Bank of tsunami scenarios for the Colombian Caribbean: case study, Cartagena de Indias

Banco de escenarios tsunami para el Caribe colombiano: caso de estudio, Cartagena de Indias

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ABSTRACT

In the Colombian Caribbean there has been no significant progress on the study of the tsunami threat, due to the low seismic activity that occurs in this area. However, according to historical records, it is not exempt from the occurrence of this type of natural phenomena that can cause economic losses and human lives. For this reason, in the present investigation the numerical simulation of seven tsunami generating seismic scenarios located in the Caribbean Sea was performed, using the COMCOT numerical model, obtained from a deterministic approach, in order to generate the flood scenarios by tsunami for the city of Cartagena.

KEY WORDS: Cartagena de Indias, numerical modelling, tsunami, tsunami flood, deterministic technique, synthetic tide graph.

RESUMEN

En el Caribe colombiano no ha habido progresos significativos sobre el estudio de la amenaza por tsunami, debido a la baja actividad sísmica que se presenta en esta zona. Sin embargo, según los registros históricos, no se encuentra exenta de la ocurrencia de este tipo de fenómenos naturales que pueden causar pérdidas económicas y de vidas humanas. Por esta razón, en la presente investigación se realizó la simulación numérica de siete posibles escenarios sísmicos generadores de tsunami ubicados en el mar Caribe, utilizando el modelo numérico COMCOT, obtenidos a partir de una aproximación determinista, con el fin de generar los escenarios de inundación por tsunami para la ciudad de Cartagena.

PALABRAS CLAVES: *Cartagena de Indias, modelación numérica, tsunami, inundación por tsunami, técnica determinista, mareograma sintético.*

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Introduction

In the Atlantic Ocean, unlike the Pacific, on the east coast of the United States and on the Mid-Atlantic Ridge, there are no tectonic plates colliding or sliding; as a consequence of this, seismic and volcanic activity is infrequent in the Caribbean Sea. The most active areas are concentrated in the Caribbean islands and in the islands of the Arc of Scotland, near Antarctica (Correa, 2013). In the Caribbean, on the tectonic limits, they originate mainly from: The Mesoamerican Trench where it limits the Cocos and Caribbean plate; the Polochic-Motagua-Swan fault system, originated by the boundary between the Caribbean and North American plates; the warped Belt of the North of Panama, considered as a zone of subduction within the Caribbean plate (Fernández, 2002). These geotectonic conditions have been responsible for 124 tsunami events reported until 1998 in O'Loughlin & Lander (2003) and 91 reported until 1997 in Lander, Whiteside & Lockridge (2002), of which 27 have been verified by different authors (Correa, 2013).

The Pacific Tsunami Warning Center, reported on July 23, 2015, the latest warning of possible tsunami in the Caribbean Sea. Indeed, the bulletin informed about an important eruption due to the submarine volcano Kick'em-Jenny, located 8 km from the north coast of the island of Granada, west of the Ronde and Caille islands in orange alert status. If the tsunami was generated, the waves would reach the north coast of Venezuela in 40 minutes, while the Leeward Islands and Puerto Rico in an hour and a half, without any danger to the Colombian Coasts (CONRED, 2015).

For 2015, it is projected that the population residing on the Colombian Caribbean coast will be approximately 19.2 % of the entire country. (Dane, 2015), also considering that an important part of this percentage is located on the coastal edge; it is possible to infer that these inhabitants are exposed to a tsunami. This means that it is important to estimate the vulnerability of threatened coastal settlements, defining potential flood areas in the event of a possible tsunami.

So that, taking into account the aforementioned, the risk to which the city of Cartagena de Indias is exposed is evident, which is why there is a need to obtain a bank of tsunami scenarios, which allows the evaluation of this type of threat and in turn provides information about the time of arrival of the first wave of a tsunami and maximum height of flood sheet. The pre-computed scenarios were obtained through the application of different techniques of the study of the phenomenon and include the following stages: as a first step, the computational domains were created from the processing and edition of the base information (topography and bathymetry). As a second stage, the seismic parameters of seven tsunami scenarios located in the Caribbean Sea were defined from the deterministic technique. Finally, the selected scenarios were simulated, making use of the numerical model COMCOT V1.7 (Cornell Multi-grid Coupled Tsunami Model); by means of which it is possible to obtain an estimate of the level of affectation that a tsunami event could cause on the coastal population evaluated and with this information in the future, it is possible to plan strategies to reduce this vulnerability. With the flood results of seven seismic scenarios for the city of Cartagena de Indias, this research presents the evaluation regarding the generation and propagation of the tsunami wave train and the level of flood that would affect the coastal population.

Study area

The Tourism and Cultural District of Cartagena de Indias (Figure 1), the area under study, is located west of the Colombian Caribbean, in the department of Bolívar, its geographical location is between latitudes 10283 ° N – 10492 ° N and longitudes between 75450 ° W - 75617 ° W. It is a city that is on the shores of the Caribbean Sea, bordering to the east with the municipalities of Santa Catalina, Santa Rosa, Turbaco and Turbaná; to the north and to the west with the Caribbean Sea and to the south with the municipality of Arjona. Due to the geographical location and the characteristics of the land, the population has a high risk in the face of a tsunami event, which although not very frequent in this area, could cause loss of human life and damage to the colonial infrastructure of its metropolis, meaning a great decline for tourism, for Cartagena attracts Colombians and visitors from all over the world.

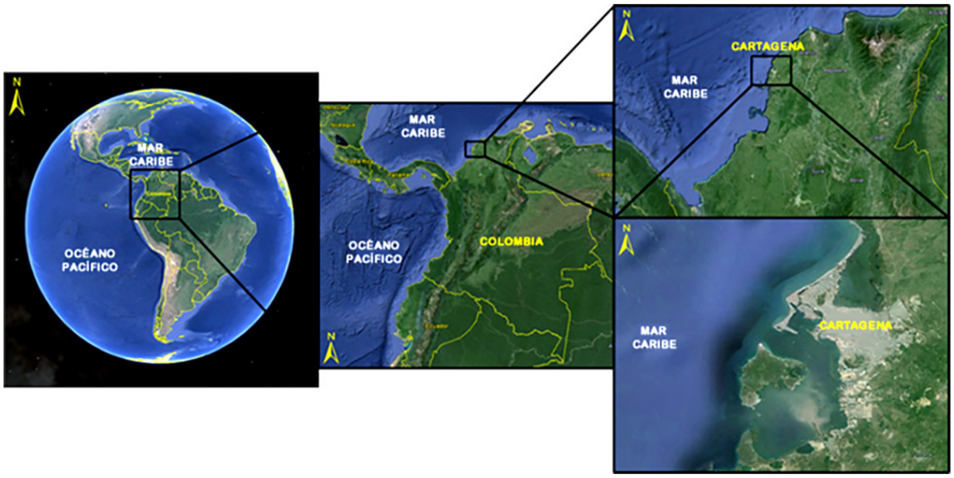

Figure 1. General study area, Cartagena de Indias.

