



Advances in tsunami preparedness at the beginning of the Ocean Decade: the Costa Rica case

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ABSTRACT

Following the 2004 Indian Ocean and the 2011 Tohoku earthquakes and tsunamis, there has been steady progress in tsunami science and preparedness worldwide. Currently, there are four Tsunami Warning and Mitigation Systems as Intergovernmental Coordination Groups (ICGs) coordinated by IOC/UNESCO. They include tsunami monitoring, warning, and response. They are mostly based on scientific knowledge including tsunami hazard assessments, 24/7 monitoring systems, agreed operational standard procedures (SOPs), redundant communication and community response mechanisms. Costa Rica has greatly increased its tsunami preparedness during the past six years, after the creation of SINAMOT (Sistema Nacional de Monitoreo de Tsunamis). SINAMOT works by characterizing the tsunami threat, encouraging, and supporting community preparedness, strengthening the existing tsunami warning SOPs and maintaining the sea level monitoring network. SINAMOT articulates with stakeholders and decision makers such as seismic monitoring networks, national and local government, emergency managers and committees. Four communities in Costa Rica have been recognized as Tsunami Ready by IOC/UNESCO, four more are recognized with pending guidelines and five more are working on fulfilling the requirements. Despite all the progress made, there is still plenty of work to do to have a safe and predictable ocean regarding tsunamis. Atypical tsunami sources are not yet incorporated in hazard assessments, there are many gaps in sea level monitoring, and capacity building is required in many aspects so that developing countries can be more autonomous in their tsunami preparedness and response. Our major challenges today worldwide are with staffing and funding, both to kick-off and to sustain the mentioned activities. Specifically, Costa Rica requires more physical oceanographers and geoscientists working on tsunami science and more funding to study the ocean (including sea level gauges and tsunami hazards assessment) to support the tsunami and other coastal hazard warning systems. This requires working together with communities and stakeholders to increase tsunami preparedness.

Descriptors: Tsunami warning and mitigation systems, Tsunami ready, UN Ocean Decade, Tsunami monitoring, Tsunami preparedness.

INTRODUCTION

Tsunamis are an infrequent threat, capable of killing hundreds of thousands of people within hours,

crossing political boundaries. The first account of a confirmed tsunami in human history is from 1610 B.C. when the caldera collapse of volcano Santorini caused a tsunami affecting Crete, Cyprus and the eastern Mediterranean (NOAA/NCEI, 2021).

Tsunami preparedness was done mostly at local levels until the 1946 Alaska and the 1960 Chilean tsunamis demonstrated the need for an international

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tsunami warning and mitigation system for the Pacific Ocean. In the wake of the XXI century, the 2004 Indian Ocean tsunami demonstrated these systems are also necessary for other basins, as tsunamis are a worldwide threat, and three more tsunami warning and mitigation systems were created (IOC/UNESCO, 2008). Then, countries outside the Pacific basin started an intense tsunami preparedness process. Almost 15 years later, the 2018 Palu (Indonesia) tsunami highlighted the importance of self-evacuation and that preparedness and mitigation should be done according to the specific threat for each coastal location (UNESCO/IOC, 2019). Together with the 2018 Anak Krakatoa tsunami, they exposed the need to account for atypical tsunami sources (IOC/UNESCO, 2019b).

Costa Rica has records of 40 tsunamis since 1746, including the recent Kermadec Island tsunami in

March 2021. The impact of those tsunamis has been moderate as only one of them caused deaths (Figure 1) and only a few caused flooding, with a maximum runup of about 7 m (Chacón-Barrantes, Murillo-Gutiérrez and Rivera-Cerdas, 2021). Nevertheless, our written history is relatively short, and our coasts have been traditionally sparsely populated (Thiel y Hoffmann, 2011), meaning larger tsunamis might have impacted us long before the XVIII century.

Tsunami warning and mitigation systems and tsunami preparedness are permanent tasks, always needing to improve and adapt. In this manuscript, we present their components and the advances on the subject in Costa Rica during the past seven years. Also, we include the gaps and challenges in tsunami preparedness worldwide, particularly for less developed countries like Costa Rica.

