EMERGENT TSUNAMI WARNING SYSTEM FOR PUERTO RICO AND THE VIRGIN ISLANDS [*]

CHRISTA G. VON HILLEBRANDT-ANDRADE

Puerto Rico Seismic Network, University of Puerto Rico, PO Box 9017 Mayagüez, PR 00681-9017, USA

VÍCTOR HUÉRFANO MORENO

Puerto Rico Seismic Network, University of Puerto Rico, PO Box 9017 Mayagüez, PR 00681-9017, USA

A tsunami warning system has been under development for the Puerto Rico/Virgin Islands (PRVI) region since 2000 as part of the Puerto Rico Tsunami Warning and Mitigation Program (PRTWMP). This system is in response to the historical tsunamis which have impacted Puerto Rico and the Virgin Islands and the potential for tsunamis to affect the region in the future. This emergent warning system has five thrust areas: definition of the tsunami scenarios, tsunami detection, tsunami protocol, communication, dissemination and education. The detection capabilities of the system are based on the detection of potentially tsunamigenic earthquakes by the Puerto Rico Seismic Network (PRSN) and the Pacific Tsunami Warning Center (PTWC). A protocol to respond to a potential tsunami has been developed. The messages would be broadcast through the Civil Emergency Alert System of the San Juan Field Office of the U. S. National Weather Service in coordination with the Puerto Rico Seismic Network and the Puerto Rico State Emergency Management Agency. Educational initiatives have been taken so that the threatened population is aware of the hazards and can respond effectively in case of a tsunami.

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1. Introduction

Historical records, paleotsunami studies, modeling and research efforts suggest that low lying coastal areas of the Puerto Rico and Virgin Islands region can be impacted by tsunamis. The main sources of tsunamis for the region are earthquakes and submarine landslides. The hazard associated with volcanic activity is low given the distance of the volcanoes.

Faults around the Puerto Rico region have the potential of generating local tsunamis. Historically there have been three earthquakes which generated destructive tsunamis in the northeastern Caribbean (Figure 1).

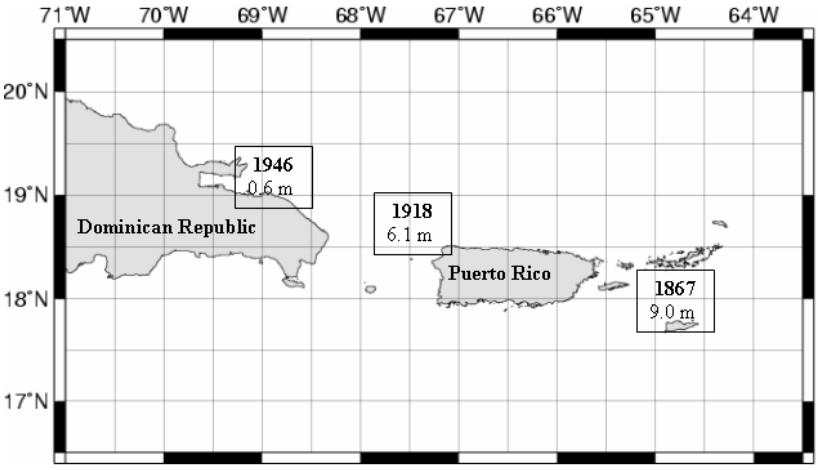

Figure1. Schematic location of the 1867, 1918 and 1946 earthquakes and the maximum runups recorded in the Virgin Islands (1918) and Puerto Rico (1918 and 1946).

The tsunami of November 18, 1867 was triggered by a Ms 7.3 (Pacheco and Sykes, 1992) earthquake in the Virgin Island Basin. Within 5 minutes waves of up to 6 meters in Charlotte Amalie, St. Thomas and 9.0 meters in Fredricksted, St. Croix were flooding low lying downtown areas. The tsunami had a runup of 6 m in southeastern Puerto Rico and almost 20 m in Guadeloupe (Lander et al, 2002). In the Virgin Islands 17 people died as a result of the tsunami, while 23 deaths were reported in Guadeloupe; no one was reported to have died in Puerto Rico as a result of the earthquake.

