Determination of the maximum flood level in the colombo-ecuadorian border by applying numerical modeling

Determinación de la cota máxima de inundación en la frontera colombo-ecuatoriana aplicando modelación numérica

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Abstract

The highest tide line was determined for the area between Candelillas de la Mar and Salahondita, located on the southern Colombian Pacific littoral (CPL). The study was made by means of a harmonic analysis, time series of sea level measured in-situ, and the series that were generated from numerical modeling (considering the limited information available of sea level in this area). The meteorological tide was simulated using statistical Montecarlo techniques; considering the stochastic character of this variable. The behavior described for the series measured in-situ and modeled. It was analyzed with a normality test (Kolmogorov-Smirnov and Shapiro-Wilk test), these were subsequently correlated through the Spearman Correlation Method, where the geomorphological changes in the coast and the limited bathymetric information in some areas, conditioned the behavior of the coefficients obtained. For the calculation of the average and extreme regimes, standard methodologies were applied, based on the coefficients obtained by Otero (2005). From this results, the highest flood levels for each study points were determined, which served to draw the highest tide line in this zone.

KEYWORDS: Astronomical tide, meteorological tide, harmonic analysis, numerical modeling, sea level, Colombian-ecuatorian border.

Resumen

En el presente estudio, se determinó la Línea de Más Alta Marea para el área comprendida entre las poblaciones de Candelillas de la Mar y Salahondita, ubicada sobre el Litoral Pacífico Colombiano (LPC), Pacífico Sudeste. Se efectuó un análisis armónico a las series de tiempo de nivel del mar medidas in situ, y a las que se generaron a partir de modelamiento numérico (considerando la escasa información disponible del nivel de mar en esta área). La marea meteorológica fue simulada empleando técnicas estadísticas de Montecarlo; considerando la naturaleza estocástica de esta variable. El comportamiento descrito por las series medidas in situ y modeladas, se analizó a partir del Test de normalidad (test de Kolmogorov-Smirnov y Shapiro-Wilk). Posteriormente, estas fueron correlacionadas por medio del método de correlación de Spearman, donde los cambios en la morfología de la costa y la ausencia de información batimétrica de algunas áreas, condicionó el comportamiento de los coeficientes obtenidos. Para el cálculo de los regímenes medio y extremal, se aplicaron las metodologías establecidas, tomando como base los coeficientes obtenidos en estudios anteriores (Otero, 2005). A partir de los resultados obtenidos, se determinaron las cotas máximas de inundación para cada uno de los puntos de estudio, que sirvieron como base para el trazado de la Línea de Más Alta Marea en el área de estudio.

PALABRAS CLAVES: *marea astronómica, marea meteorológica, análisis armónico, modelación numérica, nivel del mar, frontera colombo ecuatoriana.*

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Introduction

The effects of global warming mainly generated by human activities, are one of the more common problems afflicting the world today. The sea rising levels (has increased between 10 and 25 cm of the global average, during the last 100 years), it is probably one of the most evident consequences of this process, which have important impacts in surrounding zones ashore mainly (Cardona, Fernández, Botero & Gómez, 2003).

Periodic determination of sea level allows to evaluate the socioeconomic and environmental impacts that may arise in ecosystems and productive systems located in coastal zones, to generate procedures for reducing vulnerability against these changes. Likewise, it allows to delimit the land of public use, serving as a tool to entities as the Department of Maritime Navigation (Dimar) to establish its jurisdiction on the Colombian coasts. As stipulated under the Law 2324 of September 18th, 1984.

It should be noted that the main need of coastal nations around the world should be the understanding of ocean and coastal processes because the continuous improvement of scientific knowledge in this area depends on these countries to develop and apply territorial management policies more appropriate to the needs of the civilian population that inhabits these highly sensitive areas. Throughout these tools, coastal states guarantee a better use of the available resources, projecting a more appropriate sustainable development of the oceans and coastal zones under their jurisdiction.

Sea level is affected at any moment by two nature processes mainly: the astronomic tide, generated by the gravitational attraction force that exercises the moon and the sun over the land mass; and meteorological tide, which responds mainly to the sea level variations caused by the barometric changes, the interaction of wind with the water surface, by factors related to the configuration of the coast and the bathymetry of the zone where the tidal wave propagates (Valls & Maria, s.f.). Likewise, other lower-frequency phenomena, of different temporal scale and little local effect; such as: tsunamis, “El Niño” phenomenon or river discharges of major rivers can generate changes in the sea level. Therefore, in a determined zone, the sea level is a process that includes both deterministic variables (astronomical tide) and stochastic variables (meteorology tide) (Otero, 2005).