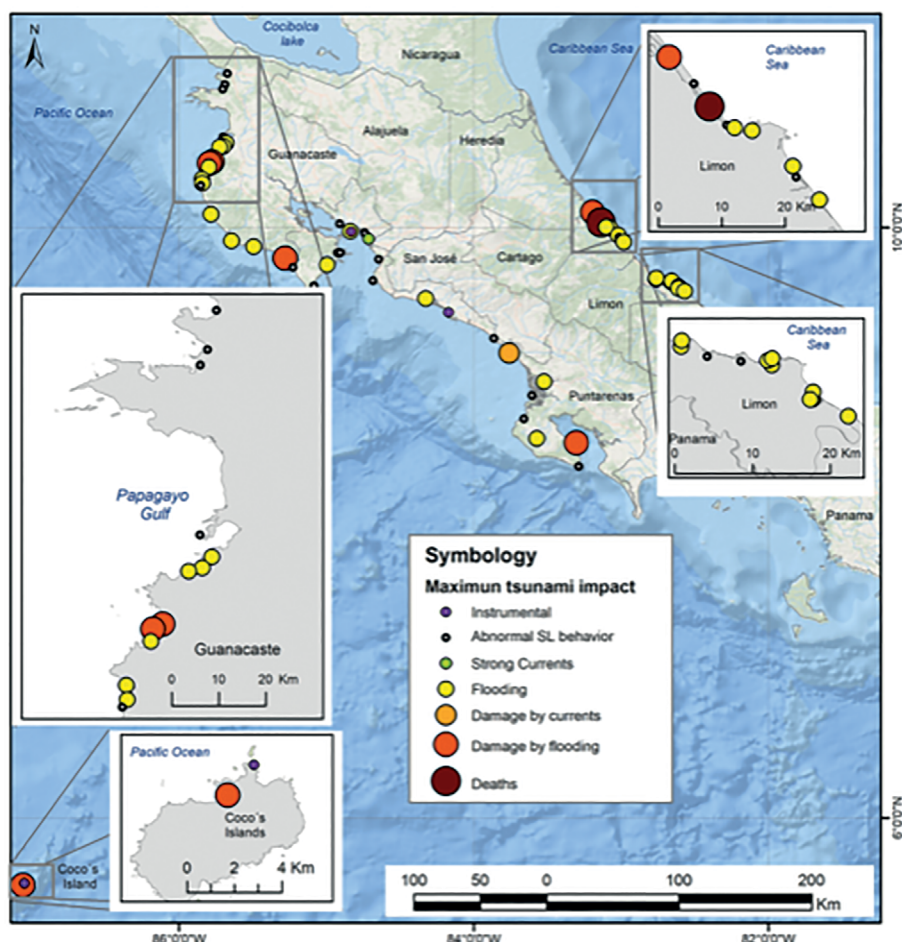


Figure 1. Map of maximum tsunami impact for Costa Rica from 1746 to 2021. Adapted from Chacón-Barrantes et al. (2021).

TSUNAMI WARNING AND MITIGATION SYSTEMS

Currently, there are four Intergovernmental Coordination Groups (ICG) for Tsunami Warning and Mitigation Systems, which are subsidiary bodies of IOC/UNESCO. The first one to be established was the ICG for the Pacific Tsunami Warning System (ICG/PTWS) in 1968. After the 2004 Indian Ocean tsunami, three more ICGs were established in 2005: the ICG for the Tsunami and Other Coastal Hazards Warning System for the Caribbean and Adjacent Regions (ICG/CARIBE-EWS), the ICG for the Indian Ocean Tsunami Warning and Mitigation System (ICG/IOTWMS) and the ICG for the Tsunami Early Warning and Mitigation System in the North-Eastern Atlantic, the Mediterranean and connected seas (ICG/NEAMTWS) (IOC/UNESCO, 2008). Costa Rica belongs to both ICG/PTWS and ICG/CARIBE-EWS since they were established, but had not participated actively in either of them until 2014.

A Working Group on Tsunamis and Other Hazards Related to Sea-Level Warning and Mitigation Systems (TOWS-WG) contributes to maintain a harmonized development of standards and guidelines throughout all four ICGs. TOWS-WG main task is therefore to advise the IOC Governing Bodies on coordinated development and implementation of tsunami warning and mitigation activities (IOC/UNESCO, 2008). TOWS-WG meets annually as well as the ICG/CARIBE-EWS and the ICG/NEAMTWS; the ICG/PTWS and the ICG/IOTWMS meet every two years.

Tsunami Warning and Mitigation Systems end-to-end require monitoring, warning, and response (Figure 2). Regional collaboration is required for all stages, particularly for monitoring and warning. The stages of Tsunami Warning and Mitigation Systems will be discussed in the following subsections.

MONITORING

Seismic stations and sea level gauges should have sufficient coverage to ensure proper earthquake and tsunami detection (IOC/UNESCO, 2016). Seismic stations include GNSS, which might also be used by Tsunami Warning Centers as sea level gauges in the future, depending on location (Kim and Park, 2019). Sea level gauges include tidal gauges, located in the coast (Figure 3), and deep-ocean buoys like DART-buoys, capable of registering a tsunami signal in the deep ocean (Comfort *et al.*, 2012; An and Liu, 2014).

Tsunamis are mostly caused by subduction earthquakes (IOC/UNESCO, 2019a; NOAA/NCEI, 2021). Thus, tsunami warning systems currently depend on seismic sensors to activate. Sea level sensors are employed to confirm whether a tsunami has been generated and how big the tsunami is. Non-subduction earthquakes usually do not cause large tsunamis, but there have been some exceptions (Legg, Borrero and Synolakis, 2003; Heidarzadeh, Muhari and Wijanarto, 2019). Having a proper sea level network is particularly important to update tsunami warnings in those cases.

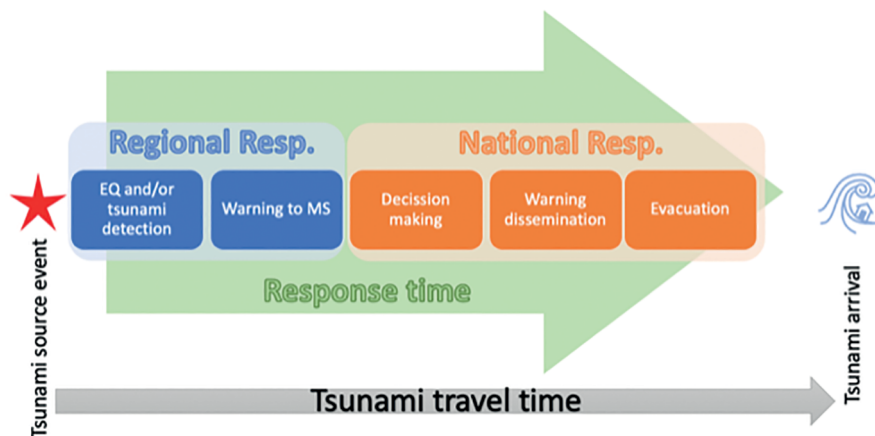


Figure 2. Tsunami Warning System end-to-end. Blue actions are regional responsibility and orange actions are national responsibility. The star marks the occurrence of the tsunami source event. The goal of the Tsunami Warning Systems is the response time to be much less than the tsunami travel time.

