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Managing tsunamis through early warning systems: A multidisciplinary approach

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ABSTRACT

This study attempts to identify the key factors that will make a tsunami warning system most effective, to develop a framework in which results of natural science and engineering research can be effectively integrated into coastal natural hazard planning, and to develop a numerical example that illustrates how benefit-cost analysis may be used to assess early warning systems. Results of the study suggest that while the science of tsunami wave propagation and inundation is relatively advanced, our knowledge on the relationships between tsunami generation and undersea earthquakes, volcanic eruptions, and landslides remains poor, resulting in significant uncertainties in tsunami forecasting. Probabilities of damaging tsunamis for many coastal regions are still unknown, making tsunami risk assessment and management difficult. Thus it is essential to develop new techniques to identify paleo-tsunami events and to compile and develop size and frequency information on historical tsunamis for different locations. An effective tsunami early warning system must include not only the ocean technologies for accurately detecting an emerging tsunami, but also a civil communication system through which the population can be timely warned by the local government and other sources. Since minimizing the evacuation time is a key factor to make a warning system effective, adequate pre-event education and preparation of the population must be a critical component of the system. Results of a numerical example of the South Pacific region suggest that investments in a tsunami warning system in the region may lead to significant economic benefits.

1. Introduction

The December 26, 2004 giant earthquake[1] and tsunami killed over 200,000 people and caused billions of dollars of damages in 12 countries around the Indian Ocean (UN, 2007). Many lives could have been saved if there had been an effective tsunami warning system in this part of the world. The tsunami exposed major deficits in developing countries' hazard management and emergency response systems. Following the 2004 tsunami, the international ocean science community is accelerating work on understanding tsunamis, their geological causes, and their impacts on coastal regions. This devastating tsunami has prompted countries around the world to reassess tsunami risks to their coastal communities and to develop response strategies for future events.

Natural hazard mitigation is a complex endeavor that requires direct links between natural and social sciences. For example, an effective early warning system must include not only the ocean technologies to accurately detect an emerging tsunami, but also a public notification system through which the population can be timely warned by the local government and other sources. Indeed, tsunami readiness involves two key components: *awareness*, which may be improved by educating key decision makers, emergency managers, and the public about the nature (physical processes) and threat (frequency of occurrence, impact) of a hazard; and *mitigation*, which may be improved through pre-event planning. In recent years, disaster management has changed from viewing a problem in isolation to a policy of *sustainable hazard mitigation* that views hazard mitigation as an integral part of a much larger context. Communities must take responsibility for choosing where and how development proceeds through land-use planning. Toward that end, each locality evaluates its environmental resources and hazards, chooses future losses that it is willing to bear, and ensures that development and other community actions and policies adhere to those goals. Disaster management and planning require a longer-term view that takes into account the overall effect of mitigation efforts on this and future generations (Mileti, 1999). An

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[1] On December 26, 2004 at 07:58 am (local time) a massive undersea earthquake occurred with an epicenter off the west coast of Sumatra, Indonesia. The magnitude of the earthquake has been measured as between 9.1 and 9.3 on the Richter scale, which is the second largest earthquake ever recorded on a seismograph.

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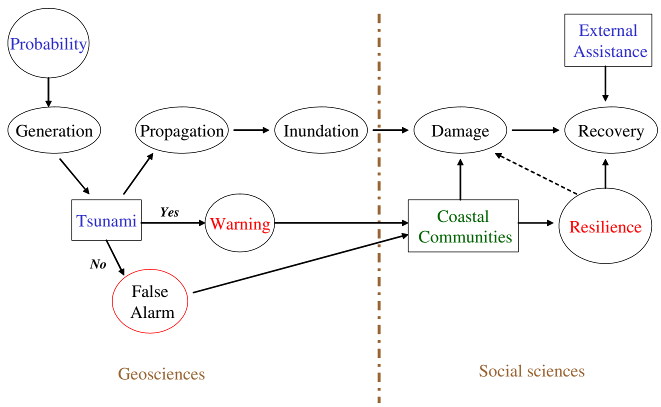

Fig. 1. A multidisciplinary approach for tsunami research.

effective early warning system must be an integral part of disaster risk reduction strategies in national development frameworks and requires cooperation amongst many partners at local, regional, national, and international levels (UN ISDR, 2006a). Thus an effective tsunami hazard mitigation program involves interdisciplinary collaboration between natural and social sciences and requires ocean researchers to work closely with hazard management officers.

The objectives of this study are to identify the key factors (e.g., science and management planning) that will make a tsunami warning system most effective, to develop a framework in which results of natural science and engineering research can be effectively integrated into coastal natural hazard planning, and to develop a numerical example that illustrates how benefit-cost analysis may be used to assess early warning systems. The study provides a comprehensive review of literature on tsunami and related research. Section 2 describes a multidisciplinary approach for tsunami research. Tsunami warning systems are explained in Section 3. Social science research and management programs for natural hazards are discussed in Section 4. Section 5 summarizes issues related to economic analyses of warning systems. Section 6 presents an example of the South Pacific region. The study is summarized in Section 7.

2. A multidisciplinary approach

Tsunamis are gravity waves that propagate near the ocean surface (Ward, 2001). The entire process of a damaging tsunami may be divided into five major components: generation, propagation, inundation, damage, and recovery (Fig. 1). The first three components, describing how waves are generated, travel across the ocean, and come ashore, are the focus of geosciences research. The last two components, the impacts of tsunami on society and how coastal communities recover from damage and destruction, are the focus of social science research.

2.1. Tsunami generation

Ranging from the most to least frequent, there are four causes of tsunamis: undersea earthquake, submarine landslide, volcanic explosion, and bolide impact[2] (Okal, 2006). Only a small proportion of strong earthquakes produce detectable tsunamis. Damaging tsunamis occur even less frequently. During the 20th century, damaging tsunamis occurred at a frequency of 5–21 times per decade worldwide (Fig. 2, NOAA, 2005). Because they are very rare for a specific place, location-specific probability distributions for these events are not known for many coastal regions of the world.

2.2. Propagation

Tsunamis are gravity waves and they are distinct from common sea waves in their mode of generation and in their characteristic period, wavelength, and velocity (Ward, 2001). Tsunamis are much slower (e.g., 220 m/s) than seismic waves (e.g., 3–10 km/s) (Okal, 2006). For the purpose of developing warning systems, tsunami travel time maps for the Atlantic, Indian and Pacific Oceans have been prepared (Nirupama et al., 2006; Bhaskaran et al., 2005; NGDC, 2007). These are charts showing tsunami travel times from a starting point (epicenter) to various locations around the rim of the ocean.