It was necessary to carry out a separate analysis of these variables, so that in this work methodologies established for this purpose will be applied in addition to determining the astronomical and meteorological tide by means of the use of numerical models, analysis of harmonic components and indirect methods of simulation, with based on the Monte Carlo techniques (statistical simulation). Moreover, a correlation analysis of simulated series with measured in situ series was carried out, to validate the simulated information, and in this way to obtain the maximum elevations of inundation, which are part of the procedure for determining the High Tide Line in coastal zones.

Study area

The study area is located in the southwest of Colombia, covering the coastline and the Continental Shelf of the Nariño department, from Candelillas de la Mar until Salahondita, with a length in a straight line over the coast of approximately 160 km and depths between 2 and 2200 m.

The municipalities of the coastal zone under study are Francisco Pizarro and Tumaco, that present a very varied tidal dynamics, depending on the coastal configuration and the bathymetry of the site, therefore 13 monitoring points were established in this study, as shown in Figure 1 and their respective geographic location (Table 1).

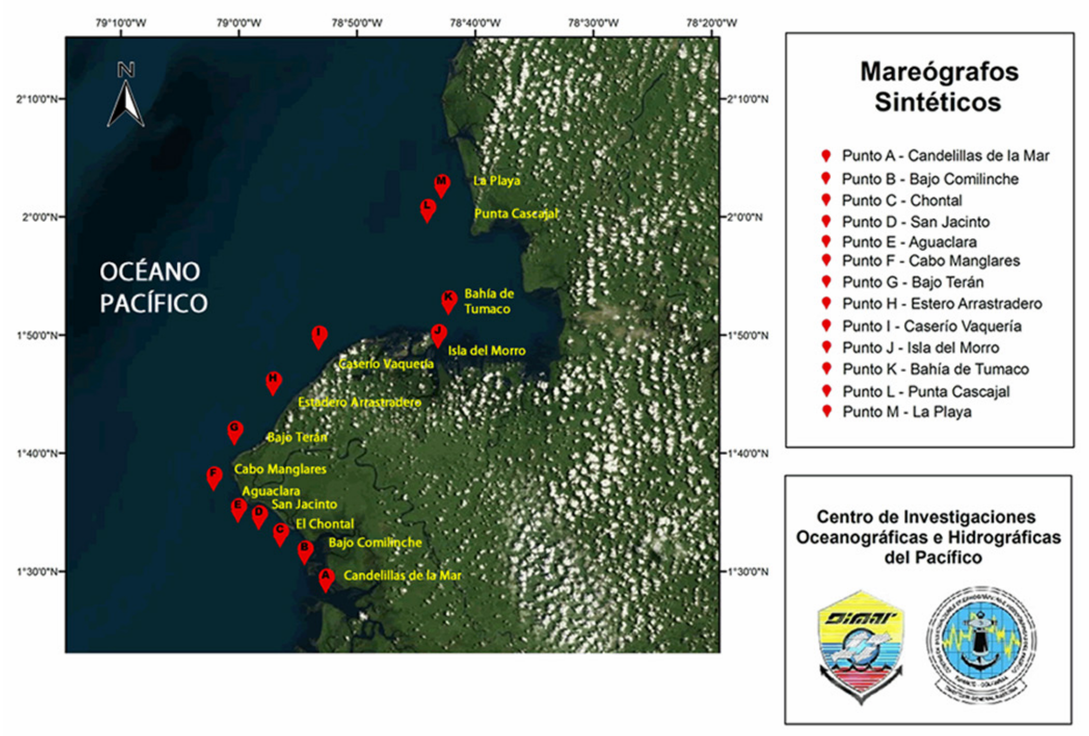

Figure 1. Monitoring points on the study area. Taken from Basical Map ESRI.

Table 1. Points of interest selected in the area between Candelillas de la Mar and Salahondita, Nariño.