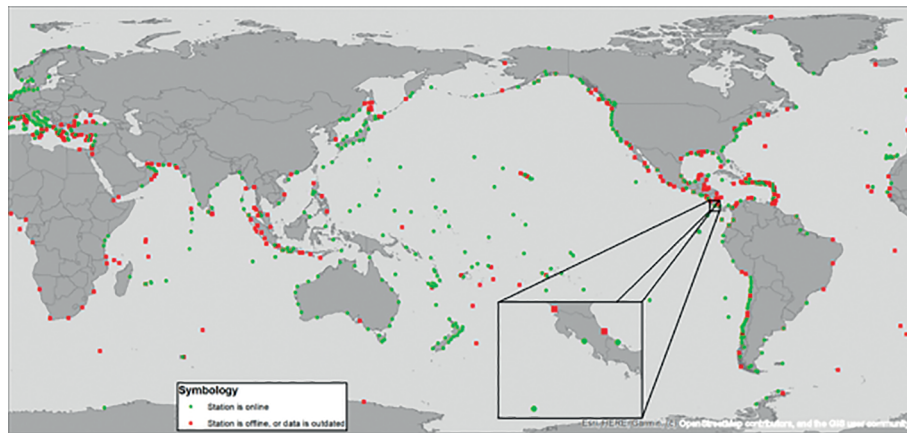


Figure 3. Sea Level stations worldwide contributing to the IOC Sea Level Facility. Stations in green are online and stations in red are offline or their data is outdated.

Tsunamis can also have non-seismic sources such as volcanic eruptions, subaerial or submarine landslides, or abrupt atmospheric pressure changes. Recent examples are the 2018 Anak Krakatoa tsunami in Indonesia and the 2017 Santa Marta tsunami in Colombia, caused by a volcano eruption and a submarine landslide, respectively. In both cases, no tsunami warning was generated for two reasons: they were not detected by sea level stations before impact and currently there are no protocols to monitor sea level gauges to detect tsunamis from non-seismic sources, either at regional or national levels, due to the absence of proper capacity.

Member States are responsible for both seismic and sea level stations within their territories and are encouraged to share their data in real time. In Costa Rica there are three seismic networks contributing to tsunami warning systems with dozens of stations: OVSICORI-UNA, RSN-UCR and LIS-UCR. There are only three tide gauges in Costa Rica managed by SINAMOT-UNA: two on the mainland: Quepos in the Pacific and Limón in the Caribbean, and one at Coco's Island, which is located about 550km southwest from the mainland in the Pacific Ocean. For these three tidal gauges, Costa Rica has support for maintenance and data quality control from the University of Hawaii Sea Level Center (UHSLC), with sponsorship from the United States National Oceanographic and Atmospheric Administration (NOAA).

Sea level monitoring gaps are a major handicap for tsunami warning worldwide (Figure 3). These gaps require more than funding to deploy all the

gauges required. Sea level gauges require trained staff to perform constant maintenance and data quality control. This can be a challenge for small island developing states (SIDS) and developing countries that have long coastlines to monitor, such as Costa Rica. Costa Rica requires more tidal gauges on both Pacific and Caribbean shores to better monitor and characterize the coastal response to tsunamis. However, SINAMOT does not have enough staff or funding to expand the sea level network. Moreover, without the support of NOAA and UHSLC, the organization probably would not be able to properly maintain the existing gauges.

Besides tsunami detection, records of tsunamis on sea level gauges or marigrams can be employed for numerical model verification. In Costa Rica, the Quepos tidal gauge has registered 17 tsunamis since its deployment in 1957. A tide gauge that operated in Puntarenas from 1941 to 1979 registered 10 tsunamis within those dates. The tide gauge at Coco's Island has registered one tsunami so far: the 2021 Kermadec Islands tsunami. Most of those tsunami records have already been used for numerical modeling verification (Chacón-Barrantes and Gutiérrez-Echeverría, 2017; Chacón-Barrantes, 2018). On the other hand, the tidal gauge deployed at Limon in 1940 has not registered tsunamis so far, it could potentially have registered the 1991 tsunami that originated nearby; however, it had been uninstalled by port authorities days before the earthquake without informing the scientific team in charge (A. Gutiérrez, pers. comm.).

WARNING

Currently, IOC/UNESCO defines a Tsunami Service Provider (TSP) as a

“Centre that monitors seismic and sea level activity and issues timely tsunami threat information within an ICG framework to National Tsunami Warning Centres/Tsunami Warning Focal Points and other TSPs operating within an ocean basin. The NTWCs/TWFPs may use these products to develop and issue tsunami warning for their countries. TSPs may also issue Public messages for an ocean basin and act as National Tsunami Warning Centres providing tsunami warnings for their own countries” (IOC/UNESCO, 2019a).

The United States hosts the Pacific Tsunami Warning Center (PTWC) that perform as TSP for the ICG/PTWS and the ICG/CARIBE-EWS. The PTWC was established in Hawaii in 1949, following the 1946 Aleutian Islands tsunami to alert Pacific countries every time a tsunami was generated and minimize the impact on distant shores. For both ICGs, a sub-regional TSP for Central America is in trial mode: the Central America Tsunami Advisory Center (CATAC), based in Nicaragua. Other TSPs for the ICG/PTWS are hosted by China (South China Sea Tsunami Advisory center) and Japan (North West Pacific Tsunami Advisory Center)

IOC/UNESCO requires that each Member State nominates their National Tsunami Warning Center (NTWC) to receive tsunami alerts from TSPs. NTWC is defined as “A center officially designated by the government to monitor and issue tsunami warnings and other related statements within their country according to established national Standard Operating Procedures” (IOC/UNESCO, 2019a).

In Costa Rica, SINAMOT was created in 2014 as an Activity at the National University (UNA), to analyze all potential tsunami events in both the Pacific and the Atlantic basins and advice the National Emergency Commission (CNE). In 2015, SINAMOT was nominated by the Costa Rican government to be NTWC for Costa Rica. SINAMOT first belonged to the RONMAC Program, which was created in the 1980s to manage the sea level network of Costa Rica. Over the years, SINAMOT merged with RONMAC and expanded its goals to increase tsunami preparedness in Costa Rica through six lines of work:

- Tsunami inundation and evacuation maps
- Tsunami capacity building
- Tsunami research
- Tsunami exercises
- Tsunami warning
- Sea level network

Currently, SINAMOT staff includes one physical oceanographer and two geographers, the latter two working part time.