2.3. Inundation

Wave run-up is a complex process (Chesley and Ward, 2006). The height and destructive forces on landing of a given offshore wave may vary significantly for different landfall locations, depending on the physical and geological features of the surrounding coastline. Because of its complexity, how tsunamis propagate and interact with shores is typically analyzed using numerical simulations (Okal, 2006).

2.4. Damage

Tsunami impacts onshore are affected by many factors including topography of the coastal area, geologic and ecological conditions (e.g., sand dunes, mangrove forests, and coral reefs), and social and economic conditions (e.g., population density).[3] Papadopoulos and Imamura (2001) have proposed a new 12-point scale to measure tsunami intensity. The scale is arranged according to a tsunami's effects on humans, vessels, buildings and other objects, and the natural environment. During the 2004 Indian Ocean tsunami, three devastating waves struck the western shore of Aceh within about 30 min. The tsunami waves ranged from 4 to 39 m high and destroyed more than 250 coastal communities (Cluff, 2007).

Research on tsunami damage consists of computer model assessment of simulated tsunami events for specific coastal communities (Papathoma and Dominey-Howes, 2003) and site investigation of past events. After the 2004 tsunami, damage analyses included both on site engineering damage assessment of houses, roads and bridges, industrial facilities, and electric power network (Cluff, 2007) and large-scale damage analysis (e.g., mapping percentage of buildings collapsed) using remote sensing techniques (Berke, 2006). Using the 12-point scale, Narayan et al. (2006) developed tsunami intensity mapping and identified damage patterns along the coast of Tamilnadu (India). Results of these analyses provide vital inputs to the development of tsunami evacuation maps (Oregon Emergency Management, 2007) and to the improvement of coastal disaster management planning.

[2] For an analysis of impact-generated tsunamis see Chesley and Ward (2006).

[3] Timing of tsunami occurrence is also an important factor. When the 2004 Indian Ocean tsunami hit Aceh, many fishermen were at sea, leaving behind women and children. It was the height of the tourist season in Thailand; Phuket alone had an estimated 35,000 visitors a day (Atwood, 2006).

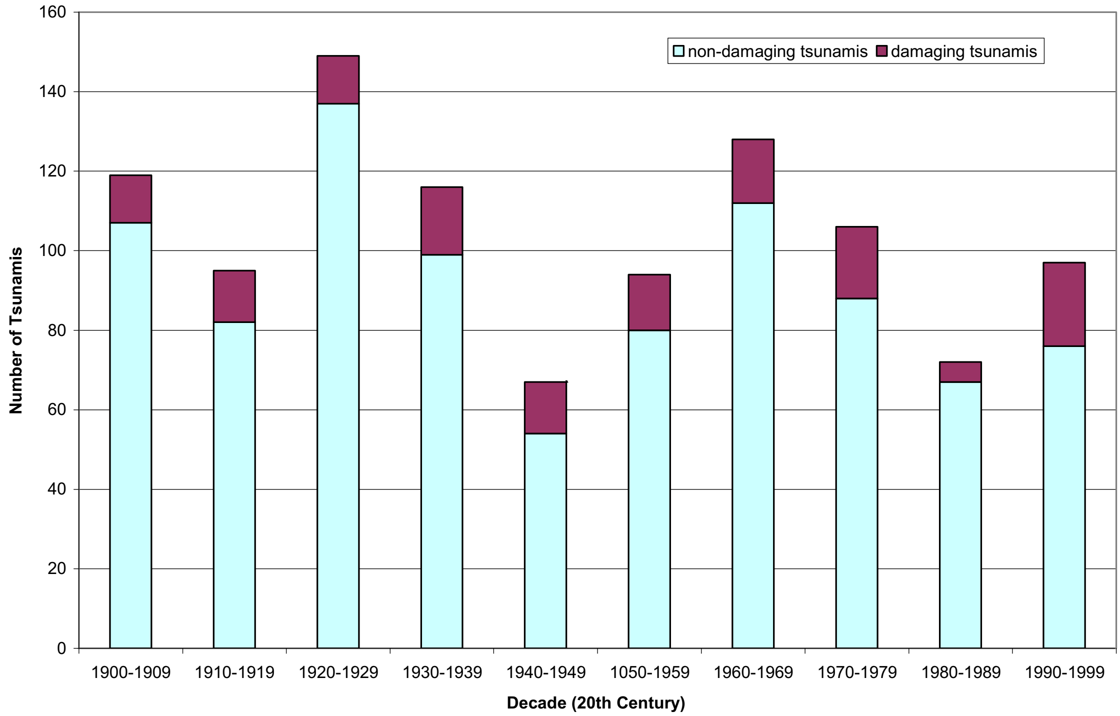

Fig. 2. Damaging tsunamis vs. non-damaging tsunamis, worldwide. Source: NOAA (2005).

2.5. Recovery

For a given level of damage severity, the recovery process is influenced by emergency response and the pace of reconstruction; both are critical to reducing human suffering and diseases. Emergency response involves not only the supply of food, medicine, and shelter, but also prevention of disease following the emergency by improving health and sanitation conditions (WHO, 2005). Both response and rebuilding typically require external assistance; this is especially true for developing countries.

Since tsunamis are much slower than seismic waves, it should be possible to provide warning based on interpretation of seismic waves, at least in the case of a far field tsunami that is created by an earthquake at great distance. However, a number of factors make the development of an effective warning system a very challenging task. It is difficult to measure the true size and seismic energy of very large earthquakes. Uncertainties remain as to factors that contribute to the generation of tsunamis. In the near field, there is little to essentially no time to issue warnings. As noted above, research on tsunami events must progress based on extremely small samples (Okal, 2006). Since 1948, 75% of all warnings issued have preceded non-destructive tsunamis. The cost of an over-predicted alarm can be substantial. For example, the evacuation of Honolulu in 1986 costed $40 million (NOAA, 2004).

Since the 2004 Indian Ocean tsunami, various efforts have been made to upgrade and expand the world's tsunami warning systems. Although the improved warning technologies (e.g., better spatial distributions of DART (Deep-ocean Assessment and Reporting of Tsunami) buoys and coastal tide gauges and better seismological and tsunami modeling capabilities) can address issues like over-predicted alarms, the implementation of effective warning procedures transcends the physical sciences (Okal, 2006). As we will discuss next, to improve the effectiveness of warning systems, researchers and hazard management agencies must work together through a multidisciplinary approach that integrating geosciences, engineering, social sciences, and emergency response and management.

