Construction of tsunami sceneries databases for the Colombian Pacific

Construcción base de datos de escenarios de tsunami para el Pacífico colombiano

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ABSTRACT

Tsunamis are natural phenomena that although rarely occurring, clearly affect coastal zones, causing flooding, loss of life, geomorphological modifications of the seabed and the coast, among others. The Colombian Pacific is part of the so-called "Belt of Fire" within which are the populations of Tumaco and Buenaventura, places where the study will be centered. For the determination of the macro-seismic parameters of each proposed scenario the deterministic and probabilistic approximations were used, and the simulation of events of near, regional and distant origin; was performed using the COMCOT (near and regional event) and MOST (distant event) models. After, a database was obtained with a total of 510 tsunami scenarios for both Tumaco and Buenaventura, from which it is possible to obtain information about the time of arrival and maximum height of the tsunami wave train to the coast. Finally, an expansion of the database is recommended, through a greater densification of tsunami scenarios for the rest of the populations of the Pacific and the Colombian Caribbean.

KEY WORDS: tsunami, numerical modeling, database, Buenaventura, Tumaco.

RESUMEN

Los tsunamis son fenómenos naturales que aunque se presentan rara vez, afectan de forma evidente las zonas costeras, produciendo inundaciones, pérdida de vidas, modificaciones geomorfológicas del lecho marino y la costa, entre otras. El Pacífico colombiano hace parte del llamado "Cinturón de Fuego" dentro del cual se encuentran las poblaciones de Tumaco y Buenaventura, lugares donde se centrará el estudio. Para la determinación de los parámetros macrosísmicos de cada escenario propuesto se utilizaron las aproximaciones determinista y probabilista, y la simulación de los eventos de origen cercano, regional y lejano; se realizó mediante los modelos COMCOT (evento cercano y regional) y MOST (evento lejano). Igualmente, se obtuvo una base de datos con un total de 510 escenarios de tsunami tanto para Tumaco como para Buenaventura, de los cuales es posible obtener información acerca del tiempo de llegada y la altura máxima del tren de olas de tsunami a la costa. Finalmente, se recomienda una ampliación de la base de datos, mediante una mayor densificación de escenarios de tsunami para el resto de poblaciones del Pacífico y Caribe colombiano.

PALABRAS CLAVES: *Tsunami, modelación numérica, base de datos, Buenaventura, Tumaco.*

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INTRODUCTION

Colombia is located within the so-called "Pacific Ring of Fire" and almost on the verge of the encounter of two tectonic plates, the South American and the Nazca, creating a subduction zone, where hundreds of earthquakes have been produced (Otero, Restrepo & González, 2014). These earthquakes were associated with the generation of tsunami, causing severe damage and loss of life along the Pacific coast of Ecuador and Ecuador.

For the benefit of this analysis, it is worth mentioning the 1979 event when a powerful earthquake registered on Wednesday, December 12, with an epicenter located in the Pacific Ocean, 75 kilometers off the coast of Tumaco affected a significant number of inhabitants of the place, leaving a balance of 450 dead and about 1000 injured (Cardona, Toro, Vélez & Otero 2005).

It is necessary to have a database of tsunami scenarios to counteract this type of effects and thus evaluate the flood caused in the largest population centers of the Pacific coast, Tumaco and Buenaventura. This database was developed for tsunami events of near, regional and distant origin, and provides information about the arrival time of the first wave to the coast and its maximum height.

The Bay of Buenaventura is located in the department of Valle del Cauca at coordinates 3 ° 53'35 "N 77 ° 4'10" W. Due to its constant dynamics of its maritime and commercial activities, since it is the main port of the Colombian Pacific, it has induced a significant increase in all its related activities, which induces a sustain in the quality of a competitive port for international trade, and hence the importance of evaluating this type of threat in this area. Regarding Tumaco, it is a municipality located in the southwest of the department of Nariño, its geographical location is at coordinates 1 ° 48'24 "N 78 ° 45'53" W. It is the second port in importance of the Colombian Pacific and represents an industrial, port, biodiverse and ecotourist area. According to the last census of the Dane, 161 490 inhabitants are reported for the population of Tumaco and 324 207 for Buenaventura (Dane, 2015), a fact that corroborates that both represent one of the places with the highest population density in the Pacific.

It is also interesting to highlight how, the scenario bank was obtained through the application of different methodologies, the first based on the editing and processing of all the topobatimetric information of the areas under study and subsequent creation of the computational domains associated with it. Secondly, the definition of tsunami scenarios was made, through the application of different approaches, the deterministic for events of regional and distant origin, and the probabilistic approach for nearby origin. Finally, for the simulation of the tsunami wave, the numerical model COMCOT V1.7 (for its acronym in English, Cornell Multi-grid Coupled Tsunami Model) (Wang, 2009) for events of near and regional origin and MOST was used. (for its acronym in English, Method of Splitting Tsunami) with its graphical interface, ComMIT V1.5.3 for events of distant origin.

Through the process of systematization, it was possible to load the simulated scenarios in the database and thus store both the graphic output of the maximum flood and the synthetic mareogram associated with it. This information is protected and preserved in a computational tool designed for the administration of precomputing scenarios, which associates the time of arrival and height of the first wave, results obtained from the application of the numerical model.

STUDY AREA

In the departments of Nariño and Valle del Cauca, population centers of Tumaco and Buenaventura, in the southeastern part of the Colombian Pacific coast, the work study area referred to here is concentrated (Figure 1). The risk in each of these populations is great due to the high vulnerability and threat of existing marine origin, in addition if the socio-economic environment is considered, and the structural conditions of the houses (palafitic constructions), it becomes an environment where Concentrate efforts to mitigate the effects of a tsunami.

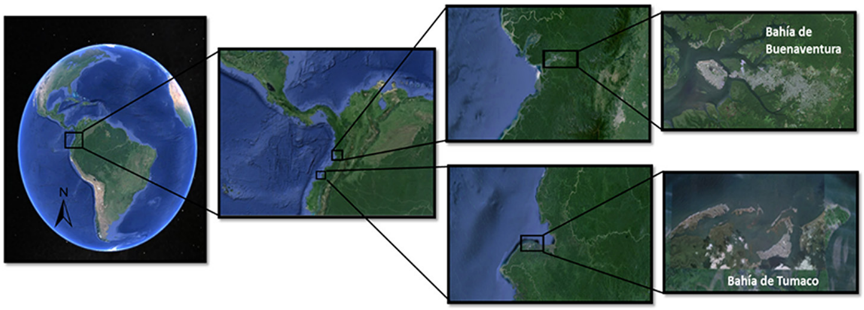

Figure 1. The general area of study shows the population of Buenaventura and Tumaco.