On October 11, 1918 a Ms 7.3 earthquake (Pacheco and Sykes, 1992) in the Mona Canyon, 40 km WNW of Aguadilla, Puerto Rico generated a tsunami. According to Reid and Taber (1919) the water was observed to have receded

within a minute of the earthquake itself along the north westernmost point of Puerto Rico. Wave heights of up to 6 meters were observed in western Puerto Rico where 40 people lost their lives and the greatest damage was observed.

Moya and Mercado (2004) documented 3 tsunami deposits in northwestern Puerto Rico, one of which corresponded to the 1918 event and the other 2 were dated at 1270-1410 AD and 820 – 400 BC. The source of these tsunami deposits is uncertain but reinforces the idea that tsunamis have been a recurrent phenomenon.

Besides these historical and prehistoric tsunamis in the PRVI, Huérfano (2003) and Mercado and Justiniano (2003) modeled 269 earthquake scenarios associated with faults in the region, determined the initial tsunami conditions and associated potential flooding. According to his results, the hazard is greatest in the western part of the island and then, then in order of decreasing exposure in the north, south and east coasts. These local tsunamis are characterized by very short travel times (can affect areas within a minute of the earthquake) and potentially high waves, 20 – 30 feet, close to the epicenter which decay quickly with distance.

Earthquakes of magnitude greater than 7.5 which occur beyond the Puerto Rico/Virgin Island region waters also have the potential of generating tsunamis which could reach Puerto Rico. On August 4, 1946 a Ms 7.6 (Pacheco and Sykes, 1992) earthquake along the north shore of eastern Dominican Republic triggered a tsunami. This tsunami, which caused much damage and fatalities in the Dominican Republic, was observed and recorded (0.6 m) in San Juan, Puerto Rico (Lander and Lockridge, 1989), but caused no damage in Puerto Rico. According to their catalogue, a strong aftershock of this earthquake on August 8 caused the sea to retreat 24 m at Aguadilla, 76 m at Mayagüez and was also recorded in San Juan (.6 m). Other sources for such large earthquakes and tsunamis could be the Lesser Antilles subduction zone, the faults located offshore of Venezuela and northern Colombia, on the Caribbean side of Central America and the North America – Caribbean plate boundary to the north. No modeling has been performed on these sources, but according to a tsunami travel time program developed by Gusiakov (2001) tsunamis generated beyond PRVI, but within the Caribbean could take from 30 minutes to four hours to reach the PR/VI platform.

The PRVI region can also be affected by distant tsunamis. These tsunamis travel more than 1000 km. On November 1, 1755 an earthquake with an estimated magnitude of 9 was generated offshore Portugal. This earthquake, which caused great destruction itself, generated a tsunami which impacted

Portugal, England and the coast of southern Europe and Africa. It reached the Lesser Antilles 7 – 8 hours later where waves of 7 meters were observed at Saba, 4.5 m at St. Martin and 3.6 m at Antigua and Dominica (Mader, 2001; Lander, Whiteside and Lockridge, 2002). There is no record that it affected Puerto Rico.

Another important source for a tsunami are submarine landslides. The deposits of submarine landslides have been mapped offshore Puerto Rico in the Puerto Rico Trench and the Mona Canyon (ten Brink, 2004). Mercado et al (2003) modeled the flooding that could have been caused by a landslide which was mapped in the Puerto Rico Trench. Although the lateral extension of these slides is less than those associated with earthquakes, the height of these waves can be substantially larger.

There are several active volcanoes in the eastern Caribbean. Gisler et al (2004) simulated catastrophic eruptions from the submarine volcanoe Kick 'em Jenny and concluded that it is unlikely to pose significant danger to Puerto Rico or the Virgin Islands. Others have studied the tsunami hazard associated with subaeral volcanoes, specifically with Soufriere Hills on Montserrat, both from partial collapse of the edifices as well as flows entering the surrounding waters. The results predict that the tsunami hazard associated with both of these phenomena is only significant for the surrounding and nearby islands.

