

## Socio-Technological Systems Integration to Support Tsunami Warning and Evacuation

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### Abstract

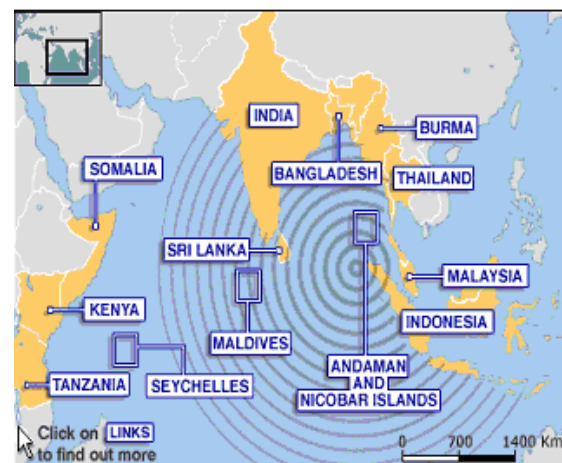
*On December 26, 2004, countries in the Indian Ocean basin were struck by a tsunami generated by a large magnitude earthquake just south of the western tip of Sumatra. Observations made during a post-tsunami visit to coastal Thailand suggest that the value of the proposed emergency warning system (EWS) for the Indian Ocean would be greatly enhanced if it was augmented by an on-shore cyber-based warning and evacuation system. Such a system would greatly increase safety with minimal disruption to the normal activities involved in tourism and other coastal industries. An integrated, cyber-based system to inform and assist the tsunami detection, warning, and evacuation process would, in essence, expand time and shorten distances. This paper describes the elements of such a cyber-infrastructure system, how system triggers could be calibrated using decision principles from judgment theory, and how the system could be tested through simulations employing agent-based models.*

### 1.0 Background

On December 26, 2004, a Magnitude 9.0 earthquake at the juncture of the Sumatran and Australian crustal plates produced the "Boxing Day Tsunami" that dispersed radially at high speed from the point of origin. Coastal Sumatra was overwhelmed within minutes but the travel time to western Thailand was on the order of 90 minutes, and the tsunami's effects in Sri Lanka, India, the Maldives, and the east coast of Africa lagged Thailand by up to several hours. Lacking buoys or tide gauges in the Indian Ocean, it was impossible to determine if a tsunami was generated by the earthquake. As a result, alarms were

not raised, evacuations were not begun, hundreds of thousands died, and entire nations were devastated. Figure 1 illustrates that no fewer than twelve nations were struck by the tsunami waves.

Consider for a moment this hypothetical alternative scenario. Within minutes of the earthquake, an alert with preliminary estimates of magnitude and location of the epicenter is sent automatically via satellite to Emergency Warning Centers (EWC) in all countries in the Indian Ocean region. As the emerging tsunami is detected by ocean-based sensors, its estimated



**Figure 1. Countries affected by the Boxing Day tsunami**

magnitude and time of arrival at various locations is again sent automatically to the EWCs. Based on pre-determined criteria, advisories and orders ranging from "stand by for further information," to "imminent danger," to "evacuate" are transmitted over multiple channels to potentially impacted coastal areas. This order is transmitted automatically unless manually

interdicted by a human decision. Alerts of various forms (sirens, warning lights, television and radio pre-emption, internet and text messages) are sounded within communities at-risk. People immediately seek higher ground or refuge in pre-designated buildings or purpose-built shelters suitable for vertical evacuation. The elapsed time from detection of the earthquake to the earliest warnings to seek shelter is on the order of 10-15 minutes. Unfortunately, many people in communities in close proximity to the epicenter are unable to flee and are killed or injured. Fortunately, many more thousands receive a warning in time to take effective action and survive the event.

Although a hypothetical example, an integrated detection, warning, and evacuation system such as that just described is achievable with existing technology. A visit to coastal Thailand in April 2005 supported by the U.S. National Science Foundation provided valuable insight into how a tsunami detection and warning system, fully integrated with national and international organizations, could reduce the enormous human losses experienced during the Boxing Day tsunami. This paper explores how technology and organizations can be melded into an effective system to prevent such a recurrence.