RESPONSE

In most cases, once a tsunami evacuation order is issued, there is little time to evacuate. Furthermore, if the tsunami was generated locally, the waves can arrive within minutes. Therefore, the public must be prepared to respond fast and properly.

Tsunami preparedness should be based on historical and scientific knowledge and includes:

- Characterization of the tsunami threat
- Definition of possible tsunami inundation areas and proper signage
- Tsunami evacuation maps for people to know where to go and how
- Tsunami evacuation plans and protocols that ensure timely warning reception, warning dissemination and response
- People to know these maps, plans and protocols in advance and exercise them, so they can react fast and properly.

All these aspects and their status in Costa Rica are discussed in the following sections.

TSUNAMI THREAT ASSESSMENTS

Local tsunami potential varies for different regions within the same basin, including variations in tsunami heights and arrival times. Also, each coastal location interacts different with local and distant tsunamis based on its geomorphology. Tsunami threat characterization is essential for tsunami preparedness, as people and stakeholders need to know how large the expected inundation area is and how fast they need to evacuate.

Tsunami threat assessments should include all possible tsunami sources, including non-seismic sources. Additionally, high-resolution bathymetry is required to perform numerical modeling of tsunami inundation, assessing the physical response of the

coast to tsunamis. Also, high-resolution bathymetry might be needed to search for submarine landslides that might have caused tsunamis in the past.

SINAMOT performed the first approach for tsunami hazard assessments from seismic sources. We propagated 57 distant and local tsunamis in the Pacific Ocean and aggregated them to obtain maximum tsunami heights nearshore, at 20 m depth. It was not possible to perform tsunami inundation modeling along most of the coastline due to the lack of high-resolution coastal bathymetry. A similar first approach of tsunami threat assessment from seismic sources is in progress for the Caribbean coast with the same goal. These assessments are part of a project to develop tsunami evacuation maps for both shores. In the Pacific, the modeling results obtained nearshore were used to create a tsunami risk index and choose the communities to map. A similar approach will be employed in the Caribbean.

Tsunami inundation modeling was performed at nine locations along the Pacific coast for which high-resolution coastal bathymetry existed or was surveyed. For these nine locations the tsunami inundation area was defined through modeling. For the rest of the Pacific coast, we defined a tsunami inundation area based in fixed height estimated from the tsunami propagation modeling results nearshore.

These threat assessments do not consider non-seismic sources, such as submarine landslides. In the Pacific margin, there are many scars of submarine landslides in the continental slope (von Huene, Ranero and Watts, 2004). Also, landslides can occur at coastal plains adjacent to fluvial and alluvial fan deltas, as happened in Palu in 2018 (Sassa and Takagawa, 2018; Carvajal *et al.*, 2019). Future tsunami hazard assessments for Costa Rica should consider these sources.

Moreover, all the seismic sources were modeled employing homogeneous slip along the fault plane. This approach might underestimate tsunami heights for local sources (Geist, 2002; Ruiz *et al.*, 2015). While the higher tsunami hazard in Costa Rica comes from distant sources, a statistical approach to heterogeneous slip should be employed in the future for better characterization of the local threat, and the inundation and evacuation maps should be updated accordingly. The maps will also need updates when

new scientific knowledge appears, when bathymetry or topography experience significant changes and when coastal communities become more populated and developed.

Local and national authorities should consider the tsunami threat in land planning, banning the construction of schools, hospitals, and other sensitive infrastructure in tsunami inundation zones. In Costa Rica, the largest hospitals on both Pacific and Caribbean shores are located directly next to the shoreline, posing a major risk for both medical staff and patients.

Tsunami Preparedness

In Costa Rica, the National Risk Management System (Sistema Nacional de Gestión del Riesgo, SNGR) articulates all stakeholders by political division of the country (regional, municipal and community emergency committees) and thematic forums (scientific forum, educational forum, etc.). SINAMOT works within this structure to increase tsunami preparedness at all levels and forums.

In 2015, SINAMOT started a project to elaborate tsunami evacuation maps for chosen communities on both shores. The methodology for building the maps includes participative cartography, done through workshops with communities; in this way, they discuss and develop their tsunami evacuation maps. These workshops involve capacity building on tsunamis and tsunami preparedness, including tsunami warning systems, tsunami natural warnings and what to do in case of tsunami. Most of the coastal communities had no knowledge of tsunamis further than movies and videos from recent tsunamis like 2010 Chile and 2011 Japan. The local threat in Costa Rica is very different from those countries, thus in these workshops, people learn to be prepared for their specific threat.

Currently, there are tsunami evacuation maps for 48 communities along Pacific and Caribbean coasts (Figure 4). It is expected that about 20 more communities on the South Pacific coast and Caribbean coast will have their tsunami evacuation maps by the end of 2022. However, this is less than a quarter; Costa Rica has over 300 coastal communities, meaning the other three quarters still need to receive capacity building and create tsunami evacuation maps and plans.

