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Róbert Jelínek and Elisabeth Krausmann

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Contact information
Address: Via E. Fermi 2749, 210 27 Ispra, Italy
E-mail: robert.jelinek@jrc.it
Tel.: +39 0332 78 9297
Fax: +39 0332 78 9007

http://ipsc.jrc.ec.europa.eu
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1. INTRODUCTION

Tsunami risk assessment is a relatively new and growing discipline that is being developed from "generic" risk approaches, which are usually applied to the general field of technological risk management (such as in the chemical and nuclear industry) or other natural risk studies (e.g. floods, earthquakes or storm surges). It is a very complex field which requires knowledge of the tsunamigenic sources with their probability of occurrence, size and their probable impact or consequences. Therefore, its results are often subject to a high level of uncertainty.

A recent increased interest in tsunami risk is probably due to a trend in natural hazard science where hazard-oriented approaches are shifted to risk approaches. Likewise, the turning point in tsunami risk research was recent tsunami events with severe consequences (e.g. the Indian Ocean tsunami on December 26, 2004, the Java tsunami in July 2006 or the Solomon Islands tsunami in April 2007). It is expected that future tsunamis can have a higher impact due to the increasing number of people, buildings and infrastructure that are being exposed to natural hazards as the pressures for urban development extend into areas of higher risk. To avoid or mitigate future tsunami events, it is necessary to study and understand this phenomenon in detail.

A variety of methods or guidelines exist to estimate the risk of different hazards. However, applications on tsunami risk are very limited. There is no generally adopted approach, no well developed common methodology or guidelines to assess tsunami risk. The assessment of tsunami hazard and risk is therefore an important issue that must be addressed to identify and quantify the risk to populated areas and property. In this report we attempt to provide an overview of the existing methods of tsunami risk assessment. The reviewed studies are classified according to the country of origin or their place of application. The analyses focus on the process of risk assessment, its basic steps and output. Therefore, the assessment of the specific components of risk - hazard and vulnerability - is not discussed in detail. Since literature on tsunami risk assessment is limited, other risk assessment methods applied for floods and landslides are briefly discussed and their commonalities with tsunami risk studied. In conclusion, a general framework for tsunami risk assessment in the TRANSFER project is proposed.

Recognizing that different terminology is used across the scientific disciplines, we summarize some basic terminologies that we use in the report in the Annex.

2. REVIEW ON TSUNAMI RISK ASSESSMENT – COUNTRY EXAMPLES

It is important to have a common understanding of tsunami risk terminology. In particular, it is necessary to clearly distinguish between the terms hazard and risk that are sometimes interchanged. In our literature review on tsunami risk we saw that the word "risk" in many cases referred to the assessment of the "tsunami hazard" and its probability. Therefore, for the purposes of this report, *hazard is defined as the probability of occurrence of a potentially damaging phenomenon within a specified period of time, within a given area and a given magnitude. The risk is a product of the frequency with which a hazardous event occurs, and the consequences of that event.* It is therefore important to remember that hazard is different from risk; even in some languages it is not clear. If we translate it to tsunami language, *the tsunami phenomenon is a hazard and its probability of occurring and causing adverse consequences is a risk.* Risk is therefore dependent on how well the hazard and its consequences are evaluated.

Although there exists a variety of studies focusing on tsunami hazard assessment, tsunami risk assessment and management[1] has received less attention. The reason may be due to the difficulties and uncertainties related to tsunami risk assessment, particularly to input data for analysis because tsunamis are a typical example of "low probability – high consequence" events. In general tsunami risk studies in the literature can be divided into the following three groups:

1) Studies associated with tsunami risk from the viewpoint of tsunami hazard zonation. The term "risk" is used just to denote a general threat. These studies focus on historical tsunamis, distribution of wave heights along the coast (run-up, inundation) and socio-economic parameters, such as damage to people or property.
2) Studies that cover tsunami risk in terms of the tsunami probability and its consequences, and
3) Tsunami risk as a part of multi-risk studies (e.g. Australia City projects, Granger et al. 1999 or "All-hazard approach" in the USA).

Applications of tsunami risk in the first group include, but are not limited to, examples in Rascon and Villarreal, 1975; Nakamura 1978, Cox 1984, Damaskinidou-Georgiadou and Johnson 1987; Qinghai and Adams 1988; Symões et al. 1992, Synolakis et al. 1998, Zahibo and Pelinovsky 2001; Hébert et al. 2001; Legg et al. 2003, CSSC 2005, Kulikov et al. 2005 etc. However, in our review, we stress our interest in the second group of the reviewed literature, which we consider as the most relevant when dealing with risk. The third group is also briefly discussed.

In addition to the review of tsunami risk approaches mentioned above (Group 2), we have also decided to analyze selected risk approaches that are applied to other natural hazards such as floods, storms or even landslides. We assume that the general concept of risk assessment for floods, storms, landslides, etc. must be the same because the origins of these approaches are usually coming from "generic" risk management standards. Therefore our objective is to find analogies between these approaches that can be further used for the estimation of the tsunami risk. A good example of this kind is the approach in Australia and New Zealand, where multi-hazard risk assessment of

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[1] The terms related to risk management, assessment, analysis, etc. and their mutual relations are described in Annex of this report.

different natural hazards is consistent with the risk management process outlined in generic AS/NZS 4030 Risk management. Similarly, the existence of analogies between different hazards can be utilized. The flood risk assessment approach is sometimes applied to tsunami risk. An example is the UK where the concept and principles of the Risk Assessment for Strategic Planning (RASP) flood methodology are applied to tsunami risk assessment (Defra, 2005). Another reason for reviewing different approaches is the limited number of existing literature on tsunami risk assessment.

2.1 USA

A number of publications on tsunami risk assessment are reported from the USA where tsunamis pose a significant treat particularly in the States along the Pacific coast. These publications mainly focus on site-specific tsunami hazard assessment ("Group 1" in our report). While applications on tsunami risk assessment in the strict sense ("Group 2") are not very common. We will briefly summarize both approaches.

Probably the first systematic approach to tsunami risk assessment can be found in Lee (1979). The author highlights the importance of assigning the probability of a physical variable of interest, e.g. the water level of the flooded area, which is the most relevant and the simplest variable of concern. Other variables can include structural integrity, foundation stability, wave forces, surge forces and currents. A *purely statistical (probabilistic) approach* to tsunami risk analysis is used for locations with sufficient data to provide a probabilistic description of the maximum water levels. An alternative procedure, in case the required historical data are not available, is to use a so-called *synthetic (semi-deterministic) approach* that involves the numerical modeling of tsunami behavior and the assigning of a realistic probability to the tsunamigenic sources. Since the purely statistical approach can be used only in a few locations with a sufficiently long historical observation, the author outlines the synthetic approach to tsunami risk analysis. In this approach, all source regions must be clearly identified (e.g. by location of centers, dimension, vertical uplift etc.) and the corresponding probability must be assigned to predict the maximum tsunami elevation or run-up.

Pararas-Carayannis (1988) proposed general guidelines and a methodology for the evaluation of the tsunami risk. *The tsunami risk is considered in terms of frequency of occurrence, severity of impact, design adequacy of important costal structures and preparedness and planning for hazard mitigation.* This basically involves the following steps:

1) **Analysis of historical studies** of local and distant tsunami origin is the first priority in the determination of tsunami risk,
2) **Frequency calculation of the tsunami hazard** using a statistical approach if historical records of past tsunami events are available, and if not tsunami modeling using physical or computer models.
3) **Zonation of the tsunami hazard** which is a final product of the historical studies on the recurrence frequency and the tsunami modeling. The tsunami hazard along coastlines and its spatial variation can be represented in the form of microzonation maps.
4) **Risk assessment** is performed for life and property but not specified in detail.

In 1997 five Pacific States (California, Hawaii, Oregon, Washington and Alaska) together with four Federal Agencies (NOAA[2], USGS[3], FEMA[4] and NSF[5]) established the partnership "The U.S. National Tsunami Hazard Mitigation Program (NTHMP)". The main goal of the NTHMP is mitigation of the tsunami hazard to all threatened U.S. coastal communities. To achieve this goal, *the production of inundation and evacuation maps* that are the fundamental basis for local tsunami hazard planning is required for the U.S. coastal communities at risk (Bernard 2005, Gonzáles et al. 2005).

Curtis and Pelinovsky (1999) consider *tsunami risk as a product of the probable frequency of tsunami occurrence and the number of people or facilities exposed.* The authors state that for a preliminary estimation of risk it is reasonable to consider the population and facilities within 15 meters elevation above sea level as possibly being at risk. The tsunami risk assessment is carried out using a statistical or deterministic approach depending on the availability of historical data. The main factors of the process of tsunami risk assessment are summarized in Figure 1; and in general involve the following:

1) Compilation of all available and reasonably valid tsunami records and their sorting by source distances, i.e. local, regional and distant. Depending on data availability of historical tsunamis, statistical (sufficient data) or scenario-based risk approaches are applied.
2) Estimation of the probability of occurrence for each distance zone, and
3) Risk calculation to a specific person or a structure.

Following the Indian Ocean tsunami in December 2004, the President of the U.S. launched an initiative in the context of a broad national effort of tsunami risk reduction (NSTC, 2005). This initiative incorporates an all-hazards approach and builds upon existing hazard programs (e.g. HAZUS-MH[6], a standardized loss estimation software package from FEMA) since tsunamis can be linked to other hazards such as earthquakes, volcanoes and landslides. The initiative covers seven areas such as determining the threat, preparedness, timely and effective warnings, mitigation, public outreach and communication, research, and international coordination. Since risk assessment is included in the first step of the initiative, which is "Determining threat" we will just analyze this part. The determination begins with *assessing the hazard by characterization of potential local and distant tsunami sources, estimating the tsunami frequency, and developing realistic models of tsunami effects. A risk assessment can then be produced by combining knowledge of the hazard with information on coastal vulnerability, including the population infrastructure, lifelines, economic activities, and level of local preparedness for such events.* Actions are required at all levels of government to complete tsunami risk assessment for the Nation's coastal areas. These assessments should identify the inventory and value of at-risk structures and population present, the fragility of the structures exposed to the hazard, and categorization and presentation of the resulting damage and causalities.

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[2] National Oceanic and Atmospheric Administration
[3] United States Geological Survey
[4] Federal Emergency Management Agency
[5] National Science Foundation
[6] Hazards U.S. – Multi-Hazards, http://www.fema.gov/plan/prevent/hazus/

TSUNAMI RISK ASSESSMENT

FACTOR		COMMENTS
EVENT PROBABILITY		
GEOLOGIC INFO		CRUDE PROBABILITY STATISTICS
HISTORICAL	BY SOURCE	ARE DEVELOPED FROM THESE
RECORDED DATA		DATA
EFFECTIVE WARNING PROBABILITY		
LOCAL - <0.4 HR	-----	NONE - EDUCATION FOR OWN ACTION
REGIONAL - 0.4><2 HR	-----	MAYBE - QUICK RESPONSE SYSTEM; EDUCATION;SIMPLE ZONES
DISTANT - > 2 HR	-----	GOOD - PTWC; ZONES; EVACUATION SYSTEM; EDUICATION
LOCATION RISK		
COAST - UNKNOWN	-----	MOST AREAS
< 15 METERS RE MSL	-----	EASILY DETERMINED
IN KNOWN INUNDATION ZONE	-----	HAWAII, SOME JAPAN, OREGON IN PROGRESS; ALL MARINE FACILITIES

ALL THESE FACTORS MUST BE CONSIDERED TO EVALUATE THE
SPECIFIC RISKS IN AN AREA AND DETERMINE WHAT ACTION,
IF ANY, MAY BE WARRANTED

Figure 1: Tsunami risk assessment according to Curtis and Pelinovsky (1999)

Knowing tsunami community risk is the first principle in a guide *"Designing for Tsunamis: Seven Principles for Planning and Designing for Tsunami Hazards"* for local government official, zoning, building officials, and those responsible for community development. The guide outlines a methodology for identifying a community's risk, and recommends the use of tsunami specialists for preparing scenarios and loss studies (Eisner, 2005).

2.2 Japan

Tsunamis cause severe damage in coastal regions in Japan and the country is considered as one of the most tsunami-prone areas in the world. According to the Japan Meteorological Agency (JMA), 66 individual regions provide tsunami warnings or advisories based on the expected tsunami height. Due to this the state-of-the-art of tsunami research in the country is very high. However, the available literature on tsunami risk assessment is limited probably due to language constraints with the majority of documentation being published in Japanese.

