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# TSUNAMI RISK ASSESSMENT AND MITIGATION FOR THE INDIAN OCEAN

## KNOWING YOUR TSUNAMI RISK – AND WHAT TO DO ABOUT IT

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# Tsunami risk assessment and mitigation for the Indian Ocean;
# knowing your tsunami risk – and what to do about it

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These guidelines have been prepared as one of the activities of Working Group 3 (Risk Assessment) of the Intergovernmental Coordination Group (ICG) of the Indian Ocean Tsunami Warning and Mitigation System (IOTWS). An international group of experts in the fields of tsunami sources, propagation and inundation, of hazard, vulnerability and risk assessment; also specialists in national and community preparedness and early warning, and in the strategic mitigation of tsunami hazard have contributed to their preparation. Their production has been facilitated by the generous support of the United Nations Development Programme Regional Centre in Bangkok in the context of their Regional Programme for Capacity Building in Risk Reduction and Recovery.

The development of the Guidelines was discussed at a specially convened Risk Assessment Workshop in Dubai in October 2007, sponsored by WAPMERR. Their production has been guided by an Advisory Committee of Working Group 3 led by John Schneider (Vice Chair of WG3, Australia), Sam Hettiarachchi (Chair of WG3, Sri Lanka), Sanny Jegillos (UNDP-Regional Centre in Bangkok) and the ICG/IOTWS Secretariat (Tony Elliott and Jane Cunneen). Two meetings of the Advisory Committee and experts were held respectively in Bangkok and Bali in September and November 2008.
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The Guidelines have been compiled with the benefit of a wealth of published and unpublished information. This has included research by individuals as well as guidance documents from national and international organisations including IOC, ISDR, and partners in the German-Indonesian GITEWS project, led by the German Research Centre for Geosciences (GFZ), Potsdam. This strong foundation to the compilation is warmly acknowledged. The text has been strengthened by advice and critical appraisal by individuals and organisations including Brian Atwater (U.S. Geological Survey), Priyan Dias (University of Moratuwa, Sri Lanka), Slava Gusiakov (Russian Academy of Sciences), Julie Leonard (USAID/Office of Foreign Disaster Assistance), Jan Sopaheluwakan (Indonesian Institute of Sciences) and John Tychsen (Geological Survey of Denmark and Greenland, GEUS).

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# Foreword

The Intergovernmental Oceanographic Commission (IOC) of UNESCO was given a mandate by its Member States to facilitate the expansion of global coverage of tsunami warning systems following the disastrous Indian Ocean tsunami in December 2004. This development builds on the experience of the Pacific Tsunami Warning and Mitigation System (PTWS), operational since 1965. Additional warning and mitigation systems are in the course of development, co-ordinated by IOC, covering the Indian Ocean (IOTWS), the North Eastern Atlantic, the Mediterranean and Connected Seas (NEAMTWS) and the Caribbean (CARIBE-EWS) regions.

The imperative for these developments stemmed from the need to reduce tsunami risk. However, the warning systems are intended to be integral components of comprehensive multi-hazard warning systems, covering, for example, storm surge and extreme wind-forced wave events. Each will link with appropriate existing hazard warning systems and established specialized centres. These include systems coordinated by IOC and the World Meteorological Organization (WMO), through the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM). The implementation plans of these multi-hazards warning systems embrace the detection, and forecasting and warning of hazard events, as well as communication and dissemination, and mitigation – an "end-to-end" system. A key component of each system is the improvement of preparedness through public awareness, education and risk assessment. Regional Watch Centres have the important role of planning and implementing regional programmes, and providing guidance on alert and information services to National Warning Centres, ensuring full coordination between National Warning Centres in the region and taking maximum advantage of this high-level cooperation. The onward communication of hazard events and the issuance of warnings by National Warning Centres to local authorities are the responsibilities of individual countries.

The purpose of these Guidelines is to facilitate the implementation of tsunami risk assessment and mitigation by IOC Member States. They have been produced as an initiative of Working Group 3 (WG3) of the Intergovernmental Coordinating Group of IOTWS (Indian Ocean Tsunami Warning and Mitigation System). They have been compiled within the context of the "Hyogo Framework for Action 2005–2015: Building the Resilience of Nations and Communities to Disasters" (UN/ISDR, 2005). They describe a process aimed at fully integrating disaster risk reduction into relief and development policies and practices.

The Guidelines have been prepared by an expert group within WG3 and with the support and cooperation of the United Nations Development Programme (UNDP). They are intended to be user-oriented and, although focused on the Indian Ocean Region, they are relevant to tsunami risk assessment and mitigation at the global scale. Their compilation has been closely allied to that of companion guidelines produced as part of the IOC-ICAM (Integrated Coastal Area Management) programme to promote hazard awareness and risk mitigation in coastal management (UNESCO, 2009). They have been developed in accord with Resolution XXIV-14, "Tsunamis and Other Ocean Hazards Warning and Mitigation Systems (TOWS)", in the 24th Session of the IOC Assembly (June 2007). This resolution recognized that 'the development and implementation of multi-hazard strategies and interoperable systems, including for tsunamis, can only be achieved through close consultation, coordination and cooperation among all stakeholders with tsunami and related ocean hazard mandates'.

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Executive Secretary of IOC
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# **Executive** Summary

**Context: The Indian Ocean Tsunami Warning and Mitigation System (IOTWS).** These guidelines aim to facilitate the assessment and mitigation of the risks from tsunamis to coastal communities, their infrastructure and other supporting systems, as a necessary complement to the various detection and warning systems under development for Indian Ocean countries within IOTWS. The Guidelines describe procedures for assessing and improving awareness of the tsunami hazard and for assessing coastal communities' vulnerabilities and deficiencies in preparedness. They provide recommendations for good practice in the management of the risks by enhancing their preparedness for emergency response and by strategic mitigation.

## UNDERSTANDING AND ASSESSING THE TSUNAMI HAZARD (B1)

In this section, the Guidelines address the possibility and the probability of a tsunami impact on a country's coast. As an introduction to the procedure for hazard assessment, the document describes the scientific background to tsunami occurrence in the Indian Ocean region, taking into account their sources and their geological causes, the ways in which tsunamis travel from those sources to shores near and far, and the challenge of preparing for catastrophic tsunamis that happen centuries apart. This section explains how the scientific understanding of tsunamis in the region is being developed from research by the international science community. This account of the hazard context is followed by guidance on the procedures for countries to carry out their own hazard assessments in respect of tsunami impacts on their coasts.

The guidance takes into account the likelihood of occurrence and also the ways in which a tsunami may be modified (in terms of its height and momentum) by the specific coastal physiography. The assessment aims to delineate the parameters of potential inundation and inform local and/or national authorities on the likelihood of such impacts in relation to a timescale relevant to their coastal management and planning.

The recommended tasks are to:
- define the geographical limits of the coastal management area;
- identify the possible tsunami sources;
- compile written and geological records of tsunami impact events on their own, and their neighbours', shores to estimate tsunami return periods;
- access information on tsunami sources and propagation patterns;
- acquire and compile data on the country's nearshore bathymetry and coastal topography;
- determine the geographical limits and heights of inundation;
- determine potential flow velocities on inundation and subsequent drainage;
- determine levels of probability, return times for specified scenarios;
- prepare hazard maps showing inundation parameters for specified scenarios; and
- communicate results of hazard assessment to emergency managers and policy makers.

The expected principal outputs from these procedures are:
- a listing of all tsunamis known to have come ashore in your region;
- analysis of pre-calculated tsunami propagation patterns for tsunamis from likely earthquake sources to determine the potential for impact on your country's coasts;
- map showing your country's coasts most prone to potential tsunami impact;
- hazard maps for specified tsunami scenarios showing limits of coastal land that is likely to be affected by those scenarios (inundation limits, run-up, erosion), water depths at maximum inundation, inundation- and drainage-flow indicators; and
- estimated return periods for the specified tsunami scenarios.

## ASSESSING VULNERABILITY (B2)

The assessment of the vulnerability of tsunami hazard receptors – the coastal community and its supporting systems – forms a key part of the guidance. Assessment of the various dimensions of a community's vulnerability – the people, their economic infrastructure and their supporting ecosystems – assists policy makers in the identification of critical areas or weak spots in respect of human safety, industrial and utilities infrastructure security, ecosystem integrity and the robustness of governance. An alternative approach applicable in a city environment – assessing vulnerability in a cross-cutting perspective as it affects specific development sectors, such as health and education – is also described. Changes over time in the levels of vulnerability must be considered, particularly those caused by coastal urbanization; also environmental changes and the changes brought about as a consequence of mitigation.

The recommended tasks are to:
- define the geographical scale and limits of the vulnerability assessment, considering the geographically determined inundation limits;
- define the temporal scale of the assessment – this may be a rolling scale;
- create an asset inventory by compilation of a geospatially referenced database for social, physical (structural), economic and environmental dimensions; or for development sectors;
- create an exposure database
- classify the assets represented in the exposure database by levels of vulnerability in respect of the specified tsunami hazard scenario(s) and the required response times for evacuation;
- produce vulnerability map(s) for the designated coastal management area; and
- communicate the vulnerability assessments to all involved in risk assessment and emergency management.

The expected principal outputs from these procedures are:
- an asset database (or inventory);
- an exposure database;
- a preliminary appraisal of vulnerability in respect of exposure due to tsunami inundation carried out (perhaps leading to a preliminary risk appraisal), so that local authorities and disaster reduction and prevention agencies may appreciate the importance of setting up a plan for vulnerability assessment of the designated coastal area;
- in-depth assessments of each dimension of vulnerability and its potential consequences in respect of specified hazard scenario(s) and the required response times for evacuation;
- vulnerability maps and reports produced, with the involvement of end users, for the designated coastal areas, whether at the regional or the local scale, covering each dimension of vulnerability, and aggregated vulnerability, for specified hazard scenario(s);
- vulnerability maps and reports covering future scenarios, taking into account the likely effects of improved emergency preparedness and mitigation; reports relating to "sectors of development" as appropriate; and
- communication of the vulnerability assessments to all involved in risk assessment and emergency management.

## ASSESSING COMMUNITY PREPAREDNESS (B3)

A critical issue that hinders the efficient and timely implementation and operation of early warning systems is a lack of consideration or recognition of vulnerable groups. There may also be weaknesses in the monitoring and forecasting of potentially catastrophic events, and weaknesses in issuing warnings, and/or ensuring that warnings reach vulnerable communities. Institutional capacities may not be adequate to respond to a warning of a potentially catastrophic event.

The recommended tasks within this element of the guidance are to:
- identify and appraise weaknesses in early warning systems and responses in the event of a warning, taking into account vulnerable groups;
- identify and appraise weaknesses related to the post-impact response; and
- assess the take-up or application of risk transfer mechanisms which would facilitate post-impact recovery.

The principal outputs associated with this assessment may include:
- a preliminary appraisal of the state of early warning practices, so that local authorities and disaster reduction and prevention agencies may appreciate the importance of setting up a plan to strengthen such early warning aspects in the designated coastal communities;
- in-depth assessment of deficiencies in each key area;
- appraisal of coverage in terms of insurance and micro-insurance schemes; and
- appraisal of institutional capacities, notably the requirements for Search and Rescue Operations; also of the results of drills and exercises.

## ASSESSING THE RISK (B4)

The integration of the probability of specified tsunami scenarios and vulnerability and preparedness assessments is the final element of the risk assessment procedure. This indicates the risks to the various community dimensions (social, physical, economic and environmental) or, alternatively, development sectors, in respect of the specified tsunami scenario(s). The levels of risk deduced by this process inform policy and decision-making, leading to the management of those risks within a coastal area management plan.
The recommended key tasks are to:

- confirm the geographical scale and limits of the assessment, using determined geographical hazard (inundation) limits (these should be the same as for the corresponding vulnerability assessment);
- confirm the temporal scale of the assessment;
- combine the tsunami inundation parameters (for specified scenarios with defined probabilities) with assessed vulnerability levels (in respect of those scenarios);
- translate the combined hazard, vulnerability and preparedness outputs into levels of risk, these denoting the probabilities of consequential damage and loss in respect of the specified tsunami scenarios;
- produce risk map(s) for the designated coastal management area; and
- communicate the risk assessment outputs to all levels involved in risk management and mitigation.

The expected principal outputs from these procedures are:
- assessments of risk for each dimension of vulnerability (or sector of development) in respect of a tsunami scenario with a defined probability;
- risk maps covering future scenarios as well as existing conditions produced for the designated coastal areas, whether at the regional or the local scale, covering each of the different dimensions of vulnerability (or each development sector) for the specified tsunami scenario(s); and
- effective communication of the risk assessment outputs to all levels involved in the coastal management process. The assessments are vital inputs to policy-making, determining the nature and level of response for risk reduction within the coastal management plan.

## ENHANCING AWARENESS AND PREPAREDNESS (C1)

The first part of the guidance in the management of the assessed risks aims to facilitate the enhancement of public awareness of the risks and to improve the capability of coastal communities to cope in emergency situations of a tsunami threat or impact.

The recommended key tasks are:
- identify an appropriate early warning framework;
- raise awareness of the risk at all levels in the community;
- plan and implement the key operational requirements of an early warning system;
- prepare all levels of the community for emergency responses;
- plan systems and procedures for evacuation; and
- promote Community-based Disaster Risk Management (CBDRM) where appropriate.

The expected principal outputs from these procedures are:
- measures for education and public awareness of risks established;
- special target audiences identified;
- an effective, tested, end-to-end early warning system in place;
- evacuation procedures and tested, and refuges in place; and
- Community-based Disaster Risk Management (CBDRM) implemented where appropriate.

## MITIGATING THE RISK (C2)

This part of the management guidance deals with the options for structural and non-structural responses for the mitigation of the assessed risks by strategic management.

The recommended tasks are:
- define the temporal and geographical scales of the management area;
- review the options for strategic mitigation;
- consider the adoption of a hybrid approach to the management response;
- incorporate other coastal management goals in the response;
- apply decision-analysis tools in the management process; and
- involve the public in the decision-making processes.

The expected principal outputs from these procedures are:
- a portfolio of effective hazard mitigation measures which are consistent with wider coastal management objectives; and
- a long-term plan for the implementation of the measures, including a monitoring programme to assess the effectiveness of the selected strategy in reducing risks in respect of the tsunami hazard.

Whatever the coastal communities' physical or developmental situations, there are ways of reducing risk in respect of the tsunami hazard which are sustainable and can be embedded in the culture of those communities. Of prime importance is the need to achieve sustained coordination of effort among the many stakeholders, whether in the assessment of the risk, the planning and implementation of mitigation measures, or the emergency response. The Guidelines are intended to promote and facilitate this objective, promoting tsunami- and other physical coastal hazard awareness and risk mitigation within a coastal management framework such as ICAM (Integrated Coastal Area Management).

# A Introduction

## A1 Tsunamis – are you prepared for them?

### A1.1 WHY SHOULD YOU CARE?

Tsunamis are natural events that become disasters when they harm people and property. Humans now have the knowledge and the capacity to reduce the cost of such disasters in terms of human lives and economic losses. Loss of life can be reduced and economies need not be so badly damaged. While it is unlikely that all loss of life can be eliminated, the tragedy of coastal devastation can be minimized. With the engagement and assistance of the international community, you can help yourselves to achieve a significant reduction in the risk to your coastal communities from tsunami impacts and inundation. It is the special responsibility of today's generations, as witnesses to the Indian Ocean tsunami disaster of 26 December 2004, to minimize the losses of lives and livelihoods to future tsunamis.

### A1.2 WHAT ARE THESE GUIDELINES FOR?

National and local governments including national disaster management agencies may use and adapt these guidelines to help identify, define, and reduce tsunami risks to people, their infrastructure, and their supporting ecosystems. The Guidelines seek to facilitate the practical and realistic assessment by countries of risk in respect of the tsunami hazard. They present achievable and sustainable strategies for the management and reduction of that risk. The Guidelines build on, and have benefited greatly from, many publications dealing with the science of tsunamis and the assessment of tsunami risk, and providing advice to coastal communities on tsunami awareness and preparedness. One of these – "Hazard awareness and risk mitigation in ICAM (Integrated Coastal Area Management)" (UNESCO, 2009) – considers tsunamis, along with a range of physical coastal hazards including storm surges, at a global scale.

### A1.3 WHO SHOULD READ THEM?

All countries have room for improving their assessment and awareness of tsunami risks.

Countries' experience of tsunami impacts over recent years has shown that inadequate preparedness and unplanned development have contributed to the loss of lives which may otherwise have been avoidable. These shortcomings have been due in part to a lack of early warning through poor regional detection and communication systems. In many cases, however, they have reflected an inadequate awareness at all levels of the risks faced by communities in respect of tsunamis. The Guidelines are addressed, in particular, to national boards for disaster management (for example, BNBP in Indonesia), coastal development agencies, to coastal risk managers, emergency managers and planners, as well as those concerned with strategic mitigation and sustainable use of coastal resources. They promote coordination among the many agencies and other organizations involved with responsibilities for raising tsunami awareness, devising emergency plans, and building capacity for emergency preparedness and strategic mitigation.

### A1.4 HOW CAN YOU KNOW THE RISK?

The Guidelines describe procedures for assessing:

- the likelihood and size of a tsunami impact on your coasts;
- your communities' vulnerability – the consequences

(damage and loss) in the event of an impact, including changes in vulnerability over time;
- your communities' state of preparedness for a tsunami impact;
- the probability of consequences for your communities in respect of the tsunami hazard (the risk), linking the hazard assessment with vulnerability.

## A1.5 HOW CAN YOU REDUCE THE RISK?

Guidance in the management of the assessed vulnerability and risk promotes two broad objectives – development of public awareness and emergency preparedness, including:

- education;
- early warning systems;
- evacuation plans and
- community-based disaster risk management;

and strategic mitigation options including:
- promotion of natural defences;
- hard and soft engineered responses; and
- non-structural approaches including buildings codes and land-use planning.

Civil protection emergency response and relief procedures are already well established in many countries, particularly where natural hazard events are commonplace. These guidelines draw from established practices, but modify or supplement such procedures in order to address the specific circumstances of tsunami impacts.

## A1.6 POLICY ISSUES AND COMMUNITY PARTICIPATION

The experience of the responses to recent coastal inundation hazard events and their ensuing disasters, notably the Indian Ocean tsunami of 2004 and the storm surges associated with Hurricane Katrina in 2005 and Cyclone Nargis in 2008, has highlighted a lack of knowledge of hazards and a poor awareness of community vulnerability. It has highlighted dysfunctional institutional structures and systems which have hindered the translation of such knowledge and awareness that does exist into responses that are effective in reducing risk. In addition, it shows the need to better understand the root causes of vulnerability in coastal populations, in particular the increasing trend of overpopulation, driven, for example, by global tourism. When a tsunami strikes a coastal area, it is the local population that makes its living in tourist-related activities as well as the tourists that suffer large losses.

The Guidelines recognise that successful management of tsunami risk demands high levels of cooperation and coordination between all the involved agencies. These are difficult to achieve, even in developed countries. The Guidelines also highlight the cost-effectiveness of focusing on the local level to help communities take simple disaster mitigation measures. These measures would put in place elementary early warning systems consisting of basic communication chains that could ensure that information reaches the people most at risk. The successful application of the risk assessment may be impeded by a lack of political commitment, but wide stakeholder involvement in the formulation of a risk management plan, through frameworks such as ICAM, may help to resolve such institutional barriers.

Whatever the level of risk, there is likely to be some potential for risk reduction, the overarching objective of these guidelines. Whatever the coastal communities' physical or developmental situation, there are ways of reducing risk in respect of these hazards which are sustainable and can be embedded in the culture of those communities. Of prime importance is the need to achieve sustained coordination of effort among the many stakeholders, whether in the assessment of risk, the planning and implementation of mitigation measures, or the emergency response. These guidelines are intended to promote and facilitate this objective, as part of the coordinated efforts of the Working Groups of the ICG-IOTWS. The successful application of these processes, whether in risk assessment, management planning or in emergency response, will depend above all on the effective operational coordination and cooperation of the many parties involved.

# A2 Guide for readers

The Guidelines are presented as a sequence of procedures for consideration by coastal emergency managers, planners and policy- and decision makers. Following this introduction (Section A), the guidance is set out in two main sections – Section B "Assessing the tsunami risk", dealing with the steps involved in the risk assessment processes; and Section C "Managing the tsunami risk", dealing with the procedures and recommendations for risk reduction. The interrelationships of these sections and their main elements are illustrated in Fig. A1.

Section B comprises four main elements. The first (B1) responds to the question, "Is your coast prone to tsunamis?" This covers information about the likely sources of tsunamis and the likelihood of a tsunami impacting your shores; it covers the assessment or estimation of the physical effects of tsunami impacts on your country's shores (the hazard) along with the nature of inundation and how tsunamis travel or propagate from their sources. Finally, it deals with the recording of information about hazard exposure for use by emergency managers and coastal engineers. The second element (B2) provides guidance in response to the question on whether your coastal communities and their supporting assets and resources are vulnerable to tsunamis to which your coasts may be prone. This describes the multifaceted nature of vulnerability and different approaches to its assessment; it then provides guidance on vulnerability assessment procedures for estimating the consequences (damage and losses) arising from a tsunami event.

The third element (B3) provides guidance on assessing the state of a community's preparedness for a tsunami impact, appraising possible deficiencies in services essential to minimizing disaster losses. The fourth element (B4) combines the assessment outputs of the first three. It explains how you can integrate the information on the tsunami hazard with the information on the consequences of a tsunami impact on your communities (their vulnerability and their state of preparedness) to provide a risk assessment in respect of a specified tsunami hazard scenario – providing a measure of the probability of those consequences.

Section C comprises two main elements which together deal with the reduction of risk in respect of the tsunami hazard. The first (C1) covers the procedures that you will need to prepare your communities for tsunami impacts. It deals with raising the levels of awareness of tsunamis, and then describes tsunami early warning systems, including the regional early warning systems and the part that national systems play in these regional facilities. It also includes information on evacuation procedures and shelters, and explains how community-based actions can contribute to risk reduction. The second element (C2) looks at your options for the strategic mitigation of the tsunami risk, both through the use of structural methods – by using natural coastal resources and engineering approaches – and also by non-structural initiatives, including regulation and land-use planning.

Each of the main elements of sections B and C is introduced by a summary list of the key tasks of the assessment and mitigation procedures, and each is concluded by a summary of the expected outcomes and products of those procedures. Each element in Section B concludes with a table of information sources for the assessment procedure. Each element in Section B and Section C is appended by a list of suggested additional reading and supplementary information. A general bibliography covering published material taken into account in the compilation of the Guidelines follows Section C; this includes addresses on the World-Wide-Web that were accessible at the time of publication.

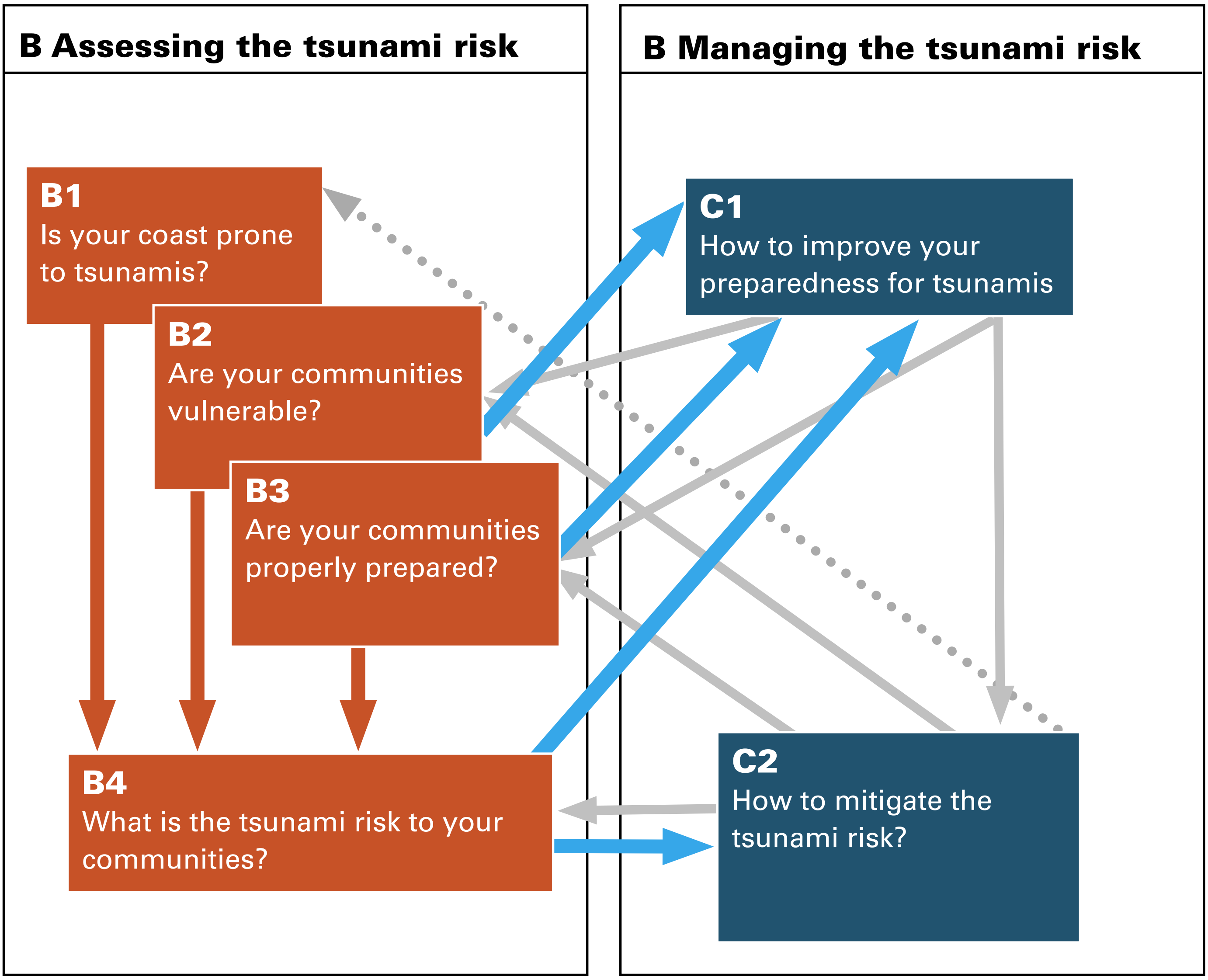


**Fig. A1.** *The main topics addressed by these guidelines and the linkages between them. Links in the risk assessment process are shown in orange, links from risk assessment to risk management in blue; feedbacks are shown in grey.*

# B Assessing the tsunami risk

**The term tsunami risk, as used in these guidelines, refers to the risk posed to a coastal community and their supporting systems by the hazard of potential tsunami impacts on their shores. The assessment of that risk depends on two main components – the physical hazard and a community's vulnerability to the hazard. Another influence on the risk is the state of the community's preparedness for a tsunami impact.**

## B1 Is your coast prone to tsunamis?

**Key tasks in the hazard assessment procedure**

- Define the geographical limits of the coastal management area.
- Identify the possible tsunami sources.
- Compile written and geological records of tsunami impact events affecting your own and neighbouring shores.
- Access information on tsunami sources and propagation patterns.
- Acquire and compile data on nearshore bathymetry and coastal topography.
- Determine the physical parameters of inundation.
- Determine levels of probability, return times for specified scenarios.
- Prepare hazard maps showing inundation parameters for, and probabilities of, specified scenarios.
- Communicate results of hazard assessment to emergency managers and policy makers.

### B1.1 KNOWING THE POTENTIAL FOR A TSUNAMI TO IMPACT YOUR COAST

This account commences with a review of the various sources of tsunamis which have affected, and are likely to affect, the Indian Ocean region. There follows a description of the characterization of tsunami hazard in the Indian Ocean Tsunami Hazard Map, developed for the IOTWS. The sources of tsunamis are described below under two broad headings – subduction zone earthquake sources and non-subduction zone sources.

**Identifying subduction zone earthquake sources of tsunamis**

The important sources of earthquake-generated tsunamis in the Indian Ocean are along the northern margin of the Arabian Sea – adjacent to the Makran coasts of Iran and Pakistan, and from the northern tip of the Bay of Bengal, through the western margin of the Andaman Sea, and skirting the southern coasts of Sumatra, Java, and the islands of Lesser Sunda. Each of these tracts is underlain geologically by a subduction zone, respectively the Makran and Sunda subduction zones (Fig. B1).

Subduction zones are dynamic features which form as a consequence of differential movement of adjoining plates of the Earth's crust or lithosphere. The term subduction refers to the process whereby one crustal plate underrides the margin of its neighbour. The process of plate movement may be continual but its manifestation at the surface tends to be spasmodic, with stresses released periodically (and usually catastrophically) by displacement on fractures called faults. It is these releases of energy that cause earthquakes.