3. Tsunami warning system

The physical science part of a typical tsunami warning system has four components: a seismographic network, a buoy (e.g., DART) and tide gauge network, computer modeling and analysis, and a warning center.[4]

3.1. Instruments

The seismic stations are installed across the globe. DART-like buoys are deployed in the deep oceans offshore, while tide gauges are located along coastal lines. Since only a small proportion of strong earthquakes produce a damaging tsunami, a warning system based solely on seismic data is prone to producing false alarms. To reduce false alarm, DART and GLOSS (Global Sea Level Observing System) instruments are used to verify if a tsunami has indeed been triggered. The DART system uses buoys and sensors stationed far out to sea. A typical DART buoy system works as follows: (1) a recorder on seabed measures water pressure periodically (e.g., every 15 min) while an unusual signal could trigger more frequent reading (e.g., every 15 s); (2) a buoy measures sea surface conditions and sends this information, plus data from the seabed, to a satellite; and (3) the satellite relays the data to ground stations. GLOSS consists of tide gauges installed along the coasts of the world's oceans. After the 2004 tsunami, there was a major upgrade of sea-level observing stations along the coast of Indian Ocean (BBC, 2005) as well as installation of new DART buoys in the Pacific, Atlantic, and Caribbean regions. The GITEWS (German-Indonesian Tsunami Early Warning System) project has led to the developments of a new set of hardware (e.g., GPS buoy) and software for Indonesia (Rudloff et al., 2009).

[4] Okal (1994) presented an excellent introduction to the physical science part of a tsunami warning system, its theoretical background, and key components (e.g., earthquake, wave analysis, and seismic moment).

3.2. System integration

All the above hardware and software need to be integrated into an efficient system. In 1987 the TREMORS (Tsunami Risk Evaluation through seismic Moment Of a Real-time System) was installed in the French Polynesia. This is an automated system that detects distant earthquakes, locates them, computes their seismic moment, and issues a seismic warning (Reymond et al., 1996). The TREMORS method relies on a magnitude scale (Mm), using mantle Rayleigh waves, that is directly related to seismic moment (M0) and improved detection algorithms (Okal and Talandier, 1989). The system has been deployed in Hawaii, Indonesia, Chile, Portugal, and other places. A TREMORS station at an epicentral distance of 15° (1667 km) can issue a useful warning 10 min before the tsunami reaches a shore located 400 km from the event. In this example, the required time for TREMORS algorithm response (about 20 min) is shorter than the time of a tsunami to travel from the earthquake epicenter to the concerned coastal location (about 30 min for a tsunami traveling at 220 m/s), thus making a warning possible. The 2004 tsunami hit Thailand approximately 2 h after the earthquake. Had a TREMORS station been in place in the region, it could have provided a warning significantly ahead of the tsunami and saved lives (Okal, 2006). Started in 2005, the GITEWS project was designed to set up a tsunami warning system optimal for the Indonesian coast. The project has developed new technologies and scientific concepts, including the integration of near real-time GPS deformation monitoring as well as new modeling techniques and decision supporting procedures. The resulting system has reduced early warning times down to 5–10 min (Rudloff et al., 2009).

3.3. Warning center operation

Even the world's most advanced tsunami warning system still requires human inputs. At the Pacific Tsunami Warning Center (PTWC) located at Ewa Beach in Hawaii, two scientists are on call 24 h a day and 7 days a week (NOAA National Weather Service, 2008a). They live on the site and can report in 2 min. The Center monitors about 120 seismic stations around the Pacific Basin (PBS, 2005) and 60 Marigraph stations (tide gauges). The automated system at the Center can detect an earthquake in 3 min and locate it in 4 min. It takes a few minutes for the scientists to quantify the earthquake and to make a preliminary assessment of its tsunami risk based on combined factors of the estimated earthquake size, pre-computed tsunami models, and historical record of tsunamis (if any) for historical earthquakes occurring in the same region. After an initial assessment is made, however, it takes significantly longer for scientists to use the DART buoy and tide gauge observations to verify if a tsunami has indeed occurred. The required time for the confirmation is controlled by the time for the tsunami wave to reach the closest DART buoys and/or tide gauges. Based on the decisions of the scientists, the Center issues warnings to Pacific-rim countries. In practice, the Center routinely issues an initial assessment of tsunami potential shortly after a significant earthquake, which is followed by updated information when more accurate tsunami and earthquake information becomes available. Such later tsunami updates could contain information on cancellation of an earlier warning.

The warning messages from the Center are disseminated to a list of designated federal, state, and local emergency management agencies and personnel, international partners, as well as other prescribed users. Depending on the severity of the tsunami warning, local authorities may decide to further disseminate the warning by patrol cars, sirens, and paging and order an evacuation. It has been estimated by the Honolulu Police Department that the evacuation of Waikiki before a tsunami would require 2.5 h (Okal, 2006). The US West Coast and Alaska Tsunami Warning Center (WC/ATWC) located in Palmer, Alaska uses similar strategy in issuing tsunami warning (NOAA National Weather Service, 2008b). Currently the WC/ATWC is responsible for issuing tsunami warning and information to the US west coast states and Alaska, while the PTWC is responsible for warning the state of Hawaii and international partners (NOAA National Weather Service, 2008a, 2008b).

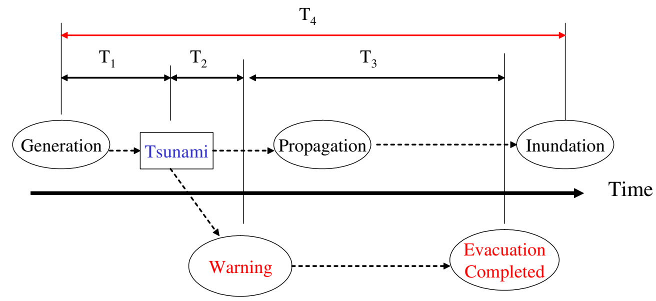

Fig. 3. Tsunami warning: time dimension.