Materials and methods

It should be noted that through the implementation of the deterministic technique, the methodology used is based on the numerical modeling of tsunami scenarios. This technique allowed us to define the extreme events of tsunami, based on scientific studies focused on historical seismicity, geodynamics and the seismic tectonics of the study area, taking into account the existence of roughness, ruggedness, or seismic lagoons generated by the occurrence of different earthquakes that have occurred in the Caribbean Sea. This allowed the determination of seven tsunami scenarios located between the limits of the Caribbean plate with significant seismic activity.

From this research work, the results of the simulation will be announced next, involving the "worst credible scenarios", which contain the flood distribution of the evaluated zones, the height information of the first wave and the time of arrival to the populated areas.

Delimitation of the study area

On the other hand, in the continuity of this observation, although it is necessary to have an excellent quality in the input data, it is also essential to have the largest amount of topo-bathymetric information, which allows an appropriate selection of work areas; to generate in this way, the computational domains used in the general configuration of the input parameters in the numerical model.

These domains contain the necessary information to represent the geomorphology of both the soil and the seabed for the entire study area. Each domain will have a set of grids, which will allow the coupling of the areas to be evaluated at different nesting levels. These computational meshes are introduced in the numerical model and are governed by the system of equations, whether linear or non-linear (in deep water, or in shallow water, respectively) (Wang, 2009), and must comply with the standards specified in (Cornell, 2015).

The numerical model selected is COMCOT (Cornell Multi-grid Coupled Tsunami model), developed by the Institution School of Civil and Environmental Engineering, Cornell University headed by Yongsik Cho and SN Seo, and modified by Wang Xiaoming in the Institute of Geology and Nuclear Sciences of New Zealand (GNS) in version 1.7, which was used for the development of this research. This model adopts the scheme of finite differences staggered by "frog jump", to solve shallow water equations in both spherical and Cartesian coordinates (Wang, 2009).

In this, a global region is selected, from which a multimodal system is taken in different levels or grid sizes, which in turn allows a correct evolution by the different regions where the tsunami waves are propagated. The region with the largest grid size is called the first level network and thereafter, they are called second level networks, third level networks and so on; it is also possible to define up to 12 grid levels (Wang, 2009).

The meshes for the city of Cartagena is represented by the spacing of 1arcs, 3arcs, 15arcs and 61arcs, where its equivalence in meters are 30, 90, 450 and 1830 m, respectively and whose spatial arrangement is shown in the Figure 2.

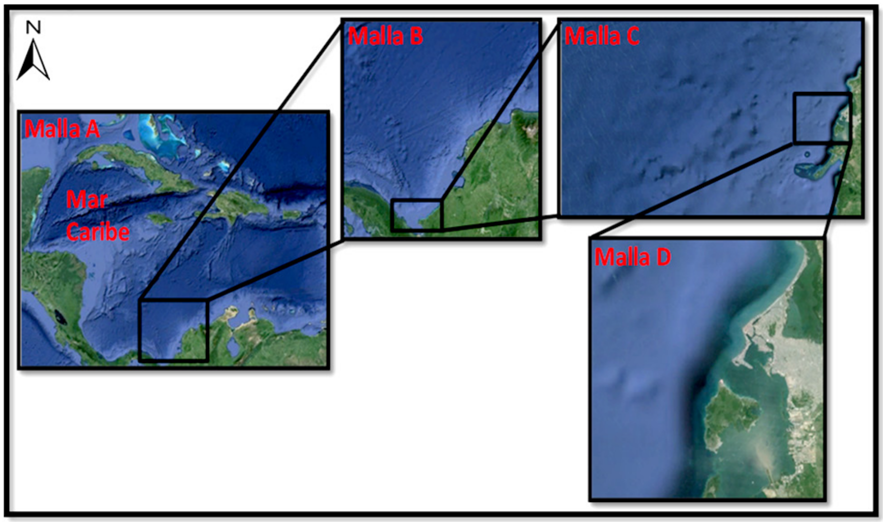

Figure 2. Arrangement of computational meshes corresponding to Cartagena de Indias, by means of the parameters defined in (Table 1).

In mesh A there is a spacing of 61 arcs and it covers the place of generation of the seismic event, while the mesh B and C, whose spacing is 15 arcs and 3 arcs, respectively, represents the propagation of the tsunami waves in deep water and finally we reach the flood phase (mesh D with spacing of 1 arc), where the effects of the tsunami on the evaluated population are analyzed in detail. The limits and sizes of each computational array are shown in Table 1.

Table 1. Characteristics of the computational mesh array using the COMCOT model, the coordinates are in WGS84.

MESH	AREA COMPRISED	INF LIMIT LEFT (O)	SUP LIMIT RIGHT (O)	CELL SIZE
A	Caribbean	-88.9877 ; 7.0038	-62.1877 ; 25.1038	61 arc-second (~1830 m)
B	Colombian Caribbean	-79.1002 ; 7.7247	-73.4127 ; 13.4997	61 arc-second (~1830 m)
C	Bolívar Departament Coast	-77.0694 ; 9.8963	-75.4519 ; 10.8513	3 arc-second(~92 m)
D	Urban Area Cartagena	-75.7119 ; 10.2669	-75.4738 ; 10.4994	1 arc-second (~30 m)

Seismic scenario definition

In the Caribbean Sea there are some natural phenomena that despite being rare, have high relevance on human activities due to their negative effects. Such is the case of tsunamis, where most of these are of tectonic origin, considering that about 90 % are produced by the movement of one plate with respect to the other (von Hillebrandt-Andrade, 2010). Figure 3 shows the Caribbean Sea region with the boundaries between the plates (area where most of the tsunamis aregenerated); these events are represented graphically with circles of different sizes and colors. The circles of red color and large size, were the most destructive and those of white color and smaller, were the least destructive. It is also possible to distinguish between the plates, the convergent limit (green line), divergent limit (red line) and transforming limit (yellow line).