## 2. Tourism and Natural Hazards

Tourism is important to the Thai economy, contributing almost 6 percent of GDP in 2002. It is particularly vital to the economy of Phuket, the province most commonly associated with tourism in southern Thailand and which is second only to the Bangkok region in its importance to the Thai tourism economy. In addition to Thailand, other nations bordering the Indian Ocean and Andaman Sea increasingly are utilizing tourism as a means to capitalize on their cultural and environmental resources in a non-consumptive, sustainable manner.

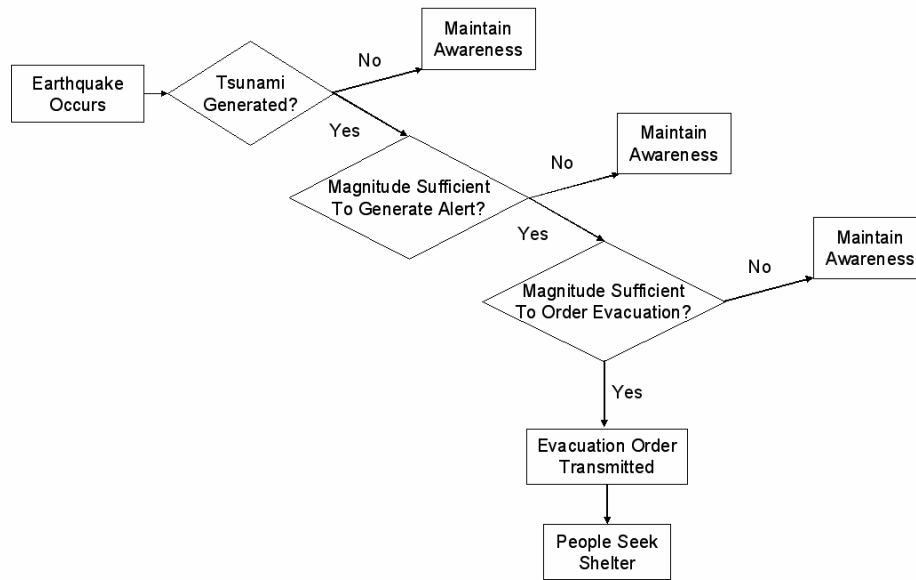
Tourism can expose people to unusual and sometimes severe risks, however. In Thailand, for example, the attraction of Phuket and Khao Lak are the beautiful sand beaches that border the Andaman Sea. However, proximity to the sea also brings with it the danger of exposure to typhoons and tsunamis. This vulnerability is compounded by the diversity of visitors who often are not aware of the threat, are unfamiliar with local geography or culture, and may not speak the languages in which hazard information is communicated [1,2]. Vulnerable populations, including those with disabilities, the elderly, the situationally disabled, and those with special needs are at particular risk in a disaster. Communicating preparedness and warning information is critical for these groups, and the experience from the tsunami and other recent events highlights that much work remains

to be done in this area [3]. Evidence from the December 2004 tsunami suggests that all these factors were in play [4]. Because the Boxing Day tsunami occurred during the high tourist season and its effects were focused on this very popular tourist area, a much higher proportion of tourists were victims of the tsunami in Thailand than in any other nation. This supports research that tourists are particularly vulnerable to natural disasters [5,6].

## 3. Risk Communication for Natural Hazards

Although the field of natural disaster risk communication is quite mature and the special needs of the tourism industry during natural disasters well chronicled [2,5,6], tsunamis pose possibly unique challenges in risk communication. First, although seismically active areas and areas vulnerable to tsunamis can be identified fairly readily, earthquakes themselves have defied prediction. Furthermore, it cannot be predicted with accuracy whether a tsunami will be generated by a particular earthquake. For example, the magnitude 8.7 earthquake that occurred on March 28, 2005 in almost the same location in Sumatra as the December 26, 2004 earthquake, generated minimal tsunami effects [7]. However, once a tsunami has been set in motion, both the timing and location of its landfall can be predicted with sufficient accuracy to serve as the basis for raising an alarm and initiating evacuation procedures. Figure 2 depicts a simplified decision sequence for the issuance of a tsunami warning following an oceanic earthquake. In many instances, only minutes will elapse between the generation of a tsunami and its first impacts on coastal areas. The first warnings that most of the areas affected by the Boxing Day tsunami received was recession of the sea prior to arrival of the initial tidal surge.