Another source for tsunamis could be the impact of an object from space but, given the low frequency and probability of such events it is not taken into consideration for tsunami warning purposes.

2. Puerto Rico and Virgin Islands Tsunami Warning System

Since 2000 the Puerto Rico and Virgin Islands Tsunami Warning System (PRVITWS) has focused on tsunamis which can be originated from earthquakes. Other scenarios have not been given priority because of the difficulty of detection (landslide generation), low hazard (volcanic eruptions) and low probability (impact from outer space). Up to the present the system has focused on the detection and location of tsunamigenic earthquakes, tsunami protocol, dissemination and response.

2.1. *Tsunami Scenarios*

There are three types of earthquake tsunami scenarios: local tsunamis, regional tsunamis and distant tsunamis.

2.1.1. *Local Tsunamis*

Curtis and Pelinovsky (1999) defined local tsunamis as those that have up 24 minutes of travel time. These tsunamis could be generated by a local earthquake within the PRVI. The PRVI is defined as the region between latitudes 17^{o} and 20 ^{o} N and longitudes 63.5^{o} and 69 ^{o} W. The 1867 and 1918 earthquakes are examples of historical local tsunamis.

2.1.2. *Regional Tsunamis*

Regional tsunamis are considered as those that would take between 24 minutes and 2 hours. For Puerto Rico and the Virgin Islands earthquakes generated within the Caribbean or just beyond the Caribbean and North America/South America plate boundary. A historical example of such a tsunami was the one generated by the August 4, 1946 earthquake.

2.1.3. *Distant tsunamis*

Distant tsunamis are those that would have travel times of over two hours to Puerto Rico and the Virgin Islands. For the PRVITWS, the source of these tsunamis would be in the Atlantic Ocean and Western Caribbean. The 1755 Lisbon earthquake generated such a tsunami.

2.2. *Detection and Location of Tsunamigenic Earthquakes*

The Puerto Rico Seismic Network (PRSN) was established by the USGS for the Puerto Rico Electrical Power Authority in 1974. In 1987 this short period network was transferred to the Geology Departmentt. of the University of Puerto Rico at Mayagüez. It presently consists of almost 30 seismic stations installed from Mona Island to the west thorough Anegada Island in the British Virgin Islands to the east (Figure 2). The PRSN consists of short and broad band stations, data of which are routinely analyzed. Strong motion data of the Puerto Rico Strong Motion Program of the University of Puerto Rico at Mayagüez are also available in the case of larger earthquakes.

In January 2003 the automatic earthquake processing system developed by the West Coast and Alaska Tsunami Warning Center (ATWC), known as Early Bird (EB), was installed in the PRSN. In Puerto Rico, this system has been tailored to detect and locate earthquakes in the Puerto Rico, Intra America Seas and the Atlantic Ocean. It monitors the data stream of the stations operated by the PRSN, the “Instituto Sismológico Universitario” (ISU) of the Autonomous University of Santo Domingo (UASD) and the “Pontificia Universidad Católica

Madre y Maestra" in the Dominican Republic as well as 17 stations of the Global Seismographic Network in the mid latitudes of the western hemisphere that are available in real time via the Internet (Figure 2).