Sugimoto et al. 2003 carried out research on human damage prediction due to a potential future tsunami for Usa town in Shikoku Island. Since the authors discuss "the prediction" of human damage, this can also be considered as a method for risk assessment. The human damage prediction is estimated from the changes in tsunami inundation height, inundation flow velocity and evacuation speed. According to

Kawata (1997) in Sugimoto et al. (2003) inundation over 2 meters can cause loss of human lives. The flow chart for tsunami damage estimation is illustrated in Figure 2:
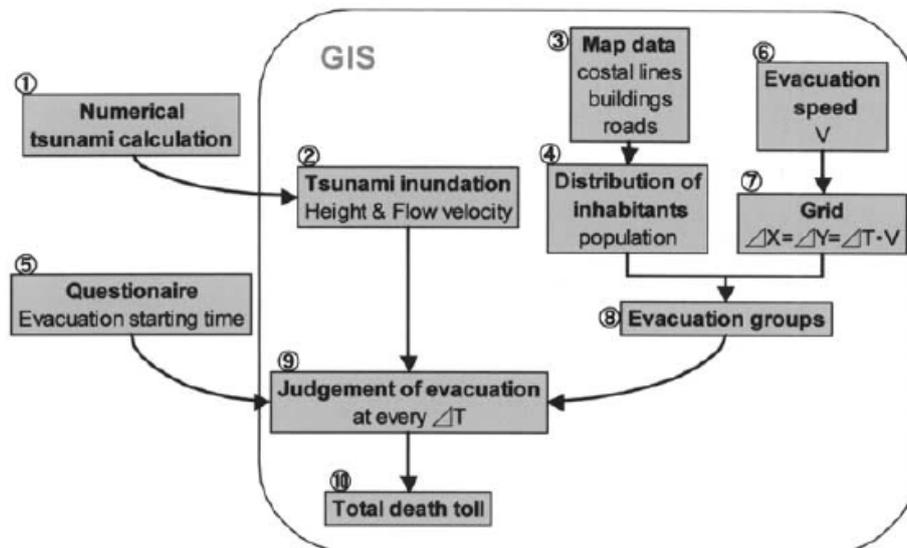
Figure 2: Flow chart of human damage prediction model, source: Sugimoto et al. 2003

This involves:
1) Numerical tsunami calculation to produce inundation maps characterized by inundation heights and flow velocity,
2) Location of the elements at risk in the inundated area that are divided into land map data (e.g. coastal lines, roads, buildings, evacuation places, etc.) and population distribution
3) Evacuation starting time, speed and judgment is considered according to results of a questionnaire survey, physical conditions of inhabitants, etc.
4) Estimation of total number of fatalities considering the inundation height, flow velocity and inhabitant's evacuation activity in a given grid of a GIS environment. The distribution of fatalities is presented in a "death rate distribution" map illustrated in Figure 3.
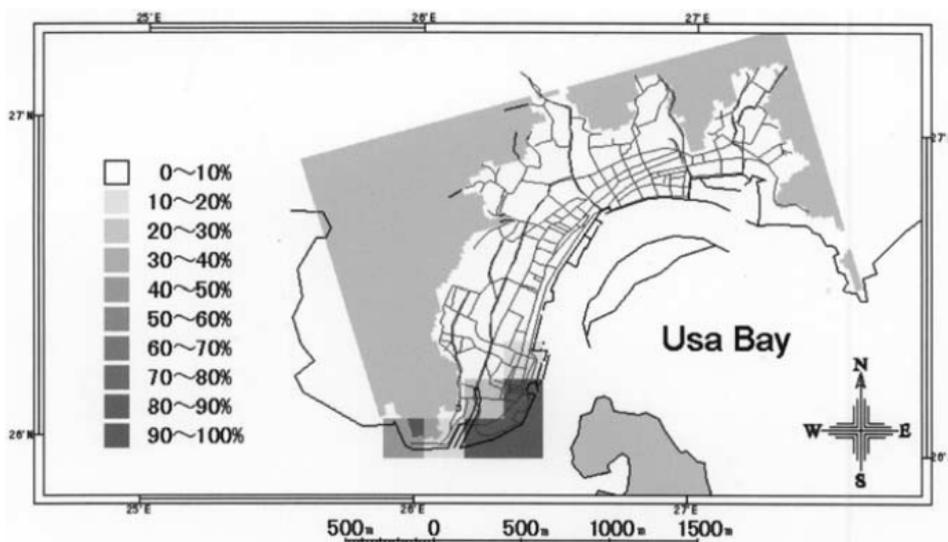
Figure 3: Death rate distribution map for Usa town, source: Sugimoto et al. 2003

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The death rate on the map is expressed in percentage and covers the whole spectrum from 0 % to almost 100 %, which means from no human damage because of the effective evacuation to total loss, respectively.

2.3 Australia and Indonesia

The UN International Decade for Natural Disaster Reduction (IDNDR) project *"Contemporary Assessment of Tsunami Risk and Implication for Early Warnings for Australia and its Island Territories"* was a pilot project which addressed the need for mitigation of tsunami risk in Australia and its Island Territories (Rynn and Davidson, 1999). The aim of the project was to assess tsunami risk, in qualitative and quantitative terms, using the approach illustrated in Figure 4:
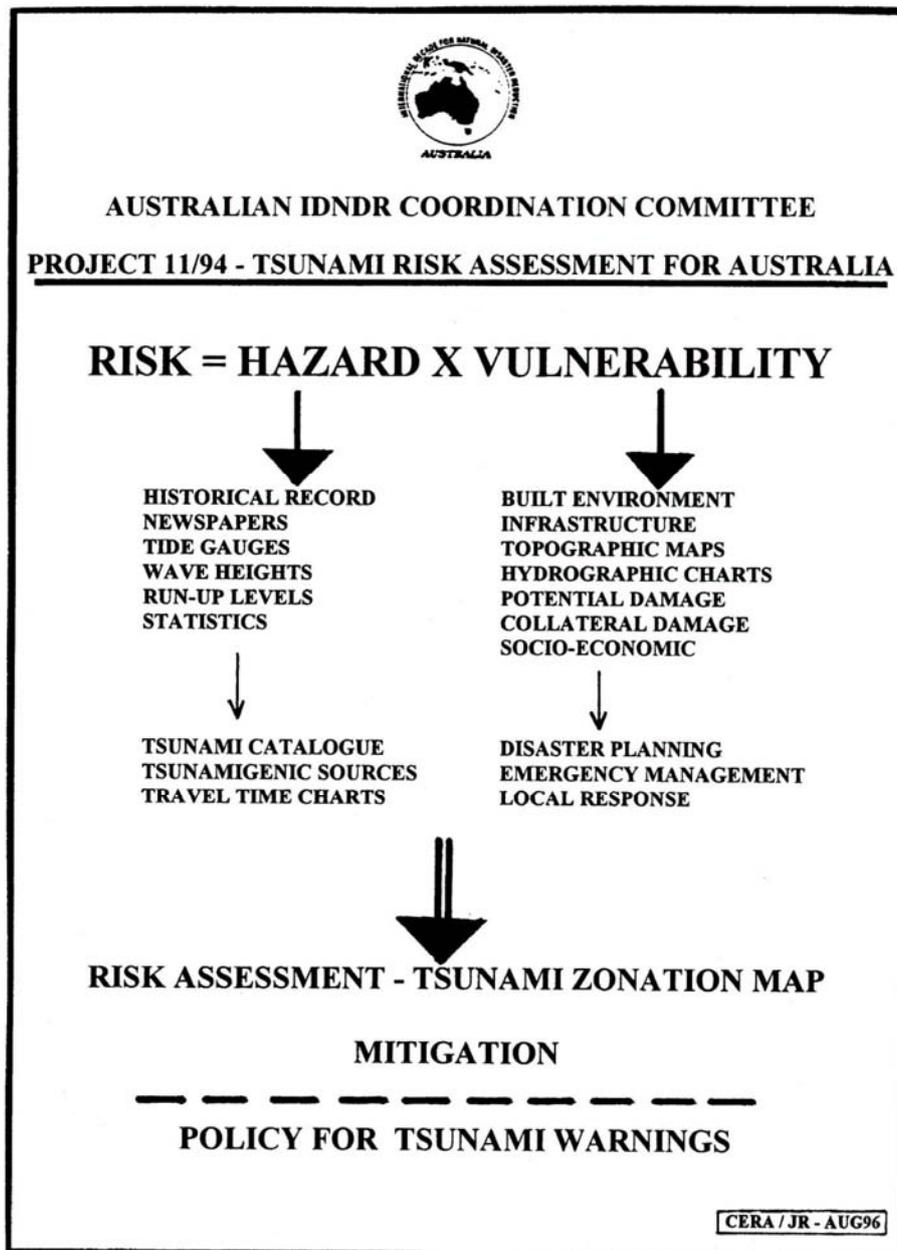
Figure 4: Tsunami risk assessment in Australia, source: Rynn and Davidson 1999

The tsunami risk is a product of the two components hazard and vulnerability. Hazard is assessed in quantitative terms and the following characteristics are considered for producing a tsunami hazard map: run-up height, tsunami magnitude, wave height, damage observed from historical tsunami, coastline adjacent to near-field tsunamigenic sources and potential tsunami inundation in the future. Based on these specific hazard characteristics the three tsunami hazard zones high, medium and low have been specified. Vulnerability is defined in qualitative terms as high, medium and low level for the built and natural environment. Once the risk components have been estimated, the resultant tsunami risk map is presented as zonation map of five zones A to E as illustrated in Figure 5.
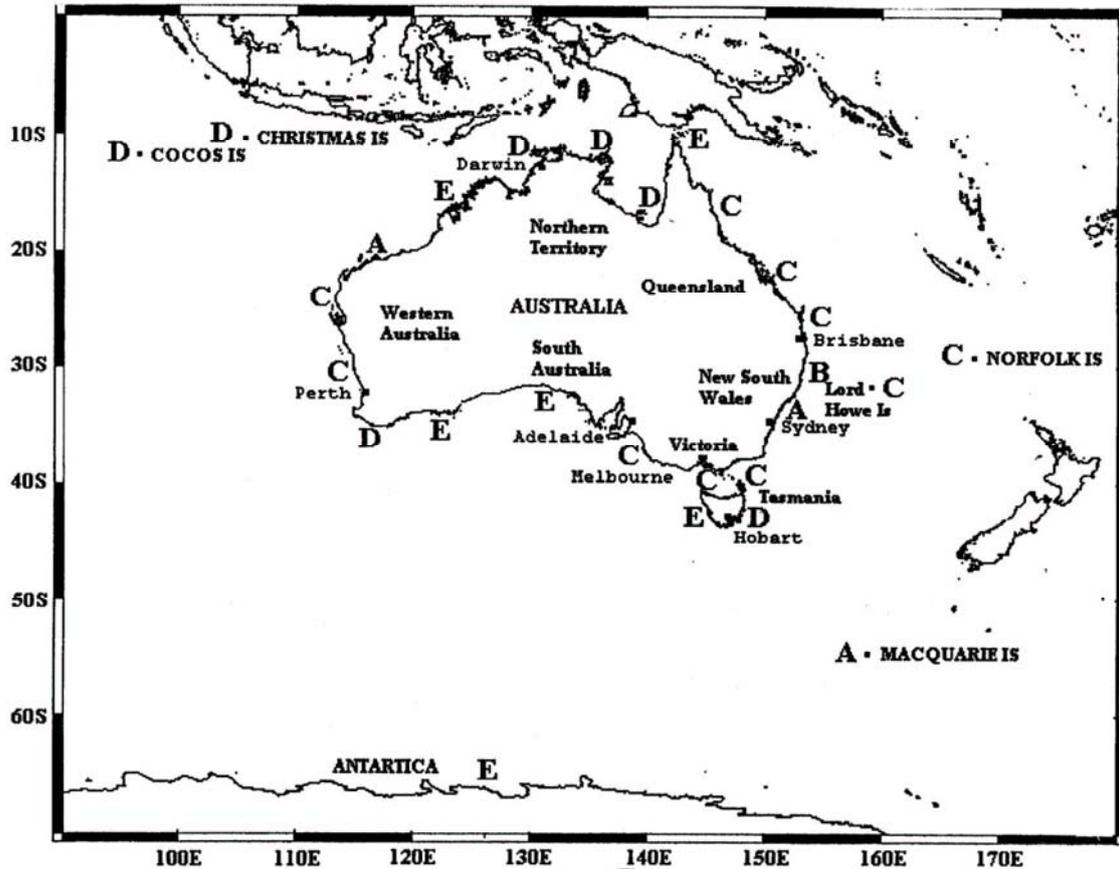
Figure 5: Zonation map of Australia and its island territories, source: Rynn and Davidson 1999

The description of each zone is supplemented with corresponding tabular data. For example, in the most dangerous Zone A, both the hazard zone (characterized by run-up height > 6 m and wave height > 1 m) and the vulnerability level are high. In addition, there is also predicted damage to the built and natural environment for this zone. This methodological approach was also applied for the Indonesian region (Rynn, 2002) and for the city of Suva in Fiji (Prasad et al. 2000).