The Makran and Sunda Arc subduction zones are both submarine features. When an earthquake occurs, the sea bed over the fracture zone may be catastrophically

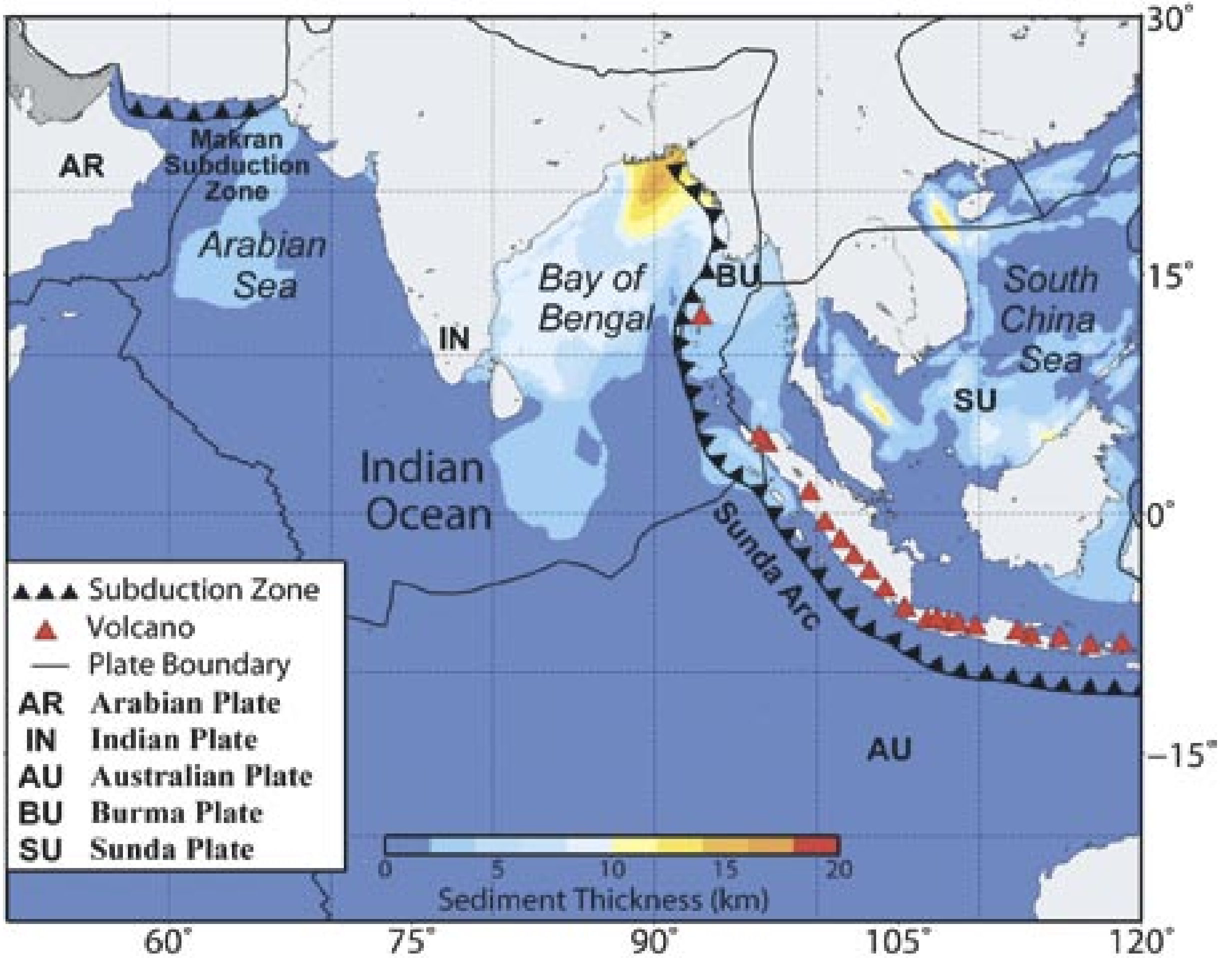


**Fig. B1.** *Major plates and subduction zones that are potential sources of Indian Ocean tsunamis. Major accumulations of seabed sediments shown in pale blue to orange.*
*Source: Geoscience Australia.*

displaced, causing a collapse or an upheaval of the overlying water mass. This is the source event that creates a tsunami. The scale of the disturbance depends upon:

- the orientation and dip of the fault;
- the location, depth and area of the earthquake rupture, and
- the direction and amount of motion during the earthquake (known as the slip).

Note that some submarine earthquakes may not generate tsunamis (for example, if they are small or deep). Depending on the lateral extent of the fault displacement in the subduction zone, the tsunami source may be compact or, in the case of the 2004 Indian Ocean tsunami, elongated over a thousand or so kilometres.

The Sunda Arc – comprising the Java, Sumatra and Lesser Sunda subduction zone – is one of the most active plate tectonic margins in the world. Many of its characteristics change significantly along its length. The Indian/Australian and Sunda plates (Fig. B1) meet 5 km beneath the sea surface at the Sumatran Trench, on the floor of the Indian Ocean about 200 km off the western coast of Sumatra and southern coast of Java. At the trench, the Indian/Australian plate is being subducted and overridden by the Sunda plate. Movement between the plates occurs on a fault termed a megathrust. As previously mentioned, the movement is not smooth, rather it occurs spasmodically. The contact between the plates may remain locked for decades or centuries, then suddenly slips by several metres, giving rise to a powerful earthquake. Studies of the Sunda Arc show that large megathrust earthquakes have not been distributed evenly along its length. Historical records spanning some 250 years show that specific sections have been active, while others, relatively quiet. However, in general, most sections of the Sunda Arc are considered to be capable of generating large megathrust earthquakes and thus have the potential to generate significant tsunamis.

The Makran subduction zone of Iran and Pakistan is seismically less active than the Sunda Arc but has produced great earthquakes and tsunamis. The last major tsunami in the Arabian Sea was in 1945, caused by a great earthquake in the eastern part of the zone. The Makran subduction zone is marked by unusually thick sedimentary cover, which itself may be prone to tsunamis caused by sediment slumping (see below). The well-defined terraces of raised seabed that feature along parts of the eastern and western Makran coasts indicate that both parts of this zone may have a potential for large earthquakes (see Box B3).

Neither of these subduction zones is fully understood. It is thus difficult to evaluate the level of tsunami hazard that they pose and to make informed decisions on level of hazard assessment appropriate for each area. The record and likelihood of earthquake occurrence in these zones and the implications for tsunami generation are discussed in B1.2.

### Identifying non-earthquake sources of tsunamis

Globally, subduction zone earthquakes are by far the commonest source of tsunamis. Three quarters of the world's tsunamis are caused by earthquakes. Of the 18 known historical Indian Ocean-wide tsunami events, only one was not caused by an earthquake. Other possible sources of tsunamis are: volcanic eruptions, submarine landslides and asteroids.

### Volcanic eruptions

The 1883 eruption of Krakatau is the only known major volcanic eruption that has triggered a tsunami which has affected the Indian Ocean. The Krakatau eruption caused a very large local tsunami which devastated the Sunda Strait coasts of Java and Sumatra (37 m and 22 m maximum run-up, respectively), killing more than 35,000 people. This tsunami also reached appreciable run-up heights at regional distances, for example, 1 m to 2 m along the coast of Western Australia. The potential for other volcanoes in the region, such as Barren Island in the Andaman Sea, of generating large tsunamis is uncertain.

### Submarine landslides

Submarine landslides have the potential to produce large, local tsunamis. Factors that contribute to the potential for landslide occurrence are steep seafloor slopes and rapid sedimentation. The Indian Ocean includes the two largest seafloor accumulations of sedimentary material in the world, the Indus and Bengal fans, fed respectively by the Indus and Ganges rivers, with sediments derived from the Himalaya range (see Fig. B1). These fans adjoin the Makran and Sunda Arc subduction zones, earthquake activity in which could provide triggers for submarine landslides. These considerations suggest that the threat of submarine slides as a source for tsunamis in the Indian Ocean may be underestimated.

### Asteroid/meteorite impacts

Research opinion is divided on the importance of asteroid impacts as damaging tsunami generators. Consideration of their probability is given in B1.2.

**Box B1. A probable submarine landslide trigger for a tsunami**

On 17 July, 1998, a magnitude 7.0 earthquake generated a 10 m to 15 m high wave along a relatively small section of the coast of Papua New Guinea. By 7 August, 2182 people had been reported dead with 500 still missing. It is unusual for an earthquake of this size to generate such a large wave. Research after the event suggests that the wave was generated by a submarine landslide triggered by the earthquake.

### Accessing regional hazard information

Databases that provide information on the hazards generated from many potential sources in the Indian Ocean are being developed with the potential for presenting this information in map form. Such a regional scale database and map, the Indian Ocean Tsunami (IOT) Hazard Map, is being developed by Geoscience Australia and is intended to provide a useful initial database of possible tsunamigenic earthquakes and their probabilities. While no database could represent all of the tsunamis that might affect a community in the Indian Ocean region, a map including subduction zone earthquakes would cover some 80 per cent of the potential sources. A regional scale IOT Hazard Map would provide countries with an excellent hazard basis for a first-order, community-wide assessment of tsunami risk (Table B1). For detailed, site-specific applications, and for areas at very high tsunami risk, additional geological studies should be conducted to identify potential tsunami sources not considered in the development of a regional scale hazard map.

An existing accessible database relating to potential credible tsunami sources that you might consider is the European Commission Joint Research Centre's (JRC) Grid Calculation System of the Tsunami Propagation Model as listed in Table B2.

## B1.2 ESTIMATING THE LIKELIHOOD OF A TSUNAMI IMPACT ON YOUR SHORES

There are three sources of information that can be used to estimate the likelihood or probability of a tsunami impacting your coast:

- historical evidence of past tsunami;
- geological evidence of past tsunami, and
- tectonic models for earthquake occurrence.

While these sources of information are complementary, they are also incomplete, and any tsunami hazard assessment should clearly express this uncertainty.

| Product | Application |
|---|---|
| Hazard curves (see Fig. B3) | These describe the relationship between the return period and the maximum tsunami amplitude for a particular model output point. The tsunami amplitude given on the y-axis is predicted to be exceeded with the average return period given by the x-axis. |
| Maximum amplitude maps | The maximum tsunami amplitude that will be exceeded at a given return period for every model output point in a region. A different map for the region can be drawn for each return period. |
| Probability of exceedance maps | For a given amplitude, these maps show the annual probability of that amplitude being exceeded at each model output point in a region. A different map can be drawn for each amplitude for that region. |
| Deaggregated hazard maps | These indicate the relative contribution of different source zones to the hazard at a single location (see B1.3). A different map will be obtained for every choice of model output point (and for different return periods), and so there are a great many possible deaggregated hazard maps that may be drawn for any given region. |
| Regional weighted deaggregated hazard maps | These give an indication of the source of the hazard to a country or region as a whole, and are not specific to a particular offshore location. Regional weighted deaggregated hazard maps provide a convenient summary of the source of hazard over a region. However, if one is interested in the hazard at a particular location, near a large town, for example, then one should consult a deaggregated hazard map for a model output point near that particular location. |

**Table B1.** *Products that may be generated from the database of the Indian Ocean Tsunami Hazard Map in preparation (Source: Geoscience Australia)*

### Historical evidence of past tsunamis

The historical record of past tsunamis, meaning the written or oral accounts of past tsunami impacts, generally provides a high level of certainty for the estimation of probability for return periods much shorter than the historical record. Historical knowledge of past hazard impact events to have affected a designated coastal area or region may be anecdotal, from the local community; and it may be derived from national archives or international tsunami databases (see Table B3). However, major, ocean-wide tsunamis occur infrequently – there may be one every few hundred years or longer - and it is rare to find historical records that extend over the many return periods needed to estimate the probability of such events. Even where the historical record extends for millennia, the completeness of records more than a few hundred years old is open to question. Despite recent research efforts, little is known about maximum earthquake magnitudes and rupture modes, or the recurrence times of tsunamigenic events in the Indian Ocean region.

While historical evidence of past tsunamis is invaluable in establishing the likelihoods of past tsunami events, it is invariably incomplete and is seldom able to confidently characterize the largest, most dangerous events that, typically, have long return periods. So, in addition to historical evidence, a tsunami hazard assessment should consider other sources of information, such as those described above.

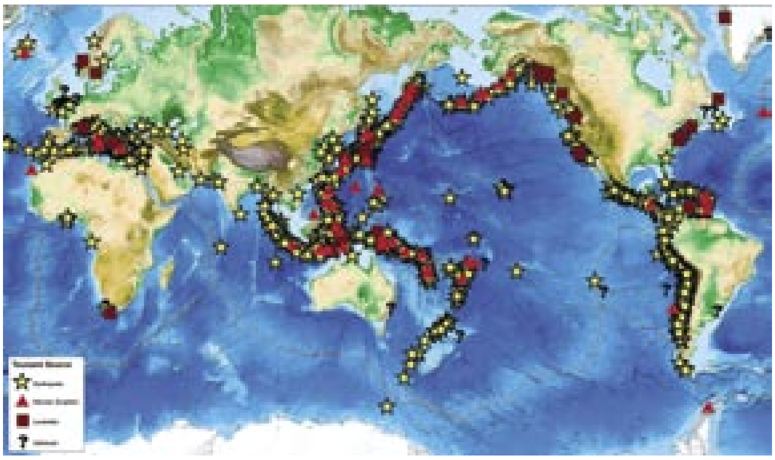

**Fig. B2.** *Verified tsunami sources 2000 B.C.–2008 from the NOAA/WDC Historical Tsunami Database.*

*Source: U.S. NGDC. (http://www.ngdc.noaa.gov/hazard/tsu_db.shtml)*

### Geological evidence of past tsunamis

Geological evidence can extend the knowledge of historical tsunami events further into the past. The information gleaned from such sources can provide a reliable indication of the return periods for tsunamis, enabling confidence in forecasting future events and thus in assessing the risk to coastal communities from tsunamis.

Researchers have pieced together evidence from a variety of sources, ranging from the recognition of

**Box B2. Recording the evidence of past events – palaeotsunami deposits in Thailand**

Sedimentary evidence for recurrent Indian Ocean tsunamis at Phra Thong Island, Thailand. A pit excavation adjacent to the shore exposes layers of sand (light brown), deposited by a series of palaeotsunamis, interlayered with soils (dark brown), accumulated during the intervals between the palaeotsunami events.

Kruawun Jankaew.

tsunami-formed sand deposits (extending back over thousands of years and providing some of the most tangible evidence of tsunami risk), through historical documentation to anecdotal material, in order to compile a record of tsunami events around the world (Fig. B2). The record of tsunami deposits provides crucial evidence for estimating tsunami return periods, adding to, or extending, the instrumental and written records. For example, current research in Thailand and on Sumatra in Indonesia has identified evidence for as many as three ancestors to the 2004 tsunami within the past few thousand years (Box B2). Efforts have also been made to interpret the magnitudes of tsunamis from the characters of these ancient tsunami deposits.

Despite the success of these efforts, geological studies of past earthquakes and tsunamis in the Indian Ocean region are not at an advanced stage. Only for the Sumatra section of the Sunda Arc have such studies enabled the building of a catalogue of the past occurrence of large earthquakes that could be regarded as complete for the past 700 years. Similar studies of other sections of the Indian Ocean subduction zones are only just beginning, and it may take many years before a similar level of information is available for them. Moreover, geological studies can provide only a minimum constraint to tsunami occurrence, because a lack of geological evidence does not prove non-occurrence (for example, tsunami-formed deposits may not have been preserved).

While geological studies are invaluable in extending the historical record and provide the best means of constraining the return probabilities of major tsunami events, geological evidence is typically sparse, and can provide only an incomplete picture of past tsunami occurrence.

### Tectonic models of earthquake occurrence

An alternative approach to estimating tsunami event probabilities that does not rely exclusively on the physical evidence of past events uses mathematical models based on the physics of earthquake occurrence. This approach combines the observed movements of the tectonic plates that cause earthquakes in subduction zones with a mathematical description of earthquake frequency and magnitude. This permits the estimation of the likelihood that earthquakes of a given magnitude will occur on a particular subduction zone. An example of the results of this work is shown in Fig. B3.

This approach has the advantage of including earthquake source zones which may be of concern, but for which there is no actual evidence of tsunami occurence. This lack of evidence could be due to the incompleteness of the historical record or to the difficulty in obtaining geological evidence for prehistoric earthquakes. The approach can also take into account other indications of the potential for earthquake occurrence, such as geodetic monitoring that may indicate a build-up of stress towards an impending earthquake (or the lack thereof).

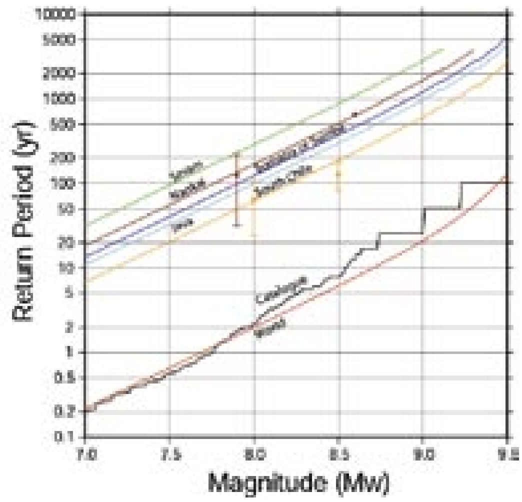


**Fig. B3.** *Curves describing the return periods as a function of exceedance magnitude. These curves give the return period for an earthquake exceeding a certain magnitude at a given subduction zone. They are derived from the fit of a curve for global subduction zone earthquake occurrence (lower red curve) to an earthquake catalogue (black curve), along with information on the length and convergence rate of the tectonic plates at each subduction zone The observed return periods for large earthquakes at the Nankai (SW Japan) and South Chile subduction zones are also shown by star-shaped symbols.*

*Source: Thomas and Burbidge, 2009.*

A major disadvantage of this approach is that the curves describing earthquake occurrence on individual subduction zones are poorly constrained by the available data. Perhaps more importantly, the use of this technique might mask this lack of information, giving the appearance of a very complete, though false, knowledge of earthquake occurrence. On the final assessment, a range of possible maximum magnitudes and earthquake recurrence relationships should be used in order to demonstrate the effect of the uncertainty in these parameters. Another disadvantage is that the technique ignores sources of tsunamis other than megathrust earthquakes; these include volcanoes, landslides, and asteroids as described above, as well as non-megathrust earthquakes.

It should be noted that a conceptually similar approach can be used to estimate tsunami impacts due to asteroids/meteorites. Statistical descriptions of the frequency at which asteroids of different sizes impact the earth can be used to estimate how often these would result in tsunami impact. However, the lack of observational data to constrain such events means there is considerable uncertainty in the generation and propagation of tsunamis excited by such impacts.

### Expressing the potential for tsunami impact

In order to implement effective tsunami mitigation measures, emergency managers and planners in coastal communities need information about how large and how likely tsunamis affecting their communities might be. There are two approaches that are widely used for expressing the potential for tsunami impact – Scenario-based Tsunami Hazard Analysis (STHA) and Probabilistic Tsunami Hazard Analysis (PTHA) – both described below. Although the two approaches may appear at first glance to be mutually incompatible, they are actually complimentary and probably most effective when used in combination. A scenario-based approach focuses on a maximum credible event and historical experience. In the case of tsunamis, this approach is normally used for developing inundation maps and evacuation procedures. A probabilistic approach considers a broad range of potential events and their likelihoods (see B1.2).

The reliability or credibility of each approach depends on an accurate characterization of the tsunami sources, an accurate representation of tsunami propagation (for example, accurate bathymetry data) and on the uncertainty in this characterization. Any hazard analysis should therefore attempt to make the best possible use of data concerning past events.

### Scenario-based Tsunami Hazard Analysis (STHA)

STHA, sometimes called deterministic tsunami hazard analysis, attempts to describe the effects that a particular tsunami scenario, or suite of tsunami scenarios, will have on a coast of interest. These scenarios are chosen to include the worst credible and/or the most likely tsunami events, according to some presumed geological framework. STHA is a straightforward and useful way to understand the potential effects of a tsunami, especially if the worst credible event is well established. Such a scenario analysis can have likelihood information associated with it, based on estimated return times of the scenarios used. However, that is not a requirement for carrying out an STHA. Finally, STHA may, or may not, include inundation modelling (B1.3). Normally, the term "hazard analysis" is used only for a broad-scale assessment affecting many communities. It would not usually involve detailed inundation modelling at the community scale.

STHA is limited in that it essentially addresses only one question: what is the potential impact of a particular suite of scenarios (and sometimes only one scenario) on a particular coast? It is of limited usefulness for broader policy and planning decisions, because it contains little or no information about the likelihood of a tsunami event. It is less suitable for a situation in which the coast of interest may be affected by a number of very different scenarios of varying likelihood; or if the relative hazard due to many scenarios needs to be evaluated over a broad geographical region; or where there is an interest (for example, for building codes, C2.3) in tsunami effects expected at various return periods. Also, STHA typically requires high-resolution bathymetric and topographic data for the shore of interest.

### Probabilistic Tsunami Hazard Analysis (PTHA)

PTHA is at an early stage of development. Its approach has been derived from, and is closely allied to, Probabilistic Seismic Hazard Analysis (PSHA). In contrast to STHA, PTHA attempts to consider a large class of tsunami scenarios, essentially all those which might cause a significant impact, and is often based on more than one geological framework. PTHA is focused less on what the effects of a particular tsunami scenario will be, and more on the question of the likelihood that a tsunami of a given height at sites of interest will be exceeded (see Box B3). PTHA produces a very information-rich result, which can be used to express hazard in many different ways – for example, maps of tsunami exceedance height for various return periods, or deaggregated hazard maps showing the relative contributions of different sources to the hazard at a particular site (see Table B1). These products can be used to answer a variety of questions about the tsunami hazard of interest to emergency managers and coastal planners.

A crucial limitation of PTHA, at least in its implementations currently available, is its inability to model the detailed effects of tsunami inundation. This is because of the large amount of computation required and, sometimes, because the lack of accurate bathymetric and topo-

**Box B3. The Makran subduction zone and its tsunami hazard**

The Makran subduction zone, located off the Indian Ocean coasts of Iran and Pakistan, is an important tsunamigenic zone for the region. On the 27th November, 1945, it was the site of a major earthquake with a moment magnitude of 8.1. This earthquake produced a tsunami which ran up to 5 m to 12 m above sea level and killed about 4000 people. Archival research has revealed at least five tsunami events in the Makran coastal region from a variety of different source types, including earthquakes, volcanoes and landslides.

The Makran tsunami hazard was investigated using semi-probabilistic and full probabilistic methods. The semi-probabilistic method infers the hazard from the maximum tsunami wave height caused by the largest expected earthquake in the region, as determined from a probabilistic seismic hazard assessment (PSHA). The results from a PSHA for this region show that the largest expected earthquake has a moment magnitude of about 8.3 and a return period of about 1000 years. Numerical modelling indicates that the tsunami produced by the largest expected earthquake for the region could reach a maximum run-up height of 9.6 m along the Makran coast.

To determine the likelihood of a tsunami affecting the Makran coast, a probabilistic tsunami hazard assessment (PTHA) was conducted. A PTHA combines the probability of an offshore earthquake occurrence with numerical modelling of a tsunami in order to determine the probability of a tsunami wave exceeding a given maximum water elevation at a coastal site. Based on the results of a PTHA for the Makran subduction zone, the probability of tsunami wave-heights exceeding 5 m along the Makran coasts during the next 50 years is 17.5 per cent. For a moderate tsunami, with a wave height in the range 1 m to 2 m, this probability is as high as 45 per cent.

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*Sources: Heidarzadeh et al., 2008a, b and 2009*

graphic data for the shore of interest. This restricts PTHA's ability to address site-specific mitigation measures, such as the identification of evacuation areas and routes. Also, because this approach requires a much more complete characterization of potential tsunami sources than STHA, its results are more sensitive to uncertainties in the specification of those tsunami sources. Applications of PTHA should take care to adequately express this. PTHA methodologies have been the subject of recent review with a view to improving tsunami hazard assessment guidance in the United States of America.

### Considering joint probability of independent extreme events

The probability of a tsunami impact coinciding with one or more other independent inundation forces – high Spring tide events, extreme wind-forced waves, storm surges or the discharge of land-water floods – may be considered. Of these forces, the state of the tidal cycle is likely to be the most significant in considering the probability of increased levels of coastal inundation from tsunamis (Box B4).

## B1.3 ESTIMATING THE PHYSICAL EFFECTS OF TSUNAMI IMPACTS ON YOUR SHORES

The physical effects of tsunami impact of concern here occur when the tsunami enters shallow water near the coast. At this point the tsunami increases in height through a process known as shoaling, and then runs over the land in a process known as inundation. Both of these are complicated phenomena best described via numerical modelling.

There are three steps to modelling a tsunami:

- In the first step, parameters describing the tsunami source are used to calculate the size and shape of the initial tsunami wave. This step is known as source modelling.
- The second step is to take this initial wave and propagate that wave to the coast. This is called tsunami propagation modelling.
- The final step is to model the tsunami as it inundates the coast. This is known as tsunami inundation modelling.

Usually these three modelling steps use three separate and distinct computer programmes. The output of one forms the input of the next modelling programme in the chain. However, some codes are capable of doing multiple steps (for example, by combining the propagation and inundation modelling steps). Hazard maps can be created by analysing the results of one or more tsunami models. A list of models is given in Table B2.

### Modelling tsunami sources

Once the tsunami source is characterized, then the size and shape of the wave it produces is calculated. For tsunamis generated by an earthquake, it is important to produce an accurate model of the way the sea floor is deformed by the earthquake. To do this, information about the location of the fault, the length and width of the rupture, the elastic properties of the crust above the fault, and the amount direction of slip must be determined.

Historical seismic events can be modelled to provide scenarios for possible future events. However, instrumental data about the earthquakes are often limited and this in turn limits the quality of the models of the event. Hypothetical scenarios can also be modelled, using plausible values for the earthquake parameters, with reference to the historical databases. Such data should be interpreted by an appropriately qualified geologist and/or geophysicist to determine the plausible ranges of possible earthquakes that could occur in the region.

Knowledge of the earthquake parameters is critical to source-modelling the tsunami. A very deep earthquake will not produce as large a tsunami as a shallow one. A wide rupture zone produces a tsunami with a longer initial wavelength than one with a narrow rupture. An earthquake where the two sides of the fault move horizontally (called a strike-slip earthquake) will not uplift the sea floor as much as an earthquake which moves vertically (called a dip-slip earthquake). A link for information on the parameters for modelling earthquake sources of tsunami is given at the end of this section.

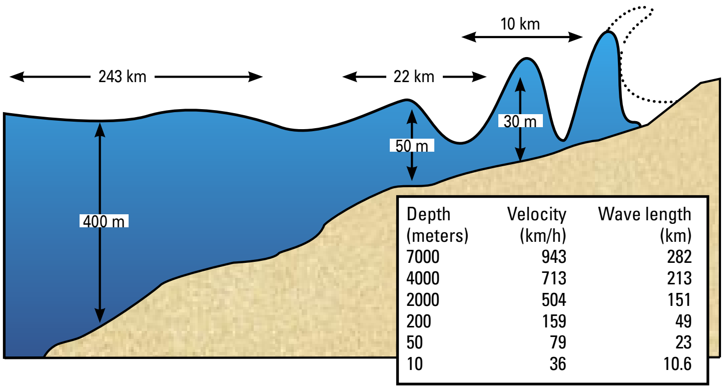
As with earthquakes, the parameters of other possible tsunami sources (landslides, volcanoes and asteroid impacts) must also be constrained in order to determine the size, direction and shape of the initial tsunami wave.

### Understanding tsunami propagation

Propagation of the tsunami is the process by which its wave or waves travel away from its source. The pattern of propagation depends on source factors such as the lateral extent of seabed displacement and its amplitude. It is usually strongly influenced by factors such as water depth and the presence of islands and headlands along its path.

Once a tsunami has been generated, its energy is distributed throughout the water column, regardless of ocean depth. A tsunami comprises a series of very long waves. The dominant wavelength of the tsunami depends on the generating mechanism and the dimensions of the source. The larger and more extensive the earthquake, the greater its initial wavelength and period will be. Conversely, if the tsunami is caused by a local landslide, both its initial wavelength and period will be shorter. The period of constituent waves in a tsunami event may range from 5 to 90 minutes. As they propagate, the wave crests can range from just a few, to more than 100 kilometres apart. In the open ocean, the tsunami wavelength may be hundreds of kilometres, many times greater than the ocean depth. In the deep ocean, the height of the tsunami from trough to crest (the wave height) may range from only a few centimetres to more than one metre, depending on its generating source. Tsunami waves in the deep ocean can travel at high speeds, covering distances of thousands of kilometres and losing little energy in the process; the deeper the water, the greater the rate of propagation. At the deepest ocean depths, the speed of propagation may be as much as 800 km/hour.

As it reaches coastal waters, the propagating tsunami may be diffracted around obstacles such as headlands and islands resulting in marked changes relative to the undisturbed wave field regime. Similarly the wave may be refracted by variations in water depth. In some cases a tsunami may be reflected from a coastline in a way similar to that of wind-forced waves being reflected off a seawall (boxes B4 and B5). Significantly, the wave height is greatly increased where the tsunami enters shallow coastal waters in the process of shoaling, resulting in heights many times greater at the coast than in the open ocean (Fig. B4).




| Depth (meters) | Velocity (km/h) | Wave length (km) |
|---|---|---|
| 7000 | 943 | 282 |
| 4000 | 713 | 213 |
| 2000 | 504 | 151 |
| 200 | 159 | 49 |
| 50 | 79 | 23 |
| 10 | 36 | 10.6 |

*Fig. B4. Tsunami shoaling: the effect of water depth on wave height and velocity.*
*In the open ocean, a tsunami is often only tens of centimetres high, but its wave height grows rapidly in shallow water. Tsunami wave energy extends from the surface to the bottom in the deepest waters. As the tsunami attacks the coastline, the wave energy is compressed into a much shorter distance creating destructive, life-threatening waves.*

Source: Tsunami Glossary, UNESCO 2006. (http://ioc3.unesco.org/itic/files/tsunami_glossary_en_small.pdf), with modification.