MATERIALS AND METHODS

The methodology used is based on the numerical modeling of tsunami scenarios; through the implementation of two types of techniques or approaches, the first is the probabilistic, PTHA (Probabilistic Tsunami Hazard Analysis), based on the synthetic generation of future tsunami scenarios. This analysis is carried out in three steps, determination of the parameters of the source of the earthquake and its associated uncertainties, establishment of its relations with the propagation of tsunamis and probabilistic calculations. The second approach is deterministic, based on the selection of the worst credible tsunami scenario, which is generally selected from historical tsunami records in the study region (Otero, 2008).

In this way, a database of tsunami scenarios was created and prepared, which has information about the height and time of arrival of the first wave, and the distribution of flooding on the coast for each of the populations under evaluation.

Delimitation of the work area

For the delimitation of the work area, the areas with the highest density of topobatimetric information were selected in order to construct the computational domains that will be the base input in the numerical modeling processes (Cornell University, 2015).

The nested grid systems or domains are dynamically coupled up to four regions with different grid resolution. In each of the regions you can choose the system of equations that will govern it, whether linear or non-linear, since for a given earthquake, the displacement of the seabed is determined from a linear theory of elastic displacement (Wang, 2009).

The use of the COMCOT numerical model was essential to assess tsunami threats of near and regional origin (Wang, 2009). It is also noteworthy that the mesh set for the zones evaluated is represented by spacings of 30, 90, 270, and 810 meters, respectively (Table 1), and whose spatial arrangement is shown in Figure 2.

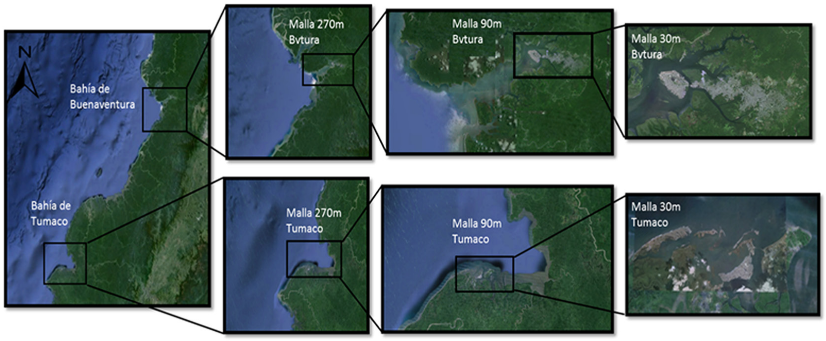

Figure 2. Arrangement of computational meshes corresponding to the areas of Tumaco and Buenaventura.

In the Table 1 the limits and sizes of each computational array are shown

Table 1. Characteristics of the computational mesh arrangement for the areas under study.

Mesh size	Area covered	Lower left limit (°)	Upper right limit (°)
810 m	Pacific	-83.010; -1.492	-76.800; 6.742
270 m	Municipality of Tumaco	-79.327; 1.335	-78.247; 2.460
	Municipality of Buenaventura	-78.002; 3.223	-76.944; 3.937
90 m	Bay of Tumaco	-79.111; 1.338	-78.241; 2.455
	Bay of Buenaventura	-77.239; 3.775	-76.944; 3.937
30 m	Buenaventura urban area	-77.090; 3.844	-76.950; 3.913

For the evaluation of threats of distant origin, the numerical model MOST (Method of splitting Tsunami) was used (Titov *et al.,* 1997) through the methodology ComMIT (Community Model Interface for Tsunami) (Titov *et al.,* 2011), developed by Vasily V. Titov of the Marine Environmental Laboratory of the Pacific and Costas E. Synolakis of the University of Southern California (Titov & Synolakis, 1995); today, the model is used at the Center for Tsunami Research (NCTR) (NOAA, 2015). The configuration of the mesh set was established as described below: the inner one has a spacing of 30m (~ 1 second of arc), and the outer ones were created with spacing of 180m (~ 6 seconds of arc) and 1080m (~ 36 second of arc).

The limits of the computational meshes are reflected in Table 2.

Table 2. Characteristics of the arrangement of computational meshes for the areas under study using the MOST model.

Mesh size	Area covered	Lower left limit (°)	Upper right limit (°)
1080 m	Municipality of Tumaco	-79.327; 1.335	-78.247; 2.460
	Municipality of Buenaventura	-78.002; 3.224	-76.944; 3.937
180 m	Bay of Tumaco	-79.111; 1.338	-78.241; 2.455
	Bay of Buenaventura	-77.239; 3.775	-76.944; 3.937
30 m	Buenaventura urban area	-77.090; 3.844	-76.950; 3.913
	Tumaco urban area	-78.832; 1.779	-78.711; 1.854

Seismic scenario definition

Based on information reported by the Colombian Geological Service, seismic precursor scenarios of tsunami were defined (UNGRD, 2013), these are the seismicity works in the Pacific (Sánchez & Puentes, 2012), and the application of different extraction techniques of scenarios, such as the probabilistic and deterministic approach (Uninorte & Dimar, 2014; Geist & Parsons, 2006).

Deterministic technique for scenarios of near origin

For the definition of the worst credible scenarios of generation of tsunamis of near origin in the Colombian Pacific coast, a classification of the area is made, essentially in two: *northern block and southern block.*

Nothern Block

The seismic activity in the area of the Bahía Solano fault and associated segments is recognized, throughout this zone several important events are recorded, among which the earthquake of 1970 (Mw 6.5) that destroyed in 80% the municipality of Puerto Mutis (Bahía Solano) (Taboada, Dimate, & Fuenzalida, 1998). It is important to highlight for the benefit of this analysis, how on January 8, 2003, two (2) earthquakes of magnitude Mw = 5.5 and Mw = 4.8, respectively, were reported. The main earthquake occurred south of Bahía Solano (west of Utría Bay), on a surface fault of the E-W course and dextral movement, which would be the continental continuation of a shear zone that segmented the Nazca plate at this latitude. The tectonic interpretation states that the subduction of the Nazca plate is slowed by collision of the Chocó block with the continental strip, transmitting the efforts (resulting from the convergence) to the two plates and fracturing them (OSSO Corporation, 2004).

The northern zone between Cabo Corrientes and the Gulf of Cupica presents a seismic activity with events up to 7.2 Mw. Although at present there are no historical records of destructive tsunamigenic events in the area, it is important to consider the seismicity presented by the Bahía Solano fault (Taboada, Dimate, & Fuenzalida, 1998).

The location of the events obtained from the Harvard CMT catalogs (The Global Centroid-Moment-Tensor)m(CMT, 2015) and SISRA (Regional seismic catalog of South America) (Ceresis, 2015) is presented in Figure 3. Initially, it is possible to identify two zones in the northern region of the Colombian Pacific, where most of the seismic activity is concentrated (red circles).