3.4. The time dimension

For an effective tsunami warning system, time is of the essence. Braddock (2003) specifies the time constraint for the system as:

$$T_1 + T_2 + T_3 \leq T_4 \tag{1}$$

where T_1 is detection time, T_2 is assessment time, T_3 is evacuation time, and T_4 is tsunami travel time (Fig. 3). Since T_4 is exogenous, to make the warning system effective the time needed for warning and evacuation ($T_1 + T_2 + T_3$) should be minimized, i.e., it is essential to

$$\min(T_1 + T_2 + T_3). \tag{2}$$

Detection time (T_1) can be shortened by optimizing locations of seismic stations, DART buoys and tide gauges,[5] by implementing global real-time data telemetry for the monitoring system (Holgate et al., 2007), and by improving data processing and model algorithms. To shorten assessment time (T_2) requires improvements in our ability to measure the true size and seismic energy of very large earthquakes, to understand factors contributing to tsunami generation, and to make warning decision using only small historical data samples. Unlike T_1 and T_2, the evacuation time (T_3) of a community is affected by its emergency planning, education, communication network, and other socio-economic, environmental, and circumstantial factors such as the time of the day when a tsunami occurs and whether it is a tourist season, etc. In many cases, significant potential exists to reduce T_3. According to the UN International Strategy for Disaster Reduction (ISDR, 2006b), among both developed and developing nations, the weakest elements are warning dissemination and preparedness to act. Warning may fail to reach those who must take action, and may not be adequately understood or address the concerns of the local authority and population.

To be effective, early warning systems must be people-centered and must integrate four elements: (1) knowledge of the risks faced,

[5] Spatial design of a tsunami warning system has been modeled by Braddock (2003). The model takes financial budget, locations of tsunami generation points, and locations of population centers as inputs, and calculates the number and locations of buoys so that the "total warning potential" (i.e., fraction of population can be saved by a warning) is maximized.

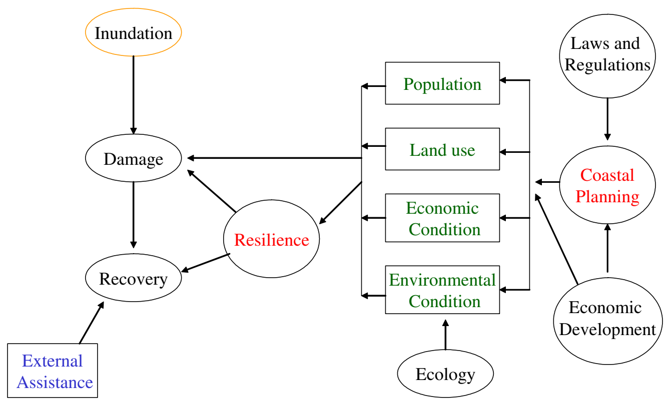

Fig. 4. Social and economic research.

(2) technical monitoring and warning service, (3) dissemination of meaningful warnings to those at risk, and (4) public actions responding to the warnings, which can be improved by pre-event awareness and preparedness to act. Failure in any one of these elements can mean failure of the whole early warning system (ISDR, 2006b).

3.5. The near field

If the distance between the earthquake epicenter and the shore is less than 400 km, it takes less than about 30 min for a tsunami to reach the shore. The 2004 tsunami hit Aceh within 15 min. In these cases of near field tsunamis, there is little lead time for tsunami warning. Coastal communities have to rely on self-evacuation triggered by evidence of tsunami danger, such as direct sensing of the earthquake by the population and anomalous behavior (retreat) of the sea.[6] Self-evacuation requires an educated population. Nevertheless, warnings may still be useful in the near field to trigger automated responses (e.g., head to high ground immediately, shut off gas lines, stop trains, close sluices, etc.), so that damages may be minimized (Okal, 2006).

4. Social science research

It has been widely recognized that natural disasters are the *joint* product of natural and human activities (Russell, 1970; Zeckhauser, 1996; NRC, 2006). The expected damage of tsunamis (D) can be expressed as

$$D = E[L(N, H, S)] \quad (3)$$

where N is a stochastic variable capturing natural events (e.g., frequency and magnitude of tsunamis), H denotes the human action, S represents the socio-economic conditions of a community, L is the loss function, and E is the expectations operator.

For a tsunami of certain magnitude, the level of damage is significantly affected by the cumulative actions that coastal communities take prior to the event. These actions include where and how to build houses, what industries to develop, investment in natural hazard mitigation, and protections of the coastal ecosystems. The actions are results of economic development decisions that are driven by socio-economic characteristics of the community (Fig. 4).

While geoscience research improves our understanding of N, the focus of social science research is on H and S. Specifically, social science research involves characterization of coastal communities and identification of policy instruments (e.g., land-use planning) that can alter human actions in these communities so that future damage can be minimized.

4.1. Characterization of coastal communities

Disasters manifest pre-existing conditions within the social, economic, physical, and environmental fabrics of a society (Villagrán de León, 2006). Thus, community studies are important in tsunami management. In summarizing lessons from Thailand and Indonesia in the 2004 tsunami, Atwood (2006) suggests that disasters lead to an exaggeration of previous inequities, enhancing the vulnerability of the most vulnerable. At the onset of a disaster, most families are equally needy, but not all are equally vulnerable. In planning a medium and long-term response it is important to identify those who are most vulnerable. Baseline data are also crucial for immediate assessment and response planning after a disaster event.[7]

Community study often starts with collection of baseline data on physical and demographic conditions (e.g., population density and infrastructure), socio-economic conditions (e.g., level of economic development and community participation), and environmental conditions (e.g., forest area and over-used area). In-depth analysis of a community involves the development of a community profile depicting formal and informal organizations, networking among members of the community, and links to external organizations. The analysis develops an assessment of *social capital* and organizational capability in the community (Berke, 2006). Social capital in a community is a measure of civic engagement (e.g., volunteer activity), social networks, trust (in other residents and internal and external organizations), and organization capability for collective action in the community (NRC, 2006).

Individual characteristics of a community (e.g., population and social network) can be quantified using indexes; and these indexes can be combined in a variety of ways into one or more aggregate indexes (e.g., social capital index) by assigning weights to each individual index and then summing across weighted index values. These indexes are used for assessing relative risks and vulnerabilities to different stresses (Yohe and Tol, 2002; Berke, 2006).

4.2. Vulnerability assessment

In studies of natural disasters, the effects of human action and socio-economic conditions (H and S) on losses are typically analyzed through vulnerability assessment. According to Adger et al. (2005), observed increases in damages associated with weather and climate events are caused by changing social vulnerabilities as much as by changing physical hazards. Villagrán de León (2006) provides an excellent review of relevant studies. Vulnerability (V) may be modeled as

$$V = g(P, Y, R) \quad (4)$$

where P is exposure, Y is susceptibility, and R is resilience. Exposure is related to the location of the community with respect to hazard;

[6] There was a considerable recession of tsunami waters at Kata Noi Beach, Phuket, Thailand, before the third, and strongest, tsunami wave on December 26, 2004 (Atwood, 2006).