One of the first indicators of an impending tsunami impact on a country's shores may be the withdrawal of the sea from the nearshore zone, with wide expanses of seabed becoming unusually emergent. This temporary lowering of sea level is a feature known to some coastal communities and knowledge of it has been the key to their survival (Section C1.4).

### Using tsunami propagation models

Once the size and shape of the initial wave is calculated from a source model, this wave is the one used as input into a tsunami propagation model. The propagation model

**Box B4. Multiple waves, wave refraction and the effect of tides**

The tsunami wave that hit the Seychelles islands on 26 December 2004 had travelled approximately 5000 km from its source, offshore Sumatra, in less than seven hours. At 1 p.m. waves 2.5 m to 4 m high hit the east coast of Praslin, La Digue and Mahé islands. The effects were felt all along the east coast of Mahé, propagating over a 30-minute period. Refracted waves hit the west coast of Praslin and Mahé 30 minutes to 1 hour after the respective east coasts were hit. Another wave occurred at 5 p.m., followed by two smaller waves at 10 p.m. and at 5 a.m. on the following day (27 December). The second wave had more or less the same effect as the first because, although smaller, it occurred at high tide. The two smaller waves caused damage only on the west coast of Praslin. The surges caused by the waves flooded the low-lying areas of Mahé, Praslin and La Digue and caused widespread damage to beaches, coastal vegetation, roads, bridges, other infrastructure and houses. The flooding continued for a period of about 6 hours. Two people lost their lives.

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**Box B5. Tsunami wave impact on Sri Lanka**

The island state of Sri Lanka was severely affected by the 2004 Indian Ocean tsunami. Its eastern coast, directly exposed to the source, was heavily inundated by shoaling tsunamis. The south-eastern and south-western coasts were also affected and, at many locations, inundation levels of 5 m to 10 m were recorded. The combined action of nearshore shoaling processes and local geomorphological features contributed to these high values.

On approaching land, the wave first interacted with the continental shelf, during which process the initial transformation took place. Part of the energy was reflected and the balance transmitted. Sri Lanka has a narrow continental shelf. The mean distance between the coast and the 200-m depth contour is about 20 km reducing to around 5 km at the southern end of the island. The narrow shelf led to wave transformation from deep to shallow water over a short distance without significant energy dissipation. On reaching shallower water, the wave heights increased. This increase was accompanied by the processes of refraction, diffraction and reflection around bays and headlands. Cities located adjacent to bays and headlands (for example, Hamabanthota and Galle) witnessed very high waves. Wide variations in inundation heights were observed over short distances along the coastline.

On the western coast, not directly exposed to the tsunami source, the highest waves recorded corresponded to those reflected from the Maldivian atolls to the west, illustrating the influence of such natural submarine features. Analysis of tidal gauge readings and measurements from equipment located off the coast of Colombo confirmed that the highest wave arrived about 3.5 hours after the first wave. Sea-bed currents at this location increased from 20 cm/s to 70 cm/s.

Inundation on the southern coast would have be greater but for the low tidal conditions on tsunami impact (albeit a microtidal shore). (see also Box C3)

Sam Hettiarachchi

incrementally solves a series of mathematical equations to take the initial wave and "bring" it to the coast. In order to model the tsunami accurately, the spatial resolution of the model must be much smaller than the smallest wavelength of the tsunami. The spatial resolution of the model controls the spatial resolution of the input data, such as the bathymetry. So, if the wavelength of a tsunami generated by an earthquake is, for example, 100 km, then the grid resolution to accurately model this wave should be much smaller than this. Grids for deep-water propagation models are typically 1 km to 2 km in spacing when modelling earthquake-induced tsunamis which are dominated by wavelengths of 100 km or more in deep water.

Countries may be able to obtain global bathymetry datasets from global data sources (such as ETOPO2 or GEBCO, see Table B3). Many countries' Geological Surveys and/or Navies may have better datasets for their respective country's waters than exist in the global datasets. Ideally, for areas closer to the coast, such data would be used instead of that from the global datasets.

Shallow water tsunami propagation typically needs a higher resolution grid than deep water propagation. Therefore one of the main limitations which influence the offshore depth chosen for a regional hazard study is the availability of high resolution, accurate bathymetry data close to the coast. Very often, regional hazard maps are made outside reefs and other areas of complex shallow bathymetry. For continental regions, the edge of the continental shelf (typically from about 50 m to 100 m in depth) can be chosen.

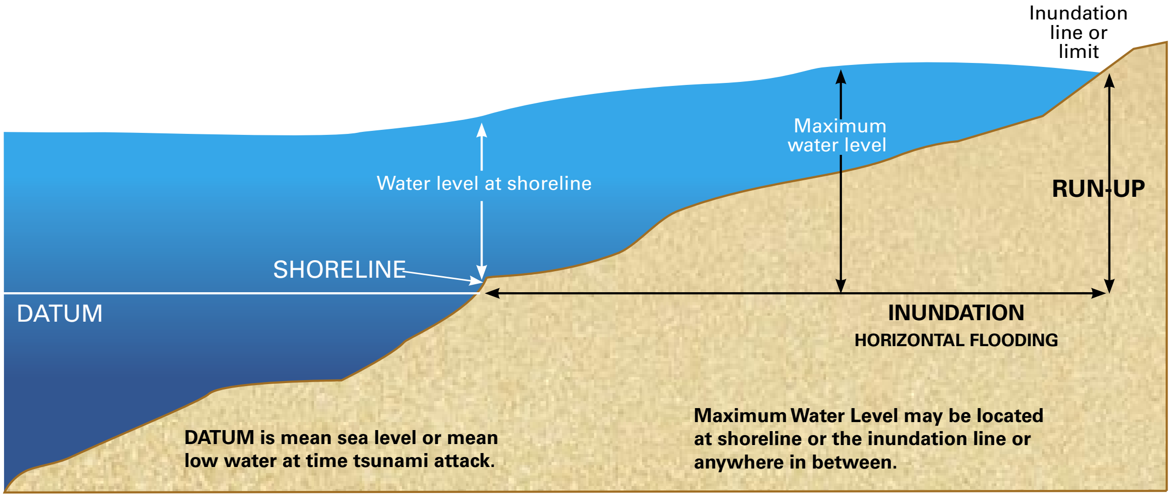



***Fig. B5.*** *Tsunami impact at the coast: an explanation of terms.*

*Source: UNESCO-IOC International Tsunami Information Centre (ITIC) with modification.*

## Understanding tsunami inundation

Observations of the impacts of the 2004 tsunami event have contributed greatly to our understanding of tsunami inundation. They have shown how variable it can be, even along a few kilometres of coastline. The form of the nearshore bathymetry is one of the key determinants. The influence of coastal bathymetry on tsunami wave height and velocity, and on the forces exerted, during the shoaling process has received considerable attention from researchers. The on-shore coastal geomorphology is also a key factor influencing the extent of inundation and run-up (Fig. B5). Other modifiers of inundation are coastal vegetation, especially mangrove, and the built environment, including any existing engineered defences. The impact of a tsunami can also be exacerbated by materials that become entrained in the course of inundation and also, importantly, during its subsequent drainage. The inundation and its drainage can result in significant erosion, e.g., by scouring around buildings foundations, and sedimentation, for example, causing degradation of coral reefs.

An essential part of the risk assessment procedure is the geospatial recording of the various parameters of tsunami inundation on maps at the local scale. These maps are referred to collectively as local hazard maps and their construction is described below.

## Using tsunami inundation models

The modelling of tsunami inundation and run-up has received considerable attention, and many models are now available (Table B2). Key inputs to these models include the open ocean (deep water) wave height (see above), and digital nearshore bathymetric and coastal elevation data. Tidal data may also be important (Fig. B6 and see Box B4).

The severity of a tsunami impact is critically dependent on complex bathymetric and topographic effects near the area of interest. Estimating the physical impact of a tsunami on a shore therefore requires modelling of the non-linear process by which waves are reflected and otherwise shaped by local bathymetry and topography. These complex effects generally require elevation data of a resolution much higher than is used by the propagation models, which typically use data resolutions in the order of kilometres or less (sufficient to model long-wavelength tsunamis in open water). The data resolution used by inundation models, by contrast, is typically in the order of metres.

Running an inundation model capable of resolving local bathymetric effects and run-up using detailed elevation data requires more computational resources than the typical propagation model. Except for the case local (near-field) tsunamis, where the tsunami is generated immediately offshore the shore site of interest, it is impractical to use an inundation model for complete end-to-end (source to run-up) modelling of a tsunami event. Instead, a hybrid approach is typically used. In this, the output from a propagation model is used as input to an inundation model at the seaward boundary of its study area. The output of the propagation model thus serves as a boundary condition for the inundation model. In this way, we restrict the computationally intensive part of the modelling to the geographical area where a detailed understanding of the inundation process is required (Fig. B6).

Furthermore, to avoid unnecessary computations, some inundation models (for example, ANUGA, see Table B2) work with an unstructured triangular mesh rather than the rectangular grids typically used by propagation models. The advantage of an unstructured mesh is that different regions can have different resolutions, allowing computational resources to be directed where they are most needed. For example, one might use very high resolution near a community or in an estuary, whereas a coarser resolution might be enough for deeper water, where the bathymetric effects are less pronounced.

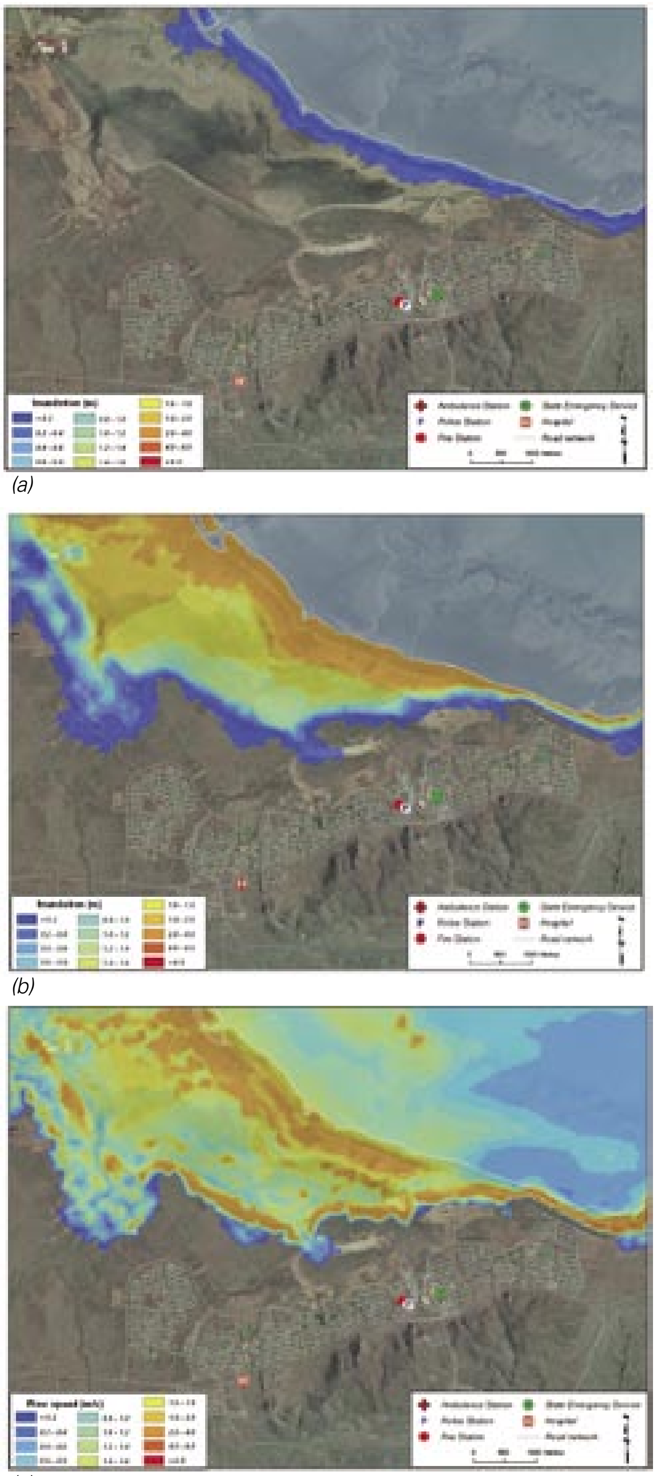
To implement a scenario, the inundation modeller requires suitable initial conditions (such as a tidal height), boundary conditions (such as data from the adjoining propagation model), forcing terms if appropriate and, importantly, bathymetric and topographic data for the study area. The calculated run-up height and resulting inundation is determined by these inputs, as well as by the cell resolution. In addition, the pattern of current velocities attained during inundation and drainage can be determined.

The data should ideally capture all complex features of the underlying bathymetry and topography, and cell resolution should be commensurate with the underlying data. Any limitations in the resolution and accuracy of the data, including the cell resolution, will introduce errors to the inundation maps as well as to the range of model approximations. National scale datasets are often held by national geological and oceanographic surveys and local scale datasets by State and Local Governments. Local data sets are usually required for an inundation model, due to the higher resolutions required. In many cases there are limitations on use between different agencies according to the licence agreements.

### Validation of tsunami models

The recent proliferation of tsunami modelling codes highlights the need for verifying that models accurately solve the appropriate hydrodynamic equations, and to ensure that they can accurately reproduce the observed phenomena. There are a number of analytical and laboratory benchmarks against which tsunami models can be verified.

Models and their input data can be validated by comparing results from modelling a historic event for which observational data exist. Typical data used to validate the source and propagation models are deep ocean pressure gauge data (for example, from the DART network) or coastal tide-gauge data. If the propagation model is coupled to an inundation model, then the observed tsunami run-up and inundation distance observations from historic events can also be used for validation. If the difference between the observed and modelled results is too large, then either the model, or (more typically) the input data, needs to be improved. This could include obtaining better/higher resolution bathymetry and topography, a better model of the source and/or using a more sophisticated numerical model. The exact requirements to reduce such misfits between observation and the model vary from one validation run to another.



*(a)*

*(b)*

*(c)*

***Fig. B6.*** *A modelled inundation and flow velocity maps for a location in Western Australia.*
*Example of a tsunami generated by earthquake on the Sunda Arc subduction zone to the south of Indonesia.*
*Modelled maximum inundation map at Mean Sea Level: the figure shows the maximum water depth caused by the tsunami.*
*(b) Modelled maximum inundation map at Highest Astronomical Tide: the figure shows the maximum water depth caused by the tsunami.*
*(c) Modelled maximum flow velocity map at Highest Astronomical Tide, the flows resulting from the inundation.*

*Source: Geoscience Australia. Images courtesy of Australian Journal of Emergency Management.*

| | |
|---|---|
| ANUGA | Geoscience Australia and Australian National University (http://www.ga.gov.au/hazards/tsunami/tools.jsp; http://sourceforge.net/projects/ANUGA) |
| COMCOT | Cornell Multigrid Coupled Tsunami model: Cornell University (http://ceeserver.cee.cornell.edu/pll-group/comcot.htm) |
| Delft3D | Deltares, Netherlands (http://www.wldelft.nl/cons/area/ehy/flood/tsunami.html) |
| FUNWAVE | Fully Nonlinear Wave Model: University of Delaware, U.S.A. (http://chinacat.coastal.udel.edu/~kirby/programs/funwave/funwave.html) |
| GEOWAVE | Combination of TOPICS (Tsunami Open And Progressive Initial Conditions System) and FUNWAVE |
| GTM | Global Tsuami Model: TRG (Tsunami Research Group) at University of Alaska, U.S.A. (http://www.sfos.uaf.edu/tsunami/) |
| MIKE21 | DHI, Denmark (http://www.dhigroup.com/Software/Marine/MIKE21.aspx) |
| MOST | Method of Splitting Tsunami: NOAA, U.S.A. (developed by University of Southern California) (http://nctr.pmel.noaa.gov/index.html) |
| TOAST | Tidal Ocean Atmosphere Surge and Tsunami simulation model: IISc, India (http://www.iisc.ernet.in/) |
| TsunamiClaw | University of Washington, U.S.A. (http://www.amath.washington.edu/~dgeorge/tsunamimodeling.html) |
| Tsunami Propagation Model | Joint Research Centre, JRC (http://tsunami.jrc.it/model/) |
| TSUNAMOS | Tsunami Open Source: NSF (National Science Foundation) funded NEES (Network for Earthquake Engineering Simulation) project, Texas A&M University, Cornell University, University of Hawaii and University of Puerto Rico – Mayaguez |
| TsunAWI | AWI, Germany (http://www.awi.de) |
| TUNA | Universiti Sains Malaysia, Malaysia (http://www.usm.my/) |
| TUNAMI | Tohoku University, Japan (www.tsunami.civil.tohoku.ac.jp) |

***Table B2.*** *A list of tsunami models.*

## B1.4 CONSTRUCTING LOCAL HAZARD MAPS

The creation of local hazard maps is a key step in the tsunami risk assessment procedure. These maps form a basis for evacuation planning and for land-use planning. They also provide the information for determining the exposure parameters within a defined coastal management area that will be used in the assessment of vulnerability of the coastal community and of their supporting assets and systems.

Local tsunami hazard maps are usually developed from specified tsunami event scenarios. At the simplest level, a local hazard map would be constructed by using contoured elevation data for the coastal land at the level of a specified wave height, using GIS (Geographical Information System) technology. The elevation data would be derived from, for example, a digital elevation model or, if available, topographic survey. Such a simplified local hazard map does not, however, take into account the dynamics of the tsunami, in which the focusing and defocusing of tsunami energy may cause the inundation level to rise above the specified wave height in some areas and never reach it in others. To some extent this shortcoming can be rectified by displaying observational information relating to past events as an event record map. The types of processes, extent of affected area and date of occur-

| Products | Variables (and standards) | Sources | Global datasets and programmes |
|---|---|---|---|
| Seismic event probability assessment | Frequency;<br>magnitude;<br>location | National seismological institutes | NOAA/WDC Historical Tsunami Database (http://www.ngdc.noaa.gov/hazard/tsu_db.shtml)<br>Novosibirsk Tsunami Laboratory Historical Tsunami Database for the World Ocean (http://tsun.sscc.ru/On_line_Cat.htm)<br>Indian Ocean Tsunami Hazard Map |
| Tsunami hazard assessment | Open ocean wave height | Satellite altimetry | |
| | shoreline wave height;<br>inundation limit;<br>run-up | Local records;<br>anecdotal accounts | |
| Bathymetric data, coastal topographic data | Bathymetry;<br>onshore topography;<br>existing defences | Hydrographic charts;<br>LIDAR survey;<br>digital terrain;<br>modelling | General Bathymetric Chart of the Oceans (GEBCO) (http://www.gebco.net/)<br>ETOPO2<br>(http://www.bodc.ac.uk/projects/gebco/index.html<br>http://srtm.csi.cgiar.org) |
| Inundation maps | | Satellite imagery;<br>modelling;<br>surveying;<br>local records;<br>anecdotal accounts | COAST-MAP-IO Project, Improving Emergency Response to Ocean-based Extreme Events through Coastal Mapping Capacity Building in the Indian Ocean<br>(http://www.ioc-cd.org/)<br>GITEWS project (http://www.gitews.org)<br>Hazard mapping methodology: Jakarta Tsunami Information Centre (www.jtic.org) |
| Tsunami models | Sources;<br>propagation;<br>ocean wave height;<br>shoreline wave height;<br>inundation;<br>run-up | National oceanographic institutes<br><br>See listing in Table B2 | |

***Table B3.*** *Information sources for tsunami hazard assessment.*

rence can be depicted. Often, however, such detailed information about past events is unavailable.

Numerical inundation models, described above, allow us to considerably improve on the use of elevation contours alone for predicting the likely behaviour of a tsunami as it impacts the shore and coastal lowland. The procedure requires either that the modelling be end-to-end (source to run-up) as for a near-field tsunami generated near the coastal community, or that the inundation model be linked to the output of a propagation model, as for a tsunami generated far from the affected coastal community.

Ideally, local hazard maps carry information about the parameters of inundation of water over the shoreline and coastal lowland – its run-up heights, its depths, and the flow parameters (velocities and directions), not only during the flood episode but also during drainage. As such, these maps represent the variations in exposure to a tsunami within a given area. Additional information might include an indication of the total flood volume and the travel time of the tsunami from its likely source. The information on such an inundation map provides the reader with a picture of the extent and level of inundation to which a coastal community and its supporting assets (B2.2) would be subject.

A basic inundation map records information for a specified tsunami scenario. The analysis in such cases is deterministic – determining the parameters of inundation resulting from that scenario. In displaying inundation limits on printed maps, it may be considered convenient to depict the limits for a range of credible scenarios on a single base. Alternatively the geospatial information relating to individual scenarios within a range may be archived as independent layers using, for example, GIS technology.

Deterministic analysis neither involves, nor implies, information on the likelihood of occurrence or probability of such a scenario (B1.2). Thus, a deterministic analysis cannot, by itself, provide an assessment of risk. Despite this shortcoming, detailed, deterministic modelling, based on particular source scenarios may best serve the purposes of emergency managers in the task of evacuation planning (C1.3) and coastal engineers and planners in their design and development of effective tsunami counter-measures and land use (C.2).

The inundation maps may be configured as true hazard maps by the attachment of probability levels expressed, e.g., as return periods, to the scenario-based map outputs. Thus a likelihood of occurrence related to a specified scenario is expressed by, for example, the inundation limits displayed on the map.

**Box B6. Hazard mapping in Indonesia – approaches within the GITEWS project**

Understanding tsunami hazard and possible local impacts is a prerequisite for local authorities and other stakeholders in tsunami preparedness in order to anticipate future tsunami events. Different initiatives concerning Tsunami Hazard Mapping are currently under way in Indonesia. For many Indonesian coastal communities in tsunami-prone regions, however, still very little information is available and it is uncertain whether such communities will receive the attention they need.

A current initiative in Indonesia, in three pilot districts in Java – Bantul, Kebumen and Cilacap, is to initiate the design of a participatory, simple, and low-tech but sufficient and adequate tsunami hazard mapping methodology that can be applied at district level in order to understand tsunami hazard and become prepared for future disasters – especially in those regions where there is a persistent lack of understanding about tsunami hazard and limited attention from existing hazard mapping initiatives.

The initiative has resulted in a preliminary tsunami hazard map for each of the three participating districts; it has increased knowledge and awareness among the participants about the potential tsunami threat as well as overall tsunami characteristics, and has developed vital capacities for tsunami preparedness. The methodology may be downloaded at: http://www.jtic.org.

A more comprehensive approach is being applied for the hazard mapping of the coastal areas of West Sumatra, South Java and Bali. The hazard maps are generated based on a multi-scenario approach. This deterministic approach uses a large number of realistic scenarios and combines the inundation results to integrated hazard maps. The analysis of probabilities of earthquake occurrences derived from historical data and geophysical research is included in the derivation of hazard probability maps. The maps are provided at 1:100,000 (map scale) for the respective coastal areas, and in greater detail – e.g., 1:25,000 (map scale) – for the pilot regions of Padang, Cilacap and Bali.

The results in the hazard maps are displayed as continuous values or as derived hazard zones. The definition of the hazard zones can be linked to the different levels of warnings provided by the Ina TEWS Early Warning System. The hazard zones are related to the levels of warning (tsunami warning or major tsunami), which are linked to the expected wave heights at the coast. An example is shown in Fig. B7.

Harald Spahn (GTZ IS), Kai Zosseder and Günter Strunz (DLR)

*Source: GITEWS project. Courtesy: GTZ-IS, DLR*

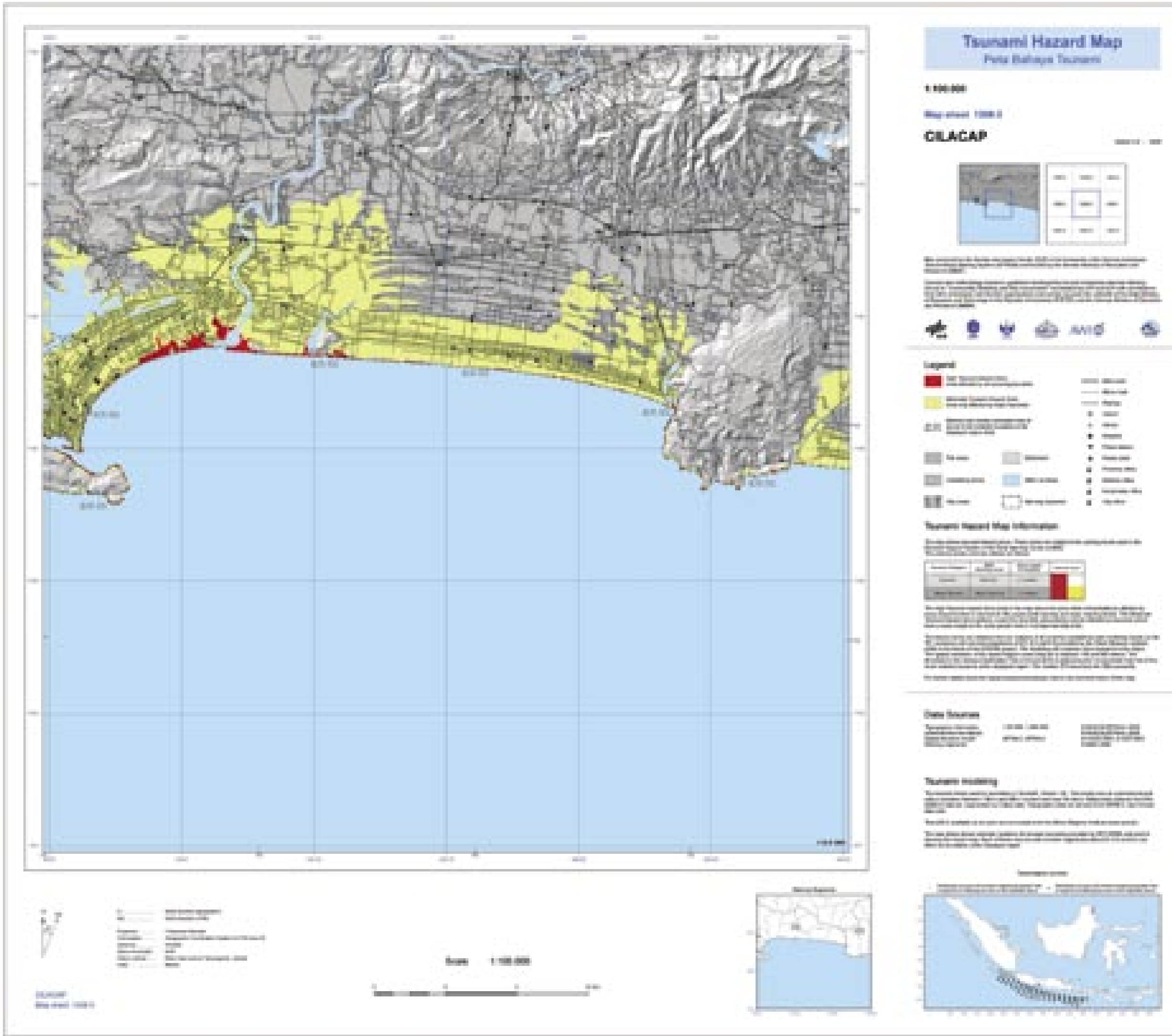



***Fig. B7.*** *Tsunami hazard map at the local scale. With modification.*
*This example covers the city of Cilacap, Java, Indonesia. The map, at 1: 100 000 (map scale), shows tsunami hazard impact zones (high=red; moderate=yellow) calculated using a multi-scenario approach. The zones comply with the tsunami warning levels issued by BMKG Indonesia in order to directly relate the tsunami warning information to hazard impact zones. Additionally, the tsunamigenic sources, which cause a tsunami impact on land for this coastal area, are shown on the map (bottom right-hand corner).*
*Source: GITEWS Project. Courtesy DLR, AWI.*

### Selecting representative scenarios

So, how do we pick representative events or scenarios? In the case of a community threatened by a local (near-field) tsunami, the obvious choice is the tsunami source area immediately offshore. For a community threatened by a more complicated mix of tsunamis generated by more distant sources, this can be done through a method called deaggregation (Table B1). If a probabilistic tsunami hazard map exists for the area (see B1.2) it can be deaggregated to allow the user to specify a location and either a hazard probability or wave amplitude of interest. The deaggregation process selects all the event scenarios (earthquake locations, magnitudes and frequencies of occurrence) that contribute to the tsunami hazard specification (probability, wave height). For very small-amplitude waves or very high probabilities, there is generally a wide range of earthquake magnitudes, locations and frequencies that contribute to the tsunami hazard. However, as the probability decreases (or the return period increases), the number of events diminishes dramatically. At return periods of 1000 years or more, it is often possible to select a single, representative event for the scenario analysis. In some cases, several events may be required for further analysis, representing either different return periods or different sources of tsunamis which might result in different characteristics or distributions of inundation and damage to a community. It is generally recommended that several events be used to capture the range of uncertainty and possible impacts of tsunami events.

Hazard maps may be elaborated to hazard danger maps by the depiction of danger zones, derived, for example, from parameters such as inundation depth, flow velocities, proximity to the shore or a channel and frequency of inundation. Such maps can be used effectively as a tool for mitigating the direct impact of the hazard, by land-use and emergency planning and site monitoring.

## B1.5 OUTPUTS FROM THE HAZARD ASSESSMENT

The following is a list of possible information outputs based on the background and procedures described in B1:

- a listing of all known tsunamigenic events to have impacted your region;
- analysis of pre-calculated tsunami propagation patterns for tsunamis from likely earthquake sources to determine potential for impact on your country's coasts;
- a map showing your coasts most prone to potential tsunami impact;
- hazard maps for specified tsunami scenarios showing limits of coastal land that is likely to be affected by those scenarios (inundation limits, run-up, erosion), water depths at maximum inundation, inundation- and drainage-flow indicators; and
- estimated return periods for the specified tsunami scenarios.

