earthquakes or other natural or human-induced hazards.

- Is able to respond, implement immediate recovery strategies and quickly restore basic services to resume social, institutional and economic activity after such an event.
- Understands that most of the above is also central to building resilience to adverse environmental changes, including climate change, in addition to reducing greenhouse gas emissions.

The above parameters can be used as a framework to assess the level of resilience of a city and has provided opportunities for city leaders to contribute towards making their city resilient to disasters.

9.2 Introduction to UN-ISDR campaign on making cities resilient

The "Making Cities Resilient: My City is Getting Ready" was a campaign launched by UN-ISDR in 2010 to address important issues relating to local governance and urban risks. The campaign aims at achieving resilient and sustainable urban communities and insists local governments to act effectively in order to reduce the risk of disasters to cities. After successful implementation of the First Phase in 2011 the campaign has now entered the Second Phase 2012-2015.

This campaign has developed 'ten essentials' for local governments to make their cities more disaster resilient and they are listed below **(UN-ISDR, 2012).**

- **Essential 1:** Institutional and Administrative Framework - Put in place organization and coordination to understand and reduce disaster risk, based on participation of citizen groups and civil society. Build local alliances. Ensure that all departments understand their role to disaster risk reduction and preparedness.
- **Essential 2:** Financing and Resources - Assign a budget for disaster risk reduction and provide incentives for homeowners, low-income families, communities, businesses and public sector to invest in reducing the risks they face.
- **Essential 3:** Multi-hazard Risk Assessment- Know your Risk - Maintain up-to-date data on hazards and vulnerabilities, prepare risk assessments and use these as the basis for urban development plans and decisions. Ensure that this information and the plans for your city's resilience are readily available to the public and fully discussed with them.
- **Essential 4:** Infrastructure Protection, Upgrading and Resilience - Invest in and maintain critical infrastructure that reduces risk, such as flood drainage, adjusted where needed to cope with climate change.
- **Essential 5:** Protect Vital Facilities: Education and Health - Assess the safety of all schools and health facilities and upgrade these as necessary.
- **Essential 6:** Building Regulations and Land Use Planning - Apply and enforce realistic, risk compliant building regulations and land use planning principles. Identify safe land for low-income citizens and develop upgrading of informal settlements, wherever feasible.

- **Essential 7:** Training, Education and Public Awareness - Ensure education programmes and training on disaster risk reduction are in place in schools and local communities.
- **Essential 8:** Environmental Protection and Strengthening of Ecosystems - Protect ecosystems and natural buffers to mitigate floods, storm surges and other hazards to which your city may be vulnerable. Adapt to climate change by building on good risk reduction practices.
- **Essential 9:** Effective Preparedness, Early Warning and Response - Install early warning systems and emergency management capacities in your city and hold regular public preparedness drills.
- **Essential 10:** Recovery and Rebuilding Communities - After any disaster, ensure that the needs of the survivors are placed at the centre of reconstruction with support for them and their community organizations to design and help implement responses, including rebuilding homes and livelihoods.

As part of the campaign, a Local Government Self-Assessment Tool (LGSAT) has been prepared which provides key questions and measurements against the Ten Essentials for Making Cities Resilient **(UN-ISDR, 2012).** The campaign insists participating local governments to report progress on the ten essentials and many participating local governments have already reported their progress on ten essentials. More details about the campaign is available on http://www.unisdr.org/campaign/resilientcities/.

10. Concluding Remarks

This report has described in detail and presented the results of an investigative study on tsunami risk assessment for the port city of Galle in Sri Lanka. The paper focuses on hazard, vulnerability and capacity analysis, the principal components of risk assessment followed by risk management measures

Hazard analysis comprised both probabilistic and deterministic hazard analysis. The probabilistic tsunami hazard analysis has revealed that for Sri Lanka the low hazard and high hazard maps developed for the two scenarios of the Indian Ocean Tsunami Hazard Map are very similar in character. Since both high and low hazard cases for Sri Lanka are dominated by the events in North Sumatra and Nicobar Islands, it seems that the Indian Ocean Tsunami (IOT) was the worst case scenario. The use of deterministic tsunami hazard modelling permitted a scenario based analysis. It was evident that from a point of view of hazard impacts, the IOT represented the worse case. This hazard scenario can therefore be used for long term strategic urban development planning, in particular to identify locations for critical infrastructure and installations. Therefore the IOT scenario was selected for risk assessment in this study. However, there are no constraints for the use of multiple scenarios for preparation of an overall hazard map and the scenario modeling carried out for this study can be used for such an exercise with the adoption of weightage factors.