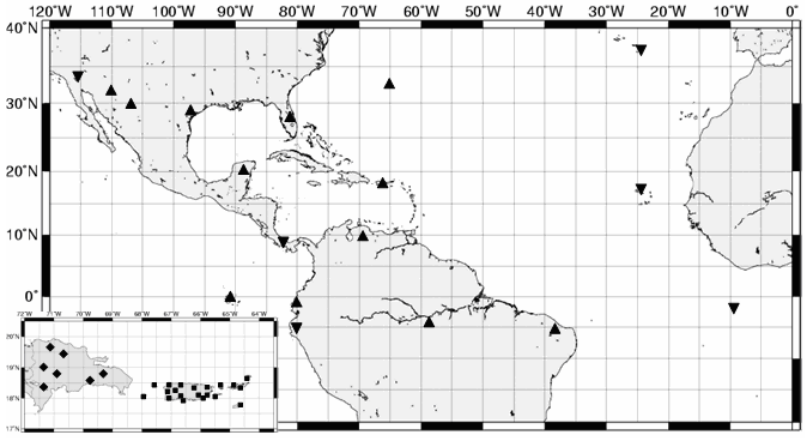

Figure 2. Seismic stations used by the Early Bird System running in the Puerto Rico Seismic Network for the detection of potentially tsunamigenic earthquakes. The insert corresponds to stations of the Puerto Rico Seismic Network (squares) and the "Instituto Sismológico Universitario" (ISU) of the Autonomous University of Santo Domingo (UASD) in the Dominican Republic. Stations of the IRIS/IDA (inverted triangles) and IRIS/USGS (triangles) networks are also used.

Between February 2004, when a significant number of global stations in the Mid Atlantic region were added to the system, and September 2004, EB detected and located 292 earthquakes. Of these events, 115 were located in the Puerto Rico region (17 – 20 N and 63.5 – 69 W), their magnitudes ranged from 2.1 to 5.3. The other events corresponded to regional and distant earthquakes, many from the Pacific Ocean. Although it is still in trial stage, for most local and regional events, Early Bird has been providing, in general, faster solutions than those available from the National Earthquake Information Center (NEIC), the Pacific Tsunami Warning Center (PTWC) and the West Coast and Alaska Tsunami Warning Center (WCATWC). The information has also been just as accurate, for tsunami warning purposes, in terms of location and magnitude. As an example of the timeliness and accuracy of the locations and magnitudes of the events located by the EB system at PRSN, Table 1 compares the location of a major earthquake which occurred November 15, 2004 offshore western Colombia.

Source	Lat.	Long.	Depth (km)	Magnitude	Time (UTC) Solution Received at PRSN
INGEOMINAS (National Seismic Network of Colombia	4.8 N	77.8 W	< 30 km	6.7	Accessed through INGEOMINAS Home page 12:00
EB-PRSN (first solution)	5.1 N	78.25 W	40	7.5	09:13
PTWC	4.8 N	77.4 W		7.2	09:20
WCATWC	4.8 N	78.25 W		7.2	09:22
EB (last solution)	5.11 N	78.25 W	40	6.9 MS	09:37
USGS/NEIC	4.61 N	77.54 W	10	7.0	10:11

Table 1. Comparison of the location, magnitudes and timeliness of the solution of a 7.0 magnitude earthquake which occurred at 9:06 UTC on November 15, 2004 off western Columbia.

Once Early Bird detects an event the information is distributed automatically over the Internet. Outside working hours, the personnel of the PRSN receive the information on pagers and cell phones. The PRSN presently only distributes earthquake information which has been reviewed by an analyst. As more confidence in the system is acquired, the automatic information could also be distributed to first responders and the NWS.

2.3. *Tsunami Protocol*

There are several earthquake and tsunami warning centers, emergency management agencies and weather offices that could be involved in the case of a significant earthquake or tsunami (Figure 4). For Puerto Rico the four lead agencies are: PRSN, the Puerto Rico State Emergency Management and Disaster Administration Agency (PRSEMA), the National Weather Service Weather Forecasting Office in San Juan and the Pacific Tsunami Warning

Center (PTWC). The PRSN would also be in contact with the U. S. Virgin Islands Territorial Emergency Management Agency (VITEMA) and the Department of Disaster Management of the British Virgin Islands (DDM). The National Earthquake Information Center (NEIC) of the USGS could also provide critical earthquake information. For regional and distant earthquakes other regional and international seismic networks and centers and emergency management agencies could be contacted in case of a significant earthquake or tsunami.