Figure 3. Tsunamis in the Caribbean Sea with border line between plates (NOAA, 2015). All earthquakes in the Caribbean Sea of the National Oceanic and Atmospheric Administration (NOAA), The Global Centroid-Moment-Tensor (CMT) and the Incorporated Research Institutions for Seismology (IRIS) catalogues.

The limit of North American-Caribbean plates consists of an area of active faults of 100 to 260 km wide and of around 2000 km of extension, fault zones Chixoy - Polochic - Motogua - Swan Fault - Oriente Fault - Northern System - Puerto Rico Fault. The seismicity of the western segment of the Caribbean-North American boundary zone is superficial, h≤30 km, with the exception of the extreme Pacific, while from the eastern side of eastern Cuba and towards Puerto Rico, the depths of the earthquakes can be even around 100 Km (Álvarez, Rubio, T. & M., 1985).

The lateral contact of the microplates is through the Bonao fault system in NE direction, which has been studied by different specialists. These microplates have two active fault systems to the north and south (Figure 4): (1) eastern fault - northern fault - Camú fault - Puerto Rico fault and (2) Walton fault - Enriquillo fault / Plantain Garden – Muertos fault.

The following representation (Figure 5) shows the lateral succession of four blocks, which although they are diverse in their composition, morphology and dynamics, depend on the system of lithospheric plates North America - Caribbean. This classification not only explains the different values of relative speed, seismicity and focal mechanisms, but resolves the dynamic independence of the microplates (or blocks) of the northern boundary zone in relation to the interior zones of the Caribbean and North America.

By using the method that Correa (2013) applies, it was possible to identify, the lengths of the faults were identified and based on the scale relationships established and proposed by (Kanamori & Anderson, 1975, Papazachos, Scordilis, Panagiotopoulos, Papazachos &Karakaisis, 2004; Rousseeuw & Leroy, 1987; Wells & Coppersmith, 1994); the geometrical dimensions (Length, Width, Area and vertical displacement) were related to the magnitudes and seismic moments Mo.

To obtain the relations of scale of magnitude, seismic moment and energy, with the faults parameters two methods were used, (1) An approximate estimate of the parameters of a relevant fault when M, Mo or seismic energy (Es) of the event are known from the evaluation of the instrumental data; (2) A magnitude, moment and / or energy estimates for historical or even prehistoric events, for which no data are available; however, some fault parameters such as rupture length and / or amount of surface displacement can still be determined from field tests.

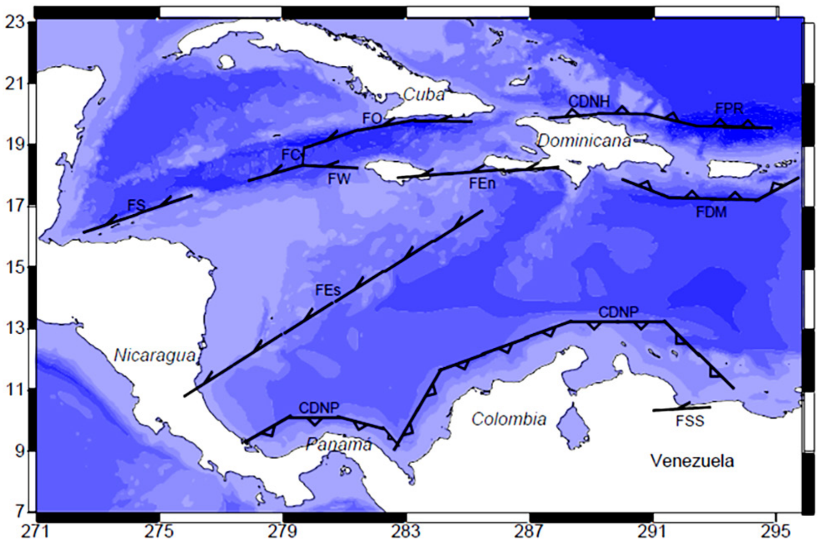

Figure 4. Faults in the Caribbean. Fs = Swan Fault; FC = Caiman Fault; FO = Oriente Fault; FW = Walton Fault; FEn = Enriquillo Fault; Fes = Escarpe Fault; CDNP = Deformed Belt of Northern Panama; FSS = San Sebastian Fault; FDM = Muertos Fault; FPR = Puerto Rico Fault; CDNH = Deformed Belt of the North of Hispaniola. (Correa, 2013).

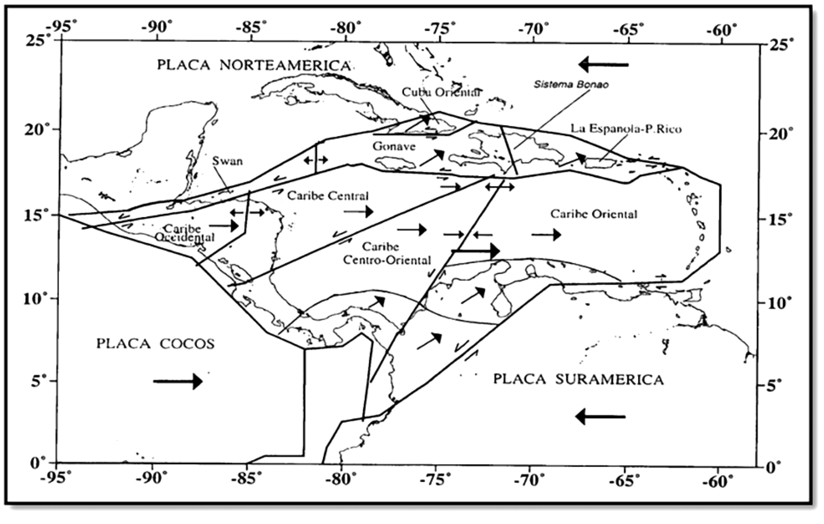

Figure 5. Main blocks of the Caribbean plate and its northern margin. (Cotilla & Udías, 1999).

Likewise, it was found through the relationship presented in (Wells & Coppersmith, 1994), that it is possible to establish a relationship between the length of the fault or the area thereof for any type of fault or specific faults. From this information we proceeded to construct the maximum breaking dimensions (Table 2).

Table 2. Maximum breaking lengths, magnitudes of scale, and epicenter, in the WGS84 system.