These relatively short timeframes pose difficult challenges both for emergency communications and management organizations and the people who must respond to the warnings issued. It has been demonstrated that in most of the disasters in recent history, information was available at some level that could have limited or prevented destruction. However, in many cases information was either held by those in authority who failed to act or by those without the power to act but who did not share it with those that could [8]. Obviously, in the case of a rapidly-advancing event such as a tsunami, the benefits of automated decision gates should be readily apparent. However, as will be shown subsequently, there are many reasons why this does not occur and life-critical decisions are still made by individuals.



**Figure 2. Decision sequence for the issuance of a tsunami evacuation order**

Warnings to evacuate must be timely and specific to local authorities who must make rapid decisions in a limited time [8]. Risk perception and behavior following a warning follows a general sequence of hear-confirm-understand-believe-personalize-respond [9]. In the case of earthquakes, the risk, while generally known in a spatial sense, remains abstract until an event actually occurs. The challenge is to motivate individuals and institutions to take actions in advance to mitigate the impacts of the event and to plan for recovery from it. Large storm events, such as hurricanes, can be tracked almost from their creation and the risk communication challenge is to predict the timing and location of landfall and the estimated impacts based on wind speed and tidal surge. The relatively long lead times give people (or the authorities) time to decide what action to take (e.g., shelter in place or order specific areas evacuated) but in many cases, landfall predictions are inaccurate and evacuations often are viewed, in hindsight, as unnecessary. Floods share a similarity with major storms in that the event can be tracked from early in its formation and the risk communication challenge becomes one of predicting flood stage at various locations and times and the adequacy of local flood control measures so that appropriate direction can be offered.

To a greater or lesser extent, all of the natural hazards just discussed offer the luxury of time for an organization or individual to work through the perception-behavior sequence and come to a rational

(for them) decision as to what to do. Tsunamis on the other hand, require that the time between awareness and decision be compressed; in some cases to just a few minutes or less. In this regard, the risk communication that needs to be embedded in a tsunami warning system more resembles that employed in building and airplane evacuation and abandon ship scenarios [10]. In these cases, time is of the essence and undue reflection could lead to injury or death. This will be an important consideration when designing the final communication interface for a tsunami warning system. The recipient of the information must understand the message, believe it, and act at once to seek safety. Places of refuge must be pre-identified and available within a short distance. A critical requirement will be to provide appropriate information on when to act, where to go, and how to get there. What was missing on December 26 was not information about a potential tsunami; rather, what was lacking were systems in the Indian Ocean basin to verify the formation of the tsunami, to warn people of the threat, and to communicate instructions on what to do in the presence of this information. The chaotic and dynamic nature of what amounts to a life or death emergency requires an exceedingly rapid assessment of the situation. The rapid onset of a tsunami means that the evacuation process needs to be self-initiating and self-organizing; there is simply not enough time for a top-down command-control approach to be effective. Although the challenge appears daunting, people continue to demonstrate their ability to act

rationally, individually and in groups, in crisis situations [11]. Improvisation, the ability to compose and execute a response in a rapidly closing window of time, has been demonstrated by individuals and organizations in extreme events [12,13]. Such organizational improvisation may be particularly relevant as technology continues to advance and is integrated into the decision process [14]. The Boxing Day tsunami showed that minutes and meters were the difference between life and death; an integrated information and communications system to warn, inform, and assist the evacuation process would, in essence, lengthen the time and shorten the distance.

#### 4. The Need to Integrate Technology in Tsunami Warning and Mitigation

Lessons learned from past extreme events offer a strategic model for addressing the impacts of future tsunamis as well as for identifying priority areas for action. A holistic approach to risk reduction in extreme events embodies the following four steps:

- 1) Prevention/Interdiction (Can the event be avoided?)
- 2) Advance Warning (Can the event be predicted and a warning raised?)
- 3) Hazard-resistant Construction (Can the impacted structures or systems be designed with sufficient robustness to resist abnormal loadings?)
- 4) Rapid Response and Recovery (Does the system possess sufficient resilience to recover quickly?)

Unfortunately, our state of knowledge and technology regarding natural hazards does not permit these events to be prevented. The only way to avoid the hazard is not to be there when it occurs. Given that tourism, fishing, and other ocean-based activities play an important, and in the case of tourism, increasing role in the economies of the Indian Ocean countries, it is unlikely that future events will be avoided in this manner. However, as has been shown, current and emerging technology provides significant opportunities to raise an alarm of an impending tsunami and transmit a warning to areas at risk while there is time to take effective action.