[7] After the 2004 tsunami, it was difficult to assess early needs in Aceh, as demographic and infrastructure data were not available. As a result, supplies were either over- or under-estimated, location of populations was difficult to identify, and percentage affected was impossible to estimate as the denominator was not known (Atwood, 2006).

Table 1
Factors affecting vulnerability.

Factors increasing vulnerability	Factors reducing vulnerability
• Increasing population • Marginality and poverty • Lack of access to credit and insurance • Unplanned land-use • Certain habits and traditions • Unemployment and illiteracy • City expansion and unplanned growth • Lack of building codes or their enforcement • Ecosystem degradation	• Improvements in social capital • More equal distribution of political and economic resources • Training and education • Land-use planning • Enforcement of building codes • Diversification of economies • Provide more opportunities, resources, and power to women and disadvantaged groups. • Ecosystem protection

Source: Villagrán de León (2006) with minor modification.

susceptibility may reflect deficiencies in preparedness; and resilience, also known as coping capacity, describes the abilities to cope with and to recover from the hazard stress. V is positively related to P and Y while negatively related to R. Indexes for variables P, Y, and R are constructed from relevant community studies. The vulnerability indicators are often used in ranking different communities for the identification of management priorities (Yohe and Tol, 2002; Villagrán de León, 2006). Key factors affecting vulnerability are summarized in Table 1.

Vulnerability needs to be understood in a broad context that includes many social, economic, and environmental components at different levels. Numerous studies have dealt with subsets of these components. For example, the issue of insurance against natural disasters has been examined by Kunreuther and Sheaffer (1970) and by Attanasi and Karlinger (1979). Rose (2004) presented an analysis of the definition and measurement of economic resilience to disasters. He showed that economic computable general equilibrium (CGE) modeling is a useful framework for analyzing the behavior of individuals, business, and markets, and could be used to quantify economic resilience. Green (2004) evaluated household vulnerability to flooding using system analysis.

Adger et al. (2005) discussed social–ecological resilience to coastal disasters. Resilience is the capacity of linked social–ecological systems to absorb recurrent disturbances such as hurricanes or floods so as to retain essential structures, processes, and feedback. Wherever ecosystems have been undermined, the ability to adapt and regenerate has been severely eroded. They suggest that resilient social–ecological systems incorporate diverse mechanisms for living with, and learning from, changes and unexpected shocks. Disaster management requires multilevel governance systems that can enhance the capacity to cope with uncertainty and surprise by mobilizing diverse sources of resilience.

4.3. Natural disaster management programs

There have been considerable efforts around the world to improve and expand natural disaster warning and management programs. The UN's International Strategy for Disaster Reduction has developed a checklist for developing early warning systems (ISDR, 2006c) that provides useful guidance for systematic program development. The checklist consists of four key elements: risk knowledge, monitoring and warning service, dissemination and communication, and response capability; and a cross-cutting issue: effective governance and institutional arrangement (Table 2).

At the community level, NOAA National Weather Service's TsunamiReady program provides a good example. The program is designed to reflect two basic concepts: education is the key to increased awareness of the hazard, while pre-event planning is the key to effective mitigation. To be recognized as TsunamiReady, a community must meet a set of requirements (Table 3). As of February of 2008, there are 50 coastal communities in the United States that have been certified as TsunamiReady (NOAA National Weather Service, 2008c).

Table 2
Developing early warning systems: a checklist.

Risk knowledge
1. Organizational arrangements established
2. Natural hazards identified
3. Community vulnerability analyzed
4. Risk assessed
5. Information stored and accessible
Monitoring and warning service
1. Institutional mechanisms established
2. Monitoring systems developed
3. Forecasting and warning systems established
Dissemination and communication
1. Organizational and decision-making processes institutionalized
2. Effective communication systems and equipment installed
3. Warning messages recognized and understood
Response capability
1. Warning respected
2. Disaster preparedness and response plans established
3. Community response capability assessed and strengthened
4. Public awareness and education enhanced
Governance and institutional arrangements
1. Early warning secured as a long-term national and local priority
2. Legal and policy frameworks to support early warning established
3. Institutional capacities assessed and enhanced
4. Financial resources secured.

Source: ISDR (2006c).

5. Benefit-cost analysis for tsunami warning

Tsunami warning systems can be very costly. For example, cost estimates for a tsunami warning system in the Indian Ocean range from \$27 million (Padma, 2004) to \$200 million (Jean, 2005; Stone

Table 3
NOAA National Weather Service (NWS) TsunamiReady program requirements.

Communications & coordination
24 h Warning Point (WP)
Emergency Operations Center (EOC)
NWS warning reception
Multiple ways for EOC/WP to receive NWS tsunami messages[a]
Hydrometeorological monitoring
Multiple systems to monitor hydrometeoroligical data[a]
Warning dissemination
Multiple ways for EOC/WP to disseminate warnings to public[a]
NOAA Weather Radio tone-alert receivers in public facilities
Communication network ensuring information flow between communities
Community preparedness
Annual tsunami/weather safety programs[a]
Tsunami shelter/area in safe zone
Evacuation areas
Evacuation routes and evacuation route signs
Written, locality specific, tsunami hazard response material to public
Tsunami hazard curriculum in schools
Practice evacuations
Administration
Formal tsunami hazard operations plan
Yearly meeting by emergency manager with NWS

[a] Note: Number grows with population in the community.Source: NOAA Weather Service (2005).

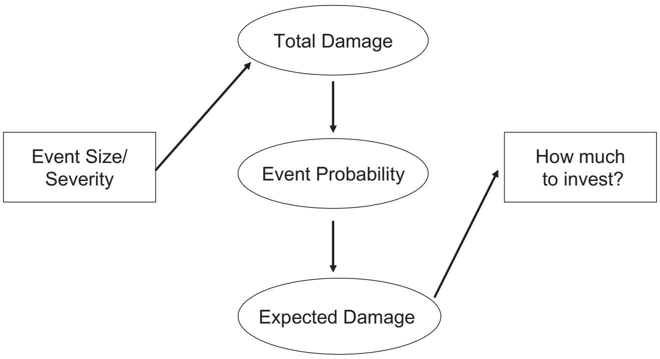

Fig. 5. Natural disasters damage estimation.

and Kerr, 2005), depending on system components and technologies (e.g., number of DART buoys and measurement precision). Because of competition for limited financial resources, investments in tsunami warning systems need economic justification using benefit-cost analysis.