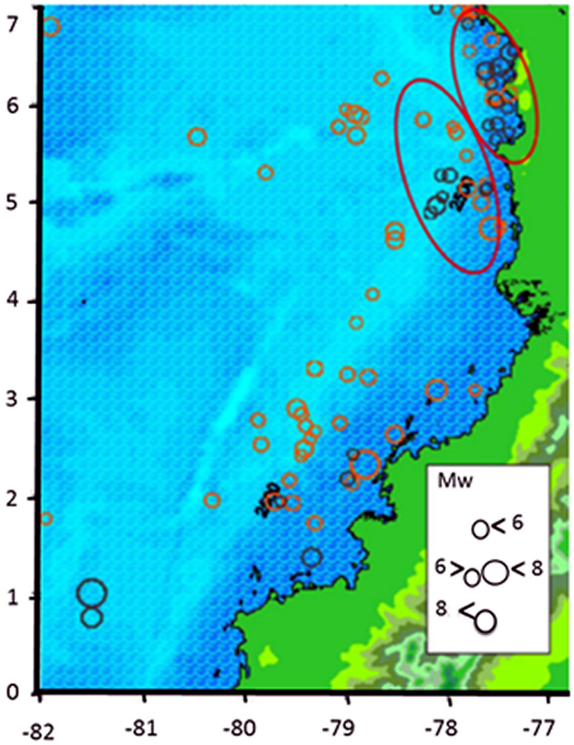

Figure 3. Surface earthquakes, of magnitude Mw> 5. Colombian Pacific North block. Taken from Kanamori & Mcnally (1982).

In the Table 3 the seismic events of the Harvard CMT catalog are presented by zones.

Table 3. Seismic events by areas of the Harvard CMT catalog.

Zone	Date	Lon (°W)	Lat (°N)	Pro (km)	Plane of failure 1			Plane of failure 1			Mw
					Str1	Dip1	Slip1	Str1	Dip1	Slip1	
I	1978/02/16	-78.24	5.84	15	249	36	-77	53	55	-100	5.6
	1988/09/20	-77.68	4.99	24.1	14	18	104	179	73	85	5.8
	1990/08/25	-77.93	5.71	35.1	350	36	79	183	54	98	5.3
	1991/12/10	-77.48	4.74	20.7	45	22	127	186	72	76	5.2
	1997/09/09	-77.82	5.47	24.1	338	28	40	211	73	112	5.1
	2002/08/08	-77.62	5.17	22.3	12	45	-140	251	63	-52	5.7
	2003/11/05	-77.81	5.14	27.6	15	38	-137	248	65	-60	5.9
	2004/11/15	-77.57	4.72	16.0	21	11	114	177	79	85	7.2
	2008/02/10	-77.95	5.76	23.7	100	72	-12	194	79	-161	5
II	1977/08/08	-77.78	6.93	15.0	287	19	25	173	82	108	5.4
	1983/01/23	-77.57	6.66	15.0	358	39	-20	104	78	-127	5.5
	1988/11/26	-77.89	6.95	21.4	316	29	-56	98	67	-107	5.4
	1990/08/25	-77.63	6.26	16.8	40	20	134	174	76	76	5.6
	1996/05/23	-77.56	6.06	15.9	349	8	82	176	82	91	5.7
	2000/07/12	-77.80	6.54	15.0	319	34	-144	167	59	-75	5.2
	2003/01/08	-77.40	6.10	25.1	299	76	172	31	82	14	5.7
	2006/01/23	-77.77	6.97	15.0	316	14	53	174	79	98	6.2
	2006/01/24	-77.73	6.96	23.7	307	29	50	170	68	110	5.4
	2006/01/29	-77.82	6.88	27.0	313	23	58	167	71	103	5.2
	2007/09/22	-77.53	6.06	20.3	8	20	90	188	70	90	5.0

Taken from González & Otero (2010).

In the Table 3, those sources from which events could generate destructive potential for the area are identified, this is how two sources of tsunami are established, the first corresponds to the Cabo Corrientes - Arusí segment and the second segment, Arusí - Cabo Marzo.

The Table 4 presents the parameters of the extreme seismic scenarios of tsunami generation for the north of the Colombian Pacific, based on the work carried out by (González & Otero, 2010).

Table 4. Seismic parameters (North Block Scenario).

Parameters	Cabo corrientes - Arusí	Arusí - Cabo Marzo
Dislocation (m)	4.0	4.2
Length (km)	140	147
Width (km)	70	73
Course (°)	329	349
Dip (°)	11	14
Pitching (°)	40	53
Depth (km)	16	15
Magnitude (Mw)	7.92	7.96

Taken from González & Otero (2010).

South Block

For the definition of the worst credible seismic scenario of generation of tsunami in the south block of the Colombian Pacific, the macroseismic parameters reported for the earthquake occurred in 1906 in the Colombian-Ecuadorian subduction zone (Otero, Restrepo, & González, 2014; Hayes, Smoczyk, Benz, Villaseñor, & Furlong, 2015; Kanamori & Mcnally, 1982). Thus, taking a maximum moment of 8.8 Mw.; a seismic moment of 2.0 * 1022 Nm is established, which is equal to the value established in (Kanamori & Mcnally, 1982).

It is also clarified that they were determined from the scale relationships proposed by Kanamori & Anderson, 1975, Papazachos, Scordilis, Panagiotopoulos, Papazachos, & Karakaisis, 2004, Rousseeuw & Leroy, 1987, Wells & Coppersmith, 1994), the parameters of the plane of failure, as width and length of the rupture, and sliding; with respect to the focal mechanisms, a strike of 31 °, a dip angle of 16 °, a dip address of 118 °; and a depth of 26.6 km, reported by (Engdah, Van der Hilst, & Buland, 1998). Finally, in Table 5 the scenario of the subduction zone is established.

Table 5. Seismic parameters (Subduction Zone Scenario).

Parameters	South Block
Dislocation (m)	8.06
Length (km)	581
Width (km)	116
Strike (°)	31
Dip (°)	25
Rake (°)	129
Depth (km)	20
Magnitude (Mw)	8.8

Deterministic technique for scenarios of regional origin

A review of historic seismicity is performed in the area between 4 ° S and 17 ° N of latitudeand 100 ° W and 75 ° W of longitude, in order to classify potentially tsunamigenic earthquakes, in this way a classification is obtained of the superficial earthquakes (depths up to 50 km) and with magnitudes greater than 6.0 Mw, which occurred in this area (Figure 4).