An ocean-based emergency warning system (EWS) for the Indian Ocean will become a reality in the not-too-distant future despite lingering issues of national security and information sharing among the affected parties. Several of the difficulties involved in transnational information sharing in Humanitarian Assistance/Disaster Relief (HA/DR) have been well documented [8]. These include the releasability of information perceived to have national security

implications, communication incompatibilities, information standardization and interoperability, and just the inherent difficulties of coordinating the activities of multiple organizations with multiple missions and cultures across international boundaries. For the system to be truly effective, these difficulties will need to be addressed through direct, pre-event negotiation. Such negotiations are common in HA/DR operations and are as likely to require intra- as well as international efforts [8].

The components of the proposed end-to-end tsunami warning and mitigation system are shown in Figure 3 [15]. The UNESCO Intergovernmental Oceanographic Commission has created a concept centered on a “coordinated network of national systems and capacities” for the Indian Ocean Tsunami Warning System (IOTWS), under which each nation would be responsible for issuing warnings within its own territory [15]. Such a “network of national systems and capacities” is a patchwork of various systems, not the same thing as a single detection and warning network. Over time, however, as capacity is expanded, this system may work well if the authorities charged with managing these systems coordinate data collection and warning with each other. However, this may be difficult to achieve if the rates of development of national components are significantly different. For example, although there are thousands of moored and free-floating data buoys and thousands of land-based environmental stations around the world and more than 50 environmental satellites orbiting the globe, all providing millions of data sets, most of these cannot yet “talk” to each other. Until they do—and until all of the individual technologies are integrated into a comprehensive system of systems—there will continue to be blind spots and scientific uncertainty [16].

As shown in Figure 3, the proposed tsunami warning system can be disaggregated into three broad functional areas—detection and warning, notification, and local action. In the simplest of concepts, some event(s) at the far left of the diagram will trigger the need for survival actions by people at its far right. Each of these functions will devolve to different levels of organizational responsibility, for example, detecting a tsunami and issuing a warning as to magnitude and expected time of arrival in various locations is most appropriately a supranational responsibility while the decision to notify communities will probably be retained at the national level. As discussed earlier, local action in the face of an imminent tsunami warning is primarily an individual decision. Each of these functions suggests differing levels of organizational involvement and decision-making [17].