A benefit-cost analysis for a warning system is straightforward in concept. The investment (C) is justified if

$$E(B) \geq C. \quad (5)$$

where B is the benefit from the system (i.e., live saved and damage avoided). In practice, there are two issues that make the analysis difficult. First, it is a very complex task to quantify benefits to the communities being served (e.g., lives saved and damages avoided across different sectors in the economy). The task becomes even more complex when the warning system is evaluated in a multi-hazard framework.[8]

In addition, the probability of tsunami events for a specific location is typically unknown. Societies are not very good at dealing with probabilistic information and related issues, particularly when the probability is very small but the damage is catastrophic. Exaggeration of risks of tsunamis can lead to over investment in warning systems (Fig. 5). Thus information on the probability of disaster events is important for formulating social policies and management decisions (Kunreuther, 2006).

5.1. Economic studies of natural hazards

The economics of tsunami warning systems is a new research topic. Both analytical and empirical studies on the subject are extremely limited in scope and number. The studies of a related natural hazard, earthquakes, provide useful analytical approaches and modeling techniques.

Liu and Hsieh (1981) developed an integrated model for earthquake risk and damage assessment. The model consists of three sub-models: physical damage functions, economic damage functions, and institutional aspects related to risk mitigation policies and community preparedness. For a given earthquake risk of a certain magnitude at a specific location, the expected damage is a function of population density, housing and other economic characteristics, mitigation policies, and time of the event (night vs. day). The economic damage is the sum of costs associated with human deaths and injuries, housing structural damages, and other economic losses. Ellson et al. (1984) constructed a regional econometric model to assess the potential economic effects of earthquakes and earthquake predictions in Charleston, South Carolina. In the model, the economic damages resulting from an earthquake are estimated in four categories: death, housing destruction, capital losses (e.g., factories, equipment, and inventories), and disruption in transportation flows.

Schulze et al. (1990) investigated the economic feasibility of earthquake prediction as a function of program performance for the San Andreas Fault region (Los Angeles area). Following Sieh (1978), they modeled earthquake risk over time using a Weibull distribution (often used to describe mechanical or structural failures from strain and wearing out). Their model explicitly considers successful vs. false predictions, and the cost of false alarms is treated as part of the total of cost of the prediction program. In addition, the model captures the effects of future population growth. Based on the increasing probability of a major earthquake in the region, the study concludes that the expected benefits of a prediction program may well exceed the expected costs.

The Multihazard Mitigation Council (2005) developed a systematic assessment of future savings from mitigation activities in the United States. They show that natural hazard mitigation activities funded by the FEMA between 1993 and 2003 were cost effective and reduced future losses from earthquake, wind, and flood events. The benefit to cost ratio was 4:1 (i.e., a dollar spent on mitigation saved society 4 dollars).

5.2. Public risk perception

Understanding public risk perception toward low probability but high-loss events is important for the evaluation and improvement of tsunami warning programs. Again, the studies of earthquake and other natural disasters are relevant.

Using property value data from Los Angeles County and the San Francisco Bay Area counties, Brookshire et al. (1985) showed that individuals paid less for houses located in relatively hazardous areas, *ceteris paribus*. The result suggests that the expected utility hypothesis (widely used in economic decision-making models) is a reasonable description of behavior for consumers who face a low probability, high-loss natural hazard event, given that they have adequate information.

Bernknopf et al. (1990) examined the effect of earthquake and volcano hazard notices on investment and recreation activities of the Mammoth Lakes, California area. The study found that the hazard notices did not affect recreation visitation, although investment was affected. Beron et al. (1997) analyzed residential housing sales data from the San Francisco Bay area together with geologic variables to estimate the hedonic price of earthquake risk before and after the 1989 Loma Prieta earthquake. Their results suggested that consumers initially overestimated the earthquake hazard.

According to Kunreuther (2006), extensive evidence indicates that residents in hazard-prone areas do not undertake loss prevention measures voluntarily. Individuals underestimate the likelihood of a future disaster, often believing that it will not happen to them.[9] Individuals are often myopic and hence only take into account the potential benefits from risk reduction investments over the next year or two. To reduce long-term future losses from natural disasters thus often requires partnerships between the private and public sectors, for example through well-enforced building codes and land-use regulations coupled with insurance

[8] The economies of scale, sustainability and efficiency can be enhanced if natural disaster warning systems and operational activities are established and maintained within a multipurpose framework that considers all hazards and end user needs.

[9] Rich context information must be available for people to be able to judge differences between low probabilities. One needs to present comparison scenarios that are located on the probability scale to evoke people's own feelings of risk (Kunreuther et al., 2001).

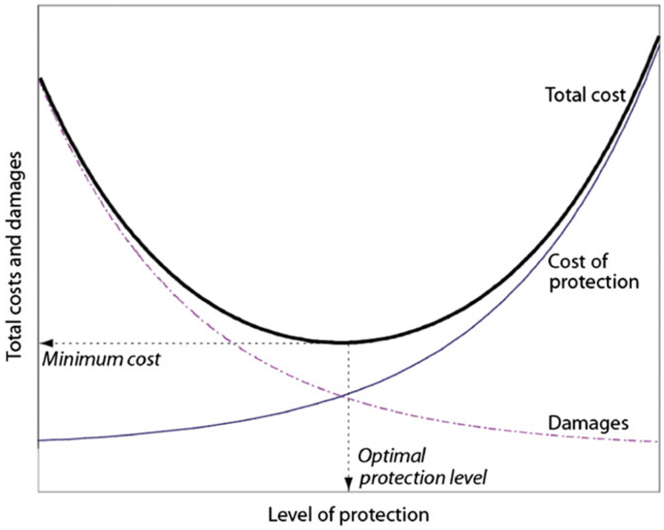

Fig. 6. Optimal level of protection.

protection. Economic incentives that make these actions financially palatable to property owners need to be provided in the form of long-term mitigation loans and subsidies to low-income residents of high-hazard areas.