### Suggested additional reading and information sources

Annunziato, A. 2007. The Tsunami Assessment Modelling System by the Joint Research Centre. *Science of Tsunami Hazards*, Vol. 26, No. 2, pp. 70–92. http://tsunamisociety.org/262Annunziato.pdf (Accessed 19 February 2009.)

IOC unified tsunami website (IOC Tsunami Home). Available at: http://www.ioc-tsunami.org/

NOAA Centre for Tsunami Research. n.d. Available at: http://nctr.pmel.noaa.gov/sim.html (This website provides information on the IOC tsunami programme, the Regional Tsunami Warning Systems (RTWS) and the National Contacts for RTWS.)

Stevens, R., Hall G. and Sexton, J. 2008. Tsunami planning and preparation in Western Australia: application of scientific modelling and community engagement. *Australian Journal of Emergency Management*, Vol. 23, No. 4, pp. 30–36.

Thomas, C. and Burbidge, D. 2009. A probabilistic tsunami hazard assessment of the Southwest Pacific Nations. *Geoscience Australia Professional Opinion*. No. 2009/02. (This paper provides information on the parameters required for tsunami source modelling.)

UNESCO. 2006. *Tsunami – The Great Waves*. IOC Brochure 2006-2. Paris, UNESCO. (available in English, Spanish, French, and Chinese.) http://ioc3.unesco.org/itic/files/great_waves_en_2006_small.pdf (Accessed 19 February 2009.) http://ioc3.unesco.org/itic/files/great_waves_en_2006_small.pdf (Accessed 19 February 2009.)

UNESCO. 2006. *Tsunami Glossary*. IOC Information document No. 1221. Paris, UNESCO. http://ioc3.unesco.org/itic/files/tsunami_glossary_en_small.pdf (Accessed 19 February 2009.)

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

# **B2 Are your communities** vulnerable?

**Key tasks in the vulnerability assessment procedure**

- Define the geographical scale and limits of the assessment.
- Define the temporal scale of the assessment.
- Create an asset (inventory) database of people and their supporting systems.
- Create an exposure database of people and their supporting systems.
- Classify assets by levels of vulnerability for specified tsunami hazard scenario(s) and required response times for evacuation.
- Produce vulnerability map(s) and reports for the management area.
- Communicate the vulnerability assessments to all involved in risk assessment and emergency management.

This part of the Guidelines provides guidance in response to the question on whether your coastal communities and their supporting assets and resources are vulnerable to tsunamis to which your coasts may be prone. It describes the multifaceted nature of vulnerability and different approaches to its assessment; it then provides guidance on vulnerability assessment procedures for estimating the consequences (damage and losses) arising from the impact of a specified tsunami scenario.

The term "vulnerability", as used in these guidelines in respect of a tsunami impact, is the state of a coastal community, determined by social, physical, economic and environmental factors or processes, which predispose that community to be damaged or suffer losses. "Coastal community", as used here, includes its social aspects, its buildings, economic aspects and infrastructure, and its supporting environmental systems.

## B2.1 UNDERSTANDING VULNERABILITY – AND HOW TO ASSESS IT

Following the 2004 Indian Ocean tsunami, impact damage and loss surveys were carried out in nearly all the affected Indian Ocean states. These surveys revealed very high levels of social, physical, economic and, in many cases, environmental vulnerability (Table B4). Many of these assessments could relate damage and loss to known tsunami heights. Such post-impact empirical observation inevitably has a potential for producing reliable vulnerability assessments. These guidelines, however, are concerned with achieving a realistic vulnerability assessment before a tsunami event, so that action can be taken to reduce the levels of vulnerability in anticipation of such an event.

There is yet no global consensus on how vulnerability to natural hazards should be assessed. Because of its multifaceted nature, it is difficult to measure and its measurements carry uncertainties. While recognising these uncertainties, this element of the Guidelines sets out options for assessment approaches that focus on measurable indicators that are relevant to achieving the overarching objective of risk reduction.

Vulnerability analysis must be adapted to the specific objectives required by the policy maker and emergency manager. The choice of approach may depend on the scale of the assessment required. For assessment of the whole national coastline or relatively large coastal areas, a broad scale resolution might be appropriate. At more local levels there are options of applying an increasing resolution to the assessment process. Managers also need to consider the time period that the assessment is intended to span. Factors that contribute to vulnerability are dynamic. They are likely to change over time because of, for example, changing (usually increasing) coastal population, economic developments, social structures, and environmental states.

Irrespective of the approach employed, there are key steps that policy makers and emergency managers should follow in assessing vulnerability. These relate to the information outputs from the hazard assessment, i.e.:

- the likely extent of inundation to affect their coastal area;
- the way in which inundation occurs (flow velocities and directions, momentum, entrained debris, etc.); and
- the likely warning time that would be available for an emergency response, including evacuation.

The procedure is summarized here and described in more detail below.

| | Category | Persons |
|---|---|---|
| Social impacts in Galle City<br>Source: Local UNV Officer, Galle District | Deaths | 767 |
| | Missing persons | 110 |
| | Affected persons | 28,440 |
| | Affected because of unemployment | 1360 |
| | Displaced families | 5579 |
| Social impacts, Educational Sector, in Southern Province, Sri Lanka<br>Source: Director, Southern Province Provincial Education Deptartment | People related to education | |
| | Deaths, teachers | 767 |
| | Deaths, children | Over 500 |
| | Number of children losing both parents | 200 |
| | Number of children losing at least one parent | 1000 |
| | Number of teachers who have lost at least one child | 74 |
| Social impacts, Fishing Sector, in Galle District<br>Source: Inspector of the Fisheries Department within the District of Galle Administration | People related to education | |
| | Deaths, fishermen | 64 |
| | Deaths, family dependants | 305 |
| | Number of families displaced | 1133 |
| | Houses destroyed (fishermen) | 1108 |
| | Houses damaged (fishermen) | 843 |
| *Source: Juan Carlos Villagran, undated. Rapid assessment of damages and coping capacities within the city of Galle, Sri Lanka. UNU-EHS internal report.* | | |

***Table B4**. Social impacts of the 2004 Indian Ocean tsunami in Sri Lanka.*

As described in B1.3, the extent and nature of the inundation determine the extent to which the community and its assets are exposed to a specified hazard scenario. Using the outputs from the hazard assessment, emergency managers will need to create a community asset database, a process known as asset mapping. The database is essentially a community census and asset inventory for the defined coastal area. The distribution of assets is then mapped in relation to the exposure information carried by the local hazard map, producing an exposure map and database for the community assets. This map should show the distribution of people, buildings, infrastructure and environmental assets in relation to information on the various hazard exposure parameters (inundation limit, run-up, depth of water, proximity to open coast, inundation and drainage flow velocities, etc.) for that hazard scenario.

In making their assessment, emergency managers will need to consider the vulnerability of people and the various community assets in terms of human and monetary loss or damage in the event of an inundation. Socio-economic factors may play a major role in the extent to which a community is exposed to the hazard and thus its vulnerability.

Vulnerability depends on a wide range of contributory factors or parameters. For any given hazard scenario, there is a range of vulnerability levels according to the parameter assessed, the approach used and the level of detail required.

## B2.2 CONSTRUCTING AN EXPOSURE DATABASE

A foundation for any assessment of vulnerability is the existence of an up-to-date knowledge of the distribution of people and their supporting assets within the coastal areas that may be exposed to tsunami inundation. Such an exposure database, derived from an asset database and information contained in the local hazard map, forms a basis for determining the vulnerability of community assets to specified tsunami scenarios. The numbers of people of defined groups, the community's buildings, the distribution of their infrastructure and their supporting environment within the coastal area together influence the total vulnerability. These data are essential to any vulnerability assessment.

Analysis of community vulnerability requires the development of extensive datasets that define the community's most vulnerable components. Key data of interest are:

- census data (population distribution, income, and statistics such as age, occupation, disability, education);
- building classifications, construction materials and techniques, ground level elevations;
- critical infrastructure (roads, water, power, sewerage, emergency facilities, hospitals, etc.);
- economic location data (business sectors, industrial production, exports, imports, etc.);
- emergency centres in potential inundation zones; and
- environmental services.

These data provide the basis for vulnerability assessments, allowing you to determine the potential impact of an inundation event in terms of loss and damage. In order to conduct vulnerability assessments on a national scale, exposure databases need to be developed beginning at the local level and integrated at district or national levels, in order to assure uniformity in the assessment process.

## B2.3 CHOOSING AN ASSESSMENT APPROACH – THE OPTIONS

Much has been written about the vulnerability of communities and their supporting economies and ecosystem services in the context of natural disasters, for example, the publications of ISDR. Some publications deal with specific dimensions of a community's vulnerability – its social fabric, its buildings, its economy and its supporting environment and institutions. Some authors include the notions of exposure, coping capacity, and susceptibility within the context of vulnerability (see Box B8), but there is no consensus on the definition of vulnerability. In this document, coping capacity is included within the concept of preparedness (B3), and exposure information provides the spatial context for integrating hazard and vulnerability (B1). The term susceptibility is taken to be synonymous with vulnerability.

Dimensional vulnerability assessments may assist policy makers in the identification of critical areas or weak spots in respect of, for example, human and buildings security, industrial and utilities infrastructure and ecosystem integrity. Another approach, recently introduced, is the assessment of vulnerability by considering sectors of development. From a policy-relevant point of view, this approach, cross-cutting dimensional boundaries, encourages agencies in charge of these sectors to take responsibility concerning vulnerability reduction within their respective sectors.

It is up to the policy maker or emergency manager to decide on the approach to be used and the level of detail required. The approach may be constrained by data availability or may be determined by the defined scale – whether for local, district or national overview purposes. Practitioners need to specify their priorities for assessment – those being of particular relevance or importance to the community.

### A first-order analysis

The most basic approach is to consider that all community assets that would be subject to inundation are vulnerable. The geospatially referenced positions and topographic levels of people and their community assets such as buildings or infrastructure would be juxtaposed with specified levels of tsunami exposure, an operation achieved by use of GIS technology. This is the least reliable of the assessment approaches described here. However, it may be appropriate for an initial assessment of relatively large coastal areas. Typically, this is the approach used to define evacuation routes (C1.4).

### A second-order analysis – dimensions of vulnerability

The complexity of communities and their support systems has led experts to recognise dimensions of vulnerability – including social, physical, economic and environmental. Each dimension is characterized through a variety of parameters (B2.4). In making such an analysis, it should be recognized that the boundaries between dimensions are generally not clear-cut. Thus, losses in, say, the physical dimension (notably, buildings) may have clear implications for losses in social and economic dimensions.

### Refining the analysis

Assessment of each dimension of vulnerability may take into account the outcome of a more refined analysis. The degree of potential damage or loss of community assets may differ considerably within the defined coastal area. This may be because of different levels of exposure (associated with a specified hazard scenario). For example, physical damage related to inundation tends to be greatest in parts of the area closest to the shore where exposure is highest. Social vulnerability in the case of tsunamis may be greatest amongst infants and small children, the old and disabled – such people having high susceptibility to harm, an intrinsic quality unrelated to the hazard exposure. These considerations offer refinement to the dimensions of vulnerability approach and may be appropriate in detailed assessments of relatively small areas.

### The sector approach

As an alternative to the dimensions of vulnerability approach, and in recognition of the (often) fuzzy boundaries between dimensions, the approach based on the notions of sectors of development may be considered (B2.5). From a risk management point of view, particularly when assigning responsibilities with respect to the mitigation of existing vulnerabilities, this approach may have an appeal. Logic dictates that responsibility for the reduction of vulnerability within each sector (for example, health, transport, education) rests with the agency in charge, irrespective of the dimensions involved.

## B2.4 USING A "DIMENSIONS OF VULNERABILITY" APPROACH

Vulnerability assessment involves the identification of indicators or proxies which may qualitatively or quantitatively capture the following factors:

- social – issues such as levels of literacy, gender, education, peace and security, access to human rights, social equity, traditional values, beliefs and organizational systems;
- physical – susceptibilities of the built environment, including infrastructure;
- economic – issues of poverty, level of debt and access to credits;
- environmental – natural resource depletion and degradation.

In practice, the boundaries between these dimensions are far from clear cut. For example, there are obvious overlaps between the social and economic dimensions in respect of gender and poverty. These dimensions are described in more detail below and information sources are listed in Table B5.

### Social dimension

Social vulnerability is a pre-existing condition that strongly determines a society's ability to prepare for, and recover from, a disruptive event. Disasters and similar shocks make social vulnerability visible since the unequal patterns of suffering and recovery become apparent.

The assessment of social vulnerability in the context of exposure to a potential tsunami impact aims to determine the predisposition of people and their livelihoods, societies, and organizations within the coastal community to be affected by a tsunami in this case. This predisposition may reflect social structures and cultural values as well as people's access to resources and opportunities. Levels of social vulnerability may also reflect social castes or ethnic differences, and tend to be highest among marginalized groups, such as the poor, women, children and the elderly (Box B7).

Other parameters which may contribute to the social dimension of vulnerability, particularly in urban areas, are:

- population growth and migration patterns, notably in coastal megacities; and
- fragmentation among different social groups and sectors in urban areas.

In rural coastal communities, people dependent for their livelihoods on inshore artisanal fishers, such as those on the Indian Ocean coasts of Somalia, Kenya and Tanzania (see boxes C2 and C3), would be particularly vulnerable to a significant tsunami impact on their shores.

While it is imperative to measure the current state of vulnerability of a community (from the typology angle, for example), it is equally important to assess the root causes related to those social, political, institutional, economic, environmental, and cultural factors which have led to the current state of vulnerability of such a community. The assessment of root causes finds uses when promoting a broader perspective within the context of risk management.

### Box B7. Gender and age-related differentials in social vulnerability

The 2004 Indian Ocean tsunami manifested gender and age-related differential aspects with respect to the social dimension of vulnerability. Children in the youngest age group (0–10 years old) and adults over 40 years old could be considered as highly vulnerable when looking at the mortality rates in the coastal cities Galle and Batticaloa in Sri Lanka. Similar results have been presented for women based on mortality rates by gender. Findings in the Ampara District of Sri Lanka confirmed the notion that children in the youngest age group are highly vulnerable, as well as people over fifty. Researchers have concluded that women are far more vulnerable than men in these same geographical areas. A mortality survey in Tamil Nadu in India similarly highlighted the differential vulnerability of children, elderly and women.

In the case of children, higher mortality can be explained by physiological differences. Their small mass means they can be readily carried away by a tsunami as they lack the strength to grasp fixed objects such as trees. For women, higher mortality may be attributed to physiological and social characteristics. Like children, women may have less strength than men. In addition, learned skills tend to differ between men and women, particularly swimming and climbing trees, activities usually taught to boys but not to girls. Finally, some authors argue that the traditional division of labour means that women spend substantial amounts of time inside houses which could collapse on tsunami impact due to structural vulnerability. In the case of Sri Lanka and India, a social aspect which could contribute to higher mortality for women is the traditional wearing of saris, which could hamper running and swimming, and become tangled with heavy objects, leading to death by drowning.

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**Box B8. Sub-national vulnerability assessment to tsunami risk in Indonesia – the GITEWS project (see also Fig. B8)**

The vulnerability assessment within the GITEWS project focuses particularly on vulnerability factors of people exposed to tsunamis in terms of loss of life, injury and loss of livelihood. The assessment framework outlines two potential paths for reducing disaster risk and vulnerability through preventive measures before a disaster manifests, and through disaster response and management in the aftermath of a disaster. As a result, the project aims at providing sound information to support:

- crisis management capacities (e.g., emergency assistance) during an early warning scenario and
- developing disaster risk reduction strategies, such as measures for adaptation and mitigation.

Accordingly, the GITEWS vulnerability assessment aims at providing indicators and assessment tools for the continuous improvement of intervention tools, such as early warning and evacuation planning, disaster response and rehabilitation. The vulnerability assessment hence addresses the following components:

- the susceptibility and degree of exposure of vulnerable elements (population, critical facilities, built environment and regions affected), and
- the ability to respond (coping) and recover from the disastrous impact of a tsunami.

The vulnerability assessment results allow monitoring and quantification of the spatial vulnerabilities within the timeline of disaster occurrence. That means that, at each location, people's vulnerabilities to tsunami warning (e.g. people's ability to receive and understand a warning, ability to take an evacuation decision), to respond immediately (ability to evacuate and to reach a safe area), and to restore their livelihoods are quantified.

At sub-national scale, the assessment of vulnerability to tsunamis, linked to the question of effective people-centered early warning, encompassed different indicators that help to estimate the ability of people to respond to a tsunami (Fig. B8). Areas where people face unusual difficulties to cope with a tsunami are disclosed and can be reduced when promoting respective adaptation and mitigation strategies. At the community level, vulnerability assessment products are being developed, taking into consideration specific local planning needs in the context of disaster management (e.g., for evacuation and contingency planning, Fig. C11). The vulnerability assessment results address specific end-users, such as early warning centres and disaster management agencies.

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### Physical dimension

The following account deals with physical vulnerability (also referred to as "structural" vulnerability) relating to tsunami impacts. It should be recognised that, in the case of near-field events, earthquake damage and loss may impact communities before a tsunami impacts. Damage and losses due to the tsunami impact will be compounded.

Physical (or structural) damage to buildings as a consequence of tsunami impact is characterised by features such as:

- failure of structural members including columns or load-bearing walls due to impact loads from hydrodynamic forcing or the momentum of floating debris;
- collapse of infill wall panels due to strong lateral loads; and
- the undermining of foundations due to scour.

The assessment of physical vulnerability would focus on the characterization of the combination of construction materials, building techniques, and the overall architectural design, which could be then related to damages which are typically observed. For example, the use of reinforced, confined masonry, using cement blocks or clay-bricks in the construction of houses, reduces the vulnerability of such houses when compared with materials without any reinforcement or confinement.

A starting point for this assessment is the compilation of a buildings exposure database which identifies the critical parameters relating to physical vulnerability. An example is the NEXIS database for residential buildings in Australia (Box B9).

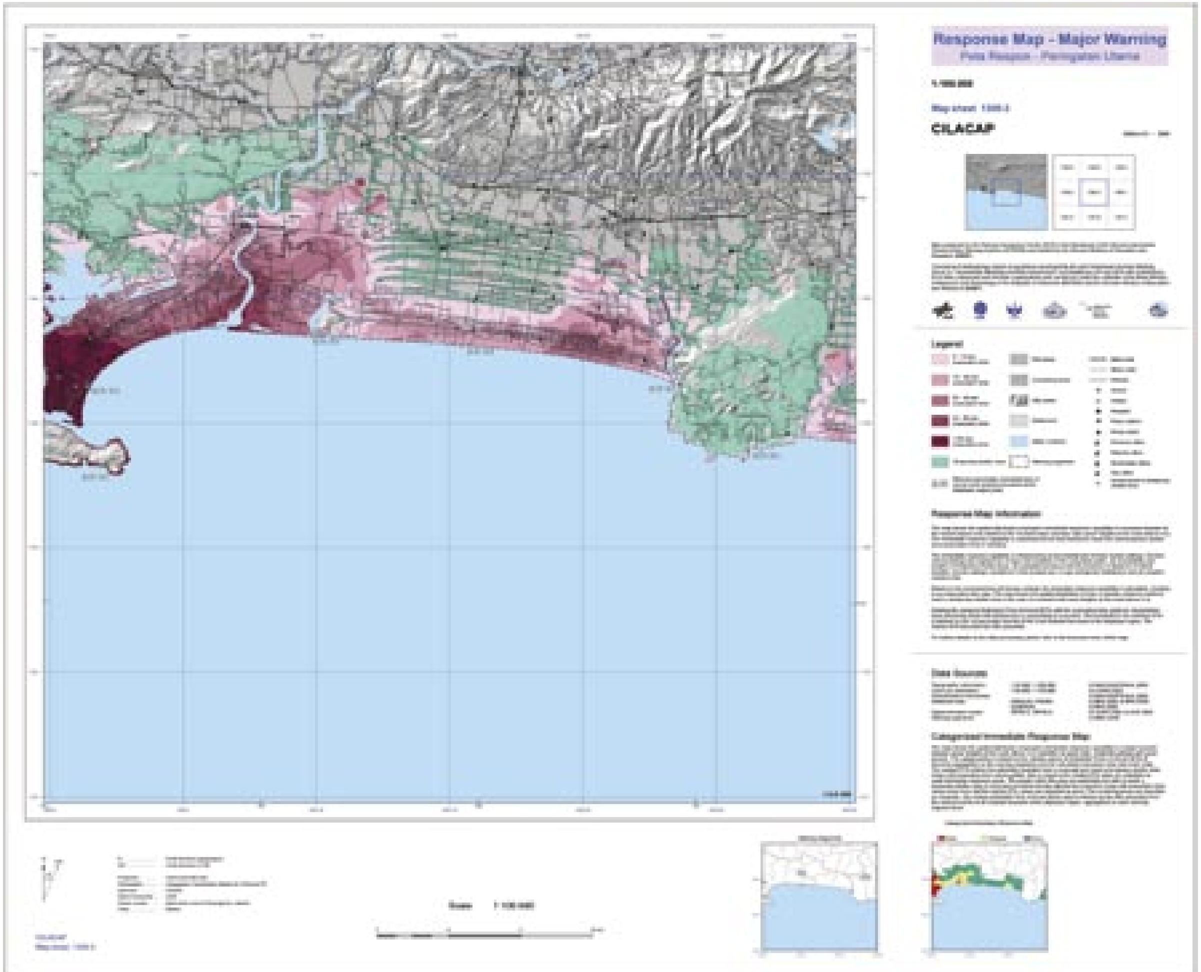


***Fig. B8***. *Tsunami vulnerability at a local scale expressed as a warning response map.*
*This example is a response map for the city of Cilacap, Java, Indonesia. The map, at 1: 100,000 (map scale), shows people's capability to respond to a potential tsunami expressed as the time people need to reach a tsunami safe area (evacuation time). Demographic parameters (population distribution, age and gender distributions) and environmental conditions (topography, properties of evacuation paths, and distance to a tsunami safe area) are incorporated in the analysis. This is an aggregated map, showing the vulnerability of people towards a tsunami threat, is based on evacuation times in combination with estimated average tsunami arrival times. The value shown for response time can be taken as an indicator for human vulnerability.*
*Source: GITEWS Project. Courtesy DLR.*

## Box B9. Buildings exposure database for Australia

The National Exposure Information System (NEXIS) is a geospatially referenced database generated for all Australian residential buildings and contains information about building type, construction type, people, replacement value and contents value at buildings level. It is built from a number of fundamental datasets, such as Census, Mesh blocks, Cadastre, ABS Housing Survey and the Geo-coded National Address Framework. NEXIS-Residential is used to estimate the number of residential buildings affected by a tsunami event. Business or commercial buildings and infrastructure are not considered in this project as this NEXIS component is not yet mature and the vulnerability models are developed only for residential buildings. The input datasets are of various qualities and resolutions; therefore NEXIS derives buildings-level information based on generic rules and assumptions which produce errors and uncertainties. Any estimates of damage based on these data therefore are compared on a relative scale, rather than in absolute figures. A similar database has been created for commercial and business buildings, and one for industrial buildings is under development. These databases are periodically updated.

Krishna Nadimpalli

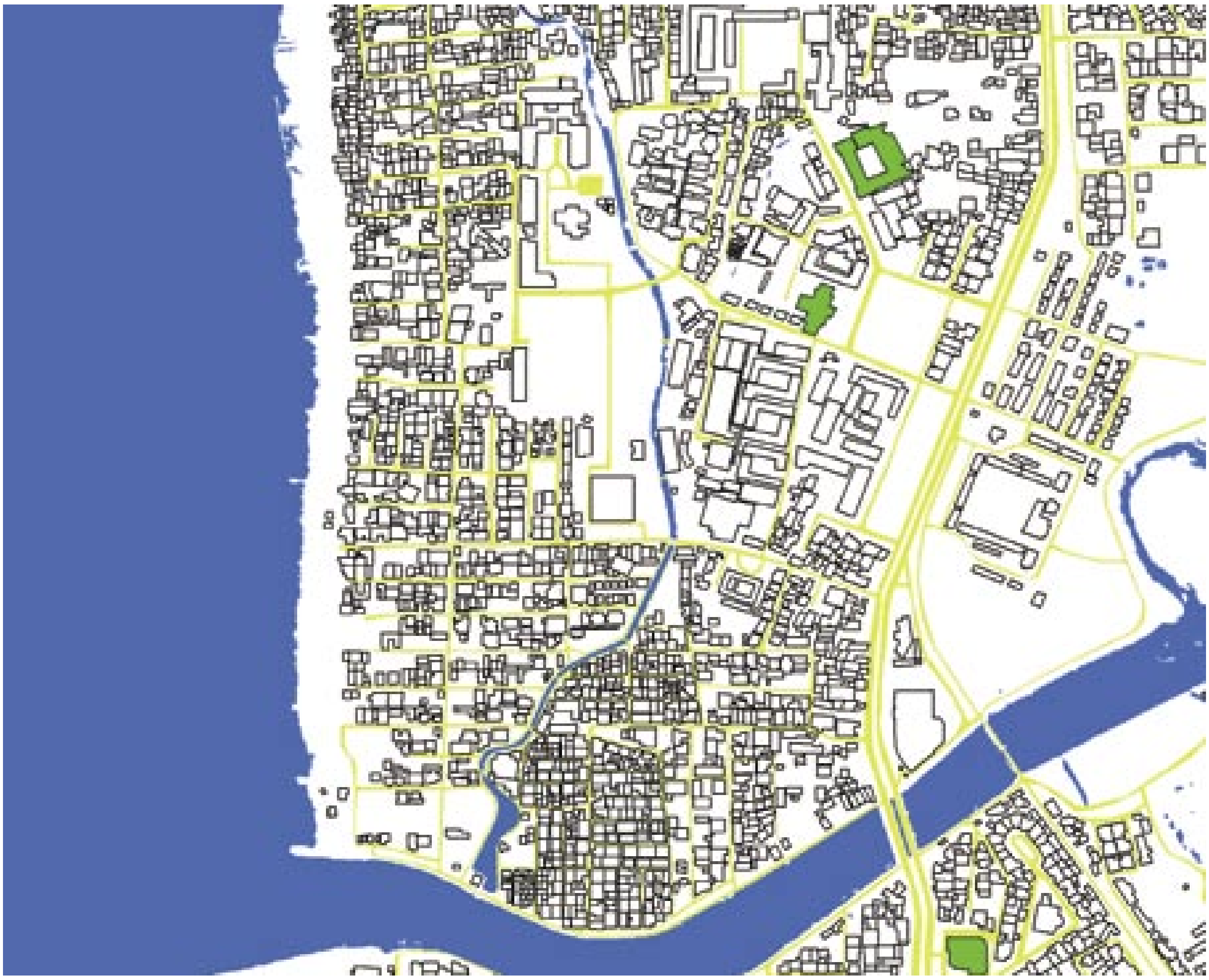

***Fig. B9***. *Buildings vulnerability map.*
*This example identifies buildings potentially suited for vertical evacuation in part of the city of Padang, Sumatra, Indonesia. The analysis is based on structural surveys combined with remote sensing techniques.*
*Source: GITEWS Project. Courtesy DLR, Andalas University Padang.*

Buildings exposed to tsunamis are subject to buoyant, hydrostatic, and hydrodynamic forces. Damage may result from a combination of these factors. The level of damage sustained is dependent on the magnitude of these forces as well as on the capacity of the structure to withstand them. The former is a function of the height and velocity of the flow, while the latter is determined by the building's physical vulnerability. Both of these factors can exhibit considerable variability across an inundation zone and thus the spatial pattern of damage may also be variable (Fig. B9). In addition, impact forces produced from debris transported by the tsunami and secondary effects such as fire may compound the level of damage. The assessment of physical vulnerability is particularly important in the identification of buildings suitable for vertical evacuation (Fig. B9 and see also C1.3).

In calculating potential damage resulting from a particular hazard scenario, the maximum water height at the structure of interest is the most important parameter. You may see this referred to as the transfer parameter. Water height plus flow velocity would provide a better understanding of the forces to which the structure is subject, though most damage models (used to link the hazard to damage or loss) do not require velocity as a parameter. The type and quality of construction can have a significant effect on the damage sustained and these should be factors should be taken into account when vulnerability assessments are being undertaken.

Available damage functions focus on empirically based (post-impact) approaches that relate observed damage to an inundation parameter, such as the water depth above ground at the structure of interest. (Damage functions are a method of linking hazard to damage or loss, which is related to risk). Observed damage is typically described qualitatively using a classification comprising four or five different damage states, some of which have been derived to be consistent with those developed for seismic damage assessment. Much of the research into damage functions has been largely exploratory, only a few studies seeking to develop actual functions that could be applied in vulnerability assessment. Although only a very approximate guideline, asset loss corresponding to the damage states in Fig. B10 can be considered as 100%, 80% and 40% for the damage states "complete", "partial (unusable)" and "partial (usable)" respectively.

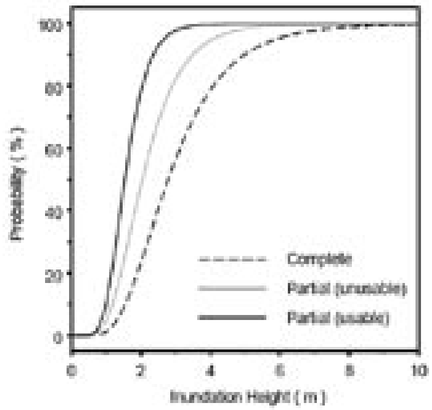


***Fig. B10***. *Vulnerability functions showing the probability of being in, or exceeding, a damage state given the tsunami inundation height.*
*Source: Peiris, 2006.*

There are several limitations apparent in the applicability of these empirical damage functions beyond the context in which they were derived. Most of the functions have been based on data from a single event at a single locality. Thus, in dissimilar settings, problems regarding their use are likely to arise. Other limitations in their use are that few building classes are considered in the functions that are available for tsunamis; also that surveys can be biased by a failure to include undamaged structures.