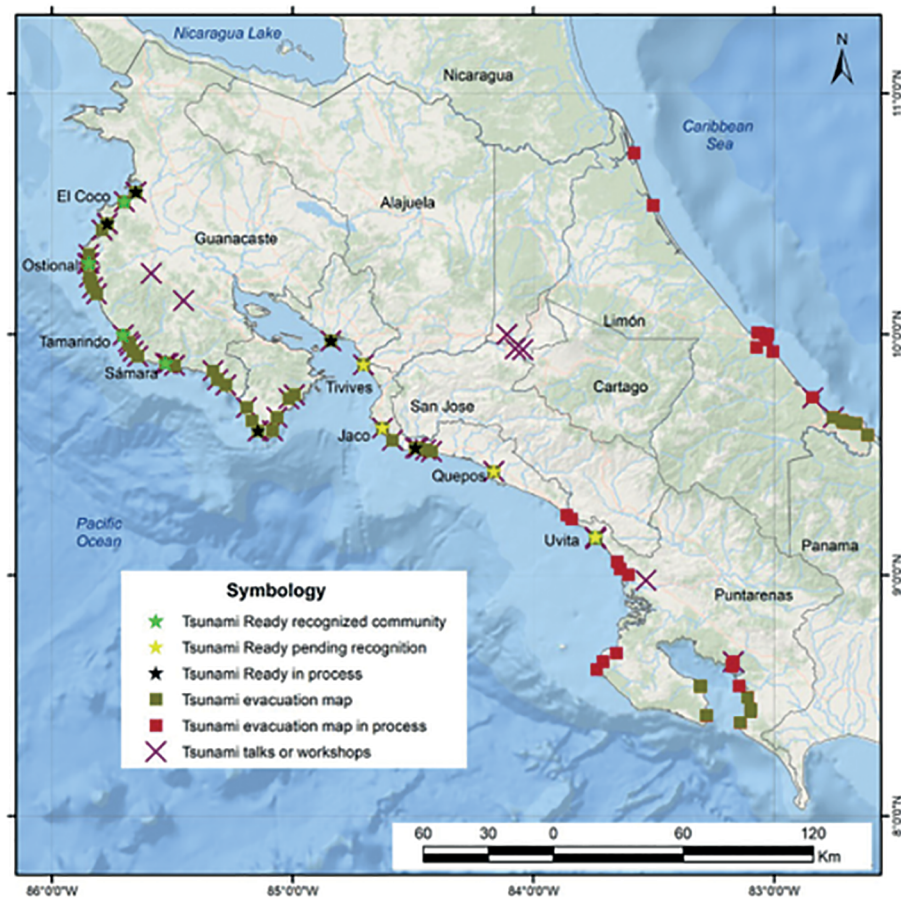


Figure 4. Tsunami preparedness in Costa Rica. Green stars are Tsunami Ready recognized communities, yellow stars are Tsunami Ready recognized with pending guidelines, black stars are communities working on their guidelines towards a Tsunami Ready recognition. Dark red squares show communities having tsunami evacuation maps and red squares show communities planning to have tsunami evacuation maps by 2022. Dark red crosses show communities that have received tsunami talks or workshops.

Tsunami Exercises

Tsunami exercises improve tsunami preparedness, particularly as tsunamis are infrequent events. In the Pacific and the Caribbean, there are basin-wide tsunami exercises, every two years and one year, respectively. Costa Rica has systematically participated in both PacWave and CaribeWave since 2014.

Our Caribbean coast has developed a tradition in tsunami exercises, because it is much less extensive than the Pacific coast and CaribeWave is more frequent than PacWave. However, so far these exercises have been mostly table-top, as there are still no tsunami evacuation plans in place to perform tsunami drills in the Caribbean. In the Pacific, the first tsunami drill was performed in 2017 at Ostional, as part of its Tsunami Ready preparation.

In August 2019, Costa Rica started yearly national earthquake drills. Four coastal communities performed a tsunami drill on that date for the first time. In 2020, no drills were possible due to pandemic conditions and the exercise had to be moved to October. Still, two coastal communities performed a table-top exercise during PacWave20: Tamarindo and Uvita. These exercises were performed remotely, using video conference tools for more realistic pandemic conditions.

Tsunami Ready Recognition Program

Tsunami Ready is a pilot community-based recognition program by the IOC/UNESCO. It started in the Caribbean in 2015, created after the TsunamiReady® Program of the United States. In 2017, the TOWS-WG-X recommended that the IOC Assembly

instructed other ICGs to consider piloting guidelines toward the development of a unified logo and guidelines. Currently, three ICGs have Tsunami Ready guidelines and communities have already obtained the recognition at the Pacific Ocean, Caribbean Sea, and Indian Ocean basins (Figure 5).

Tsunami Ready is gaining worldwide appreciation very quickly. After the devastating 2004 Indian Ocean tsunami that affected tourist-based communities, tourists feel safer with a recognition program that ensures a community has worked on its preparedness. One of the reasons that the Tsunami Ready Program should be successful is because it is community-based. Coastal communities get empowered by their tsunami preparedness and adapt it to their conditions, instead of receiving a rigid program/instruction from authorities.

In the Pacific and the Caribbean, Tsunami Ready has ten guidelines on Mitigation, Preparedness and Response (Figure 6). These guidelines include having a tsunami evacuation map and plan, to perform outreach or education activities and a tsunami community exercise annually, to raise awareness. Each one of the communities working in their Tsunami Ready recognition deal with the guidelines according to their social and spatial characteristics, giving different results within the guidelines.

Costa Rica attended as an observer in the TEMPP Pilot Course (Tsunami Evacuation Maps, Plans and Procedures) held in Honduras in 2015 and 2016; and replicated the experience in Ostional, Guanacaste, obtaining its first Tsunami Ready community in 2017. A second community was recognized in 2019, El Coco, with funding from a DIPECHO project for Central America. In February 2021, two more communities were recognized in Costa Rica: Sámará and Tamarindo, both in Guanacaste province. At that time, four other communities (Tivives, Jacó, Quepos and Uvita-Bahía) were pre-recognized pending one or two guidelines (Figure 4). Costa Rica is the Central American country with the most Tsunami Ready communities (four), followed by Honduras with three communities (one in the Pacific and two in the Caribbean), Nicaragua with two (in the Caribbean) and El Salvador also with two.

The preparation of a community to become Tsunami Ready involves many stakeholders from local and national authorities to NGOs and community organizations. Despite each coastal community having very specific characteristics, in Costa Rica we can define three main type of communities: urban communities, rural communities, and tourist communities.