Source	Longitude (°W)	Latitude (°N)	Largo (km)	Width (km)	Area (km^2)	Displacement (m)
PANAMA	-77.9978	9.9223	277.04	26.64	7380.34	4.34
ESCARPE	-82.2132	12.2581	170.21	25.23	4294.39	1.8
SWAN	-86.6556	16.9330	214.0	31.0	6634	7.42
ORIENTE	-81.2580	18.9115	175.0	32.5	5687.5	5.92
ENRIQUILLO	-72.4611	18.3392	123.52	26.54	3278.22	3.47
PUERTO RICO	-67.5000	18.5000	191.0	55.0	10505	6.0

Regarding the acquisition of the focal mechanisms, the results obtained in the methodology used in (Correa, 2013), whose selection was made from the revision of the CMT catalogue and the evaluation of the different values, were taken. Faults were represented in the Caribbean Sea, finding the STRIKE length and angle for each fault. As for the depth of the earthquake, the smallest was taken from the CMT catalogue; while for the calculation of the DIP and SLIP angles, simulation tests were carried out to select the focal mechanisms that would generate the greatest threat to the Colombian Caribbean Coast, including its insular zone, for each of the selected faults (Table 3). For the Puerto Rico fault, simulations were not carried out to evaluate the focal mechanisms since they were taken from the work of (Harbitz *et al.,* 2012).

Table 3. Focal mechanisms for the "worst credible scenarios" of the Caribbean Sea.

Source	Strike (°)	Dip (°)	Slip (°)	Prof. Focal (km)
PANAMA	292.0	88.0	84.0	12.3
ESCARPE	63.0	58.0	- 43.0	15.0
SWAN	72.0	85.0	151.0	10.0
ORIENTE	79.0	72.0	82.0	10.0
ENRIQUILLO	90.0	90.0	85.0	12.0
PUERTO RICO	100.0	80.0	85.0	16.4

In addition to the scenarios mentioned in the previous table, a final scenario was taken for the Deformed Belt of Northern Panama, based on the exercise "CARIBE WAVE / LANTEX 15" SW Caribbean Scenario (Puerto Rico Seismic Network, 2015). This is a simulation of a tsunami with two scenarios for the Caribbean and the Atlantic region of the United States and Canada: the Southwestern Caribbean Scenario and the Florida Scenario. In the present investigation, the first tsunami scenario is taken, which is generated by an Earthquake in the north of Panama. In the Southwestern Caribbean scenario, observations regarding earthquakes and tsunamis that occurred off the coast of Panama in 1882 (M8.0) and 1991 (Mw7.6) (Intergovernmental Oceanographic Commission, 2015) are used as a reference.

The hypocenter parameters of the proposed scenario are presented below (Table 4).

Table 4. Scenario proposed for the exercise "CARIBE WAVE/LANTEX 15".

Fault map	Latitude	Length	Depth Focal (km)	Long (km)	Width (km)	Displacement (m)
South East Segment	9.4819°N	77.5605°W	5.0	182.0	60.0	13.0
South West Segment	9.8742°N	80.0743°W	5.0	120.0	40.0	9.0

In itself, the fault plane is composed of two segments (1) South East Segment and (2) South West Segment.

Tide level

The sea level at any time is affected mainly by two natural processes: the astronomical tide, which is the process that most affects the periodic rise and fall of sea level, and is due to the force of gravitational attraction that the moon and the sun exert on the mass of water; and the meteorological tide, which is generated by atmospheric pressure and wind (Valls & Josep, 2009). Non-astronomical factors also have an influence, such as coastline, geographical distribution, local topography, depth of ocean basins, hydrographic influences, among others, that play an important role in their behavior (Calero, Carta & Padrón, 2006).

The amplitude of the tide increases and propagates towards the coastal regions, as a consequence of the conservation of the energy flow of the tidal wave that experiences wave shoaling (Gallegos & Czintron, 1997; Knauss, 1978) and is increased according to the extension and depth of the continental shelf on which it spreads (Lizano, 2006). Likewise, the increase may be due to geomorphological configurations of the coast (semi-enclosed bodies of water: gulfs, bays), friction or refractive effects, reflection or resonance in the course of the propagation of the wave (Forrester, 1983). On the Colombian Caribbean Coast a tidal range is experienced, of the order of centimeters, with permanent trade winds and low pressures that could generate the so-called meteorological tides (Kjerfve, 1981; Pugh, 1996), which affect the level of the sea, in this case, increasing the height of the tidal wave and therefore, also becoming a threat factor in coastal populations in the case of a possible tsunami event.

Due to the extension and the geomorphological, social conditions, among others, of the Colombian Caribbean, it has limited sea level information both temporally and spatially, that is why the methodology developed in the CCCP (Otero, 2005) is adopted, to determine the maximum flood levels when there are no instrumental records, in order to obtain probabilistically, an estimate of sea level behavior of these areas. The methodology used to obtain the results, is based on the analysis of the meteorological tide using indirect methods based on MonteCarlo techniques, due to its random nature.

Based on the work done in the Dimar Research Center, the mean sea level regime (Figure 6) obtained for the population of Cartagena in the Colombian Caribbean (Caribbean Oceanographic and Hydrographic Research Center - CIOH, 2009) is extracted. From which the high and low tide levels are obtained (because their tidal variation is very small) (Table 5), which are added to the detail meshes and with this the degree of flooding in the study area is evaluated.

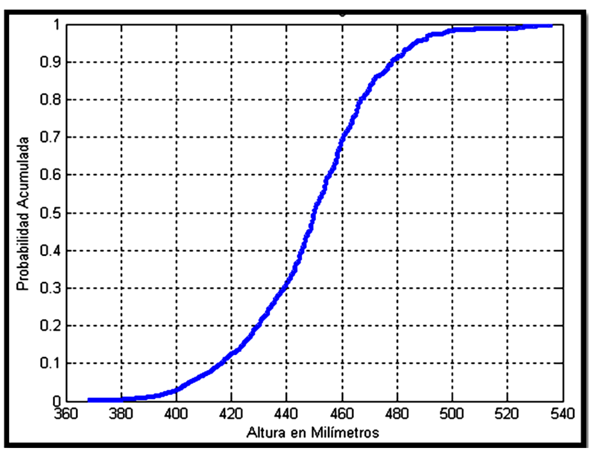

Figure 6. Average regime determined for Cartagena de Indias. [Modified by the author].

Table 5. Tidal level for Cartagena de Indias.

Area of interest	High tide level [msnm]	Low tide level [msnm]
Cartagena	0.48 m	0.43 m

Results and discussion

Through the use of the numerical model of tsunamis COMCOT V1.7, the generation, propagation and flooding of the seismic scenarios defined above were carried out using a deterministic method (Table 3 and Table 4). Flooding was calculated on the highest resolution mesh (1 arc), giving the model a time of 6 hours to simulate the event in each of the sources.