Another method for estimating damage may be the use of vulnerability models or damage curves developed for storm surge inundation and for river flooding (stage-damage curves). These may not be directly appropriate for assessing tsunami damage because they take no account of flow velocity on inundation or the momentum of entrained debris. However, in the absence of other models, and considering the uncertainties that exist within all of the damage models described, they can provide a useful initial estimate. The vulnerability models are usually developed based on limited data found in the literature as well as observations from historic events like the 2004 Indian Ocean tsunami. The models incorporate the following parameters which are considered to influence building damage:

- inundation depth at building site;
- inundation depth in building above floor level;
- building materials and types of construction; and
- distance from the shoreline or channel.

Overall, despite many research initiatives, the development of a satisfactory methodology for assessing physical vulnerability is still immature.

**Economic dimension**

The economic dimension of vulnerability is related to the susceptibility of livelihoods, income, and economic activity to be affected by a tsunami scenario. The term "economic" is so broad, that it is difficult to make generalizations. The variety of manifestations of formal and informal economies, the interconnectivity between commercial services and economic activity, and the links between local and national levels in terms of supply, demand, and routine transfer of merchandise make it difficult to structure the analysis of this dimension of vulnerability in a simple framework.

Considering the concepts of direct and indirect vulnerability; direct vulnerability focuses on the predisposition of businesses and economic activity to short-term disruption. In contrast, indirect vulnerability addresses their predisposition to long-term, or even permanent, disruption (see boxes B10 and B11).

Considering the reliance of economic activity on the commercialization of merchandise or products of a various kinds, the vulnerability of such merchandise and products is an element to assess within the scope of this dimension. Important aspects to consider would be the susceptibility of damage or destruction of merchandise when coming into contact with a tsunami wave (for example, cement powder or paper products). Other elements related to this dimension are related to commercial operations (cash or credit transactions).

Economic losses can be broadly classified as tangible or intangible, and sub-categorised into direct and indirect losses. In terms of estimating losses in respect of tsunami inundation, tangible direct losses are defined as losses resulting from the impact of the event such as physical damage to buildings, infrastructure, contents, and vehicles. Tangible indirect losses measure the disruption to businesses, transport and utility networks, clean-up costs, and emergency response and relief costs incurred as a consequence of the event.

The extent of the indirect costs is dependent on the availability of alternative sources of supply, markets for the products and the length of the production disturbance. Intangible indirect losses from natural disasters include death and injury, and loss of memorabilia. Intangible direct losses incorporate household disruption (schooling, social life), and health effects. There are no market values for intangible losses but non-market

**Box B10. Direct and indirect economic vulnerability of the fishing activity in Galle, Sri Lanka**

The fishing sector in Galle could be characterized via a formal component, which is characterized in terms of formal enterprises that make use of fishing fleets, permanent workers, and formal economic practices, leading to the commercialization of fish at the regional, national, or even international level. In contrast, there is an informal component characterized in terms of local communities of fishermen which make use of small, personal fishing vessels, and who market their products in the local fish markets through the informal economy.

Economic activity, in either case, depends on the use of fishing vessels and equipment. The use of fibreglass as a material to construct boats is typical, particularly in the informal segment. But as witnessed during the 2004 Indian Ocean tsunami, such boats are extremely susceptible to destruction. As such, it could be stated that the sector has a direct vulnerability associated with the physical vulnerability of boats and fishing gear.

In the case of indirect vulnerability, the experience in Galle showed that, although local fishing communities were provided with new fishing boats and equipment, their economic activity took several months to recover. In this case, local eating habits were changed abruptly by gossip concerning fish caught by local fishermen. It took more than three months for local people in Galle to resume the consumption of fish caught by local fishermen. As such, it can be stated that this sector faces both direct and indirect vulnerabilities in respect of economic activity.

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**Box B11. Direct economic vulnerability of petrol stations in Galle, Sri Lanka**

The city of Galle has nine petrol stations serving local and district needs. Four of these were exposed to tsunamis resulting in:

- injury of staff operating the stations;
- destruction of pumps to deliver fuel to vehicles;
- contamination of storage tanks; and
- loss of financial resources as cash and credit vouchers.

The vulnerability of pumps relates to the fact that they are not properly anchored, nor designed to resist a tsunami impact. The vulnerability of the storage tanks relates to the fact that they were not properly designed to avoid the introduction of a tsunami surge once pumps become dislodged, and the fact that fuel inside such tanks may become contaminated. The vulnerability of financial resources was high in the context of credit vouchers typically used; as such, paper vouchers have no resistance in the event of a tsunami surge.

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**Box B12. Economic impacts of the 2004 Indian Ocean tsunami in Aceh Province, Indonesia, and Sri Lanka**

In Aceh Province, the immediate economic impact (total damage and loss due to the earthquake and tsunami) was estimated by the World Bank at about US$4.45 billion. Of that amount, 60% was damage (direct loss) and 40% was loss of income flow to the economy (indirect loss). The sector most affected was agriculture, in particular, fisheries. Half of the fishermen were confirmed dead and 40%–60% of coastal aquaculture ponds were seriously damaged. It was also estimated that 60%–75% of the small-scale fishing fleet and its associated gear were destroyed.

In Sri Lanka, damage to the national economy was estimated at around US$1 billion or 4.5% of the GDP, and the cost of reconstruction at US$1.5–1.6 billion. Tourism and fishing suffered massively in the tsunami-affected areas. More than 80% of the island's fishing fleet was wiped out. Approximately 30% of the room capacity of tourist hotels was damaged. While the rice crop was not badly affected, it was noted that heavy loss of life would probably lead to a manpower shortage affecting the harvest.

*Source: Athukorala and Resosudarmo, 2005* valuation techniques can be implemented to provide proxy values.

Ideally, an assessment of economic vulnerability in respect of a potential tsunami inundation will incorporate all the above loss categories. However, in the first instance, tangible losses are likely to be sufficient in providing conservative estimates of economic losses. Intangible losses are more difficult to estimate, given the need for proxy values. In any case, as direct tangible losses follow most directly from the physical impact, and are the simplest to obtain, they are also the most readily developed and applied on a regional or national scale.

The economic assessment should establish those criteria and features of economic sectors that determine their vulnerability to tsunamis. This should cover direct impacts regarding the location of activities as well as indirect disruption of economic activities and critical infrastructures through the interruption of, for example, transport lines or distribution networks. Dependencies between different economic sectors and critical infrastructures should be assessed. Electricity can play a crucial role for business continuity in the context of the tsunami hazard; the potential losses in different sectors in the event of the destruction of a generating site should be taken into account.

Guidance on the categorization of economic vulnerability in terms of loss levels may be found in the ECLAC publication described in Box B13 (see also B2.6).

### Environmental dimension

Tsunami inundation may have a devastating effect on coastal ecosystems on-and offshore. Because of its wide-ranging parameters, this dimension may be one of the most difficult to quantify. The rapid environmental assessment carried out on behalf of UNEP after the 2004 Indian Ocean tsunami drew attention to the scale of environmental vulnerability of the shores that were impacted. The assessment highlighted the problems of contamination of water supplies from groundwater and in wells by saltwater (and in some cases faecal bacteria); and the salination of inland waters, wetlands and agricultural land fundamental to people's livelihoods (Box B14).

Anecdotal evidence and satellite photography before and after the tsunami event seems to corroborate claims that coral reefs, mangrove forests and other coastal vegetation, as well as peat swamps, provided protection from the impacts of the tsunami (Box B15, Fig. C14). Vegetated sand dunes appear to have provided an excellent first line of defence. The damage to coastal ecosystems was highly variable, and the damage to coral reefs was mostly due to the impact of debris and sediment flushed from the land.

Assessment of environmental vulnerability includes the appraisal of the predisposition of ecosystems, natural resources and environmental services to be affected (through depletion or degradation) by tsunami inundation. Elements that can influence environmental vulnerability are:

- exposure to toxic and hazardous pollutants;
- inappropriate waste management; and
- physical degradation.

Parameters that need to be taken into account are:

- surface water;
- groundwater;
- soil;
- ecosystems;
- ecosystem services including natural defences;
- landscape / topography;
- dependency of coastal community on environmental resources and services; and
- linkages between environmental resources and land management.

For each of these parameters, properties that could be affected by tsunami inundation should be identified. For example, the surface water parameter has to be assessed in terms of potential salinity, contaminants and the presence of debris. The possible impact for each selected property should be assessed, taking into account the environmental coping capacity both with, and without, human intervention. Such analysis will facilitate the prioritization of mitigation and rehabilitation measures. The level of dependency of the coastal community on the resource base, such as surface water, should also be appraised in case of contamination resulting from a tsunami impact. Thus the overall level of environmental vulnerability depends on the quality and fragility of the environmental resource base, as well as the dependence of the community on this resource base (see Box B16).

**Box B13. The ECLAC Handbook for Estimating the Socio-economic and Environmental Effects of Disasters**

The Handbook describes a tool that enables one to identify and quantify disaster damages by means of a uniform and consistent methodology that has been tested and proven over three decades. It also provides the means to identify the most affected social, economic and environmental sectors and geographic regions, and therefore those that require priority attention in reconstruction. The degree of detail of damage and loss assessment that can be achieved by applying the Handbook will, however, depend on the availability of quantitative information in the country or region affected. The methodology presented here allows for the quantification of the damage caused by any kind of disaster, whether man-made or natural, whether slowly evolving or sudden. The application of the methodology also enables one to estimate whether there is sufficient domestic capacity for dealing with reconstruction tasks, or if international cooperation is required.

*Source: ECLAC, 2003. (http://siteresources.worldbank.org/INTDISMGMT/Resources/intro.pdf)*

**Box B14. Contamination and salination in Sri Lanka**

In Sri Lanka, water wells remained contaminated months after the 2004 Indian Ocean tsunami. This forced the Red Cross and the Government to supply potable water to rural communities located on the coast for quite some time. In addition, salination of the soil used for agricultural purposes decreased agricultural yields. While it is not expected that such a condition will be permanent, restoration of affected ground by rain-fed leaching could take years.

*Source: Renaud, 2006*

**Box B15. Coastal ecosystems providing natural defences to tsunami impact in Sri Lanka**

Sri Lanka offers some of the best evidence that intact coastal ecosystems, such as coral reefs and healthy sand dunes, helped buffer aggressive waves. For example, most of Yala and Bundala National Parks were spared because vegetated coastal sand dunes completely stopped the tsunami, which was able to enter only where the dune line was broken by river outlets. Some of the severest damage to Sri Lanka's coast was where mining and damage of coral reefs had been heavy in the past.

*Source: UNEP, 2005*

**Box B16. Coral reef vulnerability and community dependency, Seychelles**

Following the tsunami that hit the Seychelles islands on 26 December 2004, two major patterns in coral reef damage were noted, dependent on the geographical location of each island, the direction of exposure at each site, and the reef substrate. The northern islands clustered around Praslin (including Curieuse, La Digue, Felicite and the rocks of Isle Coco and St Pierre) showed very high levels of damage (approaching 100%) on unconsolidated carbonate reef substrates previously weakened (in 1998) by coral bleaching and mortality. By contrast, sites around Mahé showed much lower levels of impact, generally below 10%, due to the shelter provided by the outer northern islands and dissipation of wave energy as the tsunami travelled over the greater distance of shallow water from the outer edge of the banks to Mahé. Coral reefs are very important to the economy, society and infrastructure of the Seychelles – all the damaged northern sites are prime tourist locations for the country, and the most highly damaged terrestrial locations are adjacent to degraded reef areas. Though impacts from the tsunami were less than from other threats, such as coral bleaching, their effects were compounded and possibly synergistic. The roles of, and impacts on, coral reefs with respect to the tsunami highlight the differential vulnerability between different locations; also the need to implement strong measures for reef and coastal conservation.

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| Products | Variables (and standards) | Sources | Global datasets and programmes |
|---|---|---|---|
| Vulnerability maps and reports | | | |
| social / human condition / gender | Demographic, gender and educational parameters; access to information and hazard awareness; exposure to tsunami risk (how many people are living in the hazard zone (people per ha.) | Asset maps inundation maps; local authority census; health and welfare services; tourism organizations; exposure and vulnerability surveys | |
| structural / physical | Inundation depth at building site; inundation depth in building above floor level; building materials; types of construction; distance from the shoreline. | Asset and inundation maps; local authorities; structural / vulnerability surveys; exposure surveys | |
| economic | Distribution and value of industry, agriculture and infrastructure; the built environment; public utilities; existing hazard defences | Asset and inundation maps; land-use maps; Local and National authorities; utility suppliers; trade and industry organizations including ports, agriculture and fisheries; transport companies; insurance companies; exposure and vulnerability surveys | |
| environmental | Distribution and value of habitats supporting human well-being; water supply; groundwater quality | Asset and inundation maps; agriculture and fisheries organizations; water and sewerage utilities; environmental health authorities; exposure and vulnerability surveys | |

***Table B5***. *Information sources for assessment by "dimensions of vulnerability".*

## B2.5 ASSESSING VULNERABILITY BY "SECTORS OF DEVELOPMENT"

A recently introduced approach to the assessment of vulnerability is through sectors of development. From a policy-relevant point of view, this approach encourages agencies in charge of these sectors to take responsibility concerning vulnerability reduction within their respective sectors (Table B6).

The employment of this approach has been proposed from the policy perspective. It promotes the assignation of responsibilities regarding the reduction of vulnerabilities to those private or public institutions in charge of each sector. These institutions may be government departments or agencies and may span various political-administrative levels.

Vulnerability assessment within the context of the "sector" approach starts by defining:

- the hazard scenario and geographical levels at which the assessment is being made; then
- the sector to be addressed; then
- the component of vulnerability being assessed.

The assessment then focuses on six components of vulnerability. Elements within each component are identified presumptively from a systematization of damages and losses during disasters.

- The human condition/gender component relates to the presence of human beings and encompasses issues related to deficiencies in mobility of human beings and gender.
- The physical component relates to the predisposition of infrastructure employed by the sector to be damaged by an event associated with a specific hazard.
- The functional component relates to the functions which are normally carried out in the sector and how these are prone to be affected.
- The economic component is related to income or financial issues which are inherent to the sector.
- The administrative component relates to those issues associated with the management of routine operations and how such administrative issues can be affected by an event.

| Scales of assessment | Development sectors | Components of vulnerability |
|---|---|---|
| National<br>State or Province<br>District or Municipality<br>City or local<br>Single unit or house | Housing<br>Basic lifelines<br>Health<br>Education<br>Government<br>Commerce<br>Finance<br>Industry<br>Energy<br>Communications | Human condition / gender<br>Physical<br>Functional<br>Economic<br>Environmental<br>Administrative |

***Table B6.*** *The three dimensions of the "sectors of development" approach to vulnerability assessment.*
*(Source: Villagran de Leon, 2006)*

- The environmental component relates to the interrelation between the sector and the environment and the vulnerability associated with this interaction.

The "sector" approach then identifies options for each of these components and assigns weights to each option regarding their disposition to be affected by a scenario. A simple linear combination of the elements is carried out numerically to obtain a numerical output for the intrinsic vulnerability component. This can be characterized as low, medium or high, using a table of ranges. All numerical values regarding options, as well as weights to combine the elements, have been deduced by employing expert judgment.

## B2.6 DETERMINING THE LOSSES FOR A TSUNAMI IMPACT EVENT

The combined losses from a tsunami event are determined by summing the potential losses from each location or source of loss into an aggregated value. Losses may be expressed in many ways, depending on the accuracy of the available information and the application for which the risk analysis is being conducted. In terms of physical quantities, examples of aggregated losses might include estimates for:

- length of coastline inundated;
- the exposure;
- the number of affected population;
- casualties or deaths;
- the number of buildings damaged or destroyed;
- the extent of critical infrastructure damage, etc.

In terms of environmental measures, examples would include:

- the area of salt water intrusion;
- the numbers of trees damaged;
- the extent of coastline affected, etc.

For social and economic consequences, estimates of the duration of inundation or resulting disruption to the community also represent measures of potential loss that can be quantified and ranked for different events and their probabilities. Finally, all of these factors and others expressed here can be cast into an economic model in order to estimate the total economic impact of an event. As noted above (B2.4) economic losses are generally grouped in terms of:

- direct losses (those arising from direct physical damage and cost of reconstruction); and
- indirect losses (those arising from the loss of income or utility of an asset).

Ultimately, the measures of loss and the values placed on community assets and their function must be assessed and validated at the community level. Thus, if environmental factors are highly important to the community, these factors must be weighted so that this importance is reflected in the risk assessment. On the other hand, if the potential for loss of life is the main driver for the study, the focus of the risk assessment and basis for loss estimation will naturally be placed on inundation mapping together with buildings and infrastructure damage. In any case, the measures of loss that are included must be consistent with the mitigation measures that are available or appropriate to the situation.

## B2.7 OUTPUTS FROM THE VULNERABILITY ASSESSMENT

The outputs of the vulnerability assessment are typically presented in reports and may include a range of vulnerability maps. Vulnerability maps represent the status of the coastal community in respect of a specified level of inundation (linked to a specified tsunami scenario). They are a powerful tool for emergency management.

Maps covering a range of hazard scenarios and depicting a range of vulnerability levels may be envisaged. The vulnerability levels can be expressed on the maps in broad categories – low, medium or high – or in terms of percentages (for example, percentage of vulnerable buildings). Vulnerability levels provide key guidance in the provision of specific advice to coastal managers and planners in linking the output of the vulnerability analysis to the input for mitigation. When integrated with the assessed probability of a hazard scenario, they provide an indication of the level of risk – the probability of the assessed consequences – for communities in the defined coastal area (see B4).

Key outputs and results associated with the vulnerability assessment may include:

- an asset database (or inventory);
- an exposure database;
- a preliminary appraisal of vulnerability in respect of exposure due to tsunami inundation carried out (perhaps leading to a preliminary risk appraisal), so that local authorities and disaster reduction and prevention agencies may appreciate the importance of setting up a plan for vulnerability assessment of the designated coastal area;
- in-depth assessments of each dimension of vulnerability and its potential consequences in respect of specified hazard scenario(s);
- vulnerability maps and reports produced, with the involvement of end users, for the designated coastal areas, whether at the regional or the local scale, covering each dimension of vulnerability, and aggregated vulnerability, for specified hazard scenario(s);
- vulnerability maps and reports covering future scenarios, taking into account the likely effects of improved emergency preparedness and mitigation; reports relating to "sectors of development" as appropriate; and
- communication of the vulnerability assessments to all involved in risk assessment and emergency management.

### Suggested additional reading and information sources


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# **B3 Are your communities** properly prepared?

**Key tasks in the preparedness assessment procedure**

- Identify and appraise weaknesses in early warning systems and responses.
- Identify and appraise weaknesses related to the post-impact response.
- Assess the application of risk transfer mechanisms which would facilitate post-impact recovery.

In addition to the assessment of hazards, the exposure to such hazards, and the respective vulnerability, it is also important to assess those deficiencies in preparedness which may be manifest as weaknesses of institutions, organizations and communities to deal effectively with tsunami impacts. For example, disaster-risk management agencies may not have enough resources to be able to respond in case of a tsunami in all locations exposed; there may be a lack of early warning systems and corresponding evacuation routes and standard operating procedures to ensure a quick, efficient, and timely response to minimize the impact of a tsunami (C1.2). Another possible deficiency might be related to the lack of risk transfer mechanisms, such as insurance, micro-insurances, catastrophe bonds, or national emergency funds, enabling impacts to be confronted and facilitating a quick recovery (C2.3).

Opinion is divided as to whether deficiencies in preparedness should be assessed as a dimension of community vulnerability (B2.4) – "institutional vulnerability". The presence of good institutionalized capacities, effective organizations and good governance may be seen as reducing vulnerability. However, from a policy-relevant point of view, the responsibility concerning preparedness should be placed on those agencies which are in charge of preparedness (national or local emergency committees), while vulnerability should be the responsibility of those who generate it. For the latter reason, in these guidelines the topic of "deficiencies in preparedness" is treated separately from vulnerability assessment.

In general, weaknesses in preparedness may be grouped into:

- weaknesses in early warning systems and responses in the event of a warning;
- weaknesses related to the post-impact response; and
- lack of (or weaknesses in) risk transfer mechanisms facilitating post-impact recovery.

## B3.1 ARE THE EARLY WARNING PRACTICES EFFECTIVE?

The 2004 Indian Ocean tsunami manifested major weaknesses in early warning. While scientists in charge of the Pacific Tsunami Warning Centre were able to forecast the potential tsunami, they did not have effective contacts within agencies in the various countries of the Indian Ocean to transmit the information so that such agencies could issue a warning. The only available route was through the U.S. State Department in Washington D.C., which relayed the warning through the U.S. embassies in these countries. For many countries, the message arrived too late for appropriate responses to be implemented.

A review of critical issues that hindered the efficient and timely operation of early warning systems has led to the identification of four elements:

- the implementation of technically-oriented early warning systems, without taking into consideration the notion of vulnerable groups and risk assessment;
- weaknesses in monitoring and forecasting of potentially catastrophic events;
- weaknesses in the emission of warnings, or in ensuring that warnings reach vulnerable communities; and
- weaknesses in capacities to respond to a warning and to a potentially catastrophic event.

In many Indian Ocean countries, the term "tsunami" was largely unknown before the December 2004 event. Thus, the transmission of an early warning targeting tsunamis may not have been properly understood by coastal communities, resulting in an inappropriate response. In some cases, there were limitations in communications which prevented agencies from issuing warnings. In others, people were unaware of safe areas for evacuation. The lack of awareness, compounded with a lack of evacuation route signage (Fig. C7), compounded losses.

So long as these weaknesses are present, early warning systems for natural hazards will not be effective in saving lives, as witnessed during the storm surge generated by Cyclone Nargis in Myanmar in May, 2008.

## B3.2 WOULD THE RESPONSE TO A TSUNAMI BE TIMELY AND EFFICIENT?

Another weakness in preparedness relates to the poor capacities of organizations to respond in case of an event. Such a response involves a coordinated approach that considers the type of event and the peculiarities of its manifestation.

A lack of inter-institutional coordination can lead to the duplication of effort in some places, the response voids in others, and to costly delays in decision making. In developed countries, the use of Emergency Operation Centres in conjunction with Standard Operating Procedures allows emergency managers to minimise such inefficiencies.

In any case, Search and Rescue Operations for natural hazard disasters are critical to minimizing loss of life. To this end, teams of experts in these types of activities have the task of locating trapped and injured people, so that they can be transported quickly to a health centre for treatment. In the particular case of tsunamis, it is important to be aware that the inundation may be manifest in perhaps as many as three or four huge waves. Thus, teams must be properly trained in the nature of tsunamis, so that they do not end up as victims themselves.

## B3.3 TO WHAT EXTENT IS THE RISK TRANSFERRED?

In developed countries, the use of insurance allows people to transfer their risks in time. Through the payment of premiums, people can manage the impacts of floods or other disasters in a less traumatic fashion. In developing countries, the use of insurance is still only an option for those who can afford it. To this end, it is important to find ways in which to design and operate insurance schemes which may allow people to cope with such events and to recover in a timely fashion (C2.3).

## B3.4 OUTPUTS FROM THE PREPAREDNESS ASSESSMENT

The outputs of the assessment of deficiencies in preparedness are typically presented in reports and may include a range of maps. Maps represent the status of the coastal community in respect of early warning coverage, location of emergency operations centres, shelters, and other critical sites. They are a powerful tool for emergency management. Reports highlight critical issues in the three areas: preparedness for early warning, response, and the take-up of risk transfer mechanisms.

Key outputs and results associated with this assessment may include:

- a preliminary appraisal of the state of early warning practices, so that local authorities and disaster reduction and prevention agencies may appreciate the importance of setting up a plan to strengthen such early warning aspects in the designated coastal communities;
- in-depth assessment of deficiencies in each key area;
- appraisal of coverage in terms of insurance and micro-insurance schemes; and
- appraisal of institutional capacities, notably the requirements for Search and Rescue Operations; also of the results of drills and exercises.

Table B7 presents a list of variables which could be used to assess deficiencies in preparedness.

### Suggested additional reading and information sources


Adger, W. N., Hughes, T. P., Folke, C., Carpenter, S. R., Rockström, J. 2005. Social-Ecological Resilience to Coastal Disasters. *Science*, Vol. 309, No. 5737, pp. 1036–1039. Available at: http://www.sciencemag.org/cgi/content/full/309/5737/1036

GeoHazards International. 2008. Preparing your community for tsunamis: a guidebook for local advocates published as a working draft. GeoHazards International Existing Hazard Guidelines productions – especially for tsunamis. Available at http://www.geohaz.org

Manuta, J., Khrutmuang, S., Huaisai, D. and Lebel, L. 2006. Institutionalized incapacities and practice in flood disaster management in Thailand. *Science and Culture*, Vol. 72, No. 1-2, pp. 10–22.

UNESCO. 2008. *Tsunami Preparedness: Information Guide for Disaster Planners*. IOC Manuals and Guides No. 49. Paris, UNESCO. http://unesdoc.unesco.org/images/0016/001600/160002e.pdf (Accessed 19 February 2009.)

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

U.S. IOTWS. 2007. *How resilient is your coastal community? – Coastal community resilience guide. A guide for evaluating coastal community resilience to tsunamis and other hazards.* U.S. Indian Ocean Tsunami Warning System (U.S. IOTWS) Program. U.S. IOTWS Document No. 27-IOTWS-07 Available at: http://www.iotws.org/ev_en.php?ID=2907_201&ID2=DO_TOPIC

Villagran de Leon, J. C. 2008. *Rapid assessment of potential impacts of a tsunami: Lessons from the port of Galle in Sri Lanka*. No. 9, SOURCE Publication Series of UNU-EHS. Bonn, 96 pages. Available at: http://www.ehs.unu.edu/article:545?menu=36

| Products | Variables (and standards) | Sources | Global datasets and programmes |
|---|---|---|---|
| Preparedness in the context of early warning | Tsunami early warning system in place; communication links from national warning centre to coastal communities in place; warning schemes within coastal communities in place and tested; warning schemes target vulnerable groups previously identified; evacuation routes properly identified with visible signs; drills and simulations conducted to test the state of readiness of the community to respond to a warning. | Government agencies; NGOs | IOC Unified Tsunami Website (http://www.ioc-tsunami.org/)<br><br>Jakarta Tsunami Information Centre (www.jtic.org) |
| Preparedness to respond during and after the event | Emergency Operation Centres operational; Standard Operating Procedures operational; Search and Rescue teams well trained and well equipped; temporary shelters ready to be used at any time, properly staffed and with sufficient resources to cope with the needs to evacuees. | Government agencies; NGOs | |
| Risk transfer mechanisms (see also C2.3) | Insurance and micro-insurance provide adequate coverage; catastrophe bonds in place to ensure quick recovery; transparent and efficient mechanisms in place to access national emergency or catastrophe funds. | Insurance companies; re-insurance companies; Government agencies; NGOs | |

***Table B7***. *Variables and information sources for preparedness assessment.*

# B4 What is the tsunami risk to your communities?

**Key tasks in the risk assessment procedure**

- Confirm the geographical scale and limits of the assessment.
- Confirm the temporal scale of the assessment.
- Combine the tsunami inundation parameters (for specified scenarios with defined probabilities) with assessed vulnerability levels (in respect of those scenarios).
- Translate the combined hazard, vulnerability and preparedness outputs into levels of risk, denoting the probability of damage and loss for specified scenarios.
- Produce risk map(s) and reports for the designated coastal management area.
- Communicate the risk assessment outputs to all levels involved in risk management and mitigation.

## B4.1 INTEGRATING HAZARD AND VULNERABILITY ASSESSMENTS

This part of the guidance combines the outputs of the first three sub-sections, B1 (hazard assessment), B2 (vulnerability assessment) and B3 (assessment of community preparedness). It explains how you can integrate the information on the tsunami hazard with the information on the consequences of a tsunami impact on your communities (their vulnerability and preparedness) to provide a risk assessment in respect of the tsunami hazard – providing a measure of the probability of those consequences (Fig. B11). Its assessment is a logical outcome of the processes involved in the hazard, vulnerability and preparedness assessments. As with those assessments, it assumes a definition of its spatial and temporal scales, and its geographical limits. One may consider the risk from a particular event of interest, or risk may be aggregated across a suite of events or all possible events at all probabilities (or return periods). .


***Fig. B11.*** *The elements of risk: hazard, vulnerability and deficiencies in preparedness.*
*The risk can be mitigated by reducing the vulnerability to the hazard and improving preparedness.*
*Source: Juan Carlos Villagran.*

The hazard assessment (B1) should have defined the exposure parameters relating to the specified tsunami scenario and the probability of that scenario. The vulnerability component (B2) should have defined the losses and damages in respect of the social, physical, economic and environmental dimensions of interest. The preparedness assessment (B3) should have characterized those limitations which inhibit the community from responding efficiently and in a timely way during a specific event to minimize fatalities or losses (Fig. B11).