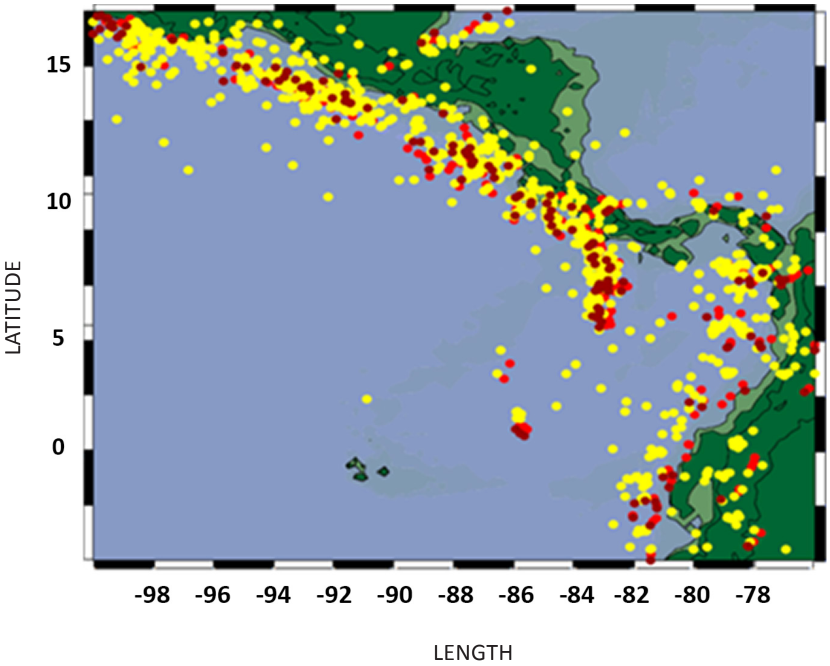

Figure 4. Earthquakes in the Pacific Ocean for the zone of Central America and Colombia. Taken from Uninorte & Dimar (2014).

From the segmentation of the subduction zone, in (Álvarez, Gutiérrez, Aniel & Gonzáles, 2012) the strike angles and the maximum lengths for the different fault segments are established. The width is obtained from the maximum depth of rupture, 20 km, while the angle of dip is selected based on the event of Nicaragua 1992. In addition, in combination with the available data of the normal faults, a set of potential sources is defined of tsunamis (Table 6), where the parameters obtained for the four segments in the subduction zone of the Mesoamerican fossa are shown.

Table 6. Worst possible scenarios for the mesoamerican fosse. The first three sources taken from Uninorte & Dimar (2014).

Source	Lon (°W)	Lat (°N)	Pro (km)	Largo (km)	Ancho (km)	Str (°)	Dip (°)	Slip (°)	Despl (m)	Mw
El Salvador	-89.53	12.50	10	260	73	292	16	90	4.0	8.1
Guatemala	-91.48	13.31	10	205	73	295	16	90	2.6	7.9
Chiapas	-93.63	14.44	10	330	73	301	16	90	5.3	8.2
Nicaragua	-87.44	10.81	10	200	73	315	16	90	2.6	7.7

Deterministic technique for scenarios of distant origin

A tsunami can travel long distances and cause serious material damage and loss of life in coastal areas. Due to the close relationship between seismic movements and tsunamis, the main generating areas of this phenomenon coincide with the most active seismic and coastal seismic areas. Based on the above, at the global level, four tsunami generating zones are defined: (1) Pacific, (2) Indica, (3) Atlantic, and (4) Mediterranean (Figure 5).

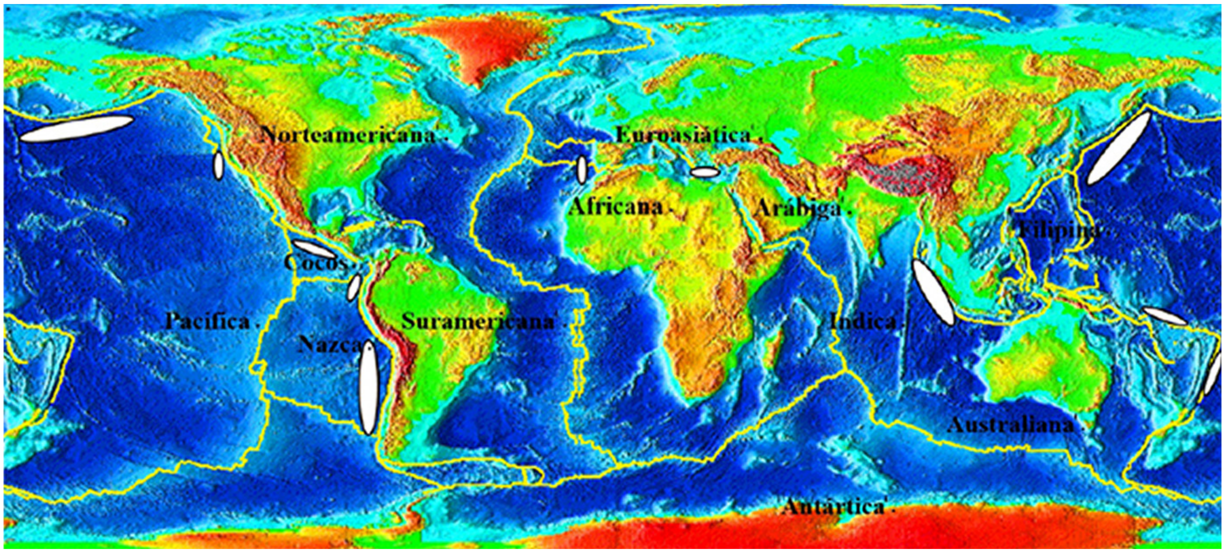

Figure 5. Tectonic plates and main areas of generation of tsunamis around the world (white ellipsoids). Taken from L. Otero (2008).

The Figure 5 shows the zones of greater seismic activity of the so-called "fire belt", demarcated by the white ovals, and where it is possible to focus the search of our sources of tsunami origin of distant origin. For this identification, the following was taken into account: compilation of information on historical events of tsunamis in the areas of interest, analysis of the historical seismicity of the region, focal mechanisms and depths of seismic events. From there, 6 potential seismic sources with tsunami capacity were selected, located in the countries of Chile, Cascadia, Salomón, Alaska, Japan and Samoa (Table 7) and based on the work carried out by (AON, 2011; Beccari, 2009 Chen, Newman, Feng & Fritz, 2009, IRIS, 2013, Johnson *et al.,* 1994, Laverov *et al.,* 2009, Miller, Huene & Ryan, 2014, Muñoz, 2010, Nourse, 2013, Wong, Dober, Pezzopane, Thomas & Terra, 2012).

Probabilistic technique for scenarios of near origin

It is possible to estimate the danger of tsunamis and its impact on the coast from the generation and modeling of possible seismic events. The approach used, proposes a model based on MonteCarlo techniques that takes into account the sea level in the definition of tsunamigenic scenarios. This allows to generate scenarios, combining tsunami events with variations in sea level, associated with astronomical and meteorological tides.

The approach includes the following stages: generation of a database of numerically simulated tsunami events for the different sources of generation, generation of a synthetic catalog of tsunami scenarios by sources, and finally, the probabilistic representation of the maximum values of the variables selected to assess the danger (Otero, 2008). In the first stage the following steps were carried out, identification and localization of the potential sources of tsunami in the Colombian Pacific, definition of seismic scenarios for each of the sources, definition of sea level, generation and propagation of events through numerical modeling and finally, the selection of maximum values with the variables of interest.