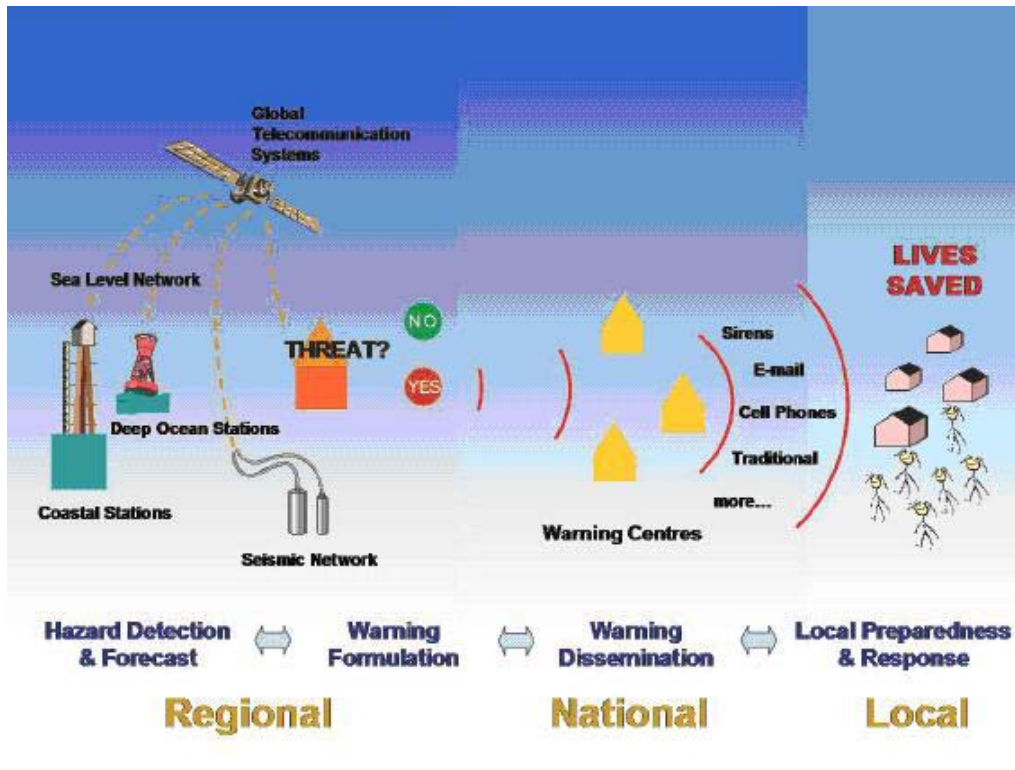


Figure 3. Components of an End-to-End Tsunami Warning and Mitigation System

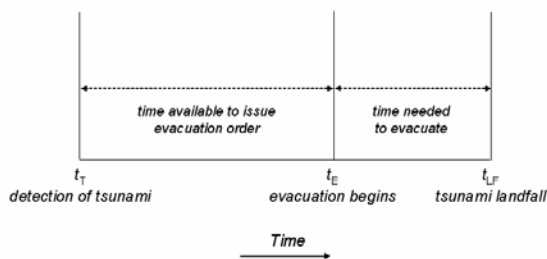
Earthquake detection is a mature science and if appropriate sensors are in place, a preliminary determination of magnitude and epicenter can be available fairly quickly. Not all oceanic earthquakes generate tsunamis, however. (There are also instances of tsunamis of non-earthquake origin caused by rapid debris slides or slope failures but they are not deemed significant for the purposes of this discussion). Another set of ocean-based sensors called tsunameters are used to determine the onset of a tsunami by measuring changes in ocean levels (as small as 1 centimeter in 6,000 meters of water) and the rate of propagation and direction of these changes. Once the presence of a tsunami has been verified, and the times and locations of its estimated landfall determined, this information can be transmitted digitally via satellites without human intervention based on pre-agreed upon decision criteria. This alone would be a vast improvement over the conditions that prevailed on December 26, 2004 when people (some absent) occupied some of the critical decision nodes shown in Figure 2. Although it cannot be stated with certainty that these conditions contributed to the loss of life, they certainly delayed communication of critical information.

Once national-level emergency centers have received an automated warning that a tsunami has formed and is likely to make landfall on their territory,

a decision must be made to notify potentially impacted areas of the impending threat and issue an evacuation order. The next step then, is to determine an appropriate threshold or cut-off point, such that a decision above the threshold would produce acceptable results within the limits or risk tolerance and one below it would not. Because no indicator is perfect, any “evacuate/don’t evacuate” decision will result in some decisions to evacuate deemed correct when they are not (false positives) and some decisions not to evacuate deemed correct when they are not (false negatives) [18]. For example, on November 17, 2003, the Deep-Ocean Assessment and Reporting of Tsunamis (DART) System in the Pacific Ocean detected a small tsunami generated by an earthquake near Adak, Alaska, but based on an assessment of data provided by DART buoys; no warning was issued for this event, which saved Hawaii an estimated \$68 million. This success story can be contrasted with an event of similar magnitude in 1986. At that time, predictions of the amplitude of tsunamis were difficult to make and evacuation of Hawaii’s coastal areas was ordered. The wave that eventually struck the coastline was less than a foot in height and caused no damage. However, the Hawaii Department of Business, Economic Development and Tourism estimated that the evacuation cost the state \$40 million in lost productivity and business [16]. This demonstrates that

sometimes the greatest benefit of a warning system is *knowing when not to evacuate*.

Although this stage of the system also could be automated, this is not viewed as likely. Even though intelligent software agents, expert systems, and other computer-driven decision tools have shown themselves the equal or superior to human judgment in many fields, as just noted, false positives can be extremely costly in monetary terms and false negatives in human lives. Coupled with the desire of most decision-makers to avoid these dramatic losses [12,19] they will often wish to personalize the apparent control of risk by postponing action while awaiting additional information. Although such risk control strategies have been discredited from the standpoint of decision theory [19], this desire to maintain personal control of the situation was observed during a meeting with senior emergency management personnel in Thailand following the December 2004 tsunami. An elaborate horizontal and vertical communication and approval sequence for issuing evacuation orders was described that, although all-inclusive, in the authors' judgment would dangerously slow the evacuation process. This is particularly critical in the case of tsunami evacuation because the time horizons are short and fixed. Figure 4 illustrates how the amount of time necessary to evacuate vulnerable areas is related to the issuance of an evacuation order and the impact of delays in issuing an evacuation order on people at risk. The difference between the time available to order an evacuation ( $t_E - t_T$ ) and the time necessary to move to safe areas ( $t_{LF} - t_E$ ) should be as large as possible. As the order to evacuate is postponed, the difference between ( $t_E - t_T$ ) and ( $t_{LF} - t_E$ ) approaches zero and the likelihood of survival decreases accordingly.