The quality of the risk estimates depends on the reliability of the hazard assessment and on the availability and quality of vulnerability data. Subject to these requirements, risk estimates may be derived for any chosen scale (for example, from individual buildings to the coastal built environment at the national scale), for any specified dimension of vulnerability, and for any specified development sector. Estimates of risk can (and should) be customised. In this way they can meet the specific requirements of the risk manager, the planner or the emergency manager within the defined geographic area.

## B4.2 MAKING AND USING RISK MAPS

A convenient and effective way of representing levels of risk (or of estimated risk) is geospatially, by means of risk maps. These maps show the extents of areas with defined risk categories (for example, high, medium, low) for the required dimension of vulnerability in respect of a specified tsunami scenario. Possible criteria for determining risk categories for specified scenarios include the following:

- No impact (or risk) = No direct damage from tsunami inundation is likely. May be suitable for staging recovery operations such as evacuation shelters and other emergency services.
- Low impact (or risk) = Damage likely to older buildings or non-engineered buildings or structures is likely. Life-threatening particularly to young, elderly and infirm. Some potential for locating or identifying structures suitable for temporary evacuation purposes. Requires emergency response planning including evacuation plan in the event of a tsunami.
- Medium impact (or risk) = Significant damage to non-engineered buildings and some damage to engineered structures likely. Highly life-threatening to all. Evacuation necessary to mitigate loss of life.
- High impact (or risk) = Buildings and human life are unlikely to survive. Evacuation is the only viable response measure.

Risk maps can be derived using GIS technology by overlaying hazard and vulnerability maps. Risk maps are often defined in relation to a specific hazard scenario and are perhaps the simplest and most effective tool at the community level for input to a wide range of decision making with a view to risk reduction (figs B12 and B13).

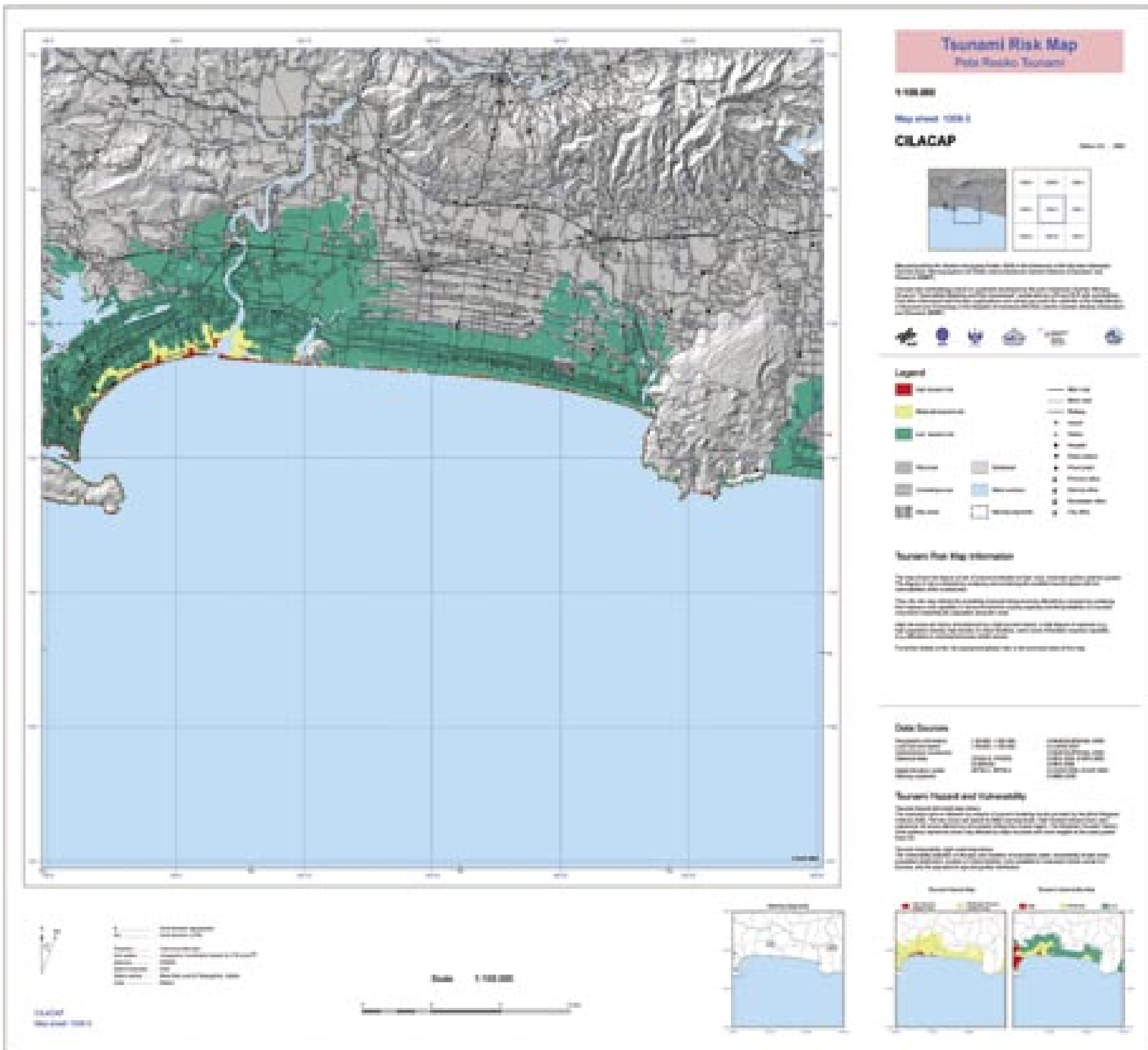



***Fig. B12.*** *Tsunami risk map at a local scale.*
*This example covers the city of Cilacap, Java, Indonesia. The map, at 1: 100,000 (map scale), shows the tsunami risk (high=red; moderate=yellow; low=green) to people. The risk map combines information on the degree of hazard impact (probability of tsunami hazard occurrence on land) and the people's vulnerability.*
*Source: GITEWS Project. Courtesy DLR.*

An assessment of risk needs to be more than just a snapshot of risk under present conditions. The assessment needs to address how risk might change with time. This might be caused by changing socioeconomic and environmental scenarios, as well as by the outcomes of existing and planned mitigation measures.

Successful mitigation can reduce risk by constraining the hazard (for example, by establishing barriers to inundation) and/or reducing the vulnerability (for example, by introducing building codes). However, environmental changes such as sea-level rise will increase the risk, because such changes modify the exposure of coastal areas to the hazard. It is also important to recognise that risk may increase over long periods due to unintended consequences of mitigation over time. The implications of these long-term trends need to be considered within the risk assessment process.

The timescales for risk assessment which country authorities may want to consider will vary from one country to another. Globally, there is a move to longer assessment periods due to the long-term implications of many mitigation measures and the recognition of the dynamic nature of risk. Some countries are explicitly considering a 100-year time scale, or even longer, for risk assessment.

Effective communication of the risk assessment outputs to all levels involved in the coastal management and emergency management processes is of paramount importance. The assessments are vital inputs to policy-making, determining the nature and level of response for mitigating tsunami risk.

## B4.3 MAKING A QUANTITATIVE RISK ASSESSMENT

The following account provides more detail in the methodology and options for combining the assessment of tsunami hazard with vulnerability to determine risk. In this more formal and quantitative approach, the estimation of risk must include information about the likelihood of a tsunami event occurring, together with information about the impact of that event or the resulting loss. The total risk is determined by combining the likelihoods and impacts or losses of the range of all possible events together.

As described in the guidance on the production of risk maps (B4.2), impact or loss can be described in terms of a wide range of consequences including physical damage, human casualties or fatalities, economic loss, loss of social and environmental services and infrastructure. All of these represent elements of impact or loss. The losses from a particular event will be a function of the dimensions of vulnerability that are of interest, as discussed in B2.4.

### Developing a "risk curve"

For some decision-making applications, it is useful to capture information about all possible damaging events that could occur, as well as their consequences, in the formation of a risk curve, where the likelihoods and consequences of damaging events can be ranked in order of their severity (Fig. B14). Risk curves are commonly used in quantitative risk assessment, including insurance and engineering applications. Risk curves can be applied to potential losses at the level of an individual household, facility or property, or at an aggregated level for an entire

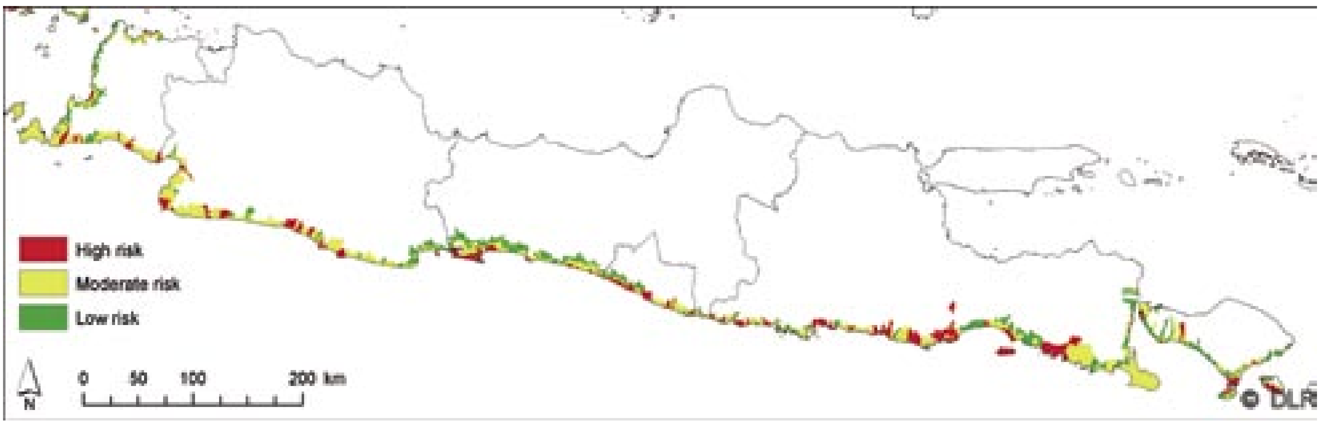



***Fig. B13.*** *Tsunami risk map at sub-national scale.*
*This map, covering the southern coasts of Java and Bali, shows the tsunami risk aggregated on village administrative level, combining hazard and vulnerability information.*
*Source: GITEWS Project. Courtesy DLR, UNU-EHS*

community. Risk curves also provide the opportunity to compare risks to a community at different levels of probability, differences in risks between communities, or between different hazards to the same community. Risk curves can also be combined for different hazards or communities to provide all-hazard estimates of risk across a range of probabilities (or return periods) such as for national-scale assessments where the allocation of mitigation resources will often compete with a variety of other disaster management priorities.

Fig. B14 demonstrates the concept of a risk curve. The risk curve is expressed as the amount of loss as a function of the probability (or likelihood) of losses of any given amount being exceeded. (For this reason, risk curves are also referred to as loss exceedance curves.) Formally, the risk curve is actually constructed by ordering all events that are possible, as derived from the hazard assessment, from smallest to largest loss. The probability of exceeding a value of loss is then determined by adding up the probabilities of all events whose losses are estimated to be greater than any given loss value.

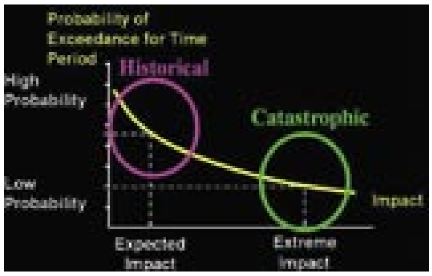



***Fig. B14.*** *A risk curve.*
*The risk curve expresses the probability of exceedance of an impact (or loss) as a function of the loss.*
*Source: Geoscience Australia.*

**Box B17. Determining hazard probabilities**

In order to demonstrate this concept, consider 5 events with losses X1 to X5 (X5>X4>X3>X2>X1), and hazard probabilities P1 to P5. We can rank the events and the exceedance probabilities as follows:

| Event # | Loss (X) | Probability | P(Loss ≥X) |
|---|---|---|---|
| 1 | X1 | P1 | P(Loss≥X1) = P1+P2+P3+P4+P5 |
| 2 | X2 | P2 | P(Loss≥X2) = P2+P3+P4+P5 |
| 3 | X3 | P3 | P(Loss≥X3) = P3+P4+P5 |
| 4 | X4 | P4 | P(Loss≥X4) = P4+P5 |
| 5 | X5 | P5 | P(Loss≥X5) = P5 |

As you can see from this table, each event has losses greater than or equal to a specific value, X1 to X5, so that the probability of Event 1 loss being met or exceeded is simply the sum of the probabilities of all events, and so on. Similarly, Event 5 has the largest loss, so the probability of this loss being met or exceeded is simply the probability of Event 5 occurring. You can see from this process that large losses will generally be rarer (i.e., small exceedance probabilities) than small losses, and, similarly, the probability of having losses greater than any value will generally decrease as the loss value increases.

As with the hazard assessment, probabilities are often expressed in terms of an annualised value. This is the probability of exceeding a given loss value in a period of one year. Using this risk-based or "loss-exceedance" construct, the "100-year event" is more accurately defined as the event whose loss has a probability of 1/100 of being met or exceeded at least once during a one-year period. For very rare events, including most tsunamis, this is roughly equivalent to the event that occurs approximately once in 100 years. However, in reality, tsunamis events do not occur at regular intervals.

Most recorded events tend to occupy the higher probability, lower impact range of the curve; whereas, catastrophic (or high impact) events tend to be low probability (i.e., rarer). The 2004 Indian Ocean tsunami is a clear exception in that, at many locations, for example, Sri Lanka and Sumatra, and certainly for the Indian Ocean region as a whole, it would be classified at the extreme end of this curve. Purely from a tsunami hazard perspective, this event is considered to represent a 500-year return period event for the Indian Ocean region. How the consequences of this event rank on any given risk curve depends on the area or community of interest and the vulnerabilities that are considered. The consequences

| Products | Variables (and standards) | Sources | Global datasets and programmes |
|---|---|---|---|
| Risk maps and reports for each identified hazard in respect of:<br>population;<br>structures;<br>economics;<br>environment;<br>or development sectors | Assessed probability of specified tsunami scenarios;<br>assessed levels of hazard based on inundation parameters; flow velocities<br><br>Assessed vulnerability parameters in respect of specified tsunami scenarios | Outputs from tsunami hazard assessment<br><br>Outputs from vulnerability assessment | |

***Table B8.*** *Information sources for risk assessment.*

also depend on the extent to which other hazards are included in the assessment. For instance, for Sri Lanka as a nation, the 2004 Indian Ocean tsunami represents the largest single loss of life from any event in its history; however, for India in the last several decades, there have been many other natural hazard events that have caused much greater loss of life. Thus, from a loss of life perspective, the 2004 Indian Ocean tsunami may represent a rare (for example, 500-year return period or greater) loss for some communities or nations, but will rank at very much higher probability for others.

## B4.4 OUTPUTS FROM THE RISK ASSESSMENT

Key outputs and results associated with tsunami risk assessment may include:

- assessments of risk for each dimension of vulnerability (or sector of development) in respect of a tsunami scenario with a defined probability;
- risk maps covering future scenarios as well as existing conditions produced for the designated coastal areas, whether at the regional or the local scale, covering each of the different dimensions of vulnerability (or each development sector) for the specified tsunami scenario(s); and
- effective communication of the risk assessment outputs to all levels involved in the coastal management process. The assessments are vital inputs to policy-making, determining the nature and level of response for risk reduction within the coastal management plan.

### Suggested additional reading

Thywissen, K. 2006. Core terminology of disaster reduction: a comparative glossary. J. Birkmann (ed.), *Measuring vulnerability to natural hazards: towards disaster resilient societies.* United Nations University Press, Tokyo, pp. 448–496.

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

# C Managing the tsunami risk

**This management-oriented part of the guidance comprises two main elements which, together, deal with the reduction of risk in respect of the tsunami hazard. These elements describe the measures to be considered by emergency managers, coastal engineers and planners in respect of preparedness and strategic mitigation. While many of the preparedness measures might (indeed, should) be implemented in the immediate timeframe, many of the mitigation measures are for the long term and, generally, are the more expensive options. It is therefore important that implementation plans consider mitigation responses that are sustainable and take account of demographic and environmental changes that might occur within the longer timeframe.**

To be successful, the management of tsunami risk demands levels of cooperation and coordination between all the involved agencies which are difficult to achieve, even in developed countries. A key issue is the take-up of vulnerability and risk assessment knowledge by policy makers and those with responsibilities for risk management and mitigation. The practical application of vulnerability and risk knowledge in actions aimed at risk reduction may be facilitated by strengthening the involvement and co-ownership of the user community and public in the assessment agenda. This helps to establish the credibility, legitimacy and relevance of the research-based knowledge output among practitioners, and to lower the barriers to the take-up of assessment findings by policy makers.

The successful application of vulnerability and risk assessments may be impeded by a lack of political commitment. However, coastal management frameworks, such as ICAM, may help to lower institutional barriers to the application of successful risk reduction measures.

In addition to the guidance on managing tsunami risk provided in this section, the reader is referred to the treatment of this subject in a multi-hazard context in the IOC-ICAM hazard guidelines (UNESCO, 2009), which deal in greater depth with the options for strategic mitigation.

## C1 How to improve your preparedness to tsunamis?

### Key tasks in the procedure for improving preparedness

- Identify an appropriate early warning framework.
- Raise awareness of the risk at all levels in the community.
- Plan and implement the key operational requirements of an early warning system.
- Prepare all levels of the community for emergency responses.
- Plan systems and procedures for evacuation.
- Promote Community-based Disaster Risk Management (CBDRM) where appropriate.

This element of the guidance covers the procedures that you will need to prepare your communities for tsunami impacts and thus reduce the scale of a potential disaster. It deals with raising the levels of awareness of tsunamis, then describes tsunami early warning systems, including the IOC-coordinated regional Tsunami Early Warning Systems and the part that National systems play in these regional facilities. It includes information on evacuation procedures and shelters, and explains how community-based actions can contribute to risk reduction.

Although addressed primarily at coastal practitioners and emergency managers, the guidance is relevant at all levels of society, at national, local and even individual levels. Thus, although this part of the guidance is entitled "How to improve your preparedness for tsunamis (as managers)", it is as much about how people at all levels can prepare themselves for tsunamis.

A country's perception of the need for preparation depends on its perceived level of risk. The risk is a measure of the probability of the consequences of an assessed hazard. Section B has described how this level can be assessed, and how this level depends not only on the likelihood of a tsunami impact (expressed perhaps as a return period for a given height) but also on the vulnerability of the community including its supporting systems. Some countries may assess their risk as being low and thus have no imperative for response. At the other end of the scale, countries might anticipate much shorter return periods of damaging events. Such countries may know from their own experience, or their culturally inherited knowledge, that awareness and preparation for tsunamis may be vital for their wellbeing and survival.

In the middle ground, there are those countries for which the tsunami risk may not be apparent because of long return periods. But even in some of those, there may be historical (including geological) records of past tsunami events impacting their shores on scales which, if they occurred today, would have serious consequences, causing major losses and damage to their coastal communities. For countries such as these, the appropriate management of tsunami risk is particularly challenging.

Programmes of preparedness including public awareness, evacuation exercises and education aimed at improving community resilience may be some of the most cost-effective management responses, particularly in developing countries. However, it may be difficult to sustain credibility and commitment amongst stakeholders where the return periods of damaging tsunami events stretch beyond the span of living memory. Such situations are especially problematic for coastal management. Coastal communities may be reluctant to forgo what they perceive as assured livelihoods in potentially tsunami-prone areas on account of a threat of impacts which may not recur even over several generations.

***Fig. C1.*** *The importance of local knowledge.*
*Everyone knew to run to high ground immediately after an earthquake in the village of Langi, on Simeulue Island off Aceh. The 2004 Indian Ocean tsunami, which reached heights of 10 m to 15 m in the village, began its attack just 8 minutes after the earthquake. Though the waves destroyed all the buildings, all of the population survived. Several months later the villagers had constructed new houses (above) on the foundations of those swept away.*
*Photo: Lori Dengler.*

***Fig. C2.*** *The transfer of local knowledge*
*Left: An elderly resident of Sur, Oman, Ahmed A.J. Al-Alawi, observed flooding in 1945 during the sole well-documented tsunami from a subduction zone in the northwest Indian Ocean. Mr Al-Alawi testified that the waters entered his home and reached the height marked by the interviewer's raised hand.*
*Photo: Emile Okal, May 2008.*

*Right: Children attend to an interview in Lampon, Indonesia, by geologists Iwan Tejakusuma (left) and Eko Yulianto (right). The elderly man at centre, Karsom, witnessed the 1994 East Java tsunami, which originated during an earthquake that few people felt.*
*Photo: Brian Atwater, April 2007.*

## C1.1 COMMUNICATING AND ENHANCING AWARENESS OF TSUNAMI RISKS

Tsunami survival can depend on education that raises awareness of tsunami risks and provides useful guidance on how to live with them. Education is especially important in communities where the felt shaking of an earthquake forewarns of a tsunami that comes ashore minutes later. Rooted in local tsunami history and passed down through generations, oral traditions of such natural warnings saved hundreds of lives during the 2004 Indian Ocean and 2007 Solomon Islands tsunamis (Fig. C1).

Such life-saving use of tsunami history can be furthered through booklets and videos that give a human face to lessons on tsunami survival. One such booklet, available online in English and in Spanish, draws on eyewitness accounts of the 1960 Chilean tsunami in Chile, Hawaii, and Japan. Advantage for others can still be gathered from eyewitnesses to even earlier tsunamis as well as from those who survived tsunamis of recent years (Fig. C2).

## C1.2 ESTABLISHING AN EARLY WARNING SYSTEM

Early warning systems will save lives. An effective tsunami early warning system is achieved when all persons in vulnerable coastal communities are prepared and respond in a timely manner upon recognition that a potentially destructive tsunami may be approaching.

The objective of a tsunami warning and mitigation system, such as the one that exists in the Pacific (PTWS) and those that are being developed in the Indian Ocean (IOTWS), the Caribbean (CARIBE-EWS), and the North Eastern Atlantic, the Mediterranean and Connected Seas

**Box C1. Teaching about past tsunamis – explaining palaeotsunami deposits in Thailand**

Scientists and public officials from India, Indonesia, Maldives, Sri Lanka, and Thailand view evidence for recurrent Indian Ocean tsunamis at Phra Thong Island, Thailand. The trip was part of a two-week programme in tsunami science and preparedness (http://www.ait.ac.th/schools/ait-extension/certificate-training-programme-in-tsunami-science-and-preparedness). Kruawun Jankaew lectures from the pit.

Brian Atwater. *Photo: Nicolas Arcos, March 2008.*

(NEAMTWS), is to effectively mitigate the hazard posed by local and distant tsunamis. Comprehensive tsunami preparedness and mitigation requires progress in three mutually dependent components:

- first, the assessment of tsunami hazards and identification of vulnerable communities (see elements B1 and B2);
- second, provision of warning guidance through a detection, threat evaluation and alert system that meets international to national to local requirements;
- and third, the adoption of preparedness and mitigation measures to reduce the impact and loss of life (this guidance and C.2).

To achieve this objective, an end-to-end tsunami early warning system is needed that establishes national and regional warning systems for local, regional, and ocean-wide tsunamis, and promotes preparedness and risk reduction against tsunami hazards within a multi-hazard approach.

Tsunami early warning requires a Regional Tsunami Watch Provider (RTWP) to monitor earthquakes and tsunamis and, when a tsunami threat exists, immediately alert National Tsunami Warning Centres. National Tsunami Warning Centres may receive information and advice from international or regional watch providers to complement their national data streams (Fig. C3).

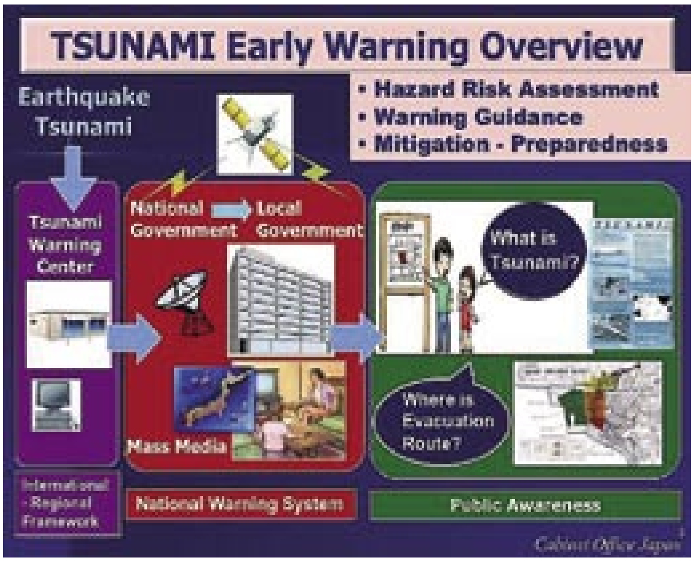



***Fig. C3.*** *The tsunami early warning process.*
*The National Tsunami Warning Centre provides warnings to a prepared and informed public to national and local emergency agencies through a number of communications channels, ideally in cooperation with the mass media.*
*Source: Cabinet Office, Japan.*

National authorities must in turn provide understandable warning messages to local jurisdictions and/or the public to ensure that people along vulnerable coasts evacuate to safe areas (see Box C2). As a key component of an early warning system, sustained campaigns of public awareness, education, and outreach must be carried out.

**Box C2. Preparedness and early warning in eastern Africa, 2004**

In eastern Africa, official information, warning and response networks were non-existent prior to the 2004 Indian Ocean tsunami. Even when an official response was generated in Kenya, the public demonstrated no faith or willingness to act on warnings from officials such as the police. Importantly, information on the tsunami and the generation of an official response were dependent on two technologies, satellite television and mobile telephony. These should be built into future warning systems as key mechanisms and back-ups to official information and warning networks.

David Obura

In detail, the architecture of an early warning system consists of the use of seismic, sea-level, and other geophysical data networks to rapidly determine the tsunamigenic potential of an earthquake and to confirm the generation of a tsunami, the dissemination of that evaluation to proper national authorities and, in turn, the warning of the public through various communication technologies (Fig. C4; see also the IOC-ICAM hazard guidelines, UNESCO, 2009).

**Box C3. The need for an effective tsunami warning system in eastern Africa**

In Kenya, the first and largest surges (1 m to 1.5 m high) of the 2004 Indian Ocean tsunami occurred around 12.30 p.m. to 2 p.m. in low tidal conditions. If these had been larger tsunamis coinciding with high tide, impacts to lives and infrastructure on the Kenya coast would have been similar to those experienced in Asian countries. While information on both the earthquake and tsunami was available on satellite television and was known to some people, the first responses occurred only when the surges started to impact the coastline. Private sector sources apparently correctly predicted the size and timing of the waves in East Africa, but this information did not go beyond individual recipients and clients of those sources. Privately, many residents and hotels along the coast responded to the obvious surges and news of the earthquake and tsunami by moving people off the waterfront. Through mobile phone calls and text messages, word about the unusual sea conditions spread among friends and, from that, into the coastal science and management community. Eventually a public response did result from communication channels originating with the Kenya Ports Authority and the National Environment Management Authority, resulting in a Ministerial alert, radio warnings and police action to clear public beaches, all by about 6 p.m. However, the public response was poor even with the evidence of the surges, and many people had to be forced away from the waterline and beaches by the authorities. The most important thing to note is that though a commendable response was eventually achieved, this happened only after observations within the country. This response was too late. The key lessons to learn are how to maximize information flow between key nodes and response capabilities, and how to link these into a warning system that filters up and down through international, national and local levels.

David Obura

Local (near-field) tsunamis can impact shores within 10 minutes of the earthquake occurrence, so warnings must reach the public well within this time if they are to be even a little effective. Distant (far-field) tsunamis might take many hours to traverse an ocean. In these cases, National Tsunami Warning Centres and national disaster management organizations may have ample time to organize evacuations so that no one should lose their life on inundation. Local preparedness and commitment at all levels of the community are the keys for success. Ultimately, warning systems will be judged on their ability to reach people on the beaches and in low-lying coastal areas and to evacuate them to safe refuges before the first wave hits the coast (Box C3).

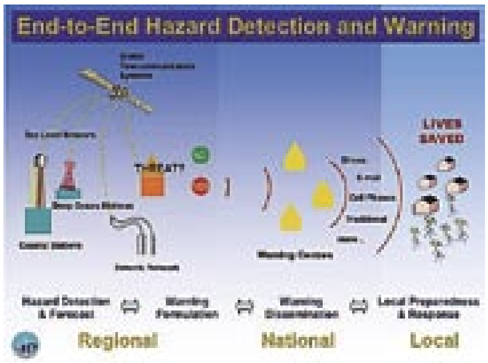



*Fig. C4.* *Components of a successful early warning system.*
*For the case of tsunamis, rapid tsunamigenic potential evaluations of earthquakes are essential to provide the fastest early warning to emergency officials, who must then issue understandable messages that result in immediate public response before the first destructive wave hits.*
*Source: ITIC.*

Substantial knowledge and expertise in natural disaster management and mitigation are available to deal with the risks of tsunamis. In particular, invaluable experience and knowledge has been amassed in the Pacific region, and now for the recent Indian Ocean tsunami, on how to assess tsunami risk at national and local levels (for example, these guidelines), how to promote awareness and preparedness, and how to build national and regional tsunami warning systems. Achieving success with early warning requires strong and sustained commitment by national governments. They must collaborate and work together in a regional framework to share data and they must jointly bear the cost for the regional elements of the network (Fig. C4). The need for regional collaboration is a result of the nature of tsunamis: local (near-field) tsunamis can be handled by National Tsunami Warning Centres; but, because regional or ocean-wide (far-field) tsunamis travel at 1000 km per hour as they propagate across the ocean, observational data is required from many countries in a region in order to accurately characterize the tsunamigenic potential of great earthquakes.