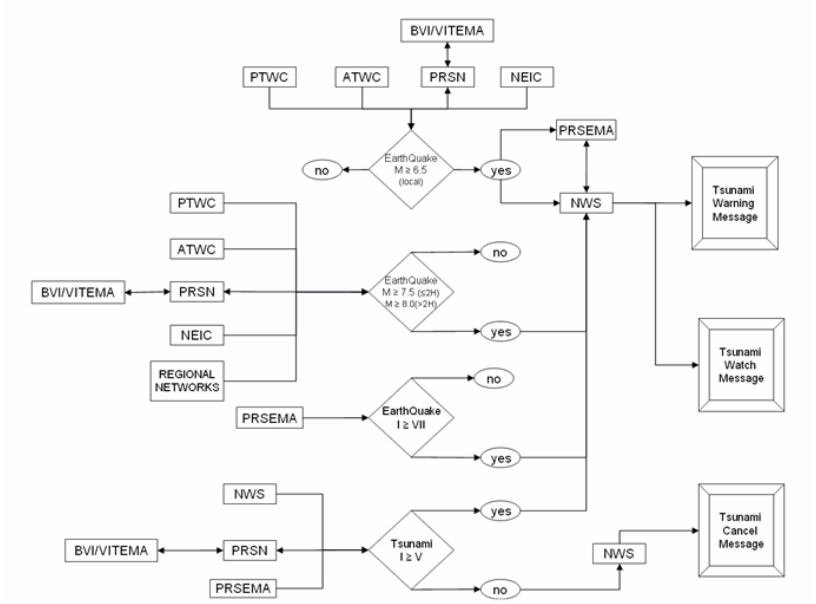

Figure 3. Flow chart of Puerto Rico and Virgin Islands Tsunami Warning System. The Puerto Rico Seismic Network will coordinate information with the British Virgin Islands Department of Disaster Management.

At the moment only PRSEMA, NWS and PTWC are manned 24 hours, 7 days a week. The established protocol has taken this into consideration.

The PRSN which is the authoritative source for earthquake information for the PRVI may take between 5 minutes (during working hours) and 2 hours (outside working hours) to respond with reviewed locations. The PTWC could provide information of earthquakes greater than 6.5 to PRSN and NWS within 20 minutes. The response time for NEIC is usually 20 minutes or more. The

protocol includes 4 different messages: felt earthquake, tsunami warning, tsunami watch and "all clear". At the moment the criteria that are used to issue the messages are earthquake magnitude and location, earthquake intensity and/or reliable reports. The criteria of intensity is very important for local earthquakes given that the tsunami can reach the shores of the region within a minute of the earthquake and the time taken to get parametric information (magnitude, location, including depth) can take much longer. At present there are no sea level data that can be used for tsunami purposes in Puerto Rico.

Felt earthquake messages are issued for all felt events which meet one or more of the following criteria and for which there is no potential for a tsunami:

1. Magnitude of less than 6.5 in the PRVI/local region, 7.5 in the region or 8.0 at greater distances.
2. Earthquakes with a focal depth greater than 60 kilometers.
3. The earthquake is generated under land.
4. The event is felt with a intensity less than VII

Between 1994 and 2004 the PRSN released between 4 and 20 felt earthquake messages a year.

A **tsunami warning** would call for an evacuation of all the low lying coastal areas vulnerable to tsunamis. The PRSN will recommend a tsunami warning if there was the possibility that a tsunami could affect the Puerto Rico and Virgin Islands within 2 hours. For this, one or more of the following conditions would have to be met:

1. An earthquake of intensity VII or greater is felt in Puerto Rico or the Virgin Islands.
2. An earthquake of magnitude 6.5 or greater and shallower than 60 km is detected by the PRSN or the PTWC offshore in the PRVI. A threshold of 6.5 is used because of the potential for seismically induced submarine landslides.
3. An earthquake of 7.5 or greater is detected by the PRSN or PTWC beyond the PRVI region, but within a two hour travel time as calculated with the Tsunami Travel Time program of Gusiakov (2000). In the Caribbean Sea, this corresponds to all regions roughly East of Longitude 80^{o} W and in the Atlantic Ocean between Longitudes 35 ^{o} and 75 ^{o} W and Latitudes 10 ^{o} and 35 ^{o} N (Figure 4). This area corresponds roughly to southern Cuba, Jamaica, Haiti, Dominican Republic, the Lesser Antilles and northern Venezuela.
4. Reliable reports were received that a tsunami has been observed locally, in the Eastern Caribbean or the western mid Atlantic Ocean as defined in 3.