**Figure 4. Postponing evacuation can decrease the likelihood of survival**

Several factors noted during the authors' post-event investigation in Thailand in April 2005 bear directly on the final phase of the system. These factors were:

- 1) Many of those killed by the tsunami were at the beach at the time the wave struck and had little more than a few moments warning.

- 2) Maximum wave heights were generally on the order of  $\pm 10$  meters.
- 3) Although damage was extensive at some resorts, many buildings survived the tsunami with damage generally limited to the lower two floors. Someone on the third floor or above in a well-designed and constructed building or structure would have likely survived with minimal injuries.
- 4) Due to the shore topography along the coast of Thailand, one need not move a great distance inland to reach a place with sufficient elevation to provide reasonable refuge.

These observations suggest that the local phase of the system would be more effective if evacuation orders were targeted to vulnerable on-shore populations and escape routes for tourists, resort workers, and residents of seaside communities were designated beforehand. The benefits of early tsunami detection and warning would be further enhanced if engineered structures were available that could serve as loci for vertical evacuation. Vertical evacuation [20] assumes that buildings are constructed in such a way that they withstand tsunami waves, while affording shelter from the highest waves. Independent observers confirmed that many taller (more than three stories) resort buildings in Thailand constructed to modern standards withstood the tsunami waves very well [21]. In Thailand at least, had people on the beach known of the impending tsunami, many might have had time to ascend to a place of safety. The location and capacity of space that meets engineering criteria for vertical evacuation can be inventoried and monitored through with available GIS technology and managed within the domain of a virtual information center [17].

The infrastructure for issuing beach and coastal evacuation warnings could range from warning sirens and announcements, to television and radio preemption, auto text messages, and cellphone alerts, to an LED array embedded in a resort ID bracelet. The bracelet is particularly interesting because RFID or other sensor technology would enable it also to serve as a universal "smart card" for all resort activities so that a vacationer would not be liable to remove it while on-site. RFID tags also would help account for people during and after an event [22].

The Tsunami Warning and Mitigation System is just the initial step and once it is in place, the opportunities to link verified regional threats to rapid and effective individual actions on land must be exploited. As the technologies necessary to create an integrated detection, warning, and evacuation system continue to mature and evolve, capability and reliability will only improve while costs continue to decrease. However,

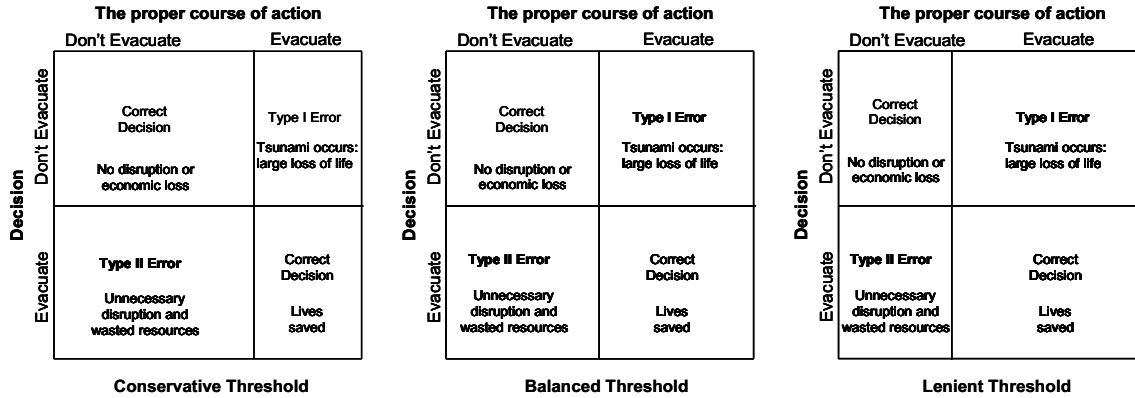


Figure 5. Balancing Risk by Varying Decision Thresholds for Evacuation Orders

technological capability must be matched with cognitive ability. Situation awareness (SA), defined as “the perception of the elements within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future” [23], offers promise in designing a system that would be effective under these conditions. Much of the research in the field has been aimed at decisions that must be made on the battlefield, aircraft cockpit, or process control center [24] but its basic principles offer promise if applied to the tsunami warning and evacuation problem. One potential issue that SA research has identified is that of information overload on the decision maker (in this case a vacationer or resort worker) [25]. The shore-based component of the system must be kept simple if it is to work effectively. This underscores the importance of the warning system being reinforced with orientation and familiarization for both indigenous peoples and transient tourist populations.