To warn people of an impending tsunami without preparing them for such an event may be ineffective. Preparing them through the provision of a public safety message that is clear, concise, and understandable to every person, with directions on what to do and where to go, is essential (Fig. C5). Tsunami alerts

| | |
|---|---|
| Proper instruments that enable the early detection of potentially harmful earthquakes and tsunamis. | The data obtained by these instruments must be readily available to all nations continuously and in real-time to be effective. |
| Warning systems that reliably inform the vulnerable populations immediately and in an understandable and culturally appropriate way. | The Warning Centre must be able to analyze and forecast the impact of tsunamis on coasts in advance of the waves' arrival. The local, regional, and/or national disaster management organizations must be able to immediately disseminate information on the threat and to enable evacuation of all vulnerable communities. The communications methods must be reliable, robust, and redundant, and work closely with the mass media and telecommunications providers to accomplish this broadcast. |
| Awareness activities that enable ordinary citizens to recognize a tsunami so that they know what to do. | Citizens should recognize a tsunami's natural warning signs and respond immediately. This is especially true for the case of a local tsunami, which may hit within minutes and before an official tsunami warning can reach their communities. Recognition and use of indigenous knowledge is important. |
| Preparedness activities which educate and inform a wide populace, including government responders and those providing lifeline and critical infrastructure services, on the procedures and activities that must be taken to ensure public safety. | Drills and exercises before an actual event, and proactive outreach and awareness activities are essential for reducing tsunami impact. Natural hazards science and disaster preparedness subjects that are part of the required curriculum taught to school children will prepare and carry awareness to the next generations. Gender-related issues in preparedness and family responses in emergencies need to be factored in. |
| Planning activities that identify and create the public safety procedures and products and build capacity for organizations to respond faster. | It is necessary to create and widely disseminate tsunami evacuation or flooding maps, and instructions on when to go, where to go, and how to go. Evacuation shelters and evacuation routes need to be clearly identified, and widely known by all segments of the coastal population. |
| Strong buildings, safe structures, and prudent land-use policies to save lives and reduce property damage that are implemented as pre-disaster mitigations. | Tall, reinforced concrete buildings may be adequate places to which people can vertically evacuate if there is no time to reach higher ground inland. Long-term planning to avoid placing critical infrastructure and lifeline support facilities in inundation zones will reduce the time needed for services to be restored. |
| Stakeholder coordination as the essential mechanism that facilitates effective actions in warning and emergency response. | Clear designation of the national or local authority from which the public will receive emergency information is critical to avoid public confusion, which would compromise public safety. |
| High-level government advocacy that ensures a sustained commitment to prepare for infrequent, high-fatality natural disasters such as tsunamis. | |

***Table C1.*** *Essential elements for an effective tsunami early warning system.*
*Source: ITIC*

from Regional Tsunami Watch Providers (RTWPs) are the technical trigger for early warning. But any system will ultimately be judged by its ability to save lives, and simply by whether people move out of harm's way before a big tsunami hits. For this, seamless communication is essential.

The most important activity for building an effective end-to-end early warning system is stakeholder coordination (Fig. C6). Additionally, high-level Government advocacy and commitment is needed to make the system sustainable. Successful systems require cooperation at all levels, a commitment of all stakeholders to work together during an actual tsunami warning emergency, and, over the long-term, a sustained effort to maintain awareness and preparedness at high levels. To build organizational support and long-term commitment, a Tsunami Coordination Committee is a mechanism that can bring together stakeholders from government and non-government agencies, science researchers, and the private sector. Such a committee, possibly embedded in an ICAM framework, can enable

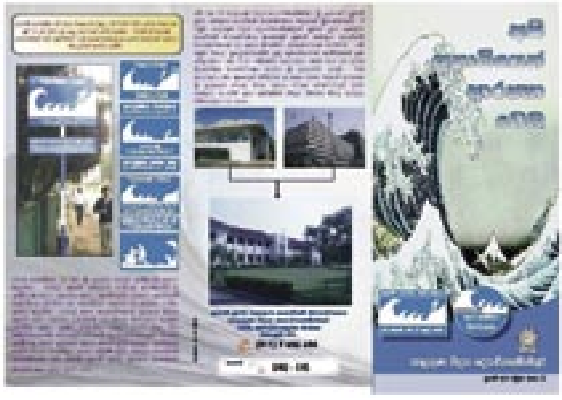


***Fig. C5.*** *Leaflet describing the tsunami early warning system, Sri Lanka.*
*Source: UNU-EHS.*


***Fig. C6.*** *Stakeholder coordination is essential.*
*A Tsunami Coordinating Committee engages all stakeholders to develop and participate in comprehensively reducing the risk from tsunamis. Key contributors are the scientists and engineers who assess and evaluate the risk, the tsunami warning centre which is responsible for rapid alerts, and government emergency services which must evacuate people before the tsunami arrives.*
*Source: ITIC.*

and advocate for policies, initiate the needed mitigation programmes, and coordinate emergency procedures before, during, and after a disaster.

We shall learn from every event, so that with time, each small step forward will contribute to building the preparedness for our future generations.

## C1.3 PREPARING FOR EVACUATION

### Evacuation zones, maps and signage

Subject to the assessed level of risk in respect of a tsunami event (B3), emergency managers should place a priority on establishing and implementing a policy for the effective, orderly evacuation of the exposed population. The vulnerability maps derived from the inundation maps (B1) and the vulnerability assessment (B2) provide key information for evacuation planning. A consistent approach to evacuation zone identification and mapping supports a common public understanding across communities of tsunami evacuation zones, maps, tsunami evacuation signage, and tsunami response actions.

### Tsunami evacuation zones

The key consideration for tsunami planning and information requirements is the number of zones that should be used for evacuation management and the way in which the information might be depicted for the public. Use of a single tsunami evacuation zone has the advantage of simplicity for both emergency planning and public understanding. However, because a single evacuation zone must accommodate the very wide range of local risk scenarios that may exist, this can result in regular "over-evacuation" of the entire zone for common, small-scale events. Recurrent over-evacuation is likely to result in decreasing levels of community trust in emergency managers. Use of more than three or four evacuation zones may better reflect the range of local tsunami risk scenarios. However, such differentiation requires far greater resources and a higher degree of coordination for planning and response, and the complexity of information may create public misunderstanding.

### Establishing evacuation zone boundaries

The elevations and methods used to establish these zones are developed at local level, based on local hazard analysis and risk assessments. Evacuation zone boundaries can be drawn based on a variety of hazard models. Zones ideally need to represent an envelope around all possible inundations from all known tsunami sources, taking into account all of the ways each of those sources may generate a tsunami. The high degree of uncertainty in tsunami source models, and the very time consuming and resource intensive nature of modelling make this comprehensive approach to tsunami risk assessment unlikely in the short term.

The recommended approach to defining tsunami evacuation zones is to map now, and progressively refine the accuracy of boundaries as the science improves over time. It is recommended that authorities proceed with mapping based on current available information and knowledge and not wait for the perceived required knowledge. Zone boundary definition can then be refined as knowledge improves over time. Often authorities defend their hesitation to define boundaries on the basis that they don't have sufficient information.

The first and basic means to define evacuation zone boundaries is what we refer to as the "bathtub" model in which inundation is determined based on a uniform maximum elevation inland from the coast. This approach provides the crudest but simplest model of inundation distances. The second step up would be an "approximation by a rule" which provides for a measure of rule-based wave attenuation inland from the coast. GIS can be used for applying the rule and it delivers a more realistic output than the "bathtub" model. Local knowledge must also be used. The third level up would be a computer derived simulation model that theoretically allows for complexities that a simpler rule cannot, such as varied surface roughness, water turning corners etc. Finally the most complete modelling would be based on an envelope around all inundations from multiple well-tested computer models. It will require a comprehensive scientific understanding of all possible tsunami sources, wave propagation and inundation behaviours across a range of magnitudes.

### Tsunami evacuation maps

Maps depicting tsunami evacuation zones, escape routes and tsunami safe areas need to be available as required by the community. It is recommended that maps are available for display in homes, holiday homes, tourist facilities, workplaces and public buildings in areas subject to tsunami risk. High use coastal areas should prominently display evacuation maps as part of tsunami information boards. Maps should be prepared and delivered in conjunction with planned tsunami signage placement depicting evacuation zones and routes on the ground.

In addition to the number and appearance of evacuation zones on maps, the basic legend, instruction messages and supporting information on maps should be nationally consistent. To ensure common understanding across communities, maps should use the same or closely similar colours, the same names for evacuation zones, and common symbols.

### Tsunami evacuation signage

Signage is an integral part of practical tsunami risk management. Signage depicting evacuation zones and routes raises public awareness of local tsunami risk and provides information to increase the efficiency and effectiveness of an evacuation (figs C7, C8). Well placed evacuation signage is the critical link between the emergency response plan and an actual event.

### Evacuation planning

Evacuation planning is a lengthy process and should be considered an ongoing endeavour which continues to improve in successive iterations. Consideration may be given to embedding such planning in the ICAM process (A1.5).The time taken for planning activities will be directly related to the:

- geographical size of the management area;
- regional topography;
- regional hazards and vulnerabilities;
- demographics;
- size and density of the population;
- number of agencies involved in the planning process; and
- resources available.

Evacuation in response to tsunamis generally implies voluntary and/or mandatory evacuation, both of which can place a significant burden on the resources of emergency managers in terms of caring for the displaced people. The demands on emergency managers will change as the evacuation progresses though each of its phases (Fig. C9).


***Fig. C7.*** *Safety instructions and signage for tsunami events.*

*Source: ISO 20712-1:2008–Water safety signs and beach safety flags–Part 1: specifications for water safety signs used in workplaces and public areas, and from ISO 20712-3:2008–Water safety signs and beach safety flags–Part 3: Guidance for use. Reproduced with the permission of the International Organisation for Standardisation, ISO. This standard can be obtained from any ISO member and from the Web site of the ISO Central Secretariat at the following address: www.iso.org/isostore. Copyright remains with ISO.*

***Fig. C8.*** *Road sign describing the tsunami hazard in the city of Padang, Sumatra.*
*Information is given in terms of height above mean sea level.*

*Photo: J.C. Villagran.*

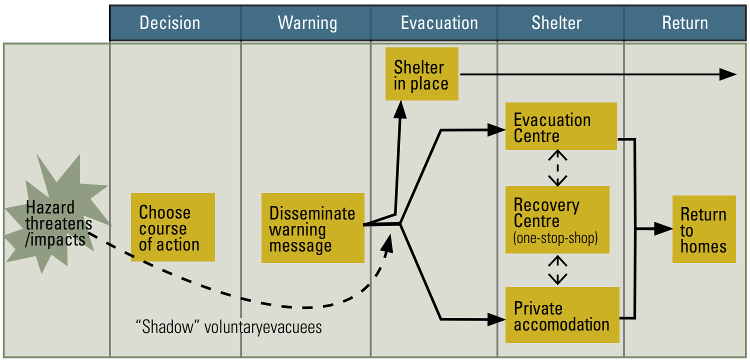



***Fig. C9.*** *Phases of the evacuation process.*
*Source: David Coetzee*

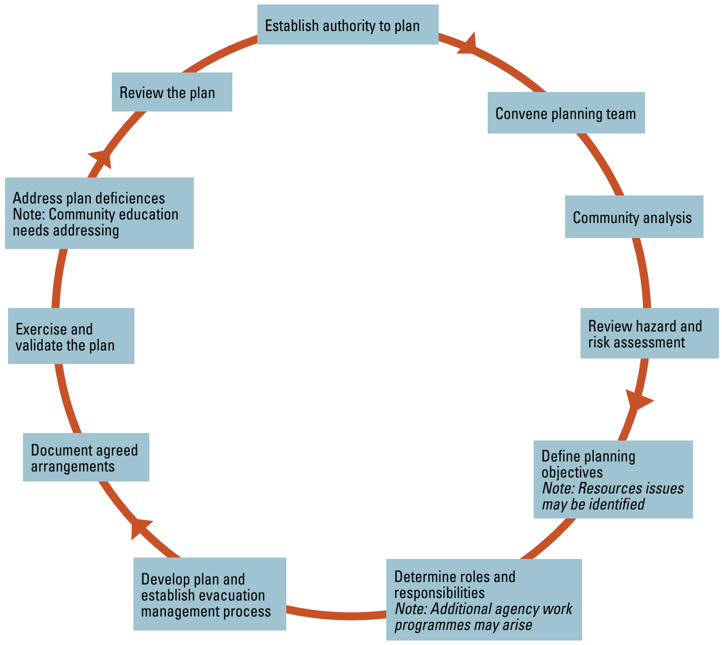



***Fig. C10.*** *A model for evacuation planning.*
*Source: David Coetzee*

As with all emergency planning, the process of evacuation planning itself is just as important as the final written plan (figs C9 and C10). In addition to developing a working knowledge of the overall plan, this process also facilitates the development of relationships between stakeholders which helps to improve operational capacities.

Aspects to be addressed in a tsunami evacuation plan include:

- conditions under which an evacuation may be necessary (see C2);
- conditions under which to support people sheltering in place, including vertical evacuation;
- identified "at risk" people/communities who may require evacuation (B2);
- command, control and coordination instructions (including designation of those authorised to order an evacuation);
- warning instructions to be issued to the media, public and businesses (C2);
- procedures for assisting special categories of evacuees (for example vulnerable communities, B2);
- specific plans and procedures that address:
  - the circumstances of the emergency;
  - transportation (for example, arrangements for those without vehicles);
  - dealing with community disregard of mandatory evacuation;
  - the evacuation of specific locations; and
  - evacuation routes
- means of accounting for evacuees;
- welfare support for evacuees; designated reception areas;
- security of evacuated areas;
- procedures for the return of evacuees; and
- maintaining the plan, drills and exercises.

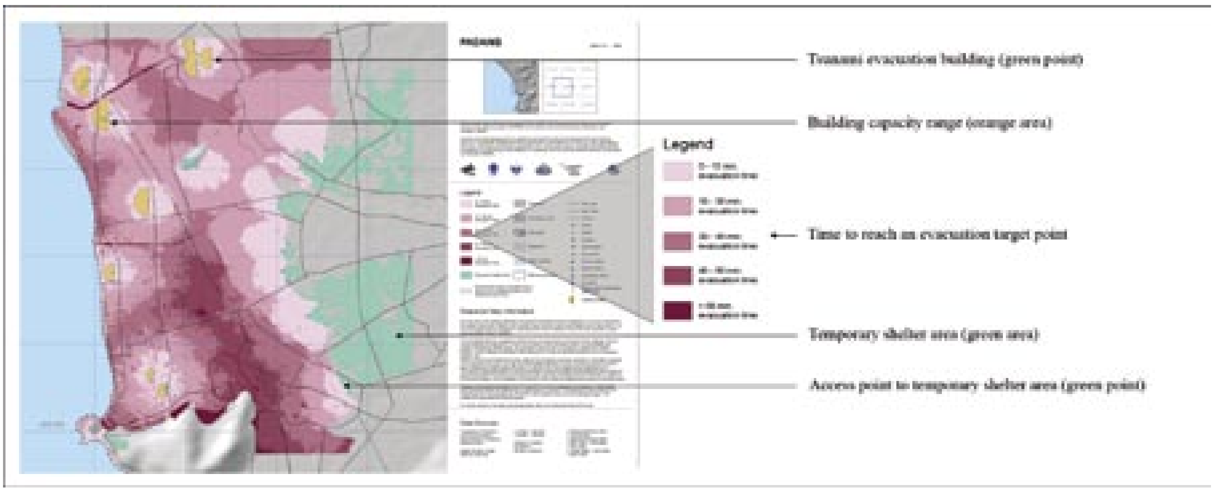



***Fig. C11.*** *Evacuation map for Padang, Sumatra.*
*Map shows the time people need to reach an evacuation building or horizontal shelter area. Evacuation constraints become evident in areas where the estimated evacuation time is very high (dark red colours). The capacities of vertical evacuation buildings are shown in orange colours. Source: GITEWS Project. Courtesy DLR, DKP.*

### Evacuation routes

Evacuation routes have to be designed to permit human and vehicle movement to safe places and evacuation structures. The design should be based on the expected volume of humans and vehicles, speed of evacuation and safety. The design should primarily present the number of routes required, the width and the overall safety of the evacuation process. The design must ensure the safe passage of evacuation and consider the risk of failure of the route itself under disaster conditions. Such an approach will identify weak links which may have to be rectified in advance and also recommend alternative routes in the event of failure of a prescribed route.

### Evacuation structures

The need for evacuation structures should be identified with respect to the population at risk and time available for evacuation to safe places, if such places have been identified. Evacuation structures are mandatory in the absence of safe places such as high ground or elevated infrastructure which can safely accommodate people at risk. Even if such safe places and facilities are available, it is necessary to be certain that the people at risk can be safely evacuated to such locations. If not, supplementary evacuation structures should be provided.

For this purpose it is necessary to determine the critical time for the tsunami to reach a proposed safe place for a worst-case scenario after the warning is issued; also the maximum time required for evacuation (figs C12 and C13). In the analysis a safety factor should be included to accommodate any potential delay in the evacuation process. Sometimes the need for evacuation structures may be avoided by having additional routes to the safe zones, thereby accommodating a reduced density of the human evacuation rate on a given route, leading to a higher rate of evacuation.

### Evacuation education and communication

The community must be educated and made fully aware of the risk of hazard, potential disaster and the evacuation routes. Evacuation drills must be conducted to ensure training of the community on disciplined evacuation. A mechanism for this entire process to be monitored on a community-led, sustainable basis should be established. In effect it is necessary to ensure community ownership of this process. The maintenance of the evacuation route should be given high priority. The community must also develop an effective mechanism for communication duration the evacuation process. This will ensure the problems and issues of panic-stricken population who are on the move are swiftly handled and resolved, thereby minimizing the level of prevalent chaos.

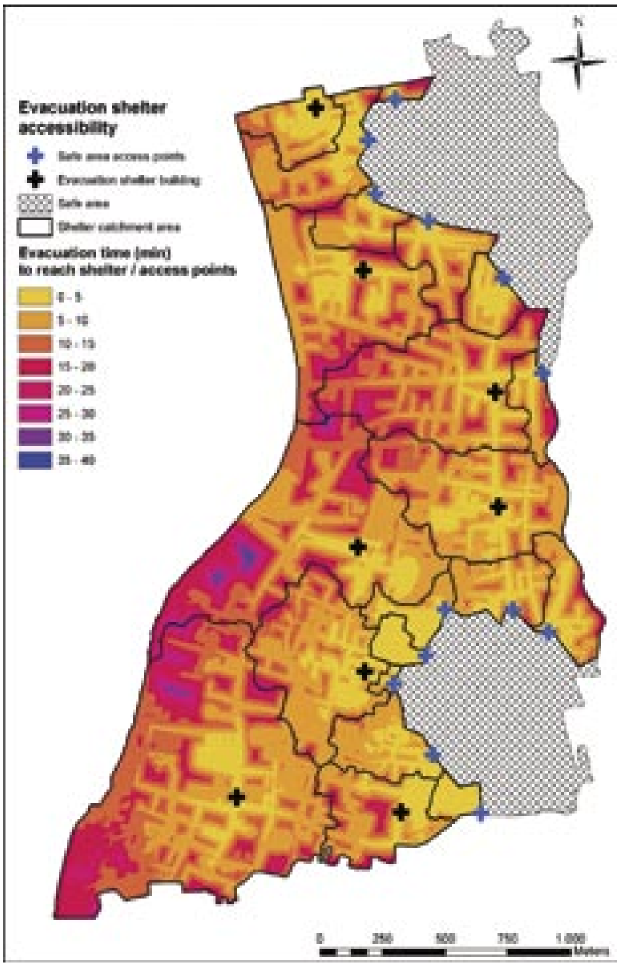



***Fig. C12.*** *Evacuation map for Kuta, Bali.*
*Map shows the time in minutes (short time=yellow; long time=red, purple) people need to evacuate to vertical shelter buildings or horizontal shelter areas.*
*Source: GITEWS Project. Courtesy DLR.*

## C1.4 PROMOTING COMMUNITY-BASED DISASTER RISK MANAGEMENT

### How do communities deal with shocks of natural disasters?

Following the Indian Ocean tsunami of 2004, sociologists have established that indigenous knowledge contributed directly in saving lives among the Moken (Thailand) and Simeulue (Indonesia) communities (see C1.1). These two success stories highlight the importance of communities' abilities to cope with hazardous events. They also focus interest on the practice known as Community-based Disaster Risk Management (CBDRM).

Sadly, however, since the 2004 tsunami, many more catastrophic events have provided additional reminders of the vulnerability of many South Asian and Pacific Ocean countries to natural disasters. These events included major earthquakes in China, Pakistan and India, devastating cyclones (typhoons) in Bangladesh, the Phil-

**Box C4. National Disaster Loss Databases**

National disaster loss databases with 30-year data are available in Sri Lanka, Tamil Nadu and Orissa in India, Indonesia, Nepal and Iran. Five-year databases are available in Indonesia, and there are limited historical data in Maldives and Fiji.

ippines and Myanmar, and widespread flooding in Nepal and India.

Interestingly, UNDP's support to the establishment of historical disaster loss databases in a number of countries indicated the increasing significance of extensive risks in comparison with intensive risks or catastrophic events (Box C4 and Table C2). Extensive risks are those related to low intensity, but more frequent events induced primarily by climate change-related pressures. Trends derived from these databases indicate that, although these events were not life-threatening like the big events making the news headlines, their impacts on the livelihoods of communities and poverty were very serious. Patterns such as these were observed in small island states (for example, the widespread sea swells in Maldives) and in countries where communities are prone to landslides and floods (for example, Nepal, Sri Lanka). Because these low-intensity events failed to capture international attention, the recovery of those affected was unaided, their losses accumulating over time.

In cases of these low intensity events, it is important to realise that it is the communities themselves that are the most important, often sole, agents for preparedness and remedial action. Recognizing this, the role of external actors is to support these communities through a systematic approach that enhances community resiliency.

**Box C5. The importance of oral history**

The tsunamis on 26 December 2004 and 28 March 2005 killed only seven people on Simeulue Island in Indonesia's Aceh province. At Langi, on the north end of Simeulue, which is 40 km south of the December earthquake's epicentre, maximum wave heights exceeded 10 m less than 10 minutes after the shaking ceased. In the more populous south, wave heights averaged 3 m and caused significant structural damage, destroying entire villages. Oral histories recount a massive tsunami that occurred in 1907 and advise running to the hills after "significant" shaking (~1 minute). All the interviewed Simeulue survivors knew of this event and of the necessary action. However, Jantang, on the Aceh mainland, suffered far more casualties. Simeulue's oral history provided an extraordinarily powerful mitigation tool that saved countless lives where even a high-tech warning system with a 15-minute response time would have been of no help.

*Source: McAdoo et al., 2006.*

**Why use a community-based approach?**

In almost all of the major disasters that have occurred in the region, lessons learned from studies of the databases strongly suggest the importance of an approach that focuses on enhancing the community's ability to reduce disaster risks. These lessons show that:

- The local people in a disaster prone area, due to their exposure and proximity, are potential victims and assume most of the responsibilities in coping with effects of disasters.
- The local people have local knowledge of vulner-

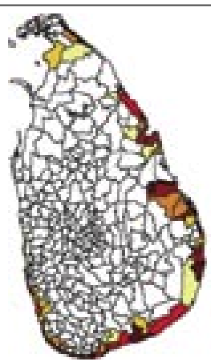
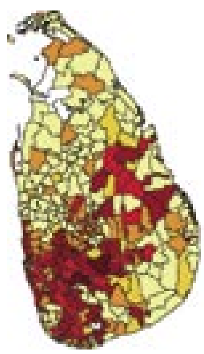
| | Intensive Event (Dec 2004 Tsunami)<br>66 out of total 331 Divisions affected | Extensive Events<br>320 out of total 331 Divisions affected |
|---|---|---|
| Mortality |  |  |

***Table C2.*** *Intensive and extensive events in Sri Lanka.*
*Many more communities had to cope with low intensity but more frequent events.*

*Source: Based on analysis of data from on-line DesInventar Database for Sri Lanka, http://www.desinventar.lk, accessed on 4 December 2008.*

abilities and are repositories of any traditional coping mechanisms suited to their own environment (boxes C5 and C6).
- The local people respond first at times of crisis and are the last remaining participants as stricken communities strive to rebuild after a disaster.

These lessons learned highlight the role of communities. They are the primary group who must understand the hazards in their environment and their vulnerability to those hazards. In the case of the tsunami hazard, it is they who are the potential key beneficiaries of tsunami risk assessments.

However, the same studies indicate that a majority of the communities, when left on their own without external support, may not be sufficiently impressed to respond positively to an official/natural warning of an impending event. Besides, even if risks from an assessment are explicitly presented, there is no guarantee that communities will undertake the appropriate risk management actions. Communities deal in different ways with different types of shocks associated with different risks (whether resulting from natural or man-made events). Communities decide what to do, depending on their perception of the risk, and of the trade-offs and perceived benefit/s of risk management options and/or indigenous methods. Noting this, a credible tsunami risk assessment within a multi-hazard framework will help communities to become more risk aware and undertake appropriate actions for risk reduction.

### What is the CBDRM practice?

The CBDRM practice was introduced systematically in the mid-1990s. The CBDRM approach provides opportunities for the local community to evaluate their own situation, based initially on their own experiences. Under this approach, the local community becomes not only part of planning and decision making, but also a major player in the implementation of those plans and decisions.

Although the community is given greater roles in the decision making and implementation process, CBDRM does not ignore the importance of scientific and objective risk assessment and planning for early warning. The CBDRM approach acknowledges that as many stakeholders as needed should be involved in the process, with the end goal of achieving capacity and resource transfer to the community, which would itself assume the main responsibility for disaster reduction.

### How would a tsunami risk assessment add value to CBDRM?

Practitioners of CBDRM typically are trained to draw the appropriate participatory methodology from a "toolbox". However, opinions persist that, although these tools had been useful, a common and key weakness was the inadequate use of scientific information in risk assessment. Therefore the opportunity to apply these tsunami risk assessment and mitigation guidelines to the CBDRM practice will be in the following, commonest CBDRM methods and procedures:

- Participatory Risk Assessment Toolbox (including transect, seasonal calendar etc.). These methodologies support community-level processes, where communities are engaged in understanding disaster risks, both realized/historical and unrealized/potential. The Guidelines should be able to foster a comprehensive understanding among communities about risk as a configuration of hazards, changing patterns of vulnerability and community coping capacity. Communities would typically know about the realized risks that occurred in their living memory (for example, the 1907 Simeulue Tsunami), but would be unable to anticipate future tsunami events including their sources.
- Community meetings, face-to-face interaction, folk songs and traditional cultural presentation, and use of change agents that build awareness and develop public and culturally adaptable information programmes for preparedness. Studies resulting from tsunami risk assessment must be able to guide community education/awareness activities being undertaken under CBDRM. Besides, community facilitators or change agents must be knowledgeable of the results of risk assessment studies.
- Community-level preparedness planning processes that engage members of the community. Results of risk assessment studies must provide an important input to stakeholders who would decide on the elements of community preparedness plan, i.e., contingency plan, evacuation plan, community-based first aid and other life-saving skills enhancement.
- Community-based warning system, including the practice of organizing and maintaining warning dissemination volunteers' structure, use of indigenous resources like church bells, mosques, horns, local radio, etc. In many coastal communities, natural warning signs maybe more useful in saving lives, particularly for tsunamis resulting from local earthquakes. A proper tsunami risk assessment study should be able to guide and enhance the effectiveness of a community-based warning system.
- Processes that promote a culture of safety, particularly for future generations. The CBDRM tools that may be improved by a tsunami risk assessment include: School-based education programmes; Education for Women; Education for people who have influence over communities, i.e., school teachers, religious leaders, local media, other traditional leaders.

**Box C6. Indigenous knowledge for disaster risk reduction**

Of the 52 people that died during the Solomon Islands earthquake and tsunami in 2007, 31 (59.6%) were immigrant Gilbertese from Titiana, New Manra and Nusa Mbaruku that did not react properly because they had no memory in their culture of such an event. Kiribati is a coral atoll nation, situated far from any regular earthquake sources. Because there have been no major, tsunamigenic earthquakes in the 50 years since their emigration, they simply lacked the indigenous knowledge of their adopted environment that could have helped save their lives. Gilbertese children were particularly vulnerable because not only were they too weak to swim against the relatively slow-moving yet deep tsunami, but they lacked the indigenous knowledge that would have kept them from exploring the emptied lagoons.

The indigenous Solomon Islanders, on the other hand, in large part responded in a way that reduced their overall mortality. Indigenous knowledge of the Solomon Islands, where active volcanoes and earthquakes are more common, mitigated the effects of this tsunami. In indigenous villages on hard-hit Ghizo Island, the effects of the tsunami were mitigated by the combination of:

- a healthy coral reef with a steep barrier front and a wide, shallow lagoon that reflected and attenuated some of the tsunami's energy;
- accessible and effective escape routes and high ground provided by the existing topography; and
- an indigenous knowledge of what to do during a strong earthquake followed by an emptying lagoon.

Immigrant Gilbertese villages with both the same physiography and who were hit by a tsunami of equal intensity, lacked indigenous knowledge which led them to suffer more casualties. Many people died at the indigenous village on Tapurai, which lacked an effective coral reef barrier due to its natural morphology that evolved on the lee side of Simbo Island.