The initial deformation of the seabed generated by each of the seismic scenarios (Figure 7) shows that the sources closest to the population in question are the Panama and Caribbean Wave; It can also be inferred that the source that generates a greater area of rupture, due to the focal parameters of the fault, is the Caribbean Wave scenario, which generates a seabed elevation of approximately 5 m in the rupture zone.

Once the deformation is generated in the seabed, this displaces the water column that is just above the rupture zone, giving rise to long waves of tsunami that propagate from deep water and when arriving at the coast, they can provoke flooding in the population in question, as shown below:

Enriquillo seismic scenario

The flood scenario (Figure 8), generated once an earthquake occurs with an epicenter at the Enriquillo source, causes a displacement on the free surface of approximately 0.7 m, which mainly affects the Bocagrande sector, and a part on the west side of Tierrabomba, managing to attenuate practically all the wave since in the internal bay of Cartagena, the increase in the level of the sea is almost null. The first wave to arrive, has a height of 10 cm in 19 minutes; however, 10 minutes later another wave arrives with an amplitude of 17 cm, which confirms that an event of this type generates a wave train and not necessarily the first one to arrive is the highest.

Caribbean Wave seismic scenario

This seismic scenario, being one of the closest to the population under study, and due to the focal parameters of the scenario,

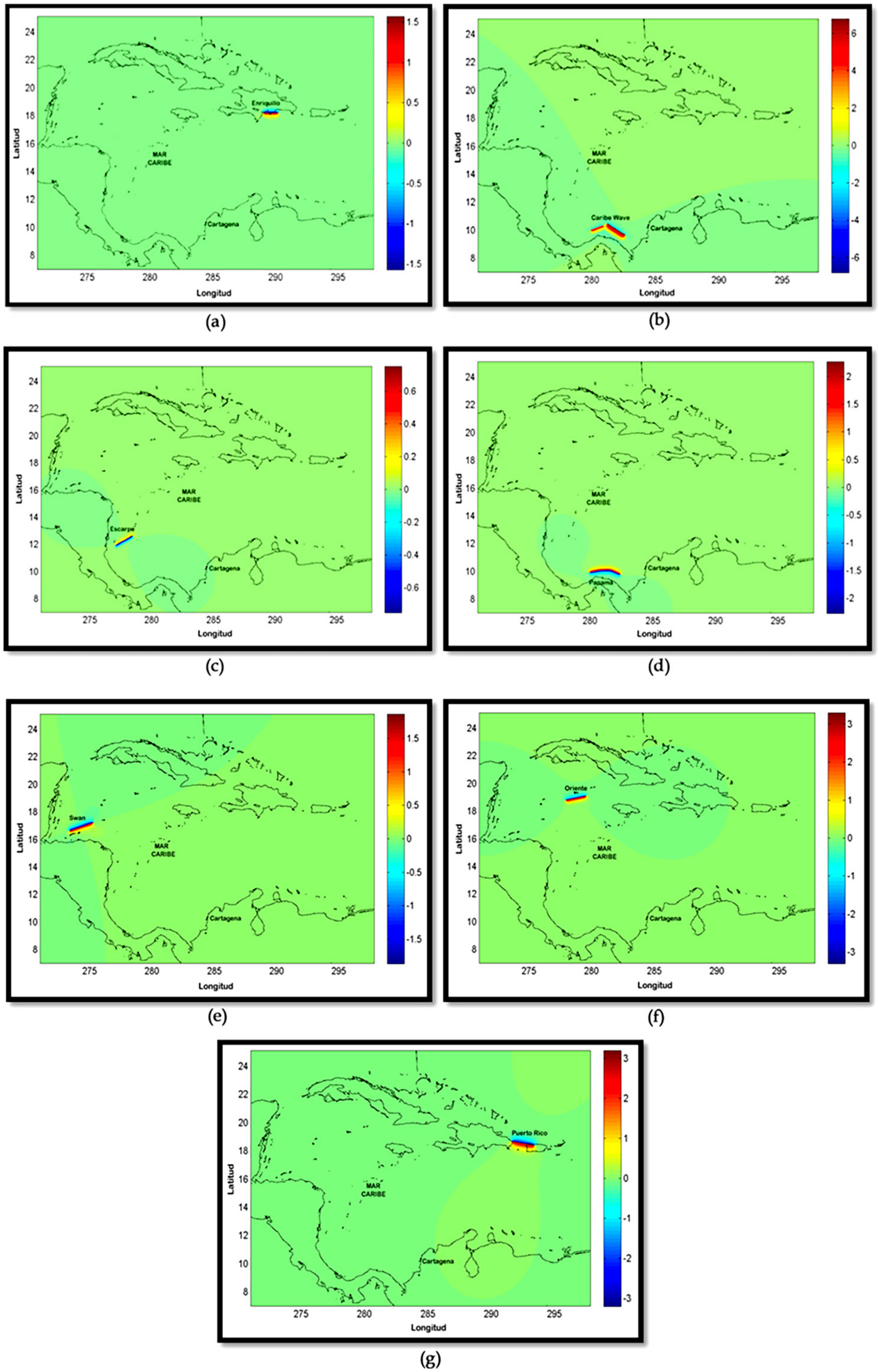

Figure 7. Initial deformation of the seabed. (a) Enriquillo, (b) Caribbean Wave, (c) Escarpe, (d) Panama, (e) Swan, (f) Oriente, (g) Puerto Rico.

is the one that generates the most flooding for the population of Cartagena (Figure 9), and on the graph that impact waves ranging from 3 m in Bocagrande, to almost 4 m in Tierrabomba are observed. These waves generate a sheet of 3 m of water in the lower areas such as: Bocagrande, Marbella and La Boquilla. However in the internal bay of Cartagena, the increase in sea level is less than 1 meter, thanks to the decrease in energy and amplitude of the wave that impacts directly on the Tierrabomba Island, serving as a natural barrier and helping considerably to protect this area.

The wave train that arrives at Cartagena in a state of high tide, has heights of 1.4 m, 1.1 m and 51 cm respectively, with arrival times of 34 min, 82 min and 121 min. This implies that the first wave would be the one that would cause greater damage to the population, and they would have no more than half an hour to evacuate the areas of less exposure safely.