### 5. Establishing Decision Thresholds

A major challenge confronting decision-makers responsible for national-level emergency warning centers is establish appropriate thresholds that achieve an acceptable balance of false positives and false negatives (i.e., Type I and Type II errors). The set of decision tables presented in Figure 5 are very helpful for visualizing and evaluating alternative threshold levels. By splitting the diagram into quadrants, the occurrence of true and false positives and negatives that result from the threshold selection can be readily seen. By positioning the vertical bar to the left of center (the rightmost table), a "lenient" decision to evacuate can be shown to reduce the costs of unnecessary evacuations, but carries the accompanying risk of making a grossly wrong

decision if a tsunami actually occurs (false positives). On the other hand, by moving the vertical bar to the right, the threshold for the decision to evacuate is lowered or made more "conservative," (the leftmost table). In this case unnecessary costs will be incurred as more unwarranted evacuations are imposed (false negatives). Thus, this tradeoff between false positives and false negatives can be readily seen and balanced based on the risk tolerance of the decision-maker(s). The initial decision threshold might initially be set based on empirical evidence, negotiation among stakeholders, and expert opinion [8,26].

### 6. Testing the System

In actuality, the regime for deciding to evacuate will change over time as the frequency of the hazard, risk tolerance, and available resources vary. Public officials have traditionally been reluctant to order mass evacuations even in the face of extreme events because of uncertainty in the scientific basis for prediction which must be weighed against the known cost and disruption of a mass evacuation. Initially, the threshold could be expected to be fairly conservative and fall well to the right of center based on the often short period of time between the initiation of a tsunami and its landfall and the high human toll experienced during the Boxing Day tsunami. The evacuation threshold probably will shift to the left if another tsunami is not experienced within the next few years and communities become complacent as time passes and the memory of past events fades. The dynamics of this situation can be summarized as follows:

- Some indicator level is set for evacuation.
- Conflicts result from application (too costly vs. too risky).
- A constituency protests one position or the other.
- Policy makers respond to the pressure.

- When policy makers set a new threshold, the opposite conflict dominates the discussion.
- The opposing constituency protests.
- The threshold oscillates over time.

Whether or not (and how much) this threshold cycles will depend to a large degree on the number and severity of future events.

Although the decision tables in Figure 5 are useful for depicting the likely outcomes of potential tradeoff decisions made by emergency management officials and organizations, they do not embody any predictive capability regarding how the people actually confronted with an evacuation alarm might behave. Options for testing the performance of the complete warning and evacuation system include full-scale tests, empirical research on group behavior during past emergencies, and modeling and simulation. Full-scale tests range from routine school and office fire drills to fully orchestrated test evacuations of actual aircraft under simulated emergency conditions (e.g. darkness, imitation smoke). However, full-scale aircraft evacuation demonstrations are costly (>\$1 million), expose participants to significant risk of injury (approximately 6 percent of participants are injured), and simulate evacuation for only a narrow range of pre-specified conditions. Notably, the most potentially vulnerable passengers (children, persons with disabilities, and non-English speakers) are excluded from such exercises [27]. A tsunami evacuation drill organized and coordinated by the Civil Defence Secretariat Office of the Department of Disaster Prevention and Mitigation was conducted on Patong Beach in Phuket, Thailand on 29 April 2005 [28]. The objectives of the drill were to:

- Assess the readiness of all agencies working in collaboration to implement existing evacuation plans in the event of a tsunami incident occurring
- Test the operability and efficiency of the evacuation plan in place
- Generate preparedness and enhance confidence among officials concerned and the general public and familiarize all parties with the systematic evacuation procedure
- Ensure the safety of lives and property of the public and tourists in high risk areas

Although the drill was judged a success—the warning systems functioned, designated evacuation routes were utilized, etc., it is difficult to determine the degree to which reality was actually simulated by such an exercise and its value in terms of the cost of conducting it. While this type of drill may be useful for fostering team building and collaboration within organizations, the degree to which they actually model how people will respond to a real emergency is somewhat questionable. A simulation model of

improvisation in emergency management has recently been described [29] and could provide valuable insight into the functioning of these organizations under alternative scenarios.