Table 7. Table of deterministic cases for tsunamigenic events of distant origin.

Source	Lon (°W)	Lat (°N)	Depth (km)	Large* (km)	Width* (km)	Mw
Chile	-72.72	-35.85	10	500	100	8.8
	-74.50	-39.50	10	900	150	9.5
Perú	-71.00	-18.50	10	600	150	9.0
Japón	142.37	38.29	10	300	150	9.0
	144.12	41.75	10	200	50	8.0
Kuril	153.77	46.70	10	400	50	8.3
Cascadia	-124.94	47.32	10	1000	50	9.1
Salomón	-172.04	-15.61	10	200	100	8.0
	165.01	-10.79	10	300	150	8.1
Samoa	172.03	-15.51	10	400	100	8.3
Alaska	-163.5	52.75	10	400	100	8.1
	-175.39	51.56	10	800	100	8.6

* The boxes named length and width correspond to the area of rupture that represents the fault plane and were represented as source units in the COMMIT model.

In the second stage, the frequency of tsunamigenic earthquakes in the area is calculated, the probability distribution function of seismic moments and the distribution of the location of the epicenter along the fault is applied. Next, the probability distribution function of sea level (High tide plus medium tide) is determined, to obtain in this way the catalog of all tsunami scenarios by source.

Finally, through the MonteCarlo simulations, it is possible to determine the numerical database for each tsunami source and thus obtain the maximum values of the variables selected to assess the danger (Uninorte & Dimar, 2014).

Thus, once the study areas were classified in the deterministic approach, north block and south block, the two zones are taken in this type of approach, with a total of three tsunami sources, two in the North Block (Cape segment) currents-Arusi - Zcca and Arusi - Cabo Marzo-Zacm) and one in the South Block (Subduction Zone).

Nothern Block

Tables 8 and 9 list the epicenters of each of the sources corresponding to the northern block of the Colombian Pacific, extracted through the implementation of the probabilistic approach.

Table 8. Epicenters corresponding to source Arusí-Cabo Marzo.

Epicenter	Longitude (°W)	Latitude (°N)
1	-77.6505807	6.11305801
2	-77.7370008	6.55545874
3	-77.5646268	5.67119327

Table 9. Epicenters corresponding to source Arusí-Cabo Corrientes.

Epicenter	Longitude (°W)	Latitude (°N)
1	-77.89117999	5.157350981
2	-78.12442452	5.543329967
3	-77.66014769	4.770793276

Tables 10 and 11 show the probabilistic cases of tsunami scenarios for the Arusí-Cabo Marzo source, together with the macroseismic parameters, epicenters and tidal level associated with each case.

Table 10. Probabilistic cases corresponding to source Arusí-Cabo Marzo.

Cases	Area (km^2)	Mw	Length (km)	Width (km)	Dislocation (m)	Epicenter	NM
1	500	6.7149906	31.622777	15.811388	0.99173273	1 al 3	3
2	1500	7.1825694	54.772256	27.386128	1.6620406	2	3
3	2500	7.3999812	70.710678	35.355339	2.1130538	2	3
4	3500	7.5431867	83.666003	41.833001	2.4750885	2	3
5	4500	7.6501483	94.86833	47.434165	2.7854068	2	3
6	5500	7.7355554	104.88088	52.440442	3.0609005	2	3
7	6500	7.8066551	114.01754	57.008771	3.3109149	2	3
8	7500	7.86756	122.47449	61.237244	3.5412578	2	3
9	8500	7.9208305	130.38405	65.192024	3.7558275	2	3
10	9500	7.9681691	137.84049	68.920244	3.9573899	2	3
11	10500	8.0107655	144.91377	72.456884	4.1479901	2	3

The focal parameters for the Zacm source are given by a heading angle of 349 °, dip of 14 ° and pitch of 53°.

Table 11. Probabilistic cases corresponding to source Cabo Corrientes - Arusí.

Cases	Area (km²)	Mw	Longitude (km)	Width (km)	Dislocation (m)	Epicenter	NM
1	500	6.7149906	31.622777	15.811388	0.99173273	1 al 3	3
2	1500	7.1825694	54.772256	27.386128	1.6620406	2	3
3	2500	7.3999812	70.710678	35.355339	2.1130538	2	3
4	3500	7.5431867	83.666003	41.833001	2.4750885	2	3
5	4500	7.6501483	94.86833	47.434165	2.7854068	2	3
6	5500	7.7355554	104.88088	52.440442	3.0609005	2	3
7	6500	7.8066551	114.01754	57.008771	3.3109149	2	3
8	7500	7.86756	122.47449	61.237244	3.5412578	2	3
9	8500	7.9208305	130.38405	65.192024	3.7558275	2	3
10	9500	7.9681691	137.84049	68.920244	3.9573899	2	3
11	10500	8.0107655	144.91377	72.456884	4.1479901	2	3

The focal parameters for the Zcca source are given by a heading angle of 329 °, dip of 40 ° and pitch of 11.

South Block (Subduction Zone)

The epicenters associated with the subduction zone are reflected (Table 12)

Table 12. Epicenters corresponding to source Zsub.

Epicenter	Longitude (°W)	Latitude (°N)
1	-77.7766724	3.6094985
2	-78.0714722	3.2650874
3	-78.3660889	2.9206491
4	-78.6605377	2.5762107
5	-78.9548416	2.2318006
6	-79.2490234	1.8874463
7	-79.3823929	1.7312667
8	-79.5431137	1.5431753
9	-79.8371277	1.1990154
10	-80.1311035	0.8549942
11	-80.4250488	0.5111392
12	-80.7189941	0.167478

For the south block, the resulting synthetic catalog is shown in Table 13. Each case corresponds to a different scenario, with each one of its macroseismic parameters, and the three levels of tide, high, medium and low.

Table 13. Probabilistic cases corresponding to Zsub source.

Case	Area (km^2)	Mw	Longitude (km)	Width (km)	Dislocation (km)	Epicenter	NM
1	500	6.7149906	50	10	0.80410762	1 al 12	3
2	1500	7.1825694	86.60254	17.320508	1.3476005	2 al 11	3
3	2500	7.3999812	111.8034	22.36068	1.7132868	2 al 11	3
4	3500	7.5431867	132.28757	26.457513	2.0068285	2 al 11	3
5	5500	7.7355554	165.83124	33.166248	2.4818112	3 al 10	3
6	7500	7.86756	193.64917	38.729833	2.8712901	3 al 10	3
7	9500	7.9681691	217.94495	43.588989	3.2086945	3 al 10	3
8	12500	8.0849718	250	50	3.6504465	3 al 10	3
9	15500	8.1765251	278.38822	55.677644	4.038817	4 al 9	3
10	18500	8.2518283	304.13813	60.827625	4.3890344	4 al 9	3
11	21500	8.3157897	327.87193	65.574385	4.7102543	4 al 9	3
12	24500	8.3713828	350	70	5.0084845	4 al 9	3
13	28500	8.435748	377.49172	75.498344	5.3774374	5 al 8	3
14	32500	8.4916457	403.11289	80.622577	5.7198344	5 al 8	3
15	36500	8.541047	427.20019	85.440037	6.0405422	5 al 8	3
16	40500	8.5853059	450	90	6.3431085	5 al 8	3
17	44500	8.6253928	471.69906	94.339811	6.630213	6 al 7	3
18	49500	8.6707131	497.49372	99.498744	6.9704805	6 al 7	3
19	54500	8.7116686	522.01533	104.40307	7.2929734	6 al 7	3
20	59500	8.7490266	545.43561	109.08712	7.600134	6 al 7	3
21	64500	8.7833685	567.89083	113.57817	7.8938949	6 al 7	3
22	67500	8.8027177	580.9475	116.1895	8.0643812	6 al 7	3