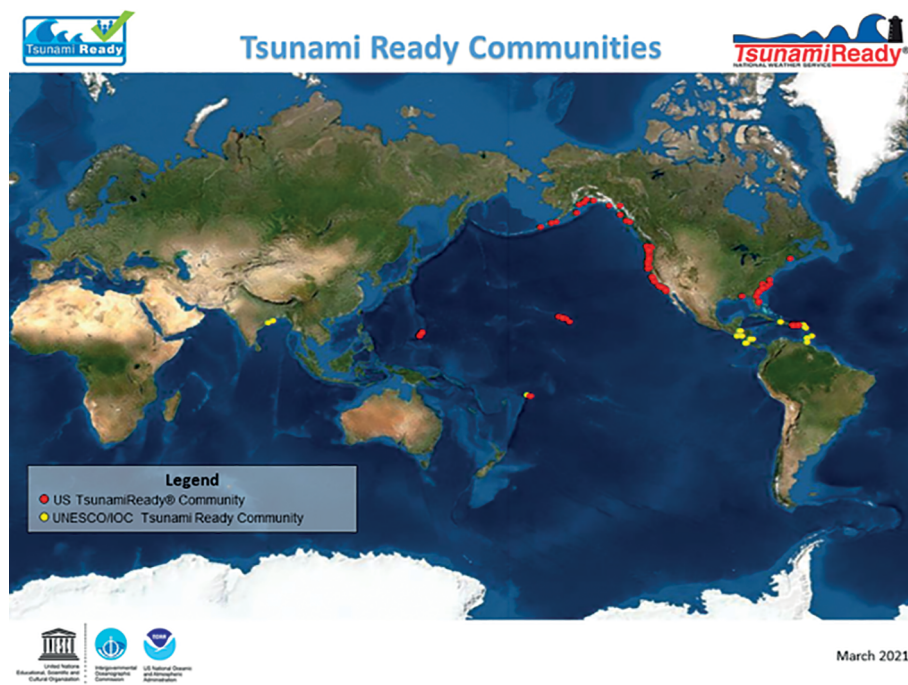


Figure 5. Tsunami Ready Communities in the world. UNESCO/IOC Tsunami Ready recognized communities are red dots and US TsunamiReady® recognized communities are yellow dots. (From ITIC website).

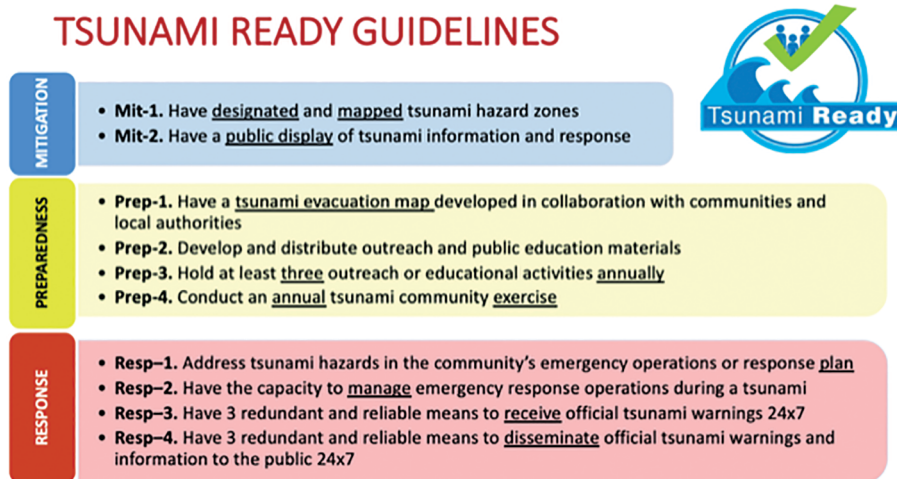


Figure 6. Tsunami Ready Guidelines for the Pacific and Caribbean basins.

Urban communities have greater vulnerability related to density of population, infrastructure, and sensitive infrastructure such as kindergartens and schools, but they have greater institutional, political, economic, and physical capacity. For example, Quepos has five schools and three first response institutions within the flood area. The evacuation plan for urban communities prioritizes the definition of institutional protocols for evacuating a large population using a dense road network.

Rural communities are mainly coordinated by community structures, where the people being part of the evacuation plan have responsibilities, but at a personal or neighborhood level as there are no large institutions within the inundation area. The plan focuses on establishing mechanisms for effective warning reception and dissemination.

For tourist communities like Tamarindo, there are no local population or government institutions within the inundation area. To the contrary, they have a large fluctuating population; therefore, the work is focused on staff and on generating information for tourists.

In Costa Rica's Tsunami Ready communities, the process has been mostly led by Community Emergency Committees (Comités Comunes de Emergencia, CCEs), but the Integral Development Associations (Asociaciones de Desarrollo Integral, ADIs) of each community have also played a major role. However, each Tsunami Ready experience is different, as is each community. In some communities, some stakeholders collaborated more than others.

The tourist sector has played a major role in all communities, though. Tsunami Ready requires permanent activities, as it should be renewed every four years.

THE WAVES TO COME

The United Nations Ocean Decade for Sustainable Development offers a unique opportunity to increase tsunami readiness worldwide related to two Decade outcomes. Safe Ocean seeks people to be protected from ocean hazards, and Predicted Ocean seeks society to have the capacity to understand current and future ocean conditions. It has been proposed as one of the goals of the Decade that 100% of at-risk communities become Tsunami Ready for 2030 (IOC/UNESCO, 2021). Also, there is a proposal to use SMART cables for tsunami detection at ocean basins (Howe *et al.*, 2019; IOC/UNESCO, 2020). Both proposals are part of the proposal for a "UN Decade Tsunami Programme" to be presented at the 31st IOC Assembly at its session in 2021.