5.3. Optimal level of investment

As discussed in Russell (1970), the benefits and costs vary as the level of protection against natural hazards is changed. In the case of tsunami hazard the level of protection may be described by the accuracy of a tsunami warning system that depends on, among other things, the density of monitoring stations along the coast. In general, we expect that the benefits of a very basic version of the tsunami warning system may be moderate but may grow rapidly as the number of coastal monitoring stations increases. At some point, the benefit of adding more monitoring stations may diminish or even approach zero. Meanwhile, the costs of investments in the warning system are expected to increase as more stations are established. The decision is to minimize the expected social costs (SC) of future tsunami events by choosing the level of protection (α):

$$\min_{\alpha} E(\mathrm{SC}) = E[D(\alpha)] + C(\alpha) \tag{6}$$

where D represents the total damages resulting from tsunami occurrences, and C represents investment in the monitoring system, including capital and labor costs. The choice variable (α) represents the "accuracy" of a monitoring system. Over the relevant range, more accurate monitoring will increase C. On the benefit side, the effect of an increase in α is captured by the reduction in damage D. The optimal level of investment in a warning system is that which minimizes the sum of C and D (Fig. 6).

6. Tsunami warning in the South Pacific region: a numerical illustration of benefit-cost analysis

To illustrate the very basic components of a benefit-cost analysis of a tsunami warning system in a specific region, we use the South Pacific and the DART buoy system as an example.[10] Managing natural disasters is an important issue in the region due to its unique characteristics. Islands in the South Pacific are environmentally and economically vulnerable due to their small territorial sizes, geographically remote locations, proximity to active zones of large earthquakes and volcanic chains, and relatively weak economies (Shea, 2003; Briguglio, 2006; UNICEF, 2006). Pacific Islands are among the most-hazard-prone areas in the world (Haque, 2003).

We start with the cost side. As noted in Section 3, the physical science part of a tsunami warning system consists of a seismographic network, a tide gauge and DART buoy network, computer modeling and analysis, and a warning center. In most cases, the tsunami warning system can utilize the existing seismic network and natural hazard management infrastructure in the region, although they may need upgrading. Most investments are for the installation of a network of tide gauges and DART buoys and related communication links. Reported unit cost estimates for DART buoys and sea-level tide gauges are summarized in Table 4.

Table 4
Unit costs of warning system components.

Components	Unit	Cost
DART buoy installation	\$/unit	250,000
DART buoy maintenance	\$/unit/year	50,000–125,000
Sea-level gauge	\$/unit	5000
Communication link	\$/unit	20,000–40,000

Sources: Bernard et al. (2001), Heilprin (2005) and Symonds (2005).

Because a warning system is typically composed of multiple offshore DART buoys and a larger number of tide gauges along the coast, system-wide cost estimates vary according to the buoy-tide gauge combination and technical complexity (Padma, 2004; Stone and Kerr, 2005). A cash-flow analysis is shown in Table 5. It is assumed, based on cost estimates in Table 4, that the low- and high-end costs for installation are \$0.29 and \$0.31 million per DART unit, respectively, while the annual costs for operation and maintenance are \$50,000 and \$125,000 per DART unit, respectively. For a designed life of 15 years and an annual discount rate of 7%, the total cost in present value terms is between \$0.75 and \$1.45 million

Table 5
Cash-flow analysis of annual system costs of a warning system.

Year	Annual cost (\$)		Present value[a] (\$)	
	Low	High	Low	High
Installation/DART unit[b]				
0	290,000	310,000	290,000	310,000
Operation & maintenance/DART unit				
1	50,000	125,000	46,729	116,822
2	50,000	125,000	43,672	109,180
3	50,000	125,000	40,815	102,037
4	50,000	125,000	38,145	95,362
5	50,000	125,000	35,649	89,123
6	50,000	125,000	33,317	83,293
7	50,000	125,000	31,137	77,844
8	50,000	125,000	29,100	72,751
9	50,000	125,000	27,197	67,992
10	50,000	125,000	25,417	63,544
11	50,000	125,000	23,755	59,387
12	50,000	125,000	22,201	55,501
13	50,000	125,000	20,748	51,871
14	50,000	125,000	19,391	48,477
15	50,000	125,000	18,122	45,306
Total system cost/DART unit	1,040,000	2,185,000	745,396	1,448,489
Annual system cost/DART unit			81,840	159,036
Number of DART units assumed			3	5
Annual system cost			245,521	795,182

[a] Note: Assuming 7% discount rate.
[b] Note: Low cost estimation includes 1 DART buoy, 4 sea-level gauges, and communication link at \$20,000/unit; high cost estimation includes 1 DART buoy, 4 sea-level gauges, and communication link at \$40,000/unit.

[10] It should be stressed that the example presented here does not constitute a detailed case study for a specific investment project evaluation, which is beyond the scope of this paper.

Table 6
South Pacific island nations: basic economic statistics.

Countries	GDP (US$)	Population	Area (sq. km)	GDP per capita	Notes
Fiji	2,821,605,888	853,485	18,270	3306	[1]
Kiribati	70,707,832	100,551	730	703	[1]
Nauru	60,000,000	13,528	21	4435	[2]
Papua New Guinea	5,653,884,928	5,995,265	462,840	943	[1]
Samoa	422,494,912	185,583	2840	2277	[1]
Solomon Islands	334,846,624	489,228	28,900	684	[1]
Tonga	222,949,600	102,448	750	2176	[1]
Tuvalu	14,940,000	11,992	26	1246	[3]
Vanuatu	387,506,304	215,341	12,190	1800	[1]
Subtotal	9,988,936,088	7,967,421	526,567	1254	
Territories					
American Samoa (U.S.)	na	59,600	200	na	[1]
Cook Islands (N.Z.)	183,200,000	18,700	236	9797	[4]
New Caledonia (France)	6,813,000,000	238,260	18,580	28,595	[5]
Niue (N.Z.)	7,600,000	1679	260	4527	[6]
Tokelau (N.Z.)	1,500,000	1449	10	1035	[7]
Wallis and Futuna (France)	60,000,000	15,480	264	3876	[8]
Total	17,054,236,088	8,302,589	546,117	2054	

Notes: Data sources and year: [1] World Bank (2008), 2006; [2] Wikipedia, GDP (PPP) 2005; Population 2007; [3] Wikipedia, GDP (PPP) 2002; Population 2007; [4] Wikipedia, GDP (PPP) 2005; Population 2005; [5] World Bank (2008), 2006, GDP from Wikipedia; [6] Wikipedia, GDP (PPP) and Population 2006/2007; [7] Wikipedia, GDP (PPP) 1993; Population 2007; [8] Wikipedia, GDP (PPP) 2004; Population 2005.

Table 7
Expected annual benefits of a warning system.