Reference tidal level

The change in sea level in the Colombian Pacific is significant, due to the effects of the tide, which is the process that most affects the periodic rise and fall of sea level (Valls & Josep, 2009). For this reason it is necessary to associate a tidal level to each modeled tsunami event; this due to the existing superposition between the waves of tsunami and the waves of tide. What could mean an increase in the level of flood or run-up of the areas under study (Cardona, 2004).

The methodology used to define the associated tide level is based on the separate analysis of the astronomical tide using a harmonic analysis, numerical models of propagation and tidal generation; and the meteorological tide, using indirect methods based on MonteCarlo techniques due to the random nature of it. Based on the work done at the DIMAR Research Center (Otero, 2005), the mean sea level regime (Figures 6 and 7) obtained for the population of Buenaventura and Tumaco, respectively, is extracted. From these graphs, it is possible to extract the high, medium and low tide levels (Table 14), values that are added to the detail meshes, in order to evaluate the degree of flooding in the study area.

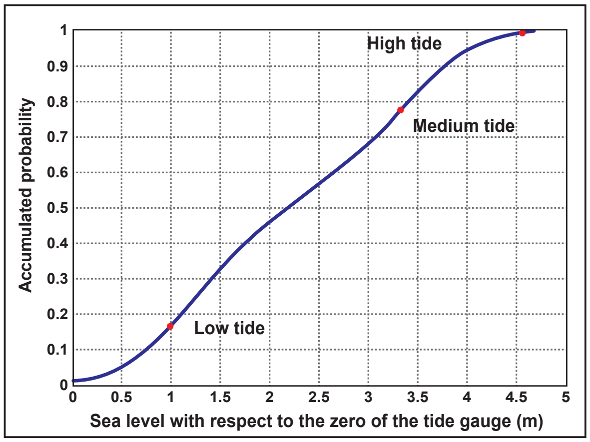

Figure 6. Average regime determined for the urban area of Buenaventura.

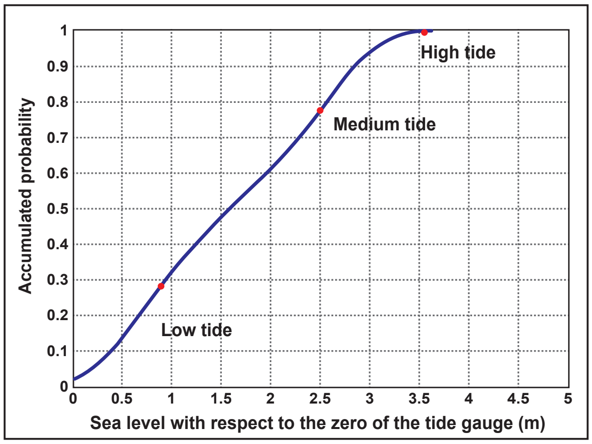

Figure 7. Average regime determined for the urban area of Tumaco.

Table 14. Tidal levels for the populations of interest.

Area of interest	High Tide Level (m)	Medium Tie Level (m)	Low Tide Level (m)
Buenaventura	4.8	3.26	1.0
Tumaco	3.6	2.50	0.80

RESULTS AND DISCUSSION

The modeling of all the scenarios proposed by both the deterministic and probabilistic techniques of each of the evaluated populations was carried out. Where it was possible to determine that the scenarios that generate the greatest impact on the populations of Tumaco and Buenaventura are the events proposed through the deterministic approach; that is, the worst credible tsunami scenario.

In order to synthesize and structure the results obtained in a more convenient way for analysis, it was decided to discuss the scenarios with the greatest impact on each coastal population. In this way, following a structure that allows to distinguish and compare the effects of the tsunami according to the origin where the event is generated.

Worst credible scenario of near origin for the Colombian Pacific

The Figure 8 shows a maximum displacement of the free surface, taking a high tide level, both for the populations of Tumaco and Buenaventura. Where it is possible to appreciate a maximum height of flood sheet of approximately 3 meters for the island of Morro and 2 meters for the island of Tumaco, while the maximum height of the wave in Buenaventura is approximately 1.3 m. As it is deduced, that the population of Tumaco due to the proximity to the subduction zone has a greater affectation, while Buenavetura, presents a minor affectation due to the geomorphology of its coast, being a closed bay that allows the energy coming from the tsunami wave train, decrease by its transit at the entrance to the bay.

In order to record the temporary evolution of the free surface in the areas of interest, coastal points were established at the entrance of Buenaventura and Tumaco Bay, as recorded in (Table 15).

Table 15. Geographical location of the interest points in the urban area of Buenaventura and Tumaco.

Population	Coordinates
Buenaventura	77.0865111ºW ; 3.8701111ºN
Tumaco	78.776466ºW ; 1.843966ºN

Figure 8 also visualizes the synthetic mareograms obtained from the selected points, where the arrival time of the first tsunami wave to the coast for the urban center of Tumaco is approximately 26 minutes, while for Buenaventura it is 35 minutes. However, Buenaventura has a particular characteristic and is due to the increase in wave amplitude at minute 132, which means that this result is particularly important when designing contingency or emergency plans; considering that with this result people should stay an hour and a half in the evacuation zone until the alert decrease.

Worst credible scenario of regional origin for the Colombian Pacific

Figure 9 shows the maximum displacement of the free surface for the high tide level in the populations of interest due to tsunamigenic events of regional origin. A scenario like this one would generate an average impact, in comparison to an event of near origin, because the maximum values reached by Tumaco and Buenaventura are 0.11 m and 0.051 m respectively. Likewise, the temporary evoltion of the free surface, is given by the arrival times of 218 minutes and 301 minutes for Tumaco and Buenaventura, respectively. In addition, in Buenaventura, it is observed that the maximum values of the free surface are found in the first wave train, which changes with respect to the results obtained in the modeling of near origin.