Empirical research on behavior during actual emergencies is more representative of what happened during the event but data collection is time consuming and subject to interpretation. However, event-based research is useful to guide the development of policy and it can provide valuable data points to calibrate simulation models. There are numerous models available for simulating human behavior during aircraft, ship, and building evacuation [30,31]. Evacuation models are generally one of four types; (1) flow based, (2) cellular automata, (3) agent-based, and (4) activity-based. A shortcoming of flow-based and cellular automata models is that they lack social interaction features. These models simulate the movement of people as though they were “things” subject to pre-set rules of networked flow but do not include the individual and group reactions that have been repeatedly noted to occur during crisis situations. Agent-based modeling is well-established and well-suited to situations with many participants, whose behavior both adapts to, and influences, emerging conditions [32]. Agent-based evacuation models can help to reveal and understand the complex and aggregate system behaviors that emerge from the interactions of the various individuals involved. This characteristic makes it extremely difficult to predict system behavior, either deterministically or stochastically, and hence appears reasonable well-suited to the question of how people might perform *in extremis*.

Agent-based simulation focuses on individuals who interact on the basis of generally simple rules. The emergent behavior of these agents based on these interactions fuels a complex system which is the basic unit of analysis. The researcher may modify rules and environmental parameters and then try to understand what the resulting outcomes are with regard to the emergent behavior of the overall system. Social norms are another extremely powerful influence on how individuals will behave in a given situation and are critical input to the modeling process. It is these aspects of appropriately constructed agent-based models that make them so attractive for evacuation simulation. As long as the rules are known or can be discovered by some sort of observation, the modeling and testing of emergent behavior (including improvisation) is a relatively straightforward (if not always satisfactory) process.

It is a fundamental premise of this paper that better and more timely information about if, when, and how to evacuate an area based on the threat of an impending tsunami would exert a strong and positive

influence on individual survival. Axelrod notes that in behavioral simulation, what works well for one individual is more likely to be used again whereas what turns out poorly is more likely to be discarded. Applying this principle to the problem at hand would suggest that if certain alert and response behaviors produced higher survival rates, over time these behaviors would become the norm. The extent to which these behaviors would emerge, based on a range of individual characteristics, assumptions regarding the many social interactions involved, and other factors, are highly amenable to agent-based simulation. Care must be exercised, however, because as Axelrod points out, "Perhaps the most important lesson of the social influence model is that intuition is not a very good guide to predicting what even a very simple model will produce [33]."

## 7. Conclusions

This paper has highlighted some of the potential capabilities of an integrated tsunami detection, warning, and evacuation system. Overall, we possess the technology not only to detect emergent tsunamis but to warn people in sufficient time so that they can take appropriate actions to enhance their likelihood of survival. However, before the EMS is widely deployed, some roll-out preparation is suggested. A better understanding gained through agent-based simulations of how people might react to personalized hazard warnings received in real-time would be an enormous benefit. Similarly, a better understanding of how emergency management organizations interact, both internally and externally, to various levels and types of warnings is also amenable to agent-based modeling. Finally, the consequences of differing evacuation alert thresholds needs to be discussed within the nations and communities at risk so that consensus on decision points is reached *before* the next event. Some other questions and issues that need to be addressed concurrently include:

- What are the needs of shore-based communities and industries for actionable tsunami warning and evacuation information?
- What are the hardware and software system requirements to address the needs of shore-based communities and industries assuming existing, emergent, and potential technologies?
- What is the order-of-magnitude cost for system development and deployment? Who should pay for the system?
- What are the technical and institutional barriers to deployment and implementation of a cyber-based tsunami warning and evacuation system?

- Are there any knowledge or technology gaps in the critical path to deploying an effective system?

An integrated tsunami warning and evacuation system would greatly increase safety with minimal disruption to the normal course of tourism and other coastal industries. It would help restore confidence in the safety of beach-related tourism and reduce human losses from future tsunamis or other disasters in this region should one occur. The cyber-rich nations could collaborate to make a meaningful contribution to the physical well-being and economic stability of a region that is using tourism to benefit from its natural and cultural resources in a sustainable, non-consumptive manner.

## 8. Acknowledgement

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