Regional GDP ($ billions)	Damage avoided (% of GDP)	Event probability	Expected benefits ($ millions)	Benefit-cost ratio	
				Low	High
10 (independent countries)	0.45	0.01	45.0	56.6	183.3
20 (entire region)	0.45	0.01	90.0	113.2	366.6
10 (independent countries)	0.45	0.002	9.0	11.3	36.7
20 (entire region)	0.45	0.002	18.0	22.6	73.3
10 (independent countries)	0.45	0.001	4.5	5.7	18.3
20 (entire region)	0.45	0.001	9.0	11.3	36.7
10 (independent countries)	0.07	0.01	7.0	8.8	28.5
20 (entire region)	0.07	0.01	14.0	17.6	57.0
10 (independent countries)	0.07	0.002	1.4	1.8	5.7
20 (entire region)	0.07	0.002	2.8	3.5	11.4
10 (independent countries)	0.07	0.001	0.7	0.9	2.9
20 (entire region)	0.07	0.001	1.4	1.8	5.7
10 (independent countries)	0.01	0.01	1.0	1.3	4.1
20 (entire region)	0.01	0.01	2.0	2.5	8.1
10 (independent countries)	0.01	0.002	0.2	0.3	0.8
20 (entire region)	0.01	0.002	0.4	0.5	1.6
10 (independent countries)	0.01	0.001	0.1	0.1	0.4
20 (entire region)	0.01	0.001	0.2	0.3	0.8

per DART unit. In terms of annuity, the low- and high-end estimates are $81,840 and $159,036 per DART unit, respectively. The warning system in the South Pacific may include from 3 to 5 DART units. Thus, for a basic system with 3 DART units, the low-end cost is $245,521/year. For a more complete system with 5 units, the high-end cost is $795,182/year.

We now look at the benefit side. Basic economic and population data for countries and territories in the South Pacific region are shown in Table 6. Note that the GDP data are not always consistent as some are in nominal (exchange rate-based) and others in PPP (Purchasing Power Parity) dollars. The total annual economic output in the region is close to $20 billion, of which $10 billion are from independent countries while the rest from the territories of other countries. There are over 8 million people living in the region.

Benefits associated with tsunami warning depend on many factors as discussed in the previous sections. Essentially, the benefits (damages avoided) may be estimated as the difference between tsunami damages associated with two different scenarios: without and with a warning system as described above:

$$B = D_o - D_w \qquad (7)$$

Damages with effective warning (D_w) are lower than those without warning (D_o), as many lives (productive forces in the economies) will be saved and the damages to infrastructure minimized through evacuations and activations of preventative systems (e.g., shutting down power lines, etc.).

Accurate benefit estimation requires multidisciplinary efforts and considerable data collection and model simulations, which is beyond the scope of the study. Here, we illustrate the concept in Table 7. Analyses of the damages associated with the 2004 Indian Ocean Tsunami suggest that island nations, due to their small geographical size and economic structure, suffered the highest losses in terms of percentage of their GDP (ADB, 2005). For example, losses in Maldives and Sri Lanka represented 45% and 7% of their GDP, respectively (RMS, 2006; Athukorala and Resosudarmo ,2005). Although the $4.5 billion losses in Aceh accounted for the entire GDP in the region, it represented only 2.3% of the total GDP of Indonesia (Athukorala and Resosudarmo, 2005). Assuming, in our example, that the damages avoided are 45% of the regional economic output, and the probability of a damaging tsunami is 1/100 (once every 100 years[11]), the expected benefits are $90 million per year for the entire region and $45 million per year for the independent countries. If the damages avoided are reduced to 7% of the economic output and the event occurs once every 500 years[12] (0.002), the annual benefits estimates are reduced to $2.8 and $1.4 million, respectively.

Combining the annual cost estimates (Table 5) with the above benefit estimates (Table 7), we can calculate the benefit-cost ratios. Note that the column showing low benefit-cost ratio in Table 7 is associated with higher-end cost estimates in Table 5. The results suggest that in most cases, the installation of a regionally operated tsunami warning system in the South Pacific is economically justified, because the benefits are significantly greater than the costs. The warning system would not be justified only for a scenario assuming the event probability is extremely low (0.001 or once every 1000 years), the damages avoided are small (1% of GDP), the high-end system cost estimates are applicable, and the independent countries finance the warning system alone (as warnings to the territories may be provided by relevant home countries). Closer international collaborations in tsunami management efforts between the independent countries and the territories of other countries could further cut down the costs and make a tsunami warning system even more justified economically for the South Pacific region.

7. Summary

The 2004 Indian Ocean tsunami was the first natural disaster in recent memory that affected many countries simultaneously, making it a truly international catastrophe. Because of its sheer

[11] For tsunami statistics in the Pacific region, see NOAA (2005).

[12] For a discussion of global tsunami hazard and event probability, see RMS (2006).

scale of impact, this disaster broke new ground in many aspects of natural hazard management and response. How coastal communities manage risks associated with major tsunamis is an issue of global importance.

Damages from natural disasters are jointly determined by nature and humans. Disaster management has evolved from dealing with an event in isolation to adopting a policy of sustainable hazard mitigation, where hazard mitigation is viewed as an integral part of the much larger context of environmental sustainability (Mileti, 1999).

Natural hazard mitigation is a complex endeavor that requires the integration of natural and social sciences (i.e., a multidisciplinary approach). A recent NRC report (2006) called for integration of five core topics of hazards and disaster research: hazard vulnerability, hazard mitigation, emergency response, disaster recovery, and disaster preparedness. The integrated framework requires an increase in collaborative work by social scientists with natural scientists and engineers.

The science of tsunami wave propagation and inundation is relatively advanced. However, our knowledge on the relationship between tsunami generation and undersea earthquakes, volcanism, and landslides remains poor. Probabilities of damaging tsunamis for many parts of the world are usually unknown. Thus it is essential to develop new techniques to identify paleo-tsunami events and to compile and develop size and frequency information on historical tsunamis for different locations. The information is critical for management decision making.

An effective tsunami warning system must include not only the ocean technologies for accurately detecting an emerging tsunami, but also a civil communication system through which the local government can effectively and timely warn the population. In fact, the evacuation time (how quickly a community can evacuate) is a key factor to make a warning system effective. Thus it is essential to invest in disaster education and training. Investments leading to an increase in social capital will enable communities to cope with disasters of all kinds.

The results of a numerical example of benefit-cost analysis for the South Pacific region suggest that investments in a tsunami warning system in the region may lead to significant economic benefits. Economic justification of a warning system is influenced by the expected benefit (damage avoided), event probability, and costs of the system. The example also highlights the fact that tsunamis affect many different countries throughout a large region. Thus, tsunami research and management require a coherent effort at the global and regional levels and broad participations from both government and private sectors.

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