Worst credible scenario of distant origin for the Colombian Pacific

An event generated by sources of distant origin (Figure 10), causes a minimum impact for Tumaco and Buenaventura, this is because the tsunami wave train that travels from its origin to the coast, decreases its energy from the generation site until the entrance to the bays, which is a product of friction with the seabed and therefore only a small alteration in sea level (approximately 5 cm) is perceived in the evaluated populations. This small change in sea level would be reflected in the bays, around 3 to 4 hours after the event occurred.

All the graphic outputs of the 1,020 simulated scenarios contain information about the maximum flood and synthetic mareogram, these results were compiled in a database; where the storage parameters are, epicenter of the earthquake, magnitude, depth and tidal level.

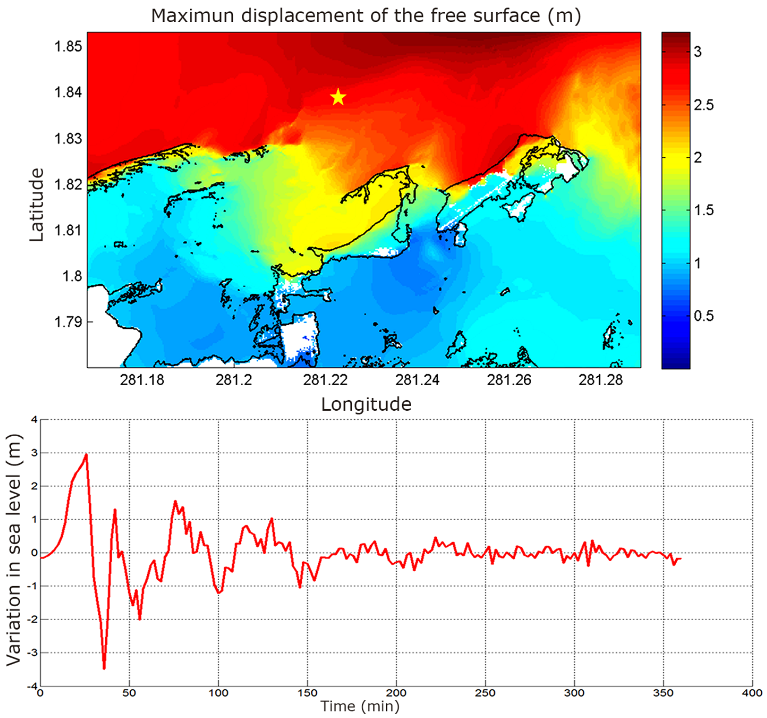

Figure 8 (a)

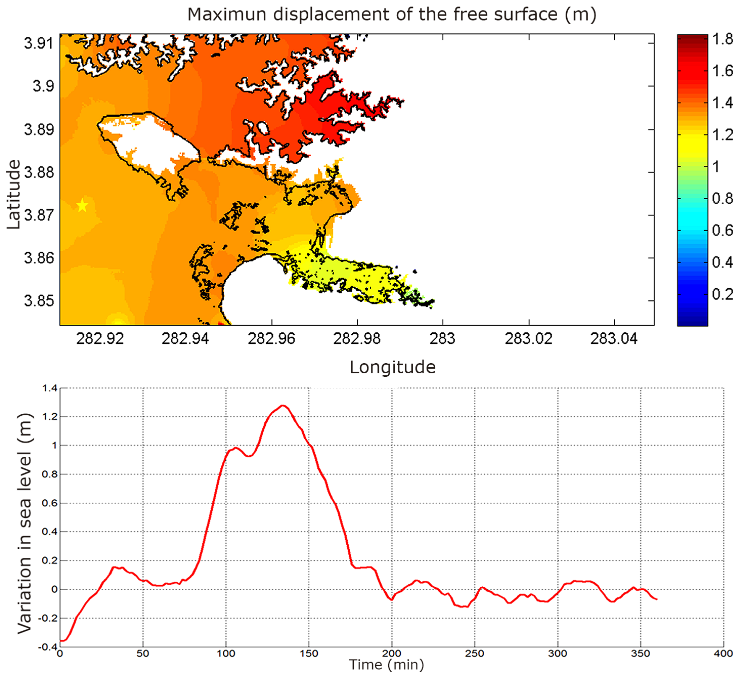

Figure 8 (b)

Figure 8. Result of the most extreme tsunami scenario of near origin with magnitude Mw 8.8 for the population of (a) Tumaco and (b) Buenaventura. The star corresponds to the location of the synthetic tide gauge.

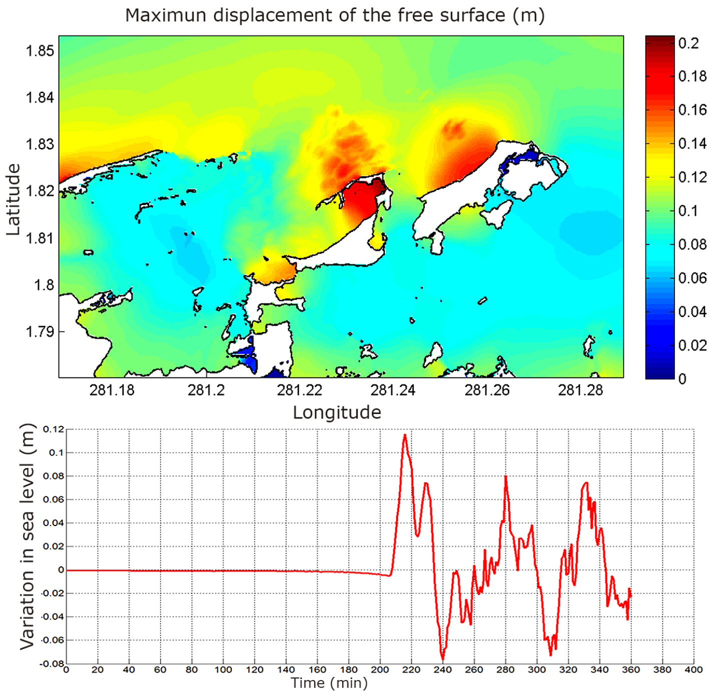

Figure 9 (a)

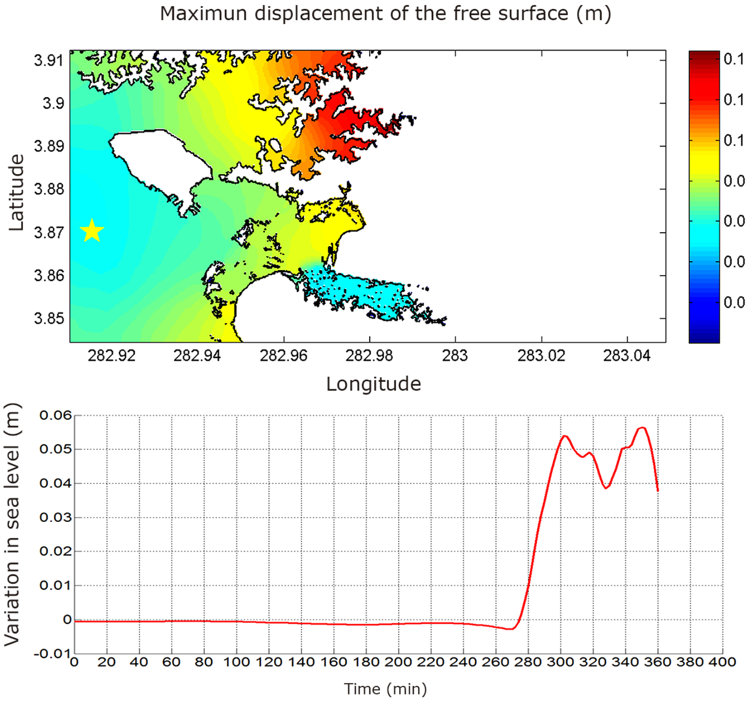

Figure 9 (b)

Figure 9. Result of the most extreme tsunami scenario of near origin (Chiapas Mw. 8.2) for the population of (a) Tumaco and (b) Buenaventura. The star corresponds to the location of the synthetic tide gauge.