Points of interest	Location	
	Longitude W	Latitude N
Candelillas de la Mar	-78.8778	1.4735
Bajo Comilinche	-78.9075	1.5132
Chontal	-78.9421	1.5381
San Jacinto	-78.9718	1.5629
Aguaclara	-79.0014	1.5728
Cabo Manglares	-79.0360	1.6175
Bajo Terán	-79.0064	1.6821
Estero Arrastradero	-78.9520	1.7516
Caserío Vaquería	-78.8877	1.8162
Isla del Morro	-78.7047	1.8112
Bahía de Tumaco	-78.7047	1.8659
Punta Cascajal	-78.7344	1.9950
La Playa	-78.7146	2.0298

Methodology

The identification of the High Tide Line (LMAM), required a separate analysis of the deterministic variables (astronomical tide), and stochastics (meteorological tide) that directly influence the sea level behavior (Otero, 2005). The methodology used to obtain these variables is presented, as well as the medium and extreme sea level system calculation.

It was necessary to use the hydrodynamic model H2D, detected the existing limitation in the study area, with the exception of the municipality of Tumaco, in terms of instrumental records of sea level, to generate the series of tides on the places where there was not sea level information.

Calculation of the astronomical tide

From the deployment of the Topex/Poseidon satellite, extensive databases of sea level with altimetric information have been created. These databases have been used in recent years and have served as the main support for the development of many models, whose purpose is to characterize the tidal wave at global level (Fu & Cazenave, 2001).

The astronomical tide obtained for study area, was generated using the hydrodynamic H2D model, developed by the GIOC (Oceanographic and Coastal Engineering Group of the University of Cantabria). This model uses the global interpolation of contour method of the AG95.1 model developed by Andersen *et al.,* (1995), which uses the "Grenoble" database. This database operates using 13 characteristic harmonics of the tidal wave (M2, S2, K2, L2, N2, T2, MU2, NU2, 2N2, K1, O1, P1 and Q1), through points in an equidistant mesh of 0.5º x 0.5º resolution. The information provided by the Grenoble database was applied to the study area, based on an interpolation algorithm in each of the selected monitoring points.

It should be noted that some of the bathymetries used in this study were assigned by the Oceanographic and Hydrographic Research Center of the Pacific (CCCP), under the confidentiality protocols stipulated by the Dimar. Likewise, for the areas where there was no own bathymetric information, the available bathymetric information from GEBCO (General Bathymetric Chart of the Oceans) was used (General Bathymetric Chart of the Oceans, 2013).

The configuration of the calculation grid was made from the base information (bathymetry and coastline), for which contours of 6 years of sea level (1985-1990) were generated. A total time of 3130 hours was recorded in the execution of the model, establishing an adequate time increase (Courant Condition) to guarantee the numerical stability of the model. This calculation was made by means of the expression (1):

$$\Delta t \leq \frac{c_r \Delta x}{\sqrt{g D_{\max}}} \quad (1)$$

Where

c_r= 1, value to consider the non-linear terms in the transformation of the tidal wave in shallow -water.

D_x is the spacing between cells.

g the gravity acceleration.

D_{max} is the maximum depth in the study mesh.

The physical parameters determined were the Chezy coefficients and the eddy viscosity 0.01 m and 55 m^2 / s respectively.

A summary of the configuration used in the generation of astronomical tide for the zone between Candelillas de la Mar and Salahondita is shown below (Table 2).

Harmonic analysis

The harmonic analysis was made to each of the hourly data of astronomical tide simulated series using the T_Tide computational tool, this package is incorporated into the computational analysis tools of Matlab, it is written in Fortran (Foreman, 1977), adjusting the tidal components by the least squares method considering the pre-established frequencies of it. The way in which

T_TIDE solves this problem and in general the aspects of tidal parameter determination are discussed by Rosenfeld, Shulman, Cook, Paduan & Shulman (2009).

Table 2. Parameters of configuration of the H2D model for the generation of the astronomical tide in the area between Candelillas de la Mar and Salahondita.