Indigenous knowledge is an effective tsunami mitigation tool when the right combination of education and physiography come together. Locations with broad coastal plains would have a hard time evacuating the coast, especially if population densities are high as is the case with Banda Aceh, Indonesia, during the 2004 Indian Ocean tsunami. Nonetheless, a barrier reef, wide lagoon and stand of mangroves were not enough to protect the residents of New Manra since they had no knowledge of tsunamis in this region.

*Source: UN/ISDR, 2008*

## C1.5 OUTPUTS FROM THE PREPAREDNESS PROCEDURES

The expected principal outputs from these procedures are:

- measures for education and public awareness of risks established;
- special target audiences identified;
- an effective, tested, end-to-end early warning system in place;
- evacuation procedures and tested, and refuges in place; and
- Community-based Disaster Risk Management (CBDRM) implemented where appropriate

### Suggested additional reading and information sources

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# **C2 How to mitigate** the tsunami risk

**Key tasks in the strategic mitigation procedure**

- Define the temporal and geographical scales of the management area.
- Review the options for strategic mitigation.
- Consider a hybrid approach to the response measures.
- Incorporate other coastal management goals in the response.
- Apply decision-analysis tools in the management process.
- Involve the public in the decision-making processes.

This part of the guidance describes your management of the tsunami risk by strategic mitigation, both through the use of structural methods, including the use of natural coastal resources and engineering approaches, and also by non-structural initiatives, including regulation and land-use planning.

## C2.1 CONSIDERING THE OPTIONS FOR STRATEGIC MITIGATION

The overarching goal of strategic risk management is effective and sustainable risk reduction. This entails choosing strategic management options for risk reduction that are appropriate to the scale of the designated coastal management area, balancing social and economic pressures against environmental considerations, including sustainability, over the long-term.

Strategic mitigation of the tsunami risk may involve structural, commonly engineered measures that aim to protect coastal communities and their supporting systems; non-structural measures that aim to reduce risk by accommodating it through changes of individual to community behaviour and practice, and those that seek to reduce risk by promoting a retreat from the tsunami hazard by means of land-use planning and financial instruments (Fig. C.13). In practice, a coastal authority may adopt a risk management plan that incorporates all three types of measures. Some of the measures may encompass long timeframes, extending perhaps over several decades (C1).

The treatment given for strategic mitigation in these guidelines should be considered only as an outline account. A more comprehensive description and review of the options open to policy makers and coastal engineers in respect of tsunami risk mitigation is available in the IOC-ICAM hazard guidelines (UNESCO, 2009).

### The application of decision-analysis tools

Decision-analysis tools including benefit-cost analysis and multi-criteria analysis can be very helpful in evaluating the benefits and drawbacks of the various options for mitigation. Benefit-cost analysis involves the comparison of the total cost of one or more strategies with the total benefits it would provide. An effective approach is one in which the benefits to the community outweigh the costs. In order to perform a benefit-cost analysis, all costs and benefits must be translated into a common denominator – typically monetary.

Multi-criteria analysis can be helpful for analysing complex, multi-disciplinary strategies with multiple criteria and objectives. Multi-criteria analysis does not require that all alternatives be placed in monetary terms but can incorporate both quantitative and qualitative data, including value judgements.

While there are many different types of decision-analysis tools to select from, policy makers should be sure that the analysis will provide a reasonable comparison of the short- and long-term costs of protection, accommodation and retreat, and account for the major socio-economic and environmental costs of the alternatives as well.

### The need for public involvement

Public opinion and wide stakeholder involvement are also valuable tools that should be included in the decision-making process as the risk management strategy is developed. Public support and "buy-in" is important for the success of the strategy as it is for the wider aspects of coastal management. To engage the public, policy makers should educate them about the risks and benefits and drawbacks of various management options. The public should have the opportunity to provide input on the level of risk that is acceptable or needs to be managed.

The concept of "living with risk" should be introduced in the context of mitigation. From a practical point of view, mitigation cannot eliminate risk and there are limits to the availability of funds for mitigation. It is important that

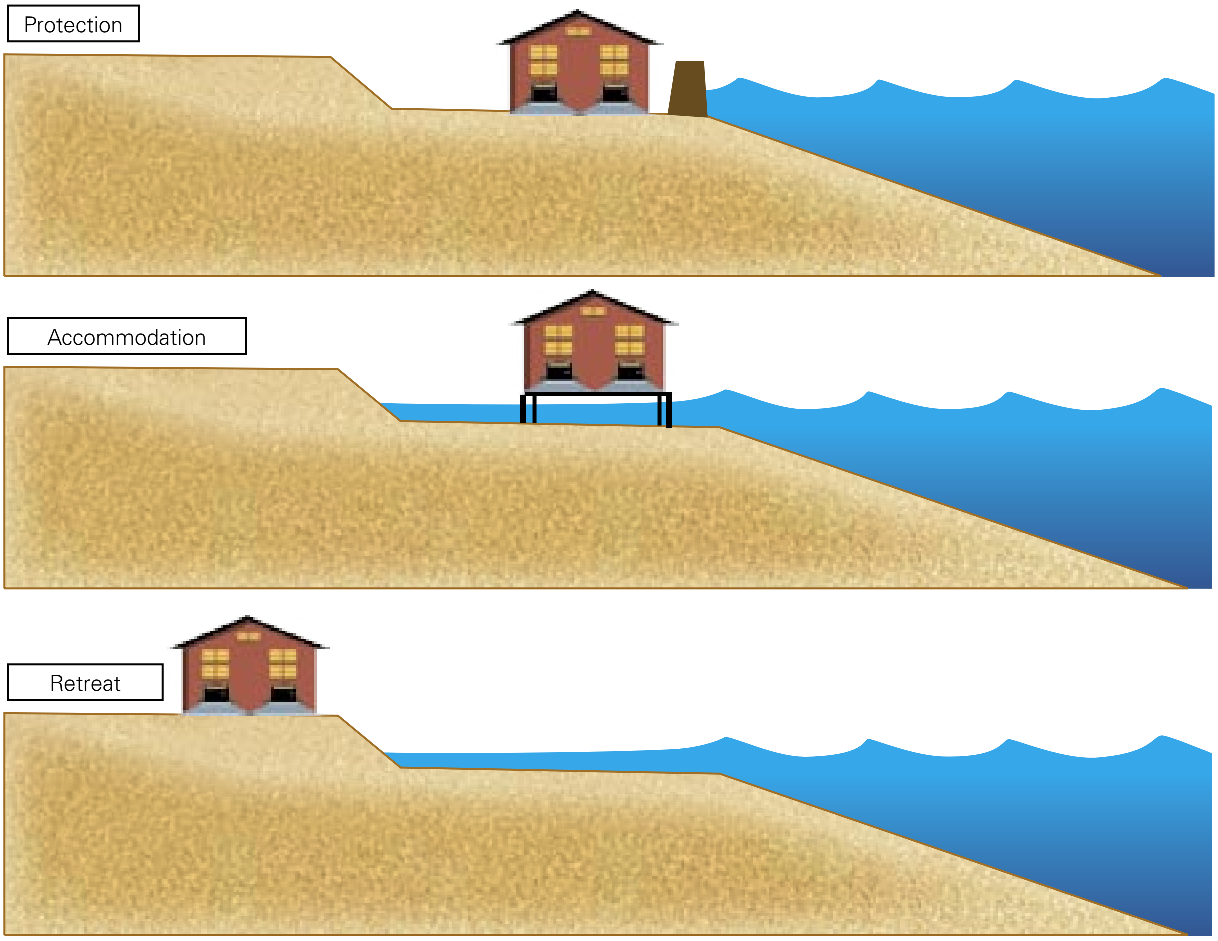


***Fig. C13.*** *The options for strategic mitigation: protection, accommodation and retreat. Blue line represents general maximum tsunami wave- and inundation height.*
*Source: Based on Bijlsma et al., 1996.*

**Box C7. Blanket no-build zones are 'neither feasible nor sustainable'**

While it is laudable to try to protect at-risk communities from hazard events, international experience clearly shows that blanket no-build zones are neither feasible nor sustainable. A practical approach is necessary, in which risk assessments are undertaken to identify where return to original sites is or is not technically and environmentally feasible. These assessments should involve community representatives working with social and technical specialists, and assess the suitability of the original site for rehabilitation, including its vulnerability to various natural hazards, disease and environmental risks, the suitability of land for agriculture, and so forth.

*Source: World Bank Update on The World Bank Response to the (2004 Indian Ocean) Tsunami Disaster (published April 2005).*

strategic mitigation measures against tsunami risk be developed within a multi-hazard coastal risk assessment framework as an integral component of an overall coastal area management plan. The possibilities of other physical coastal hazards including storm surge inundation and coastal erosion affecting the shoreline of interest should also be considered in the formulation of such a plan.

## C2.2 USING NATURAL AND ARTIFICIAL STRUCTURAL METHODS

This part of the guidance deals with the options for reducing risk by coastal protection through structural means (Fig. C13). While the underlying principles of protection against coastal inundation and erosion are similar irrespective of the type of physical hazard, the scale of the structures capable of withstanding the hydrodynamics of tsunami flow needs to reflect the perceived level of tsunami hazard (B1). Furthermore, the possibility of long-term changes in coastal sedimentation and erosion, caused by changes in nearshore bathymetry resulting from a tsunami impact, should be considered.

***Fig. C14.*** *Natural structural protection: mangrove rehabilitation in Peninsular Malaysia.*
Rhizophora apiculata *five months after planting for the rehabilitation of an eroded site (Category 1), using an innovative planting technique, COMP-MAT, with Geotubes as a front-line wave breaker. Bernam Forest Reserve, Selangor, Malaysia.*
*Source: I. Shamsudin, R. S. Raja Barizan, M. Azian and H. Mohd Nasir, Forest Research Institute Malaysia (FRIM). Picture Copyright © FRIM-JPSM & NRE National Task Force Committee of Planting Mangroves and Other Suitable Species Operation in Shoreline of Malaysia*

Because shorelines are dynamic, structural mitigation measures at a particular location should not be developed in isolation. It is important to understand the hydraulic behaviour of the wider coastline, including its sediment transport regime, which may determine the stability of the shore. Care should be taken to ensure that structural mitigation works at one location do not lead to instability on an adjacent shore.

Structural protection may be achieved not only by artificial methods employing coastal engineering design such as offshore breakwaters, dykes and revetments, but also by natural methods, harnessing the full potential of coastal ecosystems including coral reefs, sand dunes and coastal vegetation such as mangrove forests.

The type of protection adopted may mitigate other physical hazards besides tsunami (these having different magnitudes and frequencies of occurrence), while sustaining multiple uses of the coastal zone. This might be achieved through adoption of a single measure or, more usually, by a well integrated hybrid solution, comprising several measures and also satisfying environmental concerns. Hybrid methods refer to combinations of artificial methods or a combination of natural and artificial methods. Natural solutions, such as planting mangroves, provide cost effective, environmentally friendly solutions to mitigate tsunami risk where there is with a low frequency of occurrence (Fig. C14).

Within the framework of a coastal area Management Plan, measures which mitigate the impact of the tsunami hazard represent a coherent set of interventions. These may be specified in time and space to achieve a certain expected level of protection against existing or anticipated damage from tsunamis as well as other hazards. Such solutions can be proactive, leading to shoreline restoration and stability. A project monitoring and control system can also be incorporated within such a plan.

### Protecting against the tsunami hazard

Measures which prevent the impact of the tsunami hazard may be classified into three types, depending on their location and protecting function. These measures respectively:

- reduce the impacts of tsunamis before they reach the shoreline (a partial barrier located in the near-shore zone);
- protect the coastal area at risk by preventing the inland movement of tsunamis (a full barrier at the shoreline); and
- reduce the impacts of tsunamis on entry to the shoreline (a partial barrier at the shoreline).

Full and partial barriers, whether artificial or natural, are physical interventions which may be considered a protection solution for populated coasts. In designing artificial barriers it is necessary to ensure the continuity of sustaining multiple uses of the existing natural environment. From an engineering point of view, the design must be robust, functional and reliable. Due consideration should be given to convenient maintenance and effective operation. Equally it is important to minimize negative impacts on socioeconomic, livelihood and environmental issues. Sensitive landscaping of the environment is a priority.

### Partial barriers in the nearshore zone

Offshore tsunami breakwaters are usually partial barriers which dissipate part of the incoming tsunami's energy before the tsunami reaches the shore. These could also be designed as full barriers with the inclusion of a tsunami gate for complete closure. It is possible to integrate tsunami breakwaters within a strategic port development project; the principal breakwater of the proposed port would serve also as a tsunami breakwater. Coral reefs serve as natural breakwaters in dissipating tsunami- and other types of wave energy. This function is particularly effective during low-tide conditions, an aspect observed along the fringing reefs of the Kenyan coast during the Indian Ocean tsunami of 2004 (Box C3).

### Full barriers at the shoreline

High-rise seawalls (dykes) constructed on the shoreline at or above the high water mark are designed to provide a full barrier against the tsunami propagation. Where the shoreline is interrupted by river mouths, tsunami gates can be installed within seawalls to allow for normal flows and traffic access. The closure of the gate prevents tsunami propagation. Sand dunes can provide natural full barriers against tsunami inundation. Their effectiveness was proved in many countries during the Indian Ocean tsunami of 2004. When overtopped, sand dunes tend to fail progressively by erosion. Dune-cladding vegetation provides reinforcement to the dunes thus impeding erosion. It is strongly recommended that sand dunes combined with coastal vegetation are adopted as a shoreline barrier where circumstances permit.

### Partial barriers at the shoreline

Medium-rise seawalls (dykes) provide partial barriers against tsunami flow and will prevent propagation up to specific design water levels. The design permits overtopping beyond these levels. The stability of such barriers during overtopping and inland drainage issues need to be given due consideration. Coastal vegetation can be used to dissipate tsunami energy via turbulent flow through the media. The effectiveness of dissipation is dependent on the density of vegetation, its overall porosity and its tortuous characteristics of porous matrix. It is important that the vegetation is itself resilient against tsunami propagation and have a root structure that can resist the high velocity regime at the floor bed. Planting mangrove at appropriate locations can also serve to dissipate extreme wind wave energy (Fig. C14). The extent to which coastal trees, such as Casurinas, at the shoreline can act as bioshields is controversial.

## C2.3 USING NON-STRUCTURAL APPROACHES

Non-structural measures that mitigate exposure and vulnerability to the hazard include:

- hazard resilient buildings and infrastructure;
- land-use planning including development "setback"; and
- risk transfer.

### Hazard resilient buildings and infrastructure

Coasts tend to be areas of high economic activity. However, it is not feasible to transfer all activities to areas that are completely free from potential tsunami risk. Therefore there may be a need to accommodate the risk (Fig. C13). The development and application of design guidance and construction manuals for tsunami-resistant housing and infrastructure form parts of this accommodation. It may be expected that properly designed structures will withstand the impacts of tsunami with only limited damage. For coastal areas where safe evacuation refuges may be too remote for people to reach on foot, vertical evacuation structures may be necessary (C2.3). Such structures must be capable of withstanding the extreme conditions arising from a tsunami impact.

Although cost may be an impediment to tsunami-proofing structures, national authorities may choose to make tsunami-proof structures with flow-through designs, stronger buildings, and deeper scour-resistant foundations mandatory in areas of high risk. The orientation of buildings with respect to the ocean is another factor for consideration. Particular attention should be directed to the security of structures used for vertical evacuation shelters. In areas of low risk, the extent to which communities should accommodate the tsunami hazard may be difficult to determine, though the precautionary principle should prevail.

It is recommended to develop and apply codes of practice for the design of tsunami resistant structures (see B2.4). Two types of code are required:

- *Design Guidelines on Good Practice* providing advice on concept, location, layout, orientation, structural configuration, geotechnical considerations and other considerations leading to good design practice. Such designs will enhance the robustness of the structures to withstand tsunami attack and other coastal hazard impacts without total collapse or failure.
- *Detailed Design Guidelines* providing information on hydraulic and structural loads, geotechnical parameters and detailed design information. The design approach should be based on the concept of design against failure and in this context attention must be focused on failure modes and the development of a "fault tree".

The overall design guidelines could be developed from the experience gained from post-tsunami impact damage assessments from different parts of the country. Such assessments should be analyzed in the context of the hydraulic regime which would have been generated by the tsunami at that location. Relevant information from other countries that have been affected by tsunamis will also be useful for this exercise. It is important that damage assessment should cover infrastructure that was destroyed; damaged; or survived (least affected). The proposed design guidelines should be applicable to the:

- rehabilitation of damaged structures;
- strengthening of existing structures (retrofitting); and
- design of new structures.

Countries may find widely varying recommendations for tsunami design loads. Some harmonization is desirable. Some attempts have also been made to produce qualitative guidelines for "non-engineered" buildings.

### Land-use planning including development "setback"

Land-use planning can be an effective means of implementing the option of managed retreat in tsunami risk mitigation (Fig. C13). Information to inform policy on land-use planning, which countries may apply within a regulatory framework, is contained in the inundation, vulnerability and risk maps produced as outputs from the risk assessment process (B4).

Hazard maps, particularly inundation maps for scenarios that are considered to pose significant levels of risk to the community, are an appropriate tool for land-use planning. Possible criteria for determining risk (or impact) categories related to specified tsunami hazard scenarios are listed in B4.2.

A possible option for consideration in land-use planning is the introduction of development setback lines. Development setbacks to cope with, amongst other issues, the threat of coastal physical hazards (coastal erosion and storm surge inundation as well as tsunamis) have become mandatory in a number of countries. Setback lines are determined by local authorities, in some cases within a national legislative framework, to delimit exclusion zones for development in coastal areas that are perceived to be exposed to inundation or at risk from coastal erosion. In the Mediterranean region since January 2008, all countries that are signatories to the Barcelona Convention are bound to adopt setback planning regulation. Development setbacks are intended to direct new development or redevelopment out of identified hazard areas and to protect natural hazard mitigation features such as beaches and dunes by restricting development seaward of a setback line, established parallel to the shoreline. The type of setback used, including how, and from where, it is established, can vary widely. The application of setbacks is a globally accepted good practice in coastal area management (see ICAM hazard guidelines, UNESCO, 2009).

### Risk transfer (see also B3.3)

Insurance plays an important role in offering financial protection from the costs of flooding. By spreading risk across policy-holders, insurance enables householders and businesses to minimize the financial cost of damage from inundation. Furthermore, because lenders are unlikely to offer mortgages on properties that cannot obtain buildings cover, insurance plays a critical role in the operation of the property market. However, insurance can provide an effective mechanism for spreading the risk only if the risk is at a manageable level.

Reinsurance is the insurance that insurers themselves take out to deal with catastrophic events/claims. It provides a mechanism that can help insurers provide financial protection to developments located within the limits of potential inundation, and at risk from an inundation event. However, it is anticipated that reinsurers will become increasingly selective of the portfolios they are prepared to take on. Reinsurers model exposure based on the best-available estimates of risk. These are revised as more information becomes available, for instance following a catastrophic event. Where this reassessment leads to a limitation or withdrawal of reinsurance cover, insurers would need to reflect this in the extent of insurance coverage and the premiums they charge. This underlines the need to take a precautionary approach to large aggregations of new development in potential inundation zones.

## C2.4 OUTPUTS FROM THE STRATEGIC MITIGATION PROCEDURES

The expected principal outputs from these procedures are:

- a portfolio of effective hazard mitigation measures which are consistent with wider coastal management objectives; and
- a long-term plan for the implementation of the measures, including a monitoring programme to assess the effectiveness of the selected strategy in reducing risks in respect of the tsunami hazard.

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## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AWI | Alfred Wegener Institute for Polar and Marine Research, Bremerhaven |
| BMKG | Meteorology, Climatology and Geophysics Agency, Indonesia (Badan Meteorologi, Klimatologi dan Geofisika) |
| BNBP | The Indonesian National Board for Disaster Management (Pendapatan Negara Bukan Pajak) |
| CORDIO | Coastal Oceans Research and Development in the Indian Ocean |
| DKP | Department of Maritime and Fisheries Affairs, Indonesia |
| DLR | German Aerospace Center |
| CARIBE-EWS | Tsunami and Other Coastal Hazards Warning System for the Caribbean and Adjacent Regions |
| CBDRM | Community-based Disaster Risk Management |
| FRIM | Forest Research Institute Malaysia |
| GFZ | Geo-Forschungs-Zentrum (German Research Centre for Geosciences), Potsdam |
| GIS | Geographical Information System |
| GITEWS | German-Indonesian Tsunami Early Warning System |
| GTS | Global Telecommunications System |
| GTZ | German Technical Co-operation |
| GTZ IS | German Technical Co-operation International Services |
| HAT | Highest Astronomical Tide |
| HWM | High Water Mark |
| ICAM | Integrated Coastal Area Management |
| ICG | Intergovernmental Coordinating Group (of IOTWS) |
| Ina TEWS | Indonesian Tsunami Warning System |
| IOC | Intergovernmental Oceanographic Commission |
| IOTWS | Indian Ocean Tsunami Warning and Mitigation System |
| IPCC | Intergovernmental Panel on Climate Change |
| ISDR | United Nations International Strategy for Disaster Relief |
| ITIC | International Tsunami Information Centre |
| ITSU | Tsunami Warning System in the Pacific (superseded) |
| IUCN | International Union for Conservation of Nature |
| JCOMM | Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology |
| JMA | Japanese Meteorological Agency |
| JRC | Joint Research Centre, European Commission |
| JTIC | Jakarta Tsunami Information Centre |
| LIDAR | Light Detection and Ranging ground/seabed survey technique |
| LIPI | Indonesian Institute of Sciences (Lembaga Ilmu Pengetahuan Indonesia) |
| MCDEM | Ministry of Civil Defence and Emergency Management, New Zealand |
| MSL | Mean Sea Level |
| NEAMTWS | Tsunami Early Warning and Mitigation System in the North Eastern Atlantic, the Mediterranean and Connected Seas |
| NEXIS | National Exposure Information System, Australia |
| NGDC | United States National Geophysical Data Center |
| NGI | Norwegian Geotechnical Institute |
| NGO | Non-Governmental Organisation |
| NOAA | National Oceanic and Atmospheric Administration (United States Government) |
| NTWC | National Tsunami Warning Centre |
| PPEW | Platform for the Promotion of Early Warning |
| PSHA | Probabilistic Seismic Hazard Analysis |
| PTHA | Probabilistic Tsunami Hazard Analysis |
| PTWS | Pacific Tsunami Warning and Mitigation System |
| RTWP | Regional Tsunami Watch Provider |
| RTWS | Regional Tsunami Warning System |
| SOPs | Standard Operating Procedures |
| STHA | Scenario-based Tsunami Hazard Analysis |
| TOWS | Tsunami and Other Marine Hazards Warning System |
| TTT | Tsunami travel time |
| U.K. | United Kingdom |
| UNESCO | United Nations Educational, Scientific and Cultural Organisation |
| UNFCCC | United Nations Framework Convention on Climate Change |
| UN/ISDR | see ISDR |
| UN-OOSA | United Nations Office for Outer Space Affairs |
| U.S. | United States of America |
| USGS | United States Geological Survey |
| WAPMERR | World Agency of Planetary Monitoring and Earthquake Risk Reduction |
| WDC | World Data Center |
| WMO | World Meteorological Organisation |

## GLOSSARY

**Accommodation**: The continued use of land at risk, without attempting to prevent land from being damaged by the natural event. This option includes erecting emergency flood shelters, elevating buildings on piles, converting agriculture to fish farming or growing flood/salt tolerant crops (Bijlsma et al., 1996).

**Climate change**: Climate change refers to a change in the state of the climate that can be identified (for example, by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcing, or to persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes (IPCC, 2007).

**Community**: The people with common interests living in a particular area; broadly: the area itself. (http://www.merriam-webster.com/dictionary/community). In these guidelines, "Coastal community" includes its human and social aspects, its buildings, economic aspects and supporting environmental systems.

**Coping capacity**: The means by which people or organizations use available resources and abilities to face adverse consequences that could lead to a coastal disaster (UN/ISDR, 2004).

**Early warning**: The provision of timely and effective information, through identified institutions, that allows individuals exposed to a hazard to avoid or reduce their risk and prepare for an effective response (UN/ISDR, 2004).

**Ecosystem**: A system of living organisms interacting with each other and their physical environment. The boundaries of what could be called an ecosystem are somewhat arbitrary, depending on the focus of interest or study. Thus, the extent of an ecosystem may range from very small spatial scales to, ultimately, the entire Earth (IPCC, 2007).

**Emergency management**: The organization and management of resources and responsibilities for dealing with all aspects of emergencies, in particularly preparedness, response and rehabilitation (UN/ISDR, 2004).

**Exposure**: Elements at risk, an inventory of those people or artefacts that are exposed to a hazard (UNDP-BCPR, 2004). In these guidelines, "exposure" provides the spatial context for integrating hazard and vulnerability.

**Hazard**: A potentially damaging physical event or phenomenon that may cause loss of life or injury, property damage, social and economic disruption or environmental degradation. A hazard is characterized by its location, intensity, frequency and probability (UN/ISDR, 2004).

**Inundation**: The state of flooding of coastal land resulting from the impact of a tsunami, storm surge or other coastal flood hazard.

**Inundation line / limit**: The line marking the maximum horizontal inland penetration of a tsunami, storm surge or other coastal flood hazard from the shoreline.

**Joint probability**: The likelihood of two or more hazard events impacting the same coastal area coincidentally.

**Land use and land-use change**: Land use refers to the total of arrangements, activities and inputs undertaken in a certain land cover type (a set of human actions). The term land use is also used in the sense of the social and economic purposes for which land is managed (for example, grazing, timber extraction and conservation). Land-use change refers to a change in the use or management of land by humans, which may lead to a change in land cover (IPCC, 2007).

**Management unit**: The geographical area under consideration for the purposes of risk assessment and mitigation. This may be national in scale, or at the district or local levels.

**Mitigation**: Structural and non-structural measures undertaken to limit the adverse impact of natural hazards (UN/ISDR, 2004).

**Non-structural measures**: Policies, regulations and plans that promote good coastal hazard management practices to minimize coastal hazards risks

**Preparedness**: Activities and measures taken in advance to ensure effective response to the impact of hazards, including the issuance of timely and effective early warnings and the temporary evacuation of people and property from threatened locations (UN/ISDR, 2004).

**Probability**: The likelihood of a hazard event impacting a coastal area.

**Protection**: Involves the use of natural or artificial measures to protect landwards development and/or attempt to hold the shoreline in its existing position in an effort to reduce hazard impacts (Bijlsma et al., 1996).

**Public awareness**: The processes of informing the general population, increasing levels of consciousness about risks and how people can act to reduce their exposure to hazards. This is particularly important for public officials in fulfilling their responsibilities to save lives and property in the event of a disaster.

**Rapid-onset hazard**: A hazard that impacts over a short time-scale (minutes-hours), sometimes catastrophically (Bogardi, 2006).

**Resilience**: The capacity of a system, community or society potentially exposed to hazards to adapt by resisting or changing in order to reach and maintain an acceptable level of functioning and structure. This is determined by the degree to which the social system is capable of organizing itself to increase its capacity for learning from past disasters for better future protection and to improve risk reduction measures (UN/ISDR, 2004).

**Retreat**: Abandonment of coastal area and the landward shift of ecosystems. This choice can be motivated by the nature of assets to be protected (Bijlsma et al., 1996).

**Return period**: The average time between occurrences of a defined event (IPCC, 2007).

**Risk**: The probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between hazards and vulnerable conditions (UN/ISDR, 2004).

**Intensive risk**: The risk of catastrophic disasters in hotspots, where people and economic activities are intensively concentrated in areas exposed to large scale climatic and geological hazards

**Extensive risk**: The risk of low intensity asset loss and livelihood disruption over extensive areas, where people and economic activities are exposed to highly localized, principally climatic hazard events.

**Risk assessment**: A methodology to determine the nature and extent of risk by analysing potential hazards and evaluating existing conditions of vulnerability that could pose a potential threat or harm to people, property, livelihoods and the environment on which they depend (UN/ISDR, 2004).

**Run-up**: The difference between the elevation of maximum tsunami penetration (inundation line) and the sea level at the time of the tsunami.

**Scenario**: A plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from projections, but are often based on additional information from other sources, sometimes combined with a narrative storyline (IPCC, 2007). In the context of tsunamis, the scenario can be a characterisation of any or all of the parameters related to a tsunami event, including the source (earthquake magnitude), the wave height in the coastal waters, the run-up, etc.

**Sea-level change**: Sea level can change, both globally and locally, due to (i) changes in the shape of the ocean basins, (ii) changes in the total mass of water and (iii) changes in water density (IPCC, 2007).

**Storm surge**: The temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is defined as being the excess above the level expected from the tidal variation alone at that time and place (IPCC, 2007).

**Structural measures**: Structural measures refer to any physical construction to reduce or avoid possible impacts of hazards, which include engineering measures and construction of hazard-resistant and protective structures and infrastructure (UN/ISDR, 2004).

**Susceptibility**: The state of being vulnerable to a physical or socioeconomic condition. In these guidelines, the terms "susceptibility" and "vulnerability" are taken as synonymous.

**Tide gauge**: A device at a coastal location (and some deep-sea locations) that continuously measures the level of the sea with respect to the adjacent land. Time averaging of the sea level so recorded gives the observed secular changes of the relative sea level (IPCC, 2007).

**Uncertainty**: An expression of the degree to which a value (for example, the future state of the climate system) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour (IPCC, 2007).

**Vulnerability**: The conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards (UN/ISDR, 2004). The term "vulnerability", as used in these guidelines in respect of a tsunami impact, is the state of a coastal community, determined by social, physical, economic and environmental factors or processes, which predispose that community to be damaged.

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