The recently published report *Natural hazards in Australia: Identifying risk analysis requirements* (Middelmann, 2007) contains also a chapter on tsunamis. The outlined general tsunami risk assessment approach is similar to that for earthquakes. There are five sequential stages and associated models for estimating tsunami risk:

1) Source model that describes the likelihood of a source producing a tsunami of a given size and location using a combination of geophysical, geological and historical research. Once a likely source of a tsunami has been identified, the size of the tsunami it can produce at various levels of probability is estimated.

2) Propagation model to simulate the water propagation from the source to the coast of interest. If the source is very close to the location of interest, this stage can be omitted.

3) Inundation model to determine the run-up and inundation distance at a given location on the coast.

4) Vulnerability model to characterize the nature and magnitude of the damage from a wave of given velocity. The structural and human vulnerability are considered and if possible must be estimated.

5) Exposure database of the area of interest.

The report does not contain how the results from the above steps are combined to calculate the tsunami risk. It is only mentioned as the combination of the inundation, vulnerability and exposure data.

Tsunami risk is also investigated as a part of the multi-risk city projects carried out by Geoscience Australia (Granger et al. 1999). *Risk is the outcome of the interaction between a hazard phenomenon and the vulnerable elements at risk within the community.* The entire process of risk management involving the establishing of the context, identifying, analyzing, evaluating, treating, monitoring and communicating the risk is outlined in the generic guide: Australian/New Zealand Standard AS/NZS 4360.

2.4 New Zealand

In 2006 the Institute of Geological and Nuclear Science prepared a report concerning tsunami hazard and risk around the New Zealand coastline (Berryman, 2006).

The described tsunami risk assessment approach is dependent on combining the following factors:

1) Tsunami-generating sources i.e. the size and frequency of all possible sources such as earthquakes, landslides, volcanoes,

2) Wave propagation through water using numerical modeling,

3) Flooding of the water across land (inundation),

4) Location and distribution of assets at risk (people, dwellings, other buildings), and

5) How easily assets and people are damaged (fragility).

A probabilistic assessment of tsunami risk is performed to assess the level of tsunami risk at a national and regional level. Risk is calculated from all of the combinations illustrated in the flowchart in Figure 6.
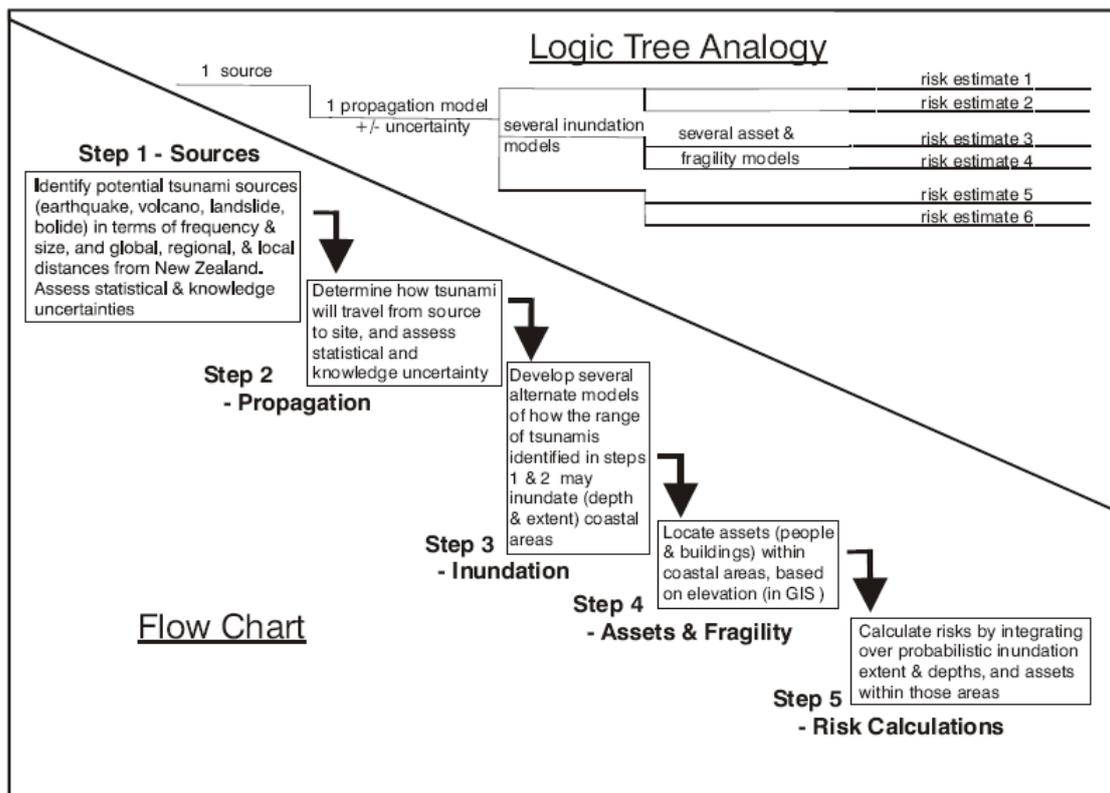
Figure 6: Probabilistic tsunami risk assessment in New Zealand, source: Berryman, 2006

The first 3 steps deal with the identification of tsunami sources, propagation and inundation. Steps 4 and 5 regard assets and their fragility. This is by our definition the vulnerability component of risk analysis and is divided into the following models:
- *building asset model* subdivided into workplace and residential dwellings,
- *population models* comprises night-time population and population as a portion of the total floor area of the buildings, and

death and injury models, where casualties are estimated as a portion of the prior population.

The tsunami risk is estimated for an *individual in urban centers* (refers here as risk to communities) or those *who live at low elevations close to the coast* (i.e. individual risk) and *for nation as a whole* (i.e. national risk). The results of the risk assessment for the communities and the nation as a whole are presented in forms of risk curves and relevant data showing the relation of the return period[7] (50, 100, 200, 500, 1000 and 2500 years) to the wave heights at the shoreline, the costs of damage to buildings, as well as the estimated numbers of deaths and injuries (Figure 7).

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[7] The return period is defined as the average interval between occurrences of the event, and is equal to the reciprocal of the probability. A return period of 200 years is equivalent to a probability of 1 in 200 that the event will occur in any one year.

Auckland City - East Coast
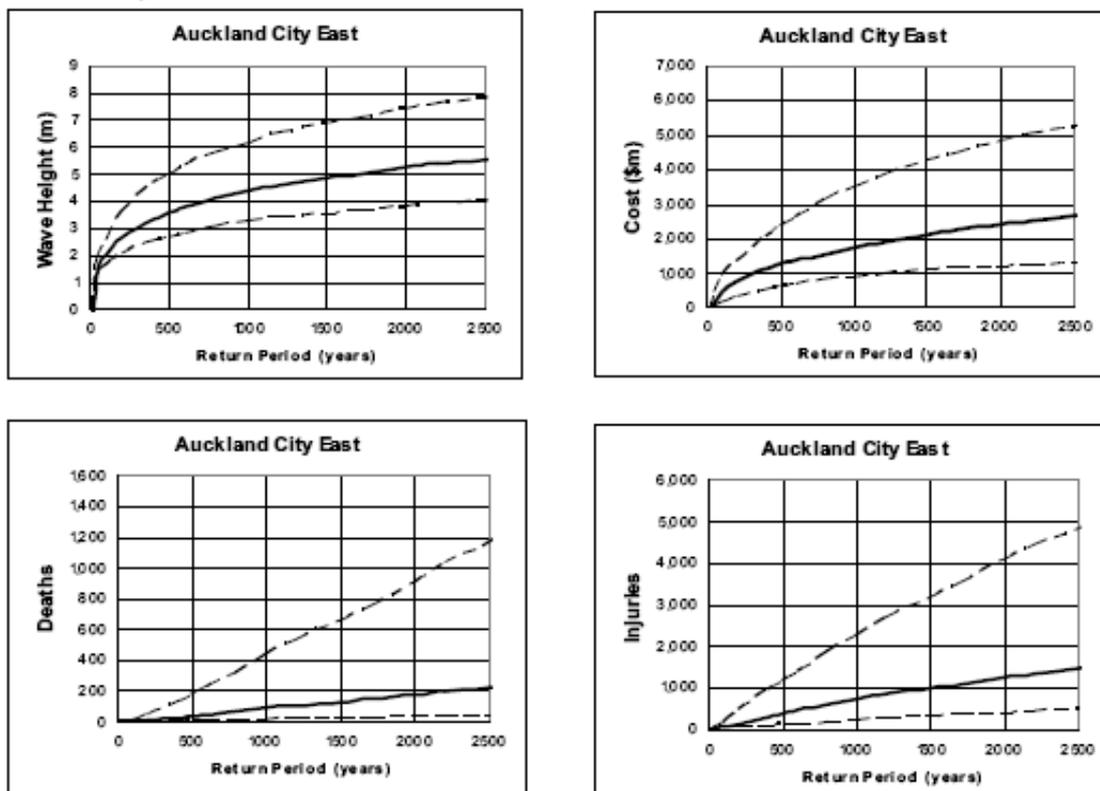
Figure 7: Examples of risk curves for individuals in urban centers for Auckland City, source: Berryman, 2006

Only the tabular results are used for the estimated annual risk of death to individuals. Examples of such results for deaths of individuals who reside at 2 and 4 m above mean sea level are summarized in Table 1.

Table 1: The estimated annual risk of death for individuals, source: Berryman, 2006

		2m	4m
Auckland East	84%	1.4×10^{-4}	4.3×10^{-5}
	50%	3.9×10^{-5}	7.7×10^{-6}
	16%	9.6×10^{-6}	9.1×10^{-7}
Auckland West	84%	3.1×10^{-7}	0
	50%	4.3×10^{-8}	0
	16%	2.0×10^{-9}	0
Christchurch	84%	2.2×10^{-4}	8.3×10^{-5}
	50%	6.1×10^{-5}	1.5×10^{-5}
	16%	1.7×10^{-5}	2.4×10^{-6}
Dunedin	84%	3.2×10^{-5}	4.6×10^{-6}
	50%	7.4×10^{-6}	3.3×10^{-7}
	16%	1.2×10^{-6}	0
Gisborne	84%	1.7×10^{-3}	9.7×10^{-4}
	50%	6.0×10^{-4}	2.8×10^{-4}
	16%	2.0×10^{-4}	6.4×10^{-5}

Table 1 has been color coded according to Taig's risk ranges (Berryman, 2006). The red color corresponds to the individual annual fatality risk of 10^{-2} to 10^{-3}, which is widely regarded as intolerable event. On the other hand, a risk level of 10^{-6} to 10^{-7} per year or lower is unlikely to be nationally significant. The assumptions made in the calculation are: no warning system exists and individuals will be at home for about half the time (thus safe for the reminder of the time).

A probabilistic approach was selected to capture uncertainties in the risk calculations. The resulting values of tsunami risk were compared to the earthquake risk. In general, the damage to property from tsunami in New Zealand is about twice what was estimated for earthquakes with similar return period, and the deaths and injuries are many times more.

2.5 Thailand

A scenario-based tsunami risk approach is described using an example from the West Coast of Thailand (Nadim and Glade, 2006). The authors argue that this approach is well suited for the evaluation of tsunami risk because the physical characteristics of the tsunami are known, i.e. the direction of the loading and the extension of the affected area by a potential tsunami scenario can be identified.

The selected approach considers several scenarios of plausible extreme, tsunami-generating earthquake, and involves the following steps:
1) **Definition of scenarios** for tsunami-generating earthquakes,
2) **Computing the tsunami inundation levels,**
3) **Estimation of tsunami risk** for the different scenarios, and
4) **Comparison of the estimated risk** with tolerable or acceptable risk levels.

The possible tsunami risk is expressed in terms of the expected value of loss (risk) and is calculated using the following general expression:

$$E[loss] = \sum_{All\,S} \sum_{All\,\underline{C}} \underline{C} \times P[\underline{C}\,|\,S] \times P[S]$$

Where,

E[loss] = The expected value of loss e.g. of human life, economic loss, reputation loss, etc
C = The particular set of losses
S = The particular scenario
P[S] = The probability of occurrence of scenario S
P[C|S] = The conditional probability of losses set C given that scenario S has occurred (week-day, time of the day, high/low tide, if tsunami warning system is operating, etc.

The presented risk approach focuses on the loss of human life only. The potentially affected population is divided into three groups: 1) *people who live in the exposed area permanently*, 2) *tourists*, and 3) locals *who do not live in the exposed areas but work there during tourist season.* The authors distinguish between *real and perceived risk*. The former is used to estimate risk for group 1, the latter for group 2, while for group 3 both the real risk and perceived risk are important. The other factors, which influence the risk, are considered in the form of conditional probability, e.g. on which day and what time of the day the tsunami occurs (Nadim and Glade, 2006).