Variable	Candelillas de La Mar, Salahondita
Parameters of the mesh	
Upper left limit	-79.4960 ; 2.2235
Upper right limit	-78.5218 ; 2.2235
Lower left limit	-79.4960 ; 1.4090
Lower Right limit	-78.5218 ; 1.4090
ΔX (meters)	550
ΔY (meters)	550
No. Nodes X	198
No. Nodes Y	165
Physical parameters	
Chezy coefficient Ks (m)	0.01
Eddy viscosity ε (m^2/s)	55
Execution parameters	
Total execution time (s)	3600
Increase in the time Δt (s)	3

Calculation of the meteorological tide

In this case, the parameters obtained by (Otero, 2005) in the analysis made to the historical sea level series of the monitoring stations of Tumaco, Buenaventura and Panama were adopted. In this analysis, the over-elevation regimes for the meteorological tide of Tumaco, Buenaventura and Naos (Panama) were determined, based on the meteorological residue obtained from historical series of continuous tides, available on the coastlines of Colombia and Panama. From which the meteorological residue and the curves of medium and extreme regimes of over-elevation were calculated by meteorological tide in Buenaventura, in order to determine the parameters of location and scale (Otero, 2005). The results obtained are shown in Figure 2 and Table 3.

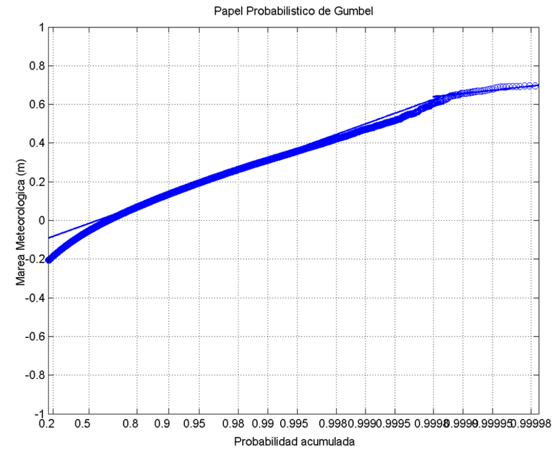

Figure 2. Over-elevation regime by meteorological tide in Buenaventura. (Otero, 2005)

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Table 3. Parameters of location and scale of the extreme and mean regimes.

Regime	Parameter	Value
Mean	Location λm	-045256623
	Scale δm	-0.07870149
Extremal	Location λe	0.43567796
	Scale δm δe	-0.02389298
Probability	F_p	0.99984541
Meteorological tide level	S_{mm}	0.645

Average mean sea leve

It is noted that the average mean sea level regime represents its behavior in an average year. Consequently, in order to build it, it was necessary to generate 100 series of 500 years of meteorological tide using MonteCarlo's statistical techniques and reconstruct a series of 500 years of astronomical tide based on the calculated harmonic constants. The sum of these series results in 100 sea level series, which, when averaged and organized in ascending order, determined the distribution curve of the mean regime (Otero, 2005). The results obtained are presented in double format: the distribution function (cumulative probability) and the number of hours per year exceeding a given level. The relationship between the two is established below:

$$N = 8760(1-F) \qquad \textbf{(2)}$$

Where N is the number of f hours per year that the given level is exceeded, 8760 is the number of hours of the year and F is the cumulative probability.

Extreme sea level regime

It is also observed that the extreme regime of level sea has a great application in construction of coastal infrastructures. Its calculation method is very similar to that of the average regime, the difference is that in this case the distribution function of the extreme regime is obtained from the annual maximums of each of the 100.

Likewise, the standard deviation and the mean for each probability value were calculated to estimate 90 % of confidence bands in this way:

$$\left(\bar{x} - 1.645\hat{s}\sqrt{n/a}, \bar{x} + 1.645\hat{s}\sqrt{n/b}\right) \qquad \textbf{(3)}$$

Where $\bar{x}$ is the point estimator of the average, $\hat{s}$ is the point estimate of the standard deviation, n is the size of the sample and a and b are coefficients that consider a variability in the standard deviation and that depends of n (Castillo & Pruneda, 2001). The values of a and b are shown in Table 4.

Table 4. Values of *a* and *b* that lead to confidence intervals of minimum amplitude for 90 % confidence band.

n	*a*	*b*
4	0.582	17.6
5	1.06	18.1
6	1.59	18.9
7	2.18	19.9
8	2.79	20.9
9	3.43	22.0
10	4.08	23.2
20	11.3	35.1
30	19.1	47.0
40	27.2	58.8
50	35.6	70.3
60	44.1	81.8
70	52.7	93.2
80	61.4	104.4
90	70.1	115.7
100	78.8	127.0

The results of the extreme regime are shown on a double scale: cumulative probability and return period. The relation between both scales is:

$$R = 1/(1-F) \tag{4}$$

Where *R i*s the return period (years) and F is the cumulative probability. The return period is no more than the average time it takes to return an event.