There are many challenges for tsunami warning and mitigation systems. Recent tsunamis have caused considerable impact, no matter how well prepared the countries were. For example, the most costly tsunami in human history (NOAA/NCEI, 2021), the 2011 Japan tsunami, exceeded expected flow depth and overtopped and/or destroyed sea walls, in some cases inundating vertical tsunami shelters (Mori *et al.*, 2011; Sugawara *et al.*, 2013). The atypical 2018 Indonesia tsunamis of Palu and Anau Krakatoa impacted a country that has strongly increased its

preparedness since the devastating 2004 event. The Palu tsunami arrived 3.5 minutes after the strike-slip earthquake and people were not expecting a significant tsunami, despite it happening three times during the past century (UNESCO/IOC, 2019). The absence of protocols for volcano-induced tsunamis was responsible for the losses caused by the tsunami originated by the Anauk Krakatoa eruption; this also occurred approximately 100 years ago, and there were many signs anticipating the eruption. The impact from both events was concentrated in the near field. The 2018 tsunamis led TOWS-WG-XIII (IOC/UNESCO, 2019b) to constitute a team *"to prepare a document on best practices for hazard assessment, monitoring and responding to tsunamis from those sources"*.

Irrespective the source, threat characterization is key for community preparedness. Tsunami hazard assessments need to be performed for all sources. In some cases, atypical sources might represent higher threat and/or shorter arrival times than tsunamis caused by subduction earthquakes. For example, for Costa Rica, the tsunami threat from local subduction earthquakes is moderated, but landslides scars on the continental slope on the Pacific margin might suggest much larger tsunami potential from this source. Also, the scarce tectonic information for the Caribbean margin hinders a proper tsunami threat assessment there. Tsunami hazard assessment requires, in turn, high-resolution bathymetry for numerical modeling of tsunami inundation at coastal locations. Hazard assessment, tsunami inundation and evacuation maps need to be constantly updated. Therefore, capacity building needs to be strengthened in many developing countries and SIDS for them to be able to perform their own modeling and hazard assessment and not depend on funding through specific projects.

For people in tropical countries, affected every year by hurricanes, cyclones, monsoons and heavy rains, there is always a more immediate threat and tsunamis are usually relegated to the back burner. It requires an enormous amount of work to keep the topic active for people to always be prepared and keep plans and protocols updated. Tsunami mainstreaming might assist in dealing with this. For example, tsunami preparedness should be included in the curricula for all educative levels. During the 2004 Indian Ocean tsunami in Thailand, one English school girl saved more than a hundred people by

recognizing the tsunami signs she learnt in school. This is particularly important in Costa Rica, as it has a long tradition of local tourism, meaning that kids from the center of the country visit the beaches several times every year.

Regardless the tsunami source, detection is required, meaning that sea level networks should be densified, to have the capacity to detect tsunamis within minutes from their origin (Angove *et al.*, 2019; IOC/UNESCO, 2020). Thus, capacity building is required in sea level station deployment, maintenance, and data quality control. SMART cables are useful in the deep ocean, but coastal stations are needed.

CONCLUSIONS

Summarizing, more investment in science and technology and intensive work in awareness will allow the world to become Tsunami Ready and to have stronger Tsunami Warning and Mitigation Systems. This includes sea level gauges, high-resolution coastal bathymetric data, and human resources, which should be a priority for governments in the years to come. Human resources should include more staff working with sea level gauges and performing tsunami hazard assessments and capacity building for them to keep up-to-date. South to south collaborations might contribute to this, for example with capacity building and regional teams for sea level gauge maintenance.

The Ocean Decade provides a once in a generation opportunity to drive stakeholders and public attention to tsunamis. Its momentum might contribute to coping with the challenges and increasing national and international collaboration for a world better prepared for tsunamis.

AUTHOR CONTRIBUTIONS

S.Ch.B.: Conceptualization, Visualization, Writing - original draft, Writing - review & editing

A.M.G.: Conceptualization, Visualization, Writing - review & editing

F.R.C.: Conceptualization, Visualization, Writing - review & editing

B.A.R.: A.M.-G.: Conceptualization, Writing - review & editing

REFERENCES

- AN, C. & LIU, P. L. F. 2014. Characteristics of leading tsunami waves generated in three recent tsunami events. *Journal of Earthquake and Tsunami*, 8(3), 1440001, DOI: <https://doi.org/10.1142/S1793431114400016>