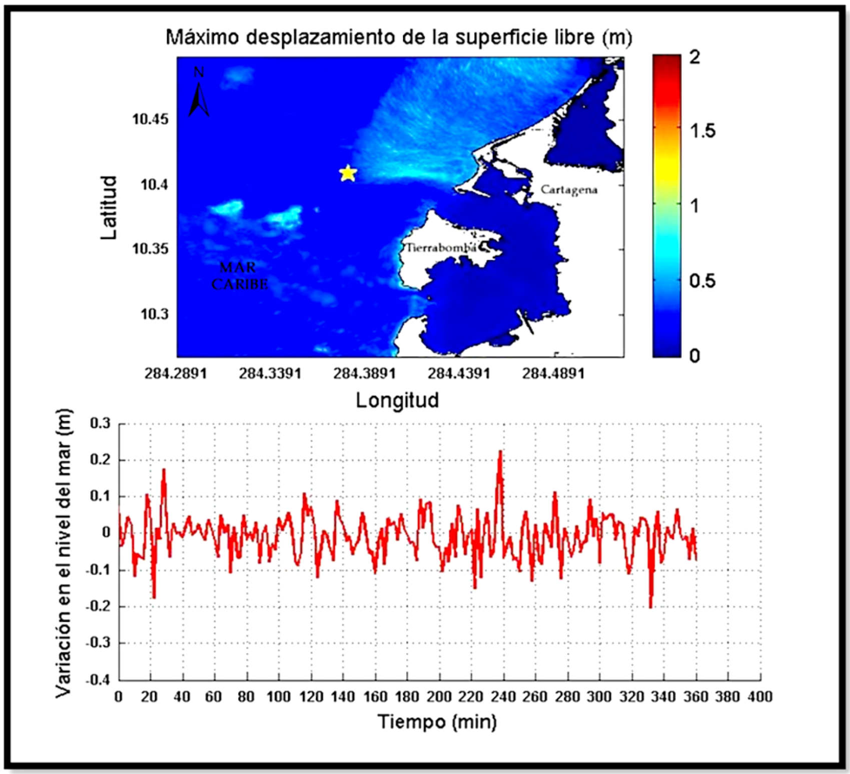

Figure 8. Result of a tsunami generator scenario of regional origin located in Enriquillo, with magnitude Mw 7.7 for the population of Cartagena. The star corresponds to the location of the synthetic tide gauge.

Seismic scenario Escarpe

When an event occurs with epicenter in Escarpe, it generates tsunami waves that impact mainly on the sector of Bocagrande (Figure 10), with an amplitude of approximately 20 cm at high tide, which do not generate a large impact on the lower areas, or in the internal bay of Cartagena, where the increaseis almost 10 cm. According to the synthetic tide graph, the arrival time of the first wave is close to 74 minutes; nevertheless, it is not the wave with greater amplitude, because 8 minutes later, a wave arrives with a height close to 4 cm, this implies that an event like this, would not have major consequences on the population under study.

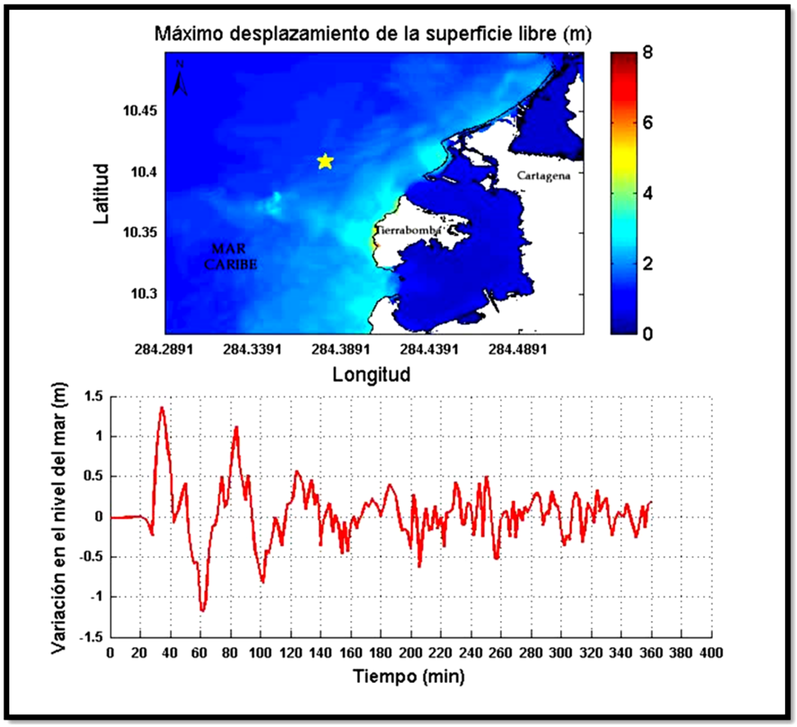

Figure 9. Result of a tsunami generator scenario of regional origin, located in the Caribbean Wave scenario, with magnitude Mw 8.5 (total for the two segments) for the population of Cartagena.

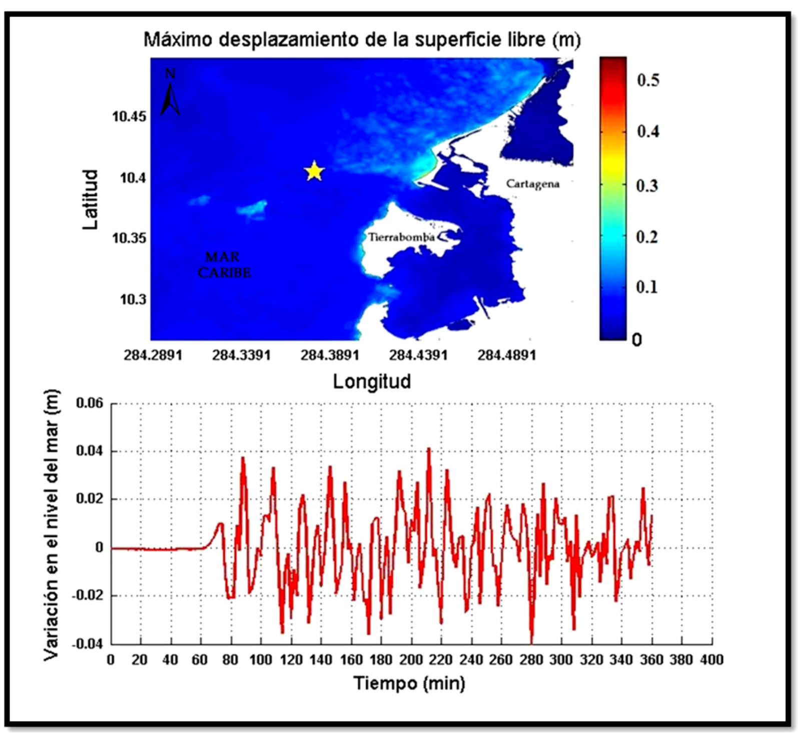

Figure 10. Result of a tsunami generator scenario of regional origin located in Escarpe, with magnitude Mw 5.8, for the population of Cartagena.