The report presents a simplified approach for vulnerability and capacity analysis whereby only the critical parameters have been used. These parameters were identified in consultation with stakeholders. The report also provides a cross comparison with a very detailed study on vulnerability assessment undertaken for the city of Galle using the Sector Approach. The Sector Approach demands a very detailed analysis based on an extensive database. It was evident that the simplified approach provides an effective vulnerability analysis on which risk assessment can be undertaken with confidence.

The risk assessment has been achieved via superimposition of hazard and vulnerability maps. It is recognized that the frequency of occurrence of tsunamis which may have severe affects on the Sri Lankan coast is small and this aspect has to be given due recognition in adopting measures for risk management. It is in this respect that that an extreme case scenario of IOT has been considered and the results of which can be used for strategic planning as identified earlier

The report then focuses on tsunami risk management. It presents a four pronged strategic approach and identifies the importance of operating within a multi hazard coastal hazard protection plan. The said approach considers measures which

- Mitigate the impact of the hazard
- Mitigate the exposure and vulnerability to the hazard
- Improve preparedness and response and promote successful evacuation from the hazard
- Encourage the use of risk transfer by insurance

In the case of the City of Galle the report presents a case for integrating national port development with tsunami hazard protection. It recommends that the breakwaters of the proposed new port in Galle can be utilized to provide protection against the tsunami hazard and modeling will have to be carried out to estimate the desired crest height of the breakwater to achieve the expected level of protection. The report has identified the approach to be adopted for the design of tsunami resilient buildings. Appropriate techniques are being currently developed under the leadership of the Disaster Management Centre of Sri Lanka. The report has developed disaster management maps with respect to safe places and routes. The report has also focused on the evaluating resilience of coastal communities which is considered on of the most important goals in risk management.

The report also focuses on Tsunami Risk Assessment within a Tsunami Forecasting and Early Warning Framework, whereby an integrated approach for the analysis of results from early warning systems and inundation modelling for risk assessment is presented for improved tsunami wave height forecasting on the shoreline. This identifies the need to refine the tsunami wave forecasting provided by the Regional Tsunami Service Providers (RTSPs) for cities having complex geometrical shoreline features and bathymetrical features. The basic concept of this approach is presented in Chapter 8 whereas a dedicated case study on improved tsunami wave height forecasting is presented as a separate report. The clearly study clearly illustrated,

- the relevance of the use of scenario modeling for long term forecasting and strategic risk assessment within the framework of coastal forecasting zones adopted by the Regional Tsunami Service Providers (RTSPs) of the Indian Ocean Tsunami Warning System
- the differences between forecasting from RTSPs and detailed modeling for risk assessment and
- some of the critical issues relating to the interpretation of the technical early warning issued by the RTSPs and its transformation to a public warning for the benefit of the coastal population.

11 References

Burbidge, D.R. Cummins, P.R. Latief, H. Mleczko, R. Mokhtari, M. Natawidjaja, D. Rajendran, C.P. & Thomas, C. A Probabilistic Tsunami Hazard Assessment of the Indian Ocean Nations. Geoscience Australia (2009). Professional Opinion No. 2009/11, September 2009.

Birkman, J. (2006) Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies. Edited by Jorn Birkman, United Nations University Press.