Figure 8 illustrates the estimated tsunami risk in Thailand, which is presented in the form of F-N curves.
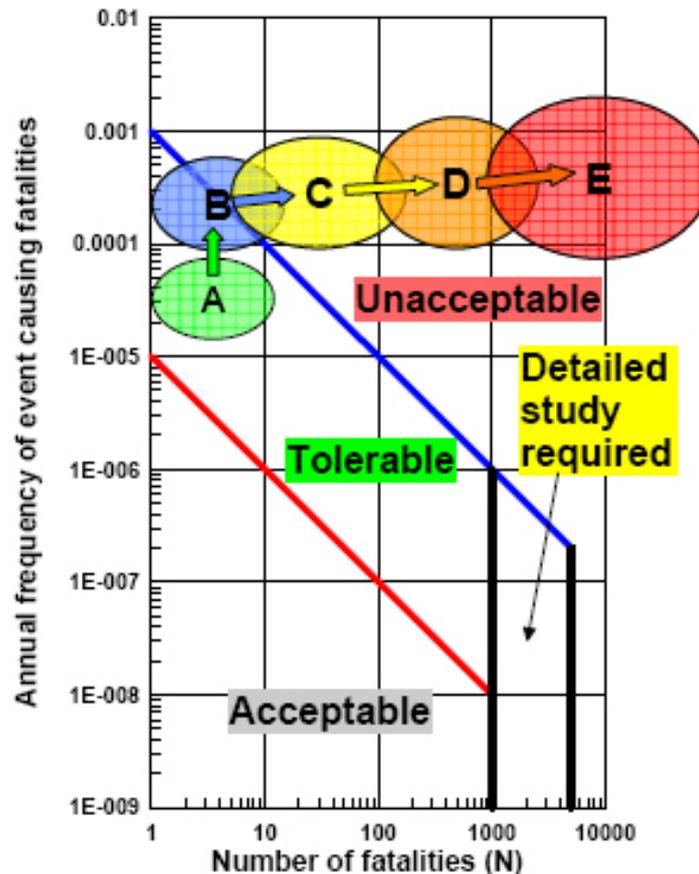
Figure 8: Estimated risk of tsunami in Thailand plotted against the societal risk tolerance criteria of Hong Kong, source: Nadin and Glade, 2006

Another contribution from Thailand to tsunami risk assessment is the CRATER project (Coastal Risk Analysis of Tsunamis and Environmental Remediation) funded by the Italian Ministry of Environment and Territory (Cavalletti et al. 2006). The project is divided into the three separates modules RAPIDO, SAVE and DATE that deal with tsunami warning and forecasting; hazard and risk assessment; and damage assessment, respectively. *The term risk as a part of the SAVE module is defined according to the UNDP guidelines as the mathematical product of hazard and vulnerability.* The hazard level is characterized by the water height at the coastal area. No probability concept is considered. The vulnerability parameters are categorized into the four groups population, built environment, socio-economic aspects and environment. For each parameter a list of impact elements is prepared. The total vulnerability is a sum of impact elements based on a weighting factor. The risk value is calculated for each vulnerability parameter and the final outcome is so-called thematic risk maps (i.e. population risk map, socio-economic risk map or building risk). An example of a building risk map is shown in Figure 9.
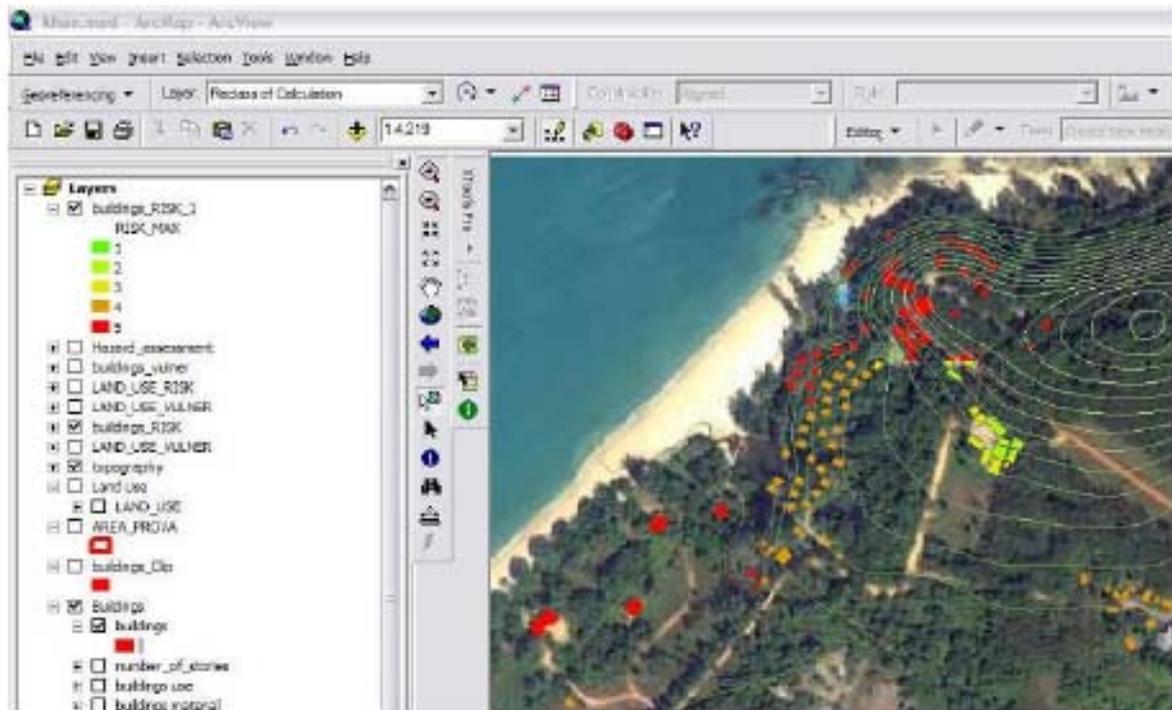
Figure 9: Example of a building risk map, source: Cavalletti et al. 2006

2.6 Greece

A semi-quantitative approach to tsunami risk management proposed by Papadopoulus and Dermentzopoulus (1998) for the city of Heraklion incorporates three consecutive stages in the tsunami risk assessment:

1) Collection and analysis of data related to the physical planning,
2) Semi-quantitative description of the potential impacts of a characteristic, extreme tsunami, and
3) Development of a series of approaches for considering prevention and mitigation measures.

A series of 12 thematic maps of 1:10,000 scale were produced to estimate the *tsunami risk, which is expressed as a product of the tsunami hazard (HA), the vulnerability of the socio-technological system (VU) and the economical value exposed to the hazard (VA):*

$$R = HA \ x \ VU \ x \ VA$$

As illustrated in Figure 10, six risk categories of high and low urban risk (A and B), high and low road network (C and D) and high and low population vulnerability (D and E) were used to construct the resultant tsunami risk map.
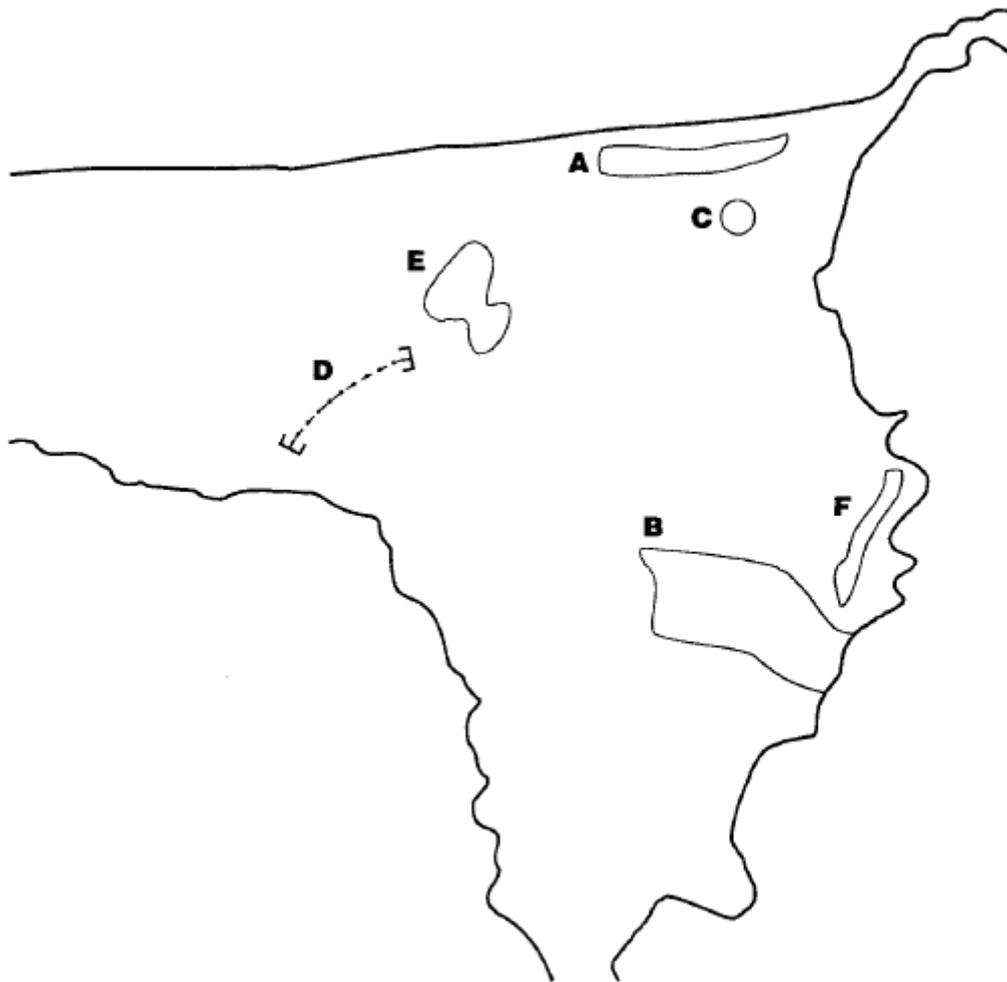
Figure 10: Example of a resultant tsunami risk map of eastern side of Heraklion city, source: Papadopoulus and Dermentzopoulus, 1998

Another interesting example from Greece can be found in Papathoma and Dominey-Howes (2003) and Papathoma et. al (2003). The authors used a new vulnerability approach for the estimation of the cost of a hypothetical tsunami impact in two coastal villages in the Gulf of Corinth and for the city of Heraklion. The authors demonstrate the importance of the vulnerability component in tsunami risk assessment as a very dynamic factor dependent on a number of parameters relating to the built environment, sociological, economic, environmental and physical data. The vulnerability parameters are ranked according to their importance and a weighting factor is applied. The tsunami source and off-shore bathymetry are neglected in this approach.

This so-called "Papathoma method" is divided into the following steps:

1) Identification of the inundation zone and inundation depth zones. The inundation zone is considered between the coastline and the 5 m contour based on probability studies of historical tsunamis, where the greatest wave height was 5 m (from 1963).

2) Identification of factors that affect the vulnerability of buildings and people. For the built environment the following parameters are considered: number of stories of each building, description of ground floor, building surroundings, material, age and design. Population density and number of people per building are basic sociological parameters.

3) Calculation of the vulnerability of individual buildings (BV) within the inundation zones using a multi-criteria evaluation method:

$$BV = (7 \times a) + (6 \times b) + (5 \times c) + (4 \times d) + (3 \times e) + (2 \times f) + (1 \times g)$$

Where,

a-g = Standardized scores that are related to the material of the building, row of the building, numbers of floors, building surroundings, condition of the ground floor, sea defence and width of the inertial zone, respectively.

Human vulnerability (HV) of each building is calculated by:

$$HV = BV \times P$$

Where, P is the population.

4) Display of building vulnerability and human vulnerability for example in a GIS environment.

Since this approach particularly focuses on vulnerability assessment, the other risk components are generalized or simplified, i.e. the tsunami sources are not considered and the inundation zone is just defined as the area between the coastline and the 5 m contour. The cost of a future hypothetical tsunami is estimated for the affected properties (such as buildings, households, businesses, etc.) and the results are presented in Euros.

2.7 Italy

Tinti et al. (2008) present a tsunami risk analysis for the eastern coast of Sicily. The authors restricted tsunami risk to the people that live permanently or temporarily in the coastal zone. The concept of tsunami risk in this approach is a function of tsunami hazard based on numerical modeling, and the vulnerability of the population based on socio-economic analysis. The probability of occurrence of a tsunami is based on the combination of statistical (seismicity) and deterministic (hydrodynamics) analysis in a so-called hybrid method (Tinti et al. 2005).

The total tsunami risk is expressed in terms of the expected number of persons that are affected by a given tsunami for a given period of time. The preliminary results are expressed in a tabular form and compared with the annual number of fatalities due to car accidents in the same region.