Seismic scenario Panama

This seismic scenario, although it is relatively close to the city of Cartagena, due to the characteristics of the event and the focal parameters, does not cause the same effects as the Caribbean Wave, because the flood scenario (Figure 11), at high tide, shows that waves impact mainly on the coastal sector of Bocagrande, Marbella and La Boquilla, waves with an amplitude that rises up to almost 1 m, causing floods that do not exceed 50 cm in the lower areas, this being more evident in La Boquilla. From the synthetic signal recordedat the point of interest, it can be inferred that the arrival time of the first wave is 30 minutes with a height of 15 cm, this being the highest wave train reaching the coast of Cartagena.

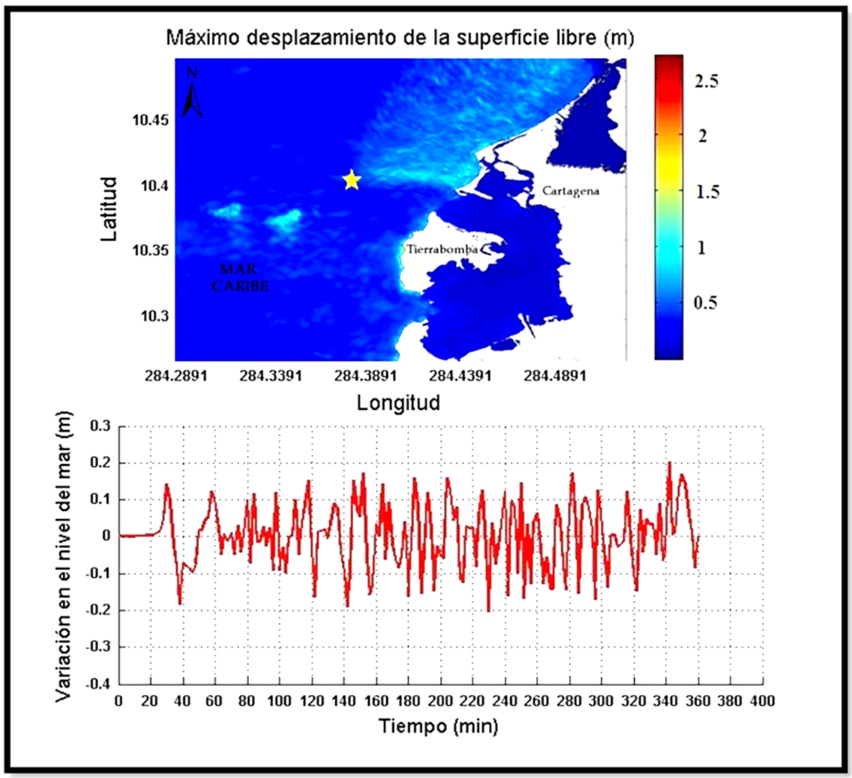

Figure 11. Result of a tsunami generator scenario of regional origin located in Panama, with magnitude Mw 7.9, for the population of Cartagena.

Swan seismic scenario

The flood generated by the Swan seismic scenario (Figure 12), at high tide, shows that like the previous scenarios, the area of greatest impact is the Bocagrande sector, which receives waves that propagate from the epicenter of the earthquake to the coast and arrive with an amplitude of approximately 15 cm, without generating a significant sheet of water. The internal bay is not badly affected, since the sea level increases a few centimeters but does not affect the population. From the synthetic signal it is inferred that this wave arrives in approximately 3.8 hours with an almost imperceptible height of 3 cm.

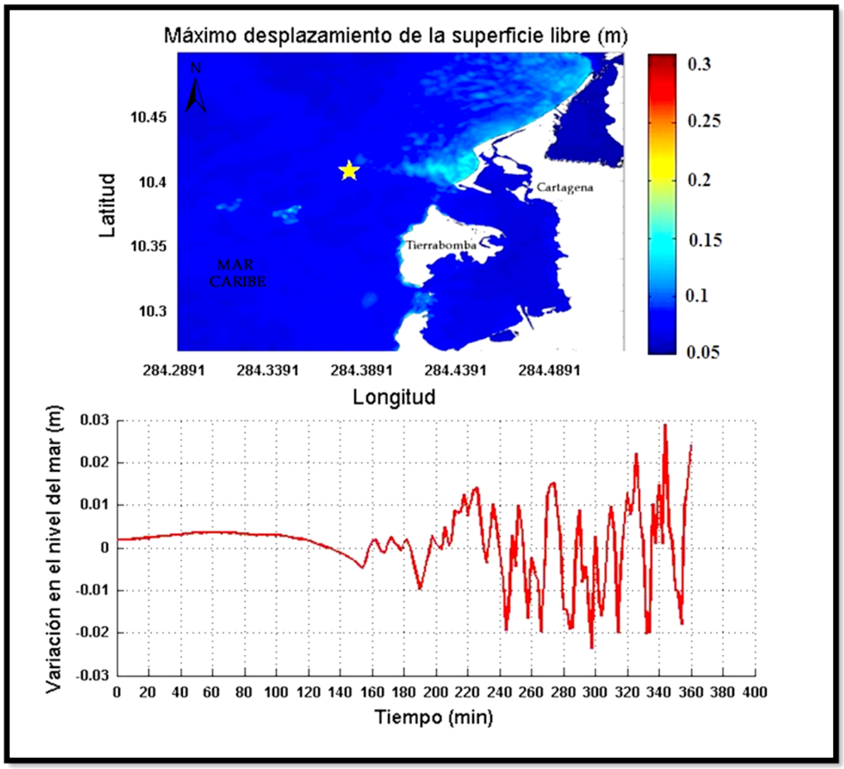

Figure 12. Result of a tsunami generator scenario of regional origin located in Swan, with magnitude Mw 7.3, for the population of Cartagena.