Department of Census and Statistics (2007) Report on Census of Buildings and People Affected by the Tsunami-2004. Colombo, Sri Lanka. Department of Census and Statistics. Accessed 25 October 2012 from <http://www.statistics.gov.lk/tsunami/>

Dias, W.P.S and Majeed, M.R. (2009). Factors influencing the rate of construction after a tsunami disaster. Presentation at the International Conference on accommodating Natural Hazards and Disasters in Social and Economic Infrastructure Development, International Institute for Infrastructure Renewal and Reconstruction, Ahungalle, Sri Lanka, July

Hettiarachchi, S.S.L. Samarawickrama, S.P. and Wijeratne, N. (2009). Risk Assessment and Design of Countermeasures Management for Tsunami Hazard, Internal Report University of Moratuwa for the US IOTWS Small Grants Programme.

Hettiarachchi, S.S.L. Ratnasooriya A.H.R and Samarasekera R.S.M (2015). Tsunami Wave Height Forecasting at coastlines with complex geometries- An Integrated Approach for the analysis of results from Early Warning Systems and Inundation Modelling for Risk Assessment. Report prepared by the University of Moratuwa for the UNESCAP-TRATE (IOTWS) Project, June 2015.

Khazai, B, Franco,G. Ingram, J.C. (2006). Post-December 2004 tsunami in Sri Lanka and its potential impacts on future vulnerability. Earthquake Spectra, 22, S829-S824

Okada, Y. (1985). Surface deformation due to shear and tensile faults in a half-space, Bull. Seism. Soc. Am. 75, 1135-1154.

Recilientcity.org. (2010), "Resilience", available at: http://www.resilientcity.org/index.cfm?id=11449 *(accessed 25 February 2010).*

Red Cross (2010), "World disasters report 2010", The International Federation of Red Cross and Red Crescent Societies, available at: http://www.ifrc.org/Global/Publications/disasters/WDR/WDR2010-full.pdf *(accessed 25 February 2010).*

Ryan, C. (2014). Indian Ocean Tsunami Warning System- Operations and Limitations. Report prepared for the IOTWS/UNESCAP- TRATE Project.

Strunz, G. Post, J. Zosseder, K. Wegscheider, S. Muck, M. Riedlinger, T. Mehl, H. Dech, S. Birkmann, J. Gebert, N. Harjono, H. , Anwar, H.Z., Sumaryono, Khomarudin, R.M. and Muhari, A. (2011). Tsunami Risk Assessment in Indonesia. Natural Hazard and Earth System Sciences. 11, 67-82.

UNESCO (2009 a). Hazard awareness and risk mitigation in ICAM. IOC Manuals and Guides No.50, ICAM Dossier No.5 Paris UNESCO 2009.

UNESCO (2009 b). Tsunami risk assessment and mitigation in the Indian Ocean; Knowing your tsunami risk-and what do about it. IOC Manual and Guides No 52, Paris: UNESCO 2009

UN-ISDR, (2010a), "My city is getting ready", United Nations International Strategy for Disaster Reduction – UN-ISDR, (http://www.unisdr.org/preventionweb/files/14043_ campaignkit1.pdf -*accessed 28 Feb 2010*).

UN-ISDR, (2010b), "Local governments and disaster risk reduction", United Nations International Strategy for Disaster Reduction – UN-ISDR, available at: http://www.unisdr.org/preventionweb/files/13627_LocalGovernmentsandDisasterRiskRedu.pdf *(accessed 28 April 2010).*

UN-ISDR, (2012), *How to make cities more resilient: a handbook for local government leaders*, United Nations, Geneva.

U.S. IOTWS Programme (2007). How resilient is your coastal community- A guide for evaluating coastal community resilience to tsunamis and other hazards. U.S. IOTWS Document No.27-IOTWS-07

Villagran de Leon, J.C. (2006). Vulnerability. A Conceptual and Methodological Review No.4, SOURCE Publication Series of UNU-EHS, Bonn. 64 pages.

Villagran de Leon, J.C. (2008). Rapid assessment of potential impacts of a tsunami: Lessons learnt from the port of Galle in Sri Lanka. No.9, SOURCE Publication Series of UNU-EHS, Bonn. 96 pages.