2.8 Canada

The final part of our review is a brief discussion of tsunami hazard and risk at Canadian coasts, which is based on Clague et al. (2003). *Tsunami risk, R, is considered as a product of hazard, H, and exposure, E:*

$$R = H \times E$$

The hazard is normally described by the maximum wave run-up, which is measured as either the elevation reached by the water, or the horizontal distance the wave floods inland, i.e. inundation. The elevation reached by water, i.e. vertical run-up is used

most often to quantify tsunami hazard. The risk is expressed qualitatively and ranges from very low to moderate, on both a regional and local scale. Tsunami risk in Canada differs considerably at the local scale due to differences in exposure to tsunami-generating earthquakes, shoreline morphology, and offshore bathymetry.

2.9 Summary of the review of tsunami risk assessment methodologies

The reviewed methodologies for assessing tsunami risk have been summarized in Table 2. The table is structured into the three groups hazard characterization, consequences and risk. The key findings of the review can be summarized as follows:

- **Methods for the tsunami risk assessment** generally include the following main steps: hazard identification and characterization, assessment of consequences (exposure) and risk characterization.

- **The tsunami hazard calculation** is usually carried out using a probabilistic (statistic) or a deterministic (also called scenario-based or synthetic) approach depending on the availability of historical data. Sometimes a combination of both approaches is used (e.g. Papadopoulos and Dermentzopoulus, 1998).

- **The consequences or outcome of the event** refer to the elements at risk and their vulnerability. The most common elements at risk include the population, buildings, roads, infrastructures and the natural environment. Vulnerability seems to be the least developed concept, the most difficult to address, and understood in many different ways. Vulnerability is generally assessed for the population and property.

- **There is no general agreement between different disciplines on the definition of risk** and the same can be said for tsunami risk applications. Tsunami risk is generally expressed as the *product of hazard and vulnerability* (e.g. Rynn and Davidson, 1999); some scientists also use the extended expression such as the *product of hazard, vulnerability and economical value* (e.g. Papadopoulos and Dermentzopoulus, 1998), or simply *hazard and consequences or exposure* (Clague et al. 2003).

- **The tsunami risk is measured and expressed in a number of different ways and using different techniques.** Some common outputs are in the form of thematic risk maps (e.g. tsunami risk zonation map, death rate distribution map, and evacuation map), tables or F-N curves.

- The reviewed tsunami risk studies were usually carried out at **local or national scale**.

- It should be noted that **the literature on tsunami risk assessment is very limited** compared to other natural hazard risk such as floods or landslides. Consequently, tsunami risk maps are not common. The U.S. NTHMP requires production of inundation and evacuation maps only.

Table 2: Summary of the reviewed tsunami risk assessment approaches

Source/level of analysis[8]	Hazard characterization (approach, source and parameters)	Consequences Including vulnerability, its indicators and elements at risk	Risk approach and results
Lee (1979)	<u>Probabilistic approach</u> in case of sufficient data regarding historical tsunamis (e.g. the maximum water level, run-up) What has happened in the past? <u>Synthetic approach</u> as alternative, based on tsunami sources, reliable numerical models and reliable probability of tsunamigenic source parameters What can happen?	<u>Building vulnerability:</u> structural integrity and basement stability <u>Elements at risk</u> includes coastal structures, e.g. power plants, breakwaters, harbors, etc.	
Pararas-Carayannis, (1988)	<u>Historical studies</u> of local and distant origin of tsunami, seismicity of region <u>for zonation of tsunami hazard</u> <u>Tsunami hazard frequency (statistical approach)</u> if data availability is good <u>Tsunami modeling studies</u> as alternative to the above using hydraulic or numerical models <u>Zonation of the tsunami hazard</u> as product of the historical studies on tsunami frequency and of the modeling studies	Consideration of public safety and protection of property (e.g. of high risk standards such as communication centers, chemical factories, nuclear power plants, and other important engineering structures; important facilities, as hospitals, fire stations or police services)	Risk in terms of frequency of occurrence, severity of impact and design adequacy of important coastal structures, and also preparedness in planning for hazard mitigation

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[8] Where applicable the study area is also included. The level of analysis is divided into the three categories national, regional and local.

Source/level of analysis	Hazard characterization (approach, source and parameters)	Consequences Including vulnerability, its indicators and elements at risk	Risk approach and results
Curtis and Pelinovsky (1999)	Statistical, deterministic (scenario based approach) or combination of both is used depending on data availability on historical tsunamis 15 m elevation a.s.l for a preliminary study	Effective warning system is considered depending on distance to the source (local, regional and distant) No. of people or facilities	Risk components are the probable frequency of occurrence and the number of people (or facilities) exposed Recommended quantitative assessment of tsunami risk Specific risk to person or structure
NTHMP[9] (1997) (USA, local and regional level)	"Credible worst case" scenario Sources considered: earthquakes, landslides, delta failures Probabilistic approach based on simulation of past events (only Hawaii)	Inundation and evacuation maps as the fundamental basis of local tsunami hazard planning Population an infrastructure	Production of evacuation maps
NSTC[10] (2005) (USAl)	Local and distant sources (offshore earthquakes, submarine landslides, and oceanic volcanoes) Frequency based on historical events Scenario (or extreme scenario) approach to estimate loss of life, threat to public health, structural damage, environmental damage and economic disruption Annual probabilities of occurrence considering risk assessment of other natural hazards (e.g. PSHA)	Coastal vulnerability including the population infrastructure, lifelines, economic activities, level of local preparedness	

[9] The U.S. National Tsunami Hazard Mitigation Program
[10] NSTC- National Science and Technology Council

Source/level of analysis	Hazard characterization (approach, source and parameters)	Consequences Including vulnerability, its indicators and elements at risk	Risk approach and results
Sugimoto et al. (2003) (local scale, Usa town, Shikoku Island, Japan)	<u>Numerical modeling</u> to produce inundation map characterized by height and flow velocity	Map data, e.g. coastal lines, roads, buildings, evacuation places, population distribution etc. Inhabitant's evacuation activity	<u>Death rate distribution map</u> for grid cell 225m x 225 m in percentage
Rynn and Davidson (1999) (Australia, national level)	<u>Hazard:</u> historical tsunami data, potential tsunamigenic sources (earthquake, submarine volcanoes, submarine landslides and extra-terrestrial impacts), probabilistic estimates and tsunami travel time charts <u>Characteristics:</u> run-up height, tsunami magnitude, wave height, observed damage, coastline adjacent to near-field tsunamigenic sources, potential future inundation <u>Tsunami hazard map</u> for the 3 zones high, medium and low, prepared using deterministic (real data) approach <u>Probabilistic estimates of frequency of exceedance</u> have not been quantified since data was not sufficient	<u>Vulnerability inventory:</u> built environment (major ports, harbors, fishing industry, offshore oil and gas fields, industrial sites, residential communities, infrastructure, tourist centers, future significant developments, near-shore communities) and natural environments (significant coastal geography, tourist areas) <u>Map of vulnerable areas</u> in qualitative terms as low, medium and high vulnerability	<u>Tsunami zonation map</u>, zones A to E in terms of hazard and vulnerability elements: Risk = Hazard x Vulnerability

Source/level of analysis	Hazard characterization (approach, source and parameters)	Consequences Including vulnerability, its indicators and elements at risk	Risk approach and results
Middelmann (2007) (Australia, national level)	Source model describing the likelihood of a source producing a tsunami of a given size and location Propagation model to simulate the wave propagation from the source to the coast of interest Inundation model to determine the run-up and inundation distance at a given locality on the coast	Vulnerability model to characterize nature and magnitude of the damage from a wave of given velocity Structural vulnerability must be estimated based on damage from past events or using an engineering modeling approach (the loads on the structures) Human vulnerability estimated from the structural vulnerability, population density, the time of day of the event, height and velocity of tsunami Exposure database of the area of interest	Tsunami risk is expressed as the combination of the inundation, vulnerability and exposure data
Berryman (2006) (New Zealand, national level)	Probabilistic approach that considers all likely future events, i.e. size, frequency and effects of all sources Sources: earthquake, landslides (submarine or coastal), volcanoes and bolides Maximum run-up (maximum wave heights) Tsunami hazard expressed as expected mean wave height above sea level for 500-year return period	Upper and lower bound, i.e. maximum and minimum inundation using DEM (10 m cell size) and ground roughness (extracting land use data, 1:50,000) Building asset model, values, floor areas and plan areas; workplace and residential buildings; tsunami forces and building strength Population model for location of people Death and injury model to asses casualties as a portion of the population, tsunami casualties (death and injury) rates versus water depth, Assumption of no warning system, night-time scenario	Risk is calculated in terms of deaths, injuries, and cost of damage in buildings Plots showing hazard and risk as a function of return period: - For individual risk in urban centers: plots of the wave height, cost, death and injuries versus return period - National risk: for costs, deaths and injuries vs. return period - Individual risk in tabular form showing the estimated annual risk of death from tsunami for individuals who reside at the coast at 2m and 4m a.s.l.

Source/level of analysis	Hazard characterization (approach, source and parameters)	Consequences Including vulnerability, its indicators and elements at risk	Risk approach and results
Nadim and Glade (2006) (Thailand, national level)	<u>Scenario-based risk approach</u> (what-if scenarios of plausible extreme event) Sources: tsunami-generating earthquake, submarine slides	Focusing on loss of human life only <u>Risk of human life</u> is dived into three groups: 1) people who live in the exposed area permanently, 2) tourists, and 3) locals who do not live in the exposed areas but work there during tourist season. <u>Conditional probability:</u> week-day, time of the day, high/low tide, warning systems are considered	QRA, societal risk presented as F-N curves $$E[loss] = \sum_{All\,S} \sum_{All\,\underline{C}} \underline{C} \times P[\underline{C}\,|\,S] \times P[S]$$ Perceived risk[11] vs. real risk[12]
Cavalletti et al. (2006) (Thailand, local level) CRATER project	<u>Deterministic approach</u> using tsunami flood simulation models for propagation and inundation Flooding model characterized by maximum water depth and maximum velocity for each grid cell	<u>Vulnerability parameters</u> included are population, built environment, socio-economic aspects, environment, combined vulnerability and its impact elements (i.e. for buildings it is building material, number of floors, etc.) <u>Thematic vulnerability maps</u> such as socio-economic vulnerability map	UNDP guidelines R = H x V <u>Thematic risk maps</u>: population risk map, socio-economic risk map or building risk Evacuation maps

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[11] Estimated particularly for tourists (group 2) who only live in the exposed areas for a specific period (1-2 weeks)
[12] Estimated for people who live in the exposed area permanently (group 1)

Source/level of analysis	Hazard characterization (approach, source and parameters)	Consequences Including vulnerability, its indicators and elements at risk	Risk approach and results
Papadopoulus and Dermentzopoulus (1998) (Heraklion, Greece, local level)	Combination of numerical modeling with probabilistic approach in semi-quantitative way Sources: large submarine earthquakes and volcanic eruptions Inundation scenario of extreme tsunami wave striking with a maximum vertical and horizontal run-up Geotechnical parameters of soils in combination with tsunami severity are incorporated	Elements at risk include: population, properties, road network, important installations and life lines Thematic maps of: - Natural environment state - Tsunami hazard impact potential on soil foundation conditions - Land use/cover types - Tsunami wave surge impact force relative magnitude characteristics on land - Property damage potential - Road network, life lines, important installations - Distribution of socioeconomic and population parameters - Indicative representation of the population and socioeconomic impact due to tsunami	Tsunami Risk Management– Prevention and Mitigation Measures Map as the final product of integration of the results from the 11 thematic maps, scale 1:10,000 R = HA x VU x VA
Papathoma and Dominey-Howes (2003) (Gulf of Corinth, Greece, local level)	Probabilistic approach, the source is not considered Probability of tsunami (return periods) for different intensity (Ko-Ambraseys-Sieberg six grade intensity scale) and maximum wave heights Inundation zone is the area between the coastline and the 5 m contour	Vulnerability of buildings, humans and the economy is ranked using 7 weighting factors	Table of the total estimated cost of different property (e.g. buildings, households) in Euros

Source/level of analysis	Hazard characterization (approach, source and parameters)	Consequences Including vulnerability, its indicators and elements at risk	Risk approach and results
Tinti et al. (2008) (Sicily, regional level)	Scenario-based approach for two scenarios: small tsunami (1 m run-up on coast) and large tsunami (5 m run-up on coast) Probability of tsunami by hybrid method (statistic and deterministic analysis)	Vulnerability of people considers people in residential houses, industrial, commercial buildings, public structures (e.g. schools, universities and hospitals)	Table of number of persons affected by tsunami per year (min and max) Impact map of number of people potentially affected by selected tsunami scenario (for summer and winter season)
Clague et al. (2003) (Canada, national level)	The hazard is evaluated by the maximum wave run-up (most often vertical run-up); any run-up exceeding 1 m is considered dangerous	Impact: inundation, forces exerted by flooding and receding waves, impact of flooding debris, contamination	Qualitative description of risk, such as low, moderate and high R = Hazard x Exposure

3. TSUNAMI RISK ASSESSMENT BASED ON ANALOGIES FROM OTHER NATURAL HAZARDS

Since literature on tsunami risk assessment is limited, other risk assessment methods that are usually applied to different natural hazards are briefly discussed. The tsunami risk is sometimes estimated using analogies with other existing risk-based approaches, most often floods. An example of this kind can be found in the UK, where the concept and principles of the Risk Assessment for Strategic Planning (RASP) methodology originally developed for fluvial and coastal flooding is also applied to tsunami risk assessment. According to the authors, risk arising from more frequently occurring flood hazards can be assessed and compared with tsunamis (DEFRA, 2005).