- ANGOVE, M., ARCAS, D., BAILEY, R., CARRASCO, P., COETZEE, D., FRY, B., GLEDHILL, K., HARADA, S., VON HILLEBRANDT-ANDRADE, C., KONG, L., MCCREERY, C., MCCURRACH, S. J., MIAO, Y., SAKYA, A. E. & SCHINDELÉ, F. 2019. Ocean observations required to minimize uncertainty in global tsunami forecasts, warnings, and emergency response. *Frontiers in Marine Science*, 6, 350, DOI: <https://doi.org/10.3389/fmars.2019.00350>
- CARVAJAL, M., ARAYA-CORNEJO, C., SEPÚLVEDA, I., MELNICK, D. & HAASE, J. S. 2019. Nearly instantaneous tsunamis following the Mw 7.5 2018 Palu earthquake. *Geophysical Research Letters*, 46(10), 5117-5126, DOI: <https://doi.org/10.1029/2019GL082578>
- CHACÓN-BARRANTES, S. E. 2018. The 2017 México tsunami record, numerical modeling and threat assessment in Costa Rica. *Pure and Applied Geophysics*, 175(6), 1939-1950, DOI: <https://doi.org/10.1007/s00024-018-1852-7>
- CHACÓN-BARRANTES, S. E. & GUTIÉRREZ-ECHEVERRÍA, A. 2017. Tsunamis recorded in tide gauges at Costa Rica Pacific coast and their numerical modeling. *Natural Hazards*, 89(1), 295-311, DOI: <https://doi.org/10.1007/s11069-017-2965-5>
- CHACÓN-BARRANTES, S. E., MURILLO-GUTIÉRREZ, A. & RIVERA-CERDAS, F. 2021. *Catálogo de tsunamis históricos de Costa Rica hasta el 2020*. Heredia: EDUNA.
- COMFORT, L. K., ZNATI, T., VOORTMAN, M., XERANDY, X. & FREITAG, L. E. 2012. Early detection of near-field tsunamis using underwater sensor networks. *Science of Tsunami Hazards*, 31(4), 231-243.
- GEIST, E. L. 2002. Complex earthquake rupture and local tsunamis. *Journal of Geophysical Research: Solid Earth*, 107(B5), ESE2-1-ESE2-15. DOI: <https://doi.org/10.1029/2000JB000139>
- HEIDARZADEH, M., MUHARI, A. & WIJANARTO, A. B. 2019. Insights on the source of the 28 September 2018 Sulawesi Tsunami, Indonesia based on spectral analyses and numerical simulations. *Pure and Applied Geophysics*, 176(1), 25-43, DOI: <https://doi.org/10.1007/s00024-018-2065-9>
- HOWE, B. M., ARBIC, B. K., AUCAN, J., BARNES, C. R., BAYLIFF, N., BECKER, N., BUTLER, R., DOYLE, L., ELIPOT, S., JOHNSON, G. C., LANDERER, F., LENTZ, S., LUTHER, D. S., MÜLLER, M., MARIANO, J., PANAYOTOU, K., ROWE, C., OTA, H., SONG, Y. T., THOMAS, M., THOMAS, P. N., THOMPSON, P., TILMANN, F., WEBER, T. & WEINSTEIN, S. 2019. SMART cables for observing the global ocean: science and implementation. *Frontiers in Marine Science*, 6, 424. DOI: <https://doi.org/10.3389/fmars.2019.00424>
- IOC (Intergovernmental Oceanographic Commission), UNESCO (United Nations Educational, Scientific and Cultural Organization). 2008. *Working group on tsunamis and other hazards related to sea-level warning and mitigation systems (TOWS-WG) first meeting*. Paris: UNESCO Publishing.
- IOC (Intergovernmental Oceanographic Commission), UNESCO (United Nations Educational, Scientific and Cultural Organization). 2016. *Tsunami watch operations. Global service definition document*. Paris: UNESCO Publishing.
- IOC (Intergovernmental Oceanographic Commission), UNESCO (United Nations Educational, Scientific and Cultural Organization). 2018. *Limitations and challenges of early warning systems. case study: Palu-Donggala Tsunami 28 September 2018*. Paris: UNESCO Publishing.
- IOC (Intergovernmental Oceanographic Commission), UNESCO (United Nations Educational, Scientific and Cultural Organization). 2019a. *Tsunami*. Paris: UNESCO Publishing.
- IOC (Intergovernmental Oceanographic Commission), UNESCO (United Nations Educational, Scientific and Cultural Organization). 2019b. *Working group on tsunamis and other hazards related to sea-level warning and mitigation systems (TOWS-WG)*. Paris: UNESCO Publishing.
- IOC (Intergovernmental Oceanographic Commission), UNESCO (United Nations Educational, Scientific and Cultural Organization). 2020. *Working group on tsunamis and other hazards related to sea-level warning and mitigation systems (TOWS-WG) thirteenth meeting* [online]. Paris: UNESCO Publishing. Available at: http://www.ioc-tsunami.org/index.php?option=com_oie&task=viewDocumentRecord&docID=26681 [Accessed: 15 June 2021].
- IOC (Intergovernmental Oceanographic Commission), UNESCO (United Nations Educational, Scientific and Cultural Organization). 2021. *Working group on tsunamis and other hazards related to sea-level warning and mitigation systems (TOWS-WG) fourteenth meeting*. Paris: UNESCO Publishing.
- KIM, S. K. & PARK, J. 2019. *Innovation: monitoring sea level change in the arctic using GNSS-reflectometry* [online]. Reston: GPS World - GNSS (GNSS Positioning Navigation Timing). Available at: <https://www.gpsworld.com/a-tidal-shift-monitoring-sea-level-in-the-arctic-using-gnss/> [Accessed: 15 June 2021].
- LEGG, M. R., BORRERO, J. C. & SYNOLAKIS, C. E. 2003. Tsunami hazards from strike-slip earthquakes. *AGU Fall Meeting Abstracts*, OS21D-06.
- MORI, N., TAKAHASHI, T., YASUDA, T. & YANAGISAWA, H. 2011. Survey of 2011 Tohoku earthquake tsunami inundation and run-up. *Geophysical Research Letters*, 38(7), 6-11, DOI: <https://doi.org/10.1029/2011GL049210>
- NOAA (National Centers for Environmental Information), NCEI (National Centers for Environmental Information). *NCEI/ WDS Global historical tsunami database*. Silver Spring: NOAA/NCEI, DOI: <https://doi.org/10.7289/V5PN93H7>
- RUIZ, J. A., FUENTES, M., RIQUELME, S., CAMPOS, J. & CISTERNAS, A. 2015. Numerical simulation of tsunami runup in northern Chile based on non-uniform k^2 slip distributions. *Natural Hazards*, 79(2), 1177-1198, DOI: <https://doi.org/10.1007/s11069-015-1901-9>
- SASSA, S. & TAKAGAWA, T. 2018. Liquefied gravity flow-induced tsunami: first evidence and comparison from the 2018 Indonesia Sulawesi earthquake and tsunami disasters. *Landslides*, 16, 195-200, DOI: <https://doi.org/10.1007/s10346-018-1114-x>
- SUGAWARA, D., IMAMURA, F., GOTO, K., MASTUMOTO, H. & MINOURA, K. 2013. The 2011 Tohoku-oki earthquake tsunami: similarities and differences to the 869 jogan tsunami on the sendai plain. *Pure and Applied Geophysics*, 170(5), 831-843, DOI: <https://doi.org/10.1007/s00024-012-0460-1>
- VON HUENE, R., RANERO, C. R. & WATTS, P. 2004. Tsunamigenic slope failure along the Middle America Trench in two tectonic settings. *Marine Geology*, 203(3-4), 303-317, DOI: [https://doi.org/10.1016/S0025-3227\(03\)00312-8](https://doi.org/10.1016/S0025-3227(03)00312-8)