It is important to point out that according to catalogues available through USGS (http://neic.usgs.gov) between 1900 and present, only 8 earthquakes met

these criteria in 1900 (2), 1906, 1918, 1943, 1946 (2) and 1974. Of these 8 earthquakes, 1 (1918) generated a destructive tsunami in the PRVI and 2 (both in 1946) generated tsunamis which were detected, but caused no damage in the region. Therefore, there is the possibility that warnings could be issued and no tsunami be generated, but we feel the level is acceptable. If local and regional sea level monitoring data existed and were incorporated into the system, unnecessary evacuations could be reduced. A **tsunami watch** would instruct the population to make preparations for a possible evacuation because of a potential tsunami. The PRSN will recommend a Tsunami Watch under the following conditions:

1. An earthquake of magnitude 8.0 or greater at a depth shallower than 60 km is generated in the Caribbean Sea roughly west of Longitude 80^{o} W, in the Gulf of Mexico or in the Atlantic Ocean beyond the longitudes 35^{o} and 75^{o} W and Latitudes 10^{o} and 35^{o} N.
2. Reliable reports are received that a tsunami has been observed which has the potential of reaching the Caribbean.

Between 1900 and the present there were only four earthquakes that met these criteria in 1929 (Sandwich Islands) and 1941, 1969 and 1975 (Azores Fracture Zone).

A **cancellation, "all clear"** of the tsunami watch or warning would indicate that the region is no longer at imminent risk from a tsunami. The PRSN would recommend a cancellation under the following conditions:

1. The PRSN determines that the conditions to issue the warning or watch were not met.
2. Within an hour of the conditions being met no reports are received that a tsunami has been generated.
3. The behavior of the sea has returned to normal levels according to reliable reports.

2.4. *Commuunication and Dissemination*

There are several levels of communications for the system to be effective, between the key responders and then to the general public. At the petition of PRSEMA and/or upon the recommendation of the PRSN, the NWS/WFO in San Juan would activate the Emergency Alert System (EAS) issuing a Civil Emergency Message with tsunami information (felt earthquake, warning, watch and all clear/cancellation). These messages would be broadcast in English and Spanish over the radio and TV stations as well as through the NOAA weather radio. The NWS has developed a protocol to respond to the earthquake and tsunami scenarios. The NWS can also issue information messages based on intensity of the felt earthquake or other information it may receive from reliable

sources, but will not issue a tsunami warning or watch unless the PRSEMA or PRSN requests them to do so. The NWS/WFO would only issues messages for Puerto Rico and the US Virgin Islands.