The RASP tiered methodology comprises a hierarchy of methods that are conceptually consistent but vary in level of detail (high, intermediate and detailed; Sayers et al. 2002). In our review, we describe the high-level method that provides a methodology for the estimation of national flood risk that is divided into the ten steps illustrated in Figure 11:
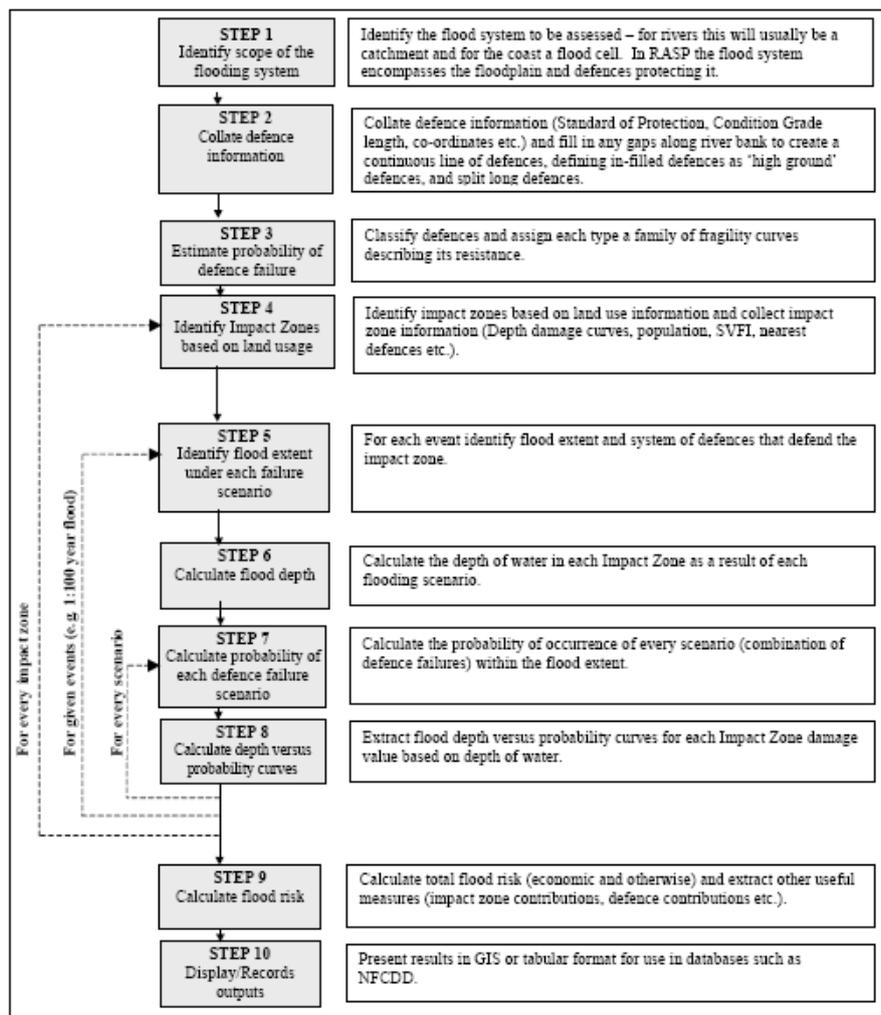
Figure 11: The RASP High Level Methodology, source: Sayers et al. 2002

The flood risk calculation (e.g. for people, property, etc) according to the RASP High Level Methodology (Step 9) requires an understanding of the damage associated with a particular flood depth and the probability of the depth being equaled or exceeded, which in general is expressed as:

Risk = Probability x Consequence

The results can be presented in the form of thematic maps in a GIS, such as the economic risk in a floodplain illustrated in Figure 12. The darker shade in the figure represents a higher risk.

Figure 12: Example of economic risk map obtained by the RASP High Level Methodology, source: Sayers et al. 2002

Another example of a similar approach can be found in Australia and New Zealand, where multi-hazard risk assessment of different natural hazards such as floods, landslides, storms, etc. is consistent with the "generic" risk management process outlined in the Standard *AS/NZS 4030 Risk management*. There the main components of the risk assessment are risk identification, analysis and evaluation, as illustrated in Figure 13.

Figure 13: Risk management process according to AS/NZ 4360

Three strategies for the management and assessment of flood and landslide risk, which are derived from *AS/NZS 4030* are discussed in the following.

URS New Zealand Limited conducted a detailed flood risk assessment along the Thames Coast based on the risk management approach shown in Figure 14.
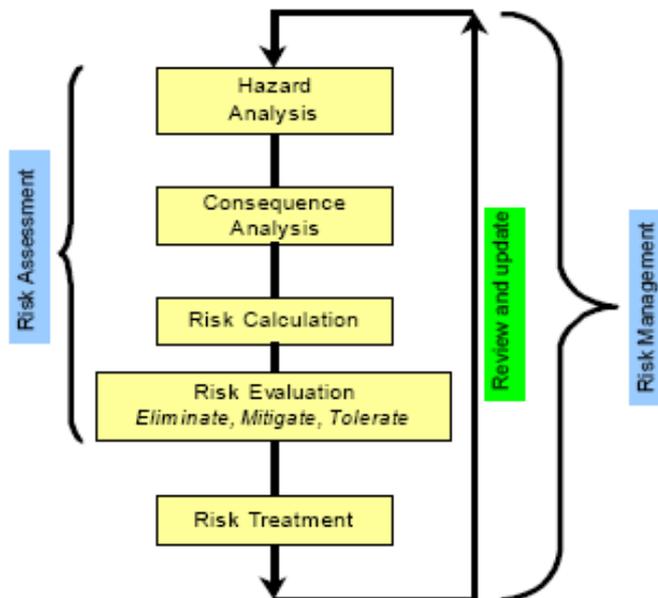
Figure 14: Risk management diagram according to URS, 2003

Here risk management consists of the following components:

1) **Definition of the problem** and setting the terms of reference for the study.

2) **Hazard analysis**, including identification of the event(s) that can cause an adverse consequence; estimation of speed and size, in this case the area of flooding, depth of flooding and water velocity, and estimation of the probability (or frequency) of the event.

3) **Consequence analysis,** including:
- Identification of the elements at risk (such as people, buildings, infrastructure etc.),
- Estimation of the vulnerability of the elements at risk,
- Assessment of the temporal and spatial variability of the elements at risk (e.g. day/night or high/low tourist season,
- Assessment of financial impacts as well as loss of life,
- Assessment of environmental impacts due to the identified hazards.

4) **Risk calculation** is performed for risk to lives and financial risk. The risk to lives is presented in terms of societal risk (F-N curves), annualized lives risk (ALR) and individual risk. The financial risk is calculated for the various risk mitigation options considered. The methods of *Event Tree Analysis* and *Quantitative Risk Assessment (QRA)* are commonly used to estimate the number of deaths, financial and environmental consequences, and their associated probabilities. For a quantitative risk assessment the following general expression is used:

$$R = P_{(H)} \times P_{(S:H)} \times P_{(T:S)} \times V \times E$$

Where,

R = The annualized risk i.e. the annual probability of fatality or property damage in financial terms.

$P_{(H)}$ = The annual probability of the flood event.

$P_{(S:H)}$ = The probability of spatial impact given the hazardous event i.e. the likelihood of homes, businesses etc. being in the path of floodwater.

$P_{(T:S)}$ = The temporal probability of the consequence occurring i.e. probability of the element at risk being present within the area affected by the flooding when the flood occurs.

V = The vulnerability of the element at risk given the presence of the element at risk within the area affected by the hazardous event.

E = The element at risk i.e. an individual, a group or community, or property.

5) **Risk evaluation and risk treatment** includes the comparison of the estimated risk with available risk criteria and a cost estimation of risk treatment.

The Australian Geomechanics Society (AGS) has published a series of guidelines developed under the National Disaster Funding Program. These guidelines consist of well defined steps of landslide risk management and its hierarchy as illustrated in Figure 15.
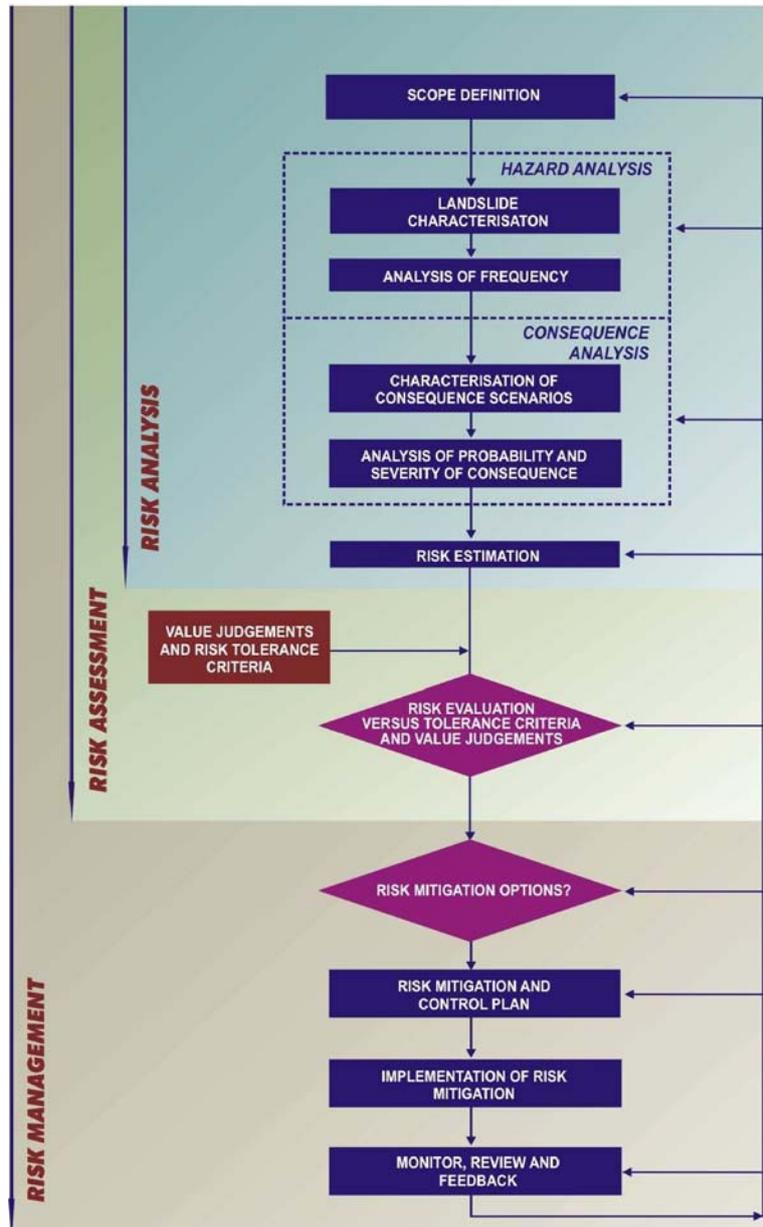
Figure 15: Framework for landslide risk management (AGS, 2007 after Fell et al. 2005)

Risk assessment according to the AGS involves six basic steps:

1) Scope definition should be clearly identified and discussed. It is important to define the site of interest, geographic limits, the purpose of the analysis (e.g. injury to persons, loss of life, property loss or damage), type of analysis, the degree of quantification etc.

2) Hazard identification requires an understanding of the landslide process that will allow classifying the types of landslides (e.g. slide, debris flow or rockfall), extent of landslide (e.g. location, area, volume), travel distance of landslide and rate of movement (e.g. creep, slow, fast).

3) Frequency analysis is the key step of the analysis because it involves much uncertainty and expert judgment. The frequency of landsliding can be expressed as the annual frequency of occurrence of landsliding in a given area based on the previous rate of occurrence, the probability of an existing landslide moving in a given period based on an understanding of the landslide mechanism, or as an annual frequency when the driving forces exceed the resisting forces in probability or reliability terms.