Normality test

In order to know the distribution of the data obtained in order to determine the treatment to be applied to this information, the Kolmogorov-Smirnov normality test was applied, which detects the differences in the location and shape of the distribution. The value of *Z* is based on the maximum absolute difference between the observed cumulative distribution and the normal (theoretical) distribution, as follow:

$$Z = \sup_{x \in R} \left| \hat{F}(x) - F_o(x) \right| \tag{5}$$

Where: $\hat{F}(x)$ is the observed cumulative frequency, $F_o(x)$ is theoretical cumulative frequency.

An alternative way of performing the Kolmogorov-Smirnov test can be carried out by using the *p-value associated* with the observed statistic Z. It si defined as:

$$p-valor = P(Z > Z_{obs} / H_o escierta) \tag{6}$$

If the *p-value is large,* it means that since the null hypothesis *H0* (normal data distribution) is true, the observed value of the statistic *Z* was expected. There is therefore no reason to reject such a hypothesis. On the other hand, if the *p-value is small*, it indicates that, since the null hypothesis is true, it is difficult for the observed *Z* value to be produced, which calls into question and rejects the null hypothesis. Thus, for a level of significance α, the decision rule for this contrast:

$$\begin{aligned} Si\_p-valor \geq \alpha &\Rightarrow AceptarH_0 \\ Si\_p-valor < \alpha &\Rightarrow \mathrm{Re}chazarH_0 \end{aligned} \tag{7}$$

For this case, choosing a significance level of 5 %, if *p-value* < 0.05, the distribution curve differs from normal, and if on the contrary, p >0.05 shows that the data conform to a Gaussian (normal) curve (Marques, 2001).

Spearman correlation

The intensity of the linear relation exists between two measured quantitative variables, when these do not have a normal distribution, can be evaluated using the Spearman correlation coefficient (r_s), which is defined by the following expression:

$$r_s = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)} \tag{8}$$

Where *n* is the number of data pairs and is the difference of the *Xi* and *Yi* ranges, which is obtained by substituting the Pearson correlation formula (Marques, 2001). This coefficient can obtain values between *1* and *-1*, passing through zero *0*, as shown in Table 5.

Table 5. Spearman correlation coefficient.

Coefficient	Correlation
Between -1 and -0.9	Strong inverse
Between -0.9 and -0.5	Moderate inverse
Between -0.5 and 0	Weak inverse
Between 0 and 0.5	Weak positive
Between 0.5 and 0.9	Moderate positive
Between 0.9 and 1	Strong positive

Where values close to *1* indicate a strong positive correlation, values close to *-1* indicate a strong negative correlation and values close to *0* indicate non-linear association (Lehman, O´Rounke, Hatcher & Stepanski, 2013).

Results and discussion

Based on the results obtained from the astronomical and meteorological tide simulations in the points mentioned above (Table 1), the extreme and average regimes were calculated.

In order to evaluate the correlation between the astronomical tide obtained by simulation and the tide obtained by *in-situ* measurements, the tide station closest to the study area was identified, choosing the tide gauge of the Colombian Institute of Hydrology, Meteorology and Environmental Studies (Ideam), located in the port society on Isla del Morro, in the municipality of Tumaco (1°49' 0.9''N - 78° 43'49''), which has long periods of sea level monitoring in this area (1952-2013). For the correlation, the 1985 series was chosen, considering that it is one of the most complete series according to the University of Hawaii Sea Level Center (UHSLC) database, which applies policies of assurance and quality of the information provided. The Figure 3 shows the measured time series in blue and the simulated time series of the point identified as Bay of Tumaco in red, during a period of 3,130 hours; a similar behavior between the two series was evidenced.