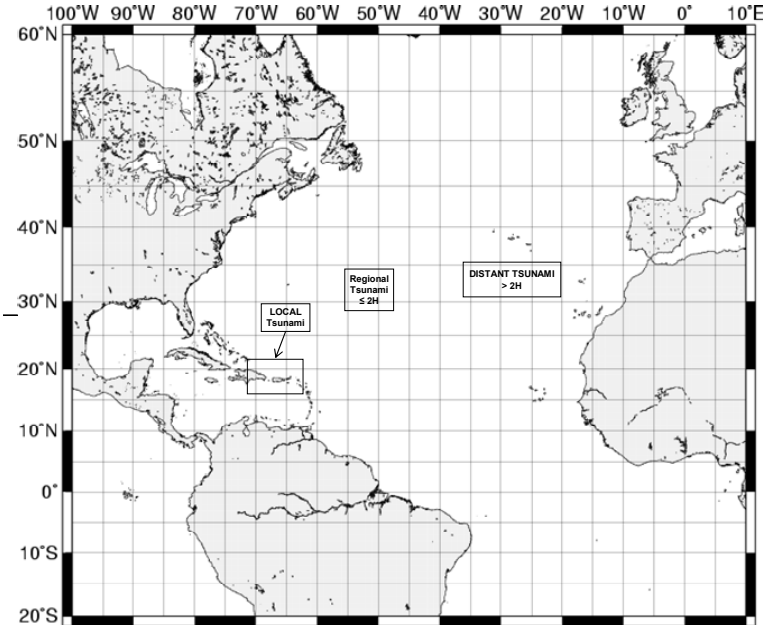

Figure 4. Schematic of areas for which tsunami warnings (Local or regional, less than 2 hours) or watches (distant, greater than 2 hours) would be issued.

In case of emergencies the main means of communication between the PRSN and the other agencies (PRSEMA, NWS, PTWC, VITEMA and DDM) is voice commercial land and cellular telephones. There is a PRSEMA radio base station at the PRSN which is also used for communication between the two agencies. FAX and Internet are also used between the agencies to share information, as well as with the media and other responders.

At present the only way to massively disseminate the information is through the EAS of the NWS. There are no alarms or sirens installed in any of the coastal communities at risk.

2.5 Education

To be able to seek an appropriate response of the public it is necessary that all those potentially at risk are conscious of the tsunami threat and know how to respond in the event of a tsunami emergency.. State, regional and local emergency management officials and the general population have been oriented to:

1. Review the tsunami inundation maps that have been prepared for Puerto Rico to become familiar with the extent of the potential flooding.
2. Learn to recognize the natural signs of an impending tsunami emergency.
    a. An earthquake of intensity VII or greater
    b. Water along the coast sea recedes or advances in an uncharacteristic fashion.

    Under either of these circumstance people should immediately move inland, towards higher ground or up a building or object.
3. Evacuate or prepare to evacuate if a tsunami warning or watch is issued.

To reach the public, the following initiatives have been carried out by the Puerto Rico Tsunami Warning and Mitigation Program.

1. Production and distribution of the documentary “Tsunami in Puerto Rico: The Forgotten Danger”. As of 2005 this video is available in VHS and DVD format, in both English and Spanish with subtitles and sign language.
2. 250 tsunami warning signs were prepared and installed throughout much of Puerto Rico’s coasts.
3. The website http://poseidon.uprm.edu is continuously updated.
4. Workshops have been held for emergency response personnel for tsunami issues
5. Four tsunami evacuation exercises have been held in schools located in tsunami flood zones. Personnel from other schools and emergency management agencies have participated so that they can carry out other drills.
6. Preparation and distribution of a tsunami fact sheet.
7. Newspapers, TV and radio stations have covered tsunamis.

In 2004 the Puerto Rico Tsunami Technical Review Committee was established to review and advise on tsunami issues. Representatives of 15 private and public institutions meet regularly to discuss the program and the protocol which has been developed for the region.

3. Conclusions and Recommendations

Since 2000 Puerto Rico has been developing a tsunami warning system that responds to the tsunami hazard in the Puerto Rico and Virgin Islands region. It is very important that the research, monitoring, protocols, communication, dissemination and education initiatives be strengthened. The priorities for the development of the system include: the establishment of a 24 X 7 operation to monitor earthquakes, the establishment of a network of tsunami ready tide gauges throughout Puerto Rico, the installation of the Tsunami (DART) buoys developed by NOAA to detect regional and distant tsunamis, strengthen the communication systems between the lead agencies and continue to educate the public on this phenomena. The possibility of extending these operations to other parts of the Caribbean has also been contemplated.

Acknowledgments

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NOTE: In the aftermath of the Tsunami of December 26, 2004 significant new resources are expected to be made available to consolidate the tsunami warning system for Puerto Rico and the Virgin Islands and the Caribbean in general.

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