4) Consequence analysis considers the identification of the elements at risk (e.g. population, building and engineering works, economic activities, public service utilities, infrastructures, environment), the calculation of the temporal probability of the mobile elements at risk (e.g. persons on foot, cars, buses, occupancy of buildings as a function of the time of day or time of year) and the vulnerability of persons and property.

5) Risk estimation may be carried out quantitatively, semi quantitatively or qualitatively. For property, the risk $R_{\mathrm{Pr}op}$ (annual loss of property) is expressed as a function of the annual probability of the landslide $P_{(H)}$, the probability of spatial impact $P_{(S:H)}$, the vulnerability of property $V_{(\mathrm{Pr}op:S)}$ and the elements at risk E:

$$R_{\mathrm{Pr}op} = P_{(H)} \times P_{(S:H)} \times V_{(\mathrm{Pr}op:S)} \times E$$

For loss of life the individual risk R_{LoL} is a function of the annual probability of the landslide $P_{(H)}$, the probability of spatial impact $P_{(S:H)}$, the temporal probability $P_{(T:S)}$ and the vulnerability of the individual $V_{(D:T)}$ according to

$$R_{LoL} = P_{(H)} \times P_{(S:H)} \times P_{(T:S)} \times V_{(D:T)}$$

For total risk (whether for property or for life) the risk for each hazard for each element is summed.

6) Risk evaluation is the final step in risk assessment to determine if the estimated risks are tolerable, and then, if required, determine the appropriate and necessary risk mitigation options to reduce risks to within tolerable limits.

In 2007 the Institute of Geological and Nuclear Science (GNS Science) published a set of comprehensive guidelines that aims to primarily assist local authority planners, developers, engineering geologist and geotechnical engineers who specialize in landslide hazard and risk assessment (Saunders and Glassey, 2007). The risk-based approach used in this guideline is compliant with AS/NZS 4360. The risk assessment is split into 5 steps, as shown in Figure 16.
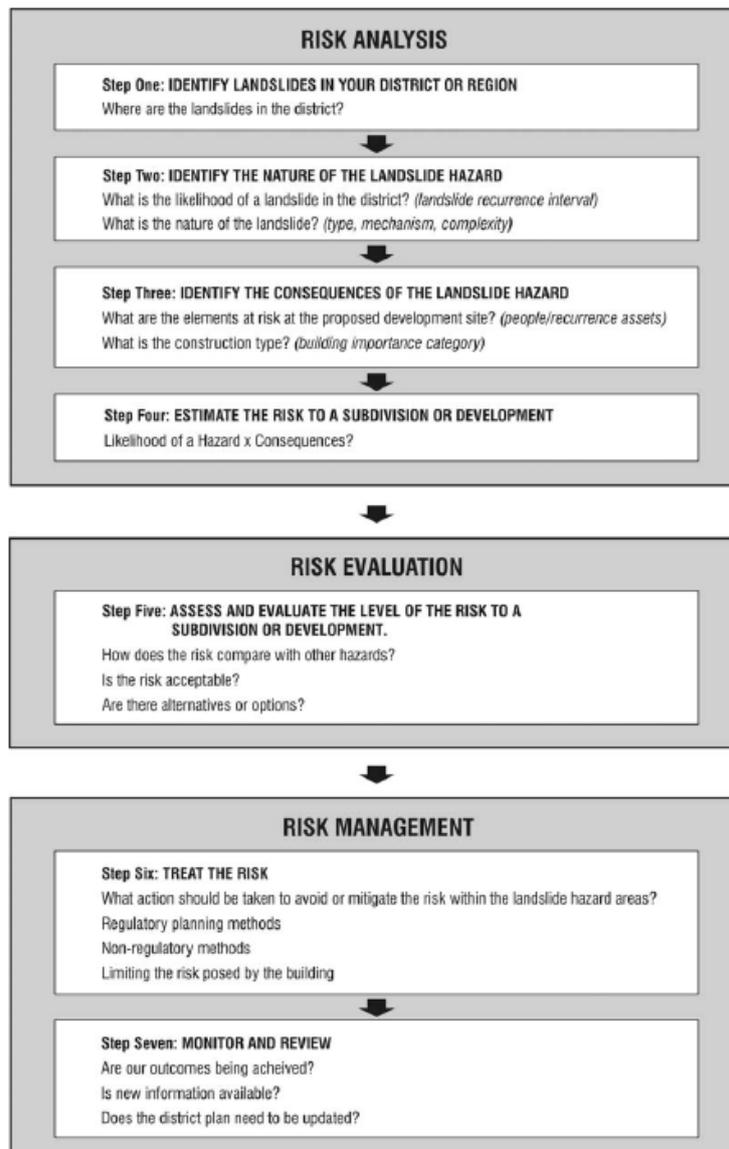
Figure 16: Risk-based planning approach according to the GNS Science

1) Landslide identification in the area of interest (e.g. region, district).
2) Identification of the nature of the landslide hazard consists of 2 parts: Part 1 involves the estimation of the frequency or likelihood of landslides in the area of interest. Part 2 related to the landslide characterization including its mechanism, type and complexity.
3) Identification of the consequences establishes the elements at risk such as people, property, assets and their classification.
4) Risk estimation is the outcome of the hazard and vulnerability calculation (the consequence of the hazard).
5) Risk evaluation compares estimated risk to tolerable or acceptable risk.

Natural risk assessment for several hazards such as floods, droughts, earthquakes, tsunamis, tropical cyclones, landslides, volcanoes and asteroids is discussed by

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Nott (2006). The author discusses the current problem regarding short-term historical records that do not reflect the natural variability of a hazard but are still often used in natural risk assessment. Long-term records are therefore the only reliable source for knowing the true nature of the behavior of natural hazards over time. The total risk is presented as a product of hazard, elements at risk and vulnerability.

Similarly as for the methods on tsunami risk assessment summarized in Table 2, the selected analogous approaches from other natural hazards are summarized in Table 3.

Table 3: Summary of selected risk approaches that can be used to assess tsunami risk

Source/Guidelines	Original field of application	Risk methodology	Results
Risk Assessment for Strategic Planning (RASP) United Kingdom	Flood and erosion risk management	10 steps in the high-level risk methodology Risk receptors include people, property (residential and non-residential), agriculture, environment, roads etc. Risk = Probability x Consequence	GIS maps (e.g. economic risk map, risk to people, environmental risk)
URS (2003) New Zealand	Flood risk assessment	For a quantitative risk assessment the following general expression is used: $$R = P_{(H)} \times P_{(S:H)} \times P_{(T:S)} \times V \times E$$	The risk to lives is presented in terms of <u>societal risk</u> (F-N curves), <u>annualized lives risk</u> (ALR) and <u>individual risk</u>. The <u>financial risk</u> is calculated for the various risk mitigation options considered. Methods: QRA, event tree
Australian Geomechanics Society (AGS)	Landslide risk management	Risk is calculated for loss of life and property: $$R_{LoL} = P_{(H)} \times P_{(S:H)} \times P_{(T:S)} \times V_{(D:T)}$$ $$R_{\mathrm{Prop}} = P_{(H)} \times P_{(S:H)} \times V_{(\mathrm{Prop}:S)} \times E$$	<u>Individual and societal risk</u> <u>For property</u>: annual loss of property value <u>For loss of life</u>: annual probability of loss of life (death) of an individual
Institute of Geological and Nuclear Science GNS Science New Zealand	Landslide risk management	Risk is an outcome of hazard and vulnerability (the consequence of the hazard)	
Nott (2006)	Natural hazards such as floods, droughts, earthquakes, tsunamis, tropical cyclones, landslides, etc.	Risk (total) = hazard x elements at risk x vulnerability	

The general concept of risk estimation for floods and landslides is similar and usually involves the probability of hazard and its consequences (or vulnerability and the elements at risk). Comparing to a tsunami risk, the new components probability of spatial and temporal impact are introduced. The results of analyses are usually expressed in the form of individual, societal and financial risk, which is typical output of a standard QRA.

4. A GENERAL FRAMEWORK FOR TSUNAMI RISK ASSESSMENT WITHIN THE TRANSFER PROJECT

The literature review on tsunami risk assessment showed a similarity in approaches that are available in different countries and applied by specific scientific communities. The observed similarity particularly regards the general concept of risk assessment. This can be explained by the origin of natural risk assessment approaches that were developed from the generic methods for risk assessment. The main differences lie in the methods used for risk estimation and the presentation of the results.

To provide a systematic framework for tsunami risk assessment within the scope of the TRANSFER project, we propose the following five steps for tsunami risk assessment (Figure 17):

    1) Scope definition
    2) Tsunami hazard analysis
    3) Estimation of the consequences of the potential hazard
    4) Risk estimation
    5) Risk evaluation

1. Scope definition consists of the definition of the problem and setting of the basic input parameters for analysis. This includes the definition of the investigated area, the scale of investigation, level of details, the purpose of the analysis (focusing on people or property), and the type of the approach used (qualitative, quantitative or semi-quantitative).

2. Tsunami hazard analysis includes both the tsunami occurrence and its frequency. The tsunami occurrence is characterized by the identification of tsunamigenic sources and their general characteristics needed for the propagation and inundation modeling. The frequency is a measure of the number of occurrences of a repeating event per unit time. The concept of a return period or recurrence interval is commonly used to describe frequency in natural science. The reciprocal of the return period is the annual exceedance probability of the event (or indicative annual probability). Tsunami hazard analysis is usually performed using a deterministic or probabilistic approach.

The required output for the estimation of tsunami risk is:
- Probability distribution of the occurrence of a tsunami at various return intervals, e.g. tsunami wave height hazard curves showing the relation between wave heights and return period (annual rate of occurrence)
- Inundation map or tsunami hazard maps showing the maximum water depth, current speed, forces, etc. for a selected scenario or associated probability

1. Scope Definition
Purpose of analysis, definition of area, scale, level of details, type of analysis, etc.

2. Tsunami Hazard Analysis
- Tsunami Characterization
(For propagation and inundation modeling)
- Frequency Analysis
(For risk estimation)

3. Consequence Analysis
- Elements at Risk
- Vulnerability

4. Risk Estimation
- People vs. Properties
- Casualties (Loss vs. Injuries)
- Direct vs. Indirect losses
- Qualitative vs. Quantitative

5. Risk Evaluation

Required Parameters
For Assessing Risk

- Run-up, water depth, current speed, Froude number, forces, etc.
- Inundation line with associated probability
- Return period (recurrence interval)
- Annual exceedance probability
- Frequency- magnitude relationships

- Distribution of the elements at risk of interest (people, property, services, roads, etc.)
- Day/night, summer/winter, tidal level
- Vulnerability of selected elements (e.g. societal, physical) and its indicators

Individual Risk

Societal Risk

Economic Risk

Outputs in GIS Environment

Data availability
(History, sources)

Probabilistic   Deterministic

Inundation Map   Hazard Map   H

x

Thematic Map of the Elements   Vulnerability Maps   C

=

Thematic Risk Map   R

Figure 17: Proposed framework for tsunami risk assessment

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3. Consequence Analysis is the part of risk analysis which considers the physical effects and the damage caused by these physical effects (EFCE No.45). Consequence analysis includes the identification of the elements at risk due to their location with respect to the potential tsunami, and the vulnerability of selected elements. Typical elements at risk may include people, property, services, infrastructures, vehicles on the road, etc. The temporal probability (e.g. persons on foot, cars, buses, occupancy of buildings during night/day, week days/weekend, summer/winter) of the mobile elements at risk should also be considered at this stage according to the level of detail of the analysis.

The purpose of vulnerability analysis is to identify the vulnerability of the selected elements at risk that are within the tsunami hazard area. The detailed assessment of vulnerability is beyond the scope of this report and is described elsewhere (see for example Birkmann, 2006).

The required output for the estimation of tsunami risk is:
- Thematic maps of the selected elements at risk, such as population distribution, building distribution with associated attributes of relevant parameters, e.g. building heights, number of floors, structure of buildings etc.
- Thematic maps of the vulnerability, e.g. societal, physical or environmental vulnerability maps

4. Estimation of Risk
Once the hazard and consequence analyses have been carried out, the next step is to estimate the risk. This can be carried out in a quantitative or qualitative way or as a combination of both, depending on the data and resources available. In practice, qualitative analysis is often used first to obtain a general indication of the level of risk. Later it may be necessary to undertake more specific or quantitative analyses. The quality of the results depends on whether the components of hazard and consequence analyses have been appropriately considered; and on the availability, quality and reliability of the required data. According to AGS (2000), whenever possible, the risk estimate should be based on a quantitative analysis, even though the results may be summarized in a qualitative terminology. This gives a value of risk that can later be used in risk evaluation and treatment.