Oriente seismic scenario

In the flood generated by the seismic scenario located in Oriente (Figure 13), it can be observed that at high tide, the greatest impact is in the area of Bocagrande, with heights ranging from 30 cm to 40 cm. This elevation of the surface generates minimum floods of approximately 10 cm in the northern part of Cartagena. This implies that an event with these characteristics would not generate significant damage to the city of Cartagena, because due to the distance and conditions of the seabed, the wave disperses and decreases its amplitude to such an extent that the fraction that reaches the Cartagena beaches is not of great importance.

The synthetic tide graph, indicates that the arrival time of the first wave to the control point, occurs in about 2 hours with a wave height close to 5 cm; however, an hour later, a wave arrives with an amplitude close to 10 cm, which confirms that in a tsunami event the first wave is not always the biggest.

Puerto Rico seismic scenario

Once an earthquake like the one represented by the Puerto Rico scenario has occurred, it generates waves that directly impact on the beaches of Bocagrande, Marbella and La Boquilla, with a height above the surface that rises to approximately 75 cm, generating floods of 50 cm mainly in the lower areas of the northern part of Cartagena (Figure 14).

As for the internal bay, the increase is of almost 30 cm, due to the reduction in wave height when it hits the barrier island of Tierrabomba. It is appreciated from the synthetic signal, that the first wave arrives in 2.13 hours, but the wave of greater amplitude arrives 2 hours later with a height of 12 cm.

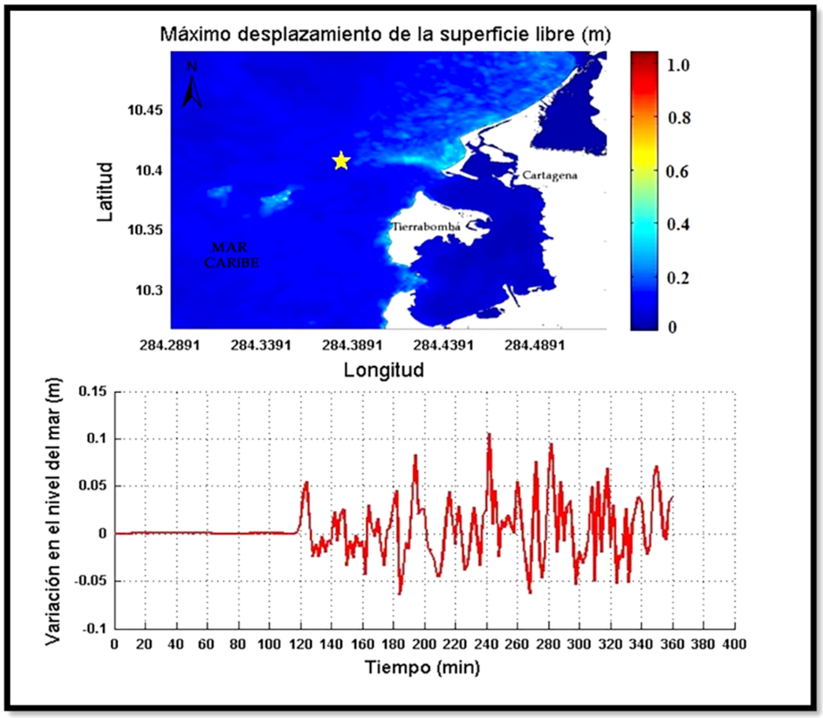

Figure 13. Result of a tsunami generator scenario of regional origin located in Oriente, with an Mw 7.1 magnitude, for the population of Cartagena.

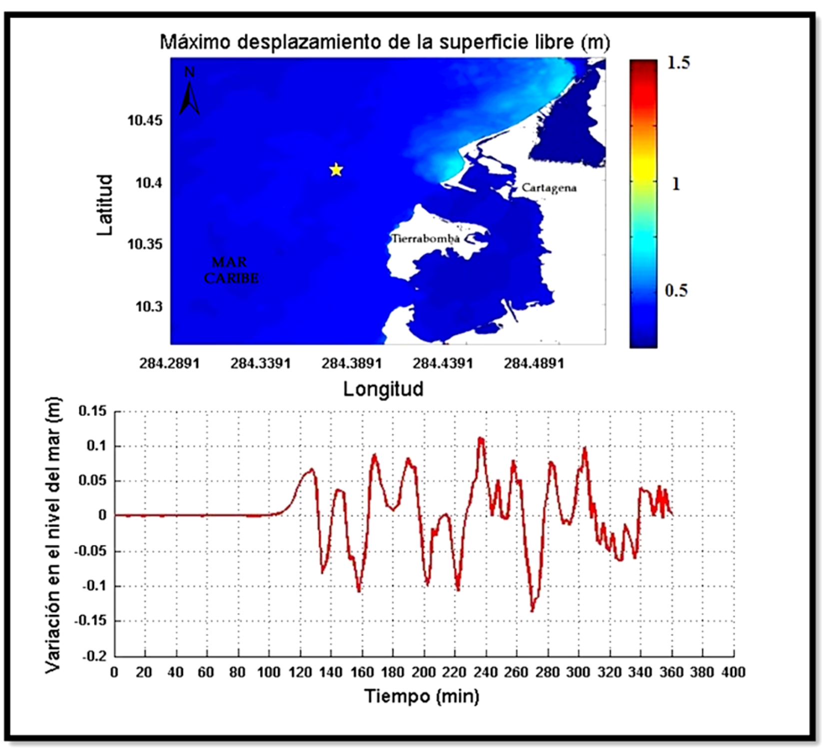

Figure 14. Result of a tsunami generator scenario of regional origin located in Puerto Rico, with magnitude Mw 7.5, for the population of Cartagena.

Conclusions

The scenario that has the most impact on the city of Cartagena, is the seismic scenario represented in the CARIBEWAVE / LANTEX 15 exercise, generating waves of up to approximately 5 m, which impact the island of Tierrabomba, which in turn represents a natural barrier for the internal bay of Cartagena. However, in the northern part, floods of up to 3 m are generated in the Bocagrande sector and the lower areas of Marbella and La Boquilla.

The most affected areas by all scenarios according to their geological formation, the bathymetry of the area and the direction of propagation of events, is the sector of the beaches of Bocagrande, Marbella and La Boquilla; because all the events impact mainly on these zones. On the other hand, the Island of Tierrabomba, plays an important role in protecting a large part of the city, since being the first to receive the impact of the generated wave train, it attenuates and absorbs in greater quantity the energy coming from the tsunami, causing the wave amplitude to decrease by up to 70 % upon arrival in the city of Cartagena.

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