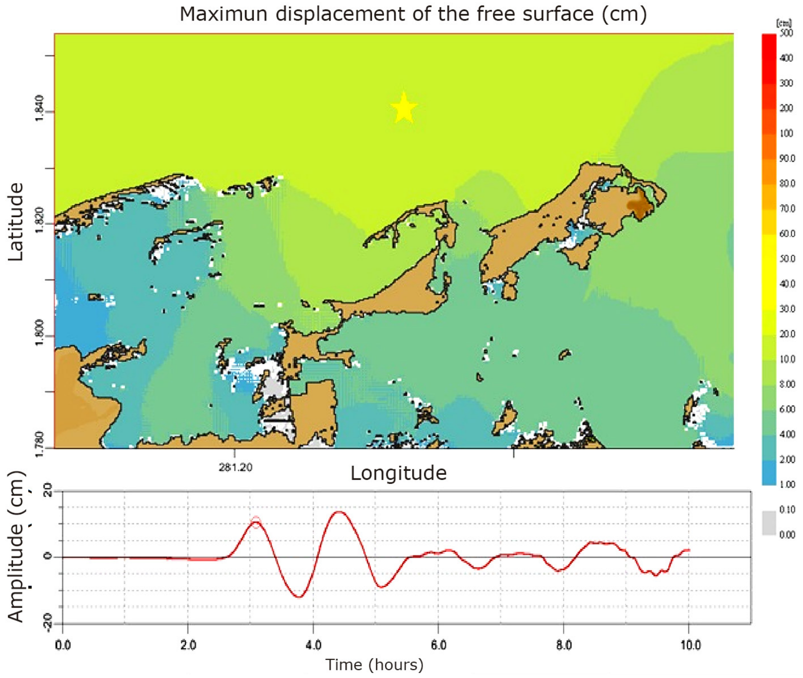

Figure 10 (a)

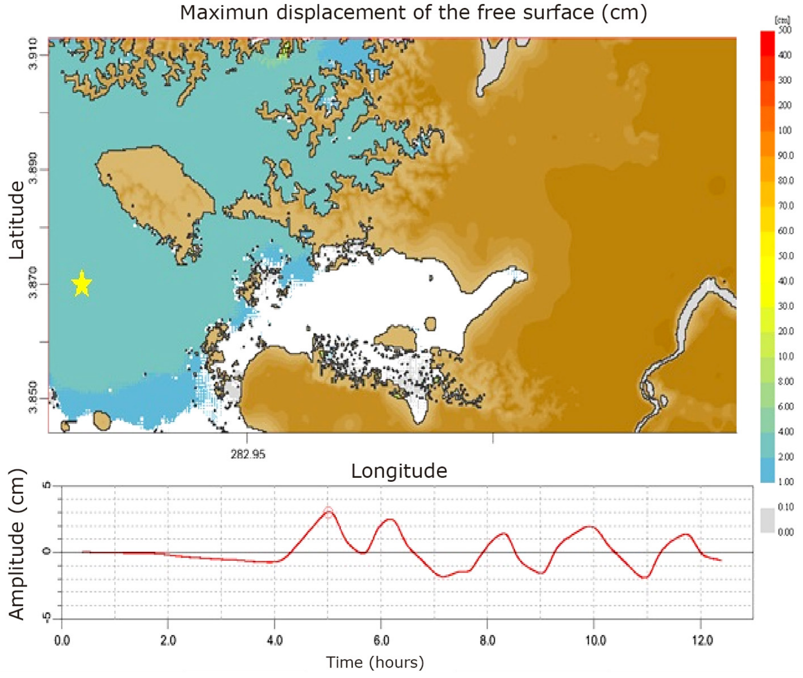

Figure 10(b)

Figure 10. Result of the most extreme tsunami scenario of distant origin (Chile Mw 9.0) for the population of (a) Tumaco and (b) Buenaventura. The star corresponds to the location of the synthetic tide gauge. The star corresponds to the location of the synthetic tide gauge.

CONCLUSIONS

The database is a fundamental tool in the evaluation of a real tsunami event, because it helps mitigate this threat by allowing preventive measures to be taken in risk areas. In the event of an event similar to the maximum credible of near origin, the population of Tumaco would only have approximately 26 minutes to evacuate the shelter areas before the arrival of the tsunami waves, while the population of Buenaventura would have 106 minutes more, than the previous one. Therefore, it is recommended, and especially in Tumaco, that the local and departmental authorities must establish rapid and effective contingency plans in their population centers, in order to reduce the effects of this type of threat.

The flood zones demarcated in the detail mesh were obtained with greater precision thanks to the high resolution LiDAR information, because it is possible to represent in a way closer to reality, the morphology of the terrain and the transition of water-land of the tsunami wave, to obtain in this way a run-up height with more detail and clarity.

To obtain a greater density of the database of tsunamigenic events, the modeling was performed for epicenters of near, regional and distant origin, in the three levels of tide, high, medium and low and for the populations under study, Buenaventura and Tumaco. In this way it is possible to evaluate the threat and establish responses to a real event, depending on the macroseismic parameters; finally, it was determined that the deterministic scenario of near origin is the event that most affects the populations evaluated. This is corroborated with the results obtained, where it is observed that flood values for near-by origin are greater than for an event of distant origin, where only a small disturbance of sea level occurs, which means that in the latter there is no disturbance in the water column capable of generating tsunami waves in the evaluated populations.

The results shown here suggest that it is important to further densify the scenario bank for the most populated regions of the Colombian Pacific, such as Bahía Málaga, Juanchaco, Ciudad Mutis, Bahía Solano and Curay, because the behavior of the tsunami wave train differs According to the geomorphology of the seabed and therefore the results are variants according to each coast. Likewise, it is convenient to carry out flood scenarios for Caribbean populations, due to the fact that, according to the consulted bibliography, seismically active faults are identified in this area. Which means a significant advance in the study of this phenomenon for the Colombian Caribbean.

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