In the proposed framework, we use a definition of risk as the product of hazard and consequences. The consequences are a product of the vulnerability and the elements at risk. Different types of risk (i.e. individual, property) are calculated due to different vulnerability (i.e. physical, societal, economic, environment). In mathematical form the following formula is used:

$$R = H \times C \ \text{or}$$

$$R = H \times V \times E$$

Where, R = risk, H = probability of tsunami hazard occurrence, C = consequence, V = vulnerability, and E = elements at risk.

Depending on the purpose of the analysis, risk is calculated in terms of casualties (deaths, injuries) and economic losses (direct or indirect e.g. due to business interruption). In most of the studies, it is limited to people loss or direct economic losses.

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Risk may be presented in many different formats depending on the analysis performed and the quality of the input parameters. The most common results of a *Quantitative Risk Assessment (QRA)* are the *Individual Risk* and the *Societal Risk*. The Individual Risk is presented as contour lines on a topographic map with frequencies of 10^{-4}, 10^{-5}, 10^{-6}, 10^{-7} and 10^{-8} per year (CPR, 1999). In a GIS environment, the results can be presented in a thematic risk map showing e.g. the annual probability of loss (people or damage) in each grid cell. The Societal Risk is plotted in the form of frequency-number curves (F-N curves). The x-axis represents the numbers of deaths N, while the y-axis represents the cumulative frequency of the events. If risk to property is calculated the results are presented as frequency-damage curves (F-D). The damage, D, represents e.g. economic damage in Euros.

If data availability is not sufficient to carry out QRA, *a qualitative (or semi-quantitative) assessment relying on expert judgment is applied. The output of a qualitative risk assessment can be presented in the form of a *risk matrix* showing for example the relationship between the tsunami hazard and its potential consequences. A risk matrix can be further translated into a thematic risk map in a GIS environment. Relative terms such as low, moderate and high are used to express the results. In semi-quantitative analysis qualitative scales are given numerical values. Table 4 summarizes the applicability of each approach depending on data availability.

Table 4: Recommended approaches for the estimation of tsunami consequences and risk

Data availability on tsunami hazard	Hazard and consequences	Risk assessment method and results
No historical records on past events	Bathtub approach for selected run-up Selection of specific contour line based on local conditions	Qualitative approach Risk matrix
	Numerical modeling Worst-case scenario	Semi-quantitative approach Risk matrix
Sufficient historical data (e.g. historical catalogue of tsunamis)	Probabilistic approach using historical records on run-up	Quantitative approach (QRA) Individual risk Societal risk Economic risk

The quantitative approach is usually recommended for the assessment of tsunami risk, since the obtained values can be further compared with other areas or risks. This is not always possible therefore the results may be presented in a semi-quantitative or qualitative way.

5. Risk Evaluation

Risk evaluation is the final step in the process of risk assessment. The main objective of risk evaluation is to compare the estimated risk against given risk criteria and to determine the acceptability of the risk. Risk treatment closes the overall process of risk management. It deals with the selection and implementation of measures to modify risk. Since our main interest focuses on risk assessment a detailed discussion of risk treatment is beyond the scope of this report.

5. UNCERTAINTIES IN TSUNAMI RISK ASSESSMENT

Risk assessment is an uncertain science and this uncertainty affects all specific components of risk analysis. Uncertainty estimation within risk analysis is therefore a key factor for a successful analysis. We attempt to assign a qualitative value of uncertainty such as low, medium and high to the each main tsunami risk component. The selected three categories of uncertainty could be further refined upon availability of more detailed information. The results of this uncertainty characterization are summarized and described in Table 5.

Table 5: Characterization of uncertainty in tsunami risk analysis

Component		Uncertainty	Notes
Hazard	Sources	High	Complexity of the tsunami process, magnitude, location, dimensions, etc.
	Probability	High	No precise estimation of probability since historical data on past tsunamis are limited, short-term records
	Propagation	Medium	Uncertainty depends on the model applied and the accuracy of bathymetric data
	Inundation	Medium	Uncertainty depends on the model applied and the accuracy of topographic data about the coast (DEM), soil characteristics, etc.
Vulnerability	People, property	High	Very complex parameter depending on hazard magnitude and susceptibility of the selected elements at risk
Risk		High	

Tsunamis are most frequently generated by earthquakes, slope movements or volcanic eruptions. These natural events are characterized by a wide range of variations through time, location, specific parameters and methods for their identification. Tsunamigenic sources are therefore considered to be highly uncertain.

An estimation of the probability of a tsunami is traditionally made based on historical data. Since tsunamis occur very rarely in a specific area, to correctly estimate the probability is difficult. The uncertainties of the tsunami propagation and inundation depend on the accuracy of the model applied.

Other uncertainties can be associated with the estimation of vulnerability and its indicators. Since vulnerability is a very complex parameter, which generally involves the three variables exposure, susceptibility and coping capacity and is also dependent on the hazard assessment, the associated uncertainty is high. The resultant tsunami risk depends on the components hazard and vulnerability and their errors; therefore the associated uncertainty in tsunami risk estimation is also high. A good example to illustrate variations of outcomes can be found in Nott (2006), where hundreds to thousands more homes may be affected by tsunami inundation depending upon whether the tsunami run-up height is 1 or 2 m.

6. CONCLUSIONS

During the course of the European TRANSFER project a need was identified for a supporting document to guide the assessment of the tsunami risk within the frame of the project. In support of this the JRC decided to review the existing approaches to tsunami risk assessment with the aim to help clarify the concept of tsunami risk assessment and to provide a basis for the preparation of guidelines for tsunami risk assessment.

This report provides a general overview of existing concepts and methods to assess tsunami risk, which are summarized and analyzed based on a uniform scheme. The report provides general recommendations on the steps necessary for assessing the tsunami risk based on the examples from the reviewed countries. The following countries listed in an alphabetic order have been included in the document: Australia, Canada, Greece, Indonesia, Italy, Japan, New Zealand, Thailand and USA. These represent areas affected by tsunamis and therefore we consider that the most important and relevant studies are included in the report.

Tsunami risk assessment is a multi-disciplinary issue that should include the following main steps: hazard identification and characterization, assessment of consequences, and risk estimation and evaluation. Tsunami hazard assessment is generally performed in two different ways using a probabilistic (statistic) or a deterministic (scenario-based) approach. Sometimes a combination of both approaches is used. The question could be which approach (probabilistic or deterministic) to use for the purposes of tsunami risk assessment? In general, the probabilistic approach relies on historical records of past tsunamis, while the deterministic one is based on information about the tsunamigenic sources. Data availability about the tsunami hazard is therefore one of the main criteria to select the approach. Consequences are the outcome of an event and refer to the elements at risk and their vulnerability. The most common elements at risk include the population, buildings, roads, infrastructures and the natural environment. Vulnerability was not discussed in detail in this report. However, this parameter seems to be the least developed, understood in many different ways and most difficult to address. Risk estimation may be carried out quantitatively, semi-quantitatively or qualitatively, depending on the availability, quality and reliability of the required data and the purpose of the analysis. In practice, qualitative analysis is often used first to obtain a general indication of the level of risk or to perform an analysis for a large area with a low resolution (e.g. national or regional). Quantitative analysis can be used in later stage to obtain more specific information for a small area with a high resolution (local). If quantitative analysis is performed, the obtained numerical values of risk can be later used in the final step of risk assessment, which is risk evaluation. It is important to realize that the results of risk assessment are dependent on its components and its errors. Therefore the report also briefly discusses the issue of uncertainty within tsunami risk analysis. A qualitative value of uncertainty such as low, medium and high was assigned to each of the main tsunami risk components.

In addition, other risk assessment methods, which are applied for example for floods or landslides, are reviewed to study their commonalities or differences with tsunami risk assessment. The observed similarity is found in the general concept of risk assessment. This can be explained by the origin of natural risk assessment approaches that were developed from the generic methods for risk assessment. The main differences lie in the methods used for risk estimation and the presentation of the results.

Further research is needed to develop detailed guidelines targeted to tsunami risk assessment and management. The proposed report can provide a basis for such guidelines. This work has also highlighted a need for clarifying terminology which differs across the various disciplines and for harmonisation of at least the output of the various tsunami risk-assessment methodologies (e.g. tsunami risk maps) for better comparability.

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ANNEX

They are differences relating to the definitions of risk and its estimation, therefore we have prepared a brief summary of some basic terms and definitions of risk that are used in this report. The summarized terminologies are consistent with the ISO/IEC Guide 73 or modified from the Australian Geomechanics Society [AGS 2007].

Consequence (C) is the outcome of an event. There can be more than one consequence from one event. With respect to a tsunami event the consequences are adverse.

Elements at Risk (E) are population, buildings and engineering works, economic activities, public services utilities, infrastructure and environmental features in the area potentially affected by the tsunami hazard.

Frequency is a measure of the number of occurrences of a repeating event per unit time. The concept of a return period or recurrence interval is commonly used to describe frequency in natural science. The reciprocal of the return period is the annual exceedance probability of the event (or indicative annual probability).

Hazard (H) is a potential source of harm. The tsunami hazard can be expressed as the probability of occurrence of a damaging tsunami of a given magnitude.

Qualitative Risk Analysis is an analysis which uses word form, descriptive or numeric rating scales to describe the magnitude of potential consequences and the likelihood that those consequences will occur.

Quantitative Risk Analysis is an analysis based on numerical values of the probability, vulnerability and consequences and resulting in a numerical value of the risk.

Quantitative Risk Assessment (QRA) is the generic term used for techniques which allow the risk associated with a particular activity to be estimated in absolute quantitative terms rather than in relative terms such as "high" or "low". The most common results of a QRA are the *Individual Risk* and the *Societal Risk*. The Individual Risk is presented as contour lines on a topographic map with frequencies of 10^{-4}, 10^{-5}, 10^{-6}, 10^{-7} and 10^{-8} per year, if in existence (CPR, 1999). The Societal Risk is plotted in the form of frequency-number curves (F-N curves). The x-axis represents the numbers of deaths N, while the y-axis represents the cumulative frequency of the events.

Risk (R) is the combination of the probability of an event and its consequence [ISO Guide 73]. In the case of natural hazards, this traditional concept of risk is extended to new components, such as vulnerability (V) of the elements at risk (E) within the affected area. The general expression for quantitatively estimating risk that can be applied also to tsunamis is therefore: R = H x C, while C = V x E.
Risk can also refer to the potential outcomes of an event occurring.

Risk Management, according to ISO/IEC Guide 73, coordinates activities to direct and control an organization with regard to risk. It comprises four components such as risk assessment, risk treatment, risk acceptance and risk communication.

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│ RISK MANAGEMENT ( 3.1.7)                                            │
│  ┌─────────────────────────────────────────────────────────────┐   │
│  │ RISK ASSESSMENT (3.3.1)                                      │   │
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│  │  │ RISK ANALYSIS (3.3.2)                                 │   │   │
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│  │  │   │ SOURCE IDENTIFICATION (3.3.4)                 │  │   │   │
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│  │  │   │ RISK ESTIMATION (3.3.5)                       │  │   │   │
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│  │  │ RISK EVALUATION (3.3.6)                                  │   │
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│  │ RISK TREATMENT (3.4.1)                                          │
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│  │  │ RISK AVOIDANCE (3.4.6)                                   │   │
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│  │  │ RISK OPTIMIZATION (3.4.3)                                │   │
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│  │  │ RISK TRANSFER (3.4.7)                                    │   │
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│  │ RISK ACCEPTANCE (3.4.10)                                        │
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│  │ RISK COMMUNICATION (3.2.4)                                      │
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Risk Acceptance is a decision to accept risk.

Risk Analysis is described as systematic use of information to identify sources and to estimate the risk. Risk analysis provides a basis for risk evaluation, risk treatment and risk acceptance.

Risk Assessment is an overall process of risk analysis and risk evaluation.

Risk Evaluation is the process of comparing the estimated risk against given risk criteria to determine the significance of the risk.

Risk Treatment is the process of selection and implementation of measures to modify risk. It may include avoiding, optimizing, transferring or retaining risk.

Vulnerability (V) is understood in many different ways. For the purposes of this report we define vulnerability as a set of conditions and processes resulting from physical, social, economic, and environmental factors, which increase the susceptibility of a community to the impact of hazards.
(UN-ISDR terminology, http://www.adrc.or.jp/publications/terminology/top.htm#V)

Abstract

This report provides an overview of the existing methods of tsunami risk assessment. The analyses focus on the process of risk assessment, its basic steps and output. Therefore, the specific components of risk, such as hazard, consequence or vulnerability are not discussed in detail. The reviewed studies are classified according to the country of origin or their place of the application. Since literature on tsunami risk assessment is limited, other risk assessment methods applied for floods and landslides are briefly discussed and studied their commonalities with tsunami risk.

In conclusion, the report suggests a possible strategy for addressing the tsunami risk in the TRANSFER project. For this purpose, a general framework for tsunami risk assessment has been prepared.

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