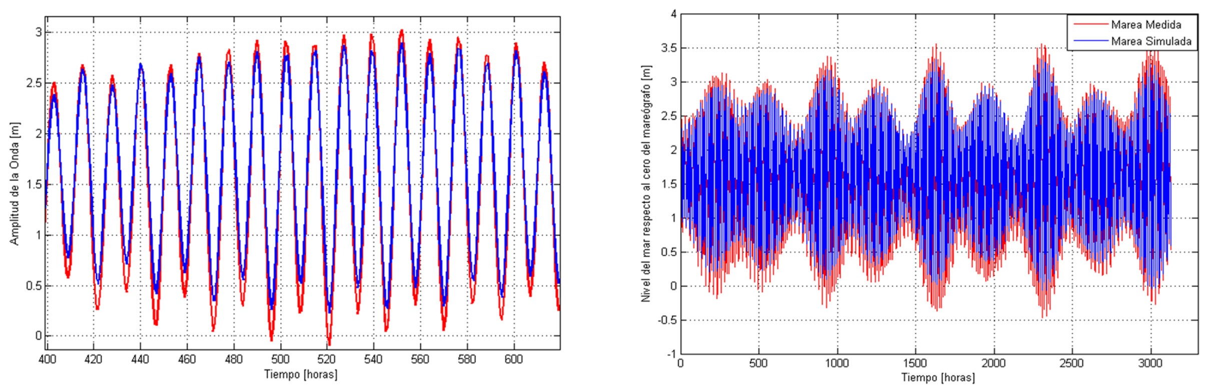


Figure 3. Measured and Simulated Tide Series of the year 1985, Tumaco-Nariño.

In order to determine the relationship between the measured series and the series obtained by simulation, a normalization test (Kolmogorov-Smirnov) was carried out, showing a behavior different from the normal distribution (Figure 4), so the Spearman correlation was applied.

A weak, moderate positive and strong positive correlation was shown in the statistical analyzes performed on the data from the simulated series, specifically with respect to the series observed, as it is related below (Table 6). It is also observed that, in areas where there are changes in the morphology of the coast or where there is not enough bathymetric information, the variation in the correlation is presented.

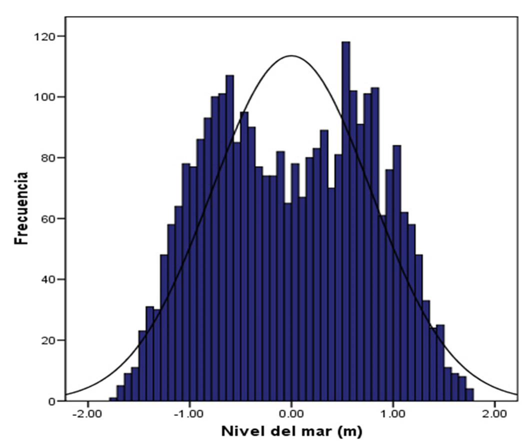


Figure 4. Distribution of the data obtained from the simulated series in Candelillas de la Mar.

Table 6. Correlation of spearman associated with simulated tidal series with respect to the observed tide.

Point of interest	r_s
Candelillas de la Mar	0.99598
Bajo Comilinche	0.97700
Chontal	0.89807
San Jacinto	0.81597
Aguaclara	0.70871
Cabo Manglares	0.50641
Bajo Teran	0.20916
Estero Arrastradero	0.02730
Caserío Vaquería	0.08119
Island of El Morro	0.99665
Bay of Tumaco	0.99602
Punta Cascajal	0.97197
La Playa	0.98644

As previously mentioned, 100 time series of 500 years of sea level were generated, taking as a mean reference level, the one determined for the port of Tumaco of 1.61m (Ideam, 2013). The figures 5, 6 and 7 show the results obtained for three selected points within the study area, showing the behavior of the sea level in the north, center and south of the area of interest.

From the analyses carried out, it can be inferred that the maximum height of the sea level in an average year is 3.0790, 2.2995 and 3.0484 meters for Candelillas de la Mar, Cabo Manglares and Island of El Morro respectively, with a probability of not exceeding 99 %. Likewise, it can be observed from the curve of the extreme regime for the same points, that in a return period of 20 years, there is a 90 % probability that the sea level exceeds 3.6350, 2.8080, 3.6070 meters respectively. Table 7 shows the maximum flood levels for all the points under study.

Table 7. Maximum flood elevation for points in investigations.

Point of interest	Sea level (m)
Candelillas de la Mar	3.0790
Bajo Comilinche	2.7990
Chontal	2.6627
San Jacinto	2.4971
Aguaclara	2.4058
Cabo Manglares	2.2995
Bajo Teran	2.1807
Estero Arrastradero	2.1498
Caserío Vaquería	2.1380
Island of El Morro	3.0484
Bay of Tumaco	2.9307
Punta Cascajal	2.5915
La Playa	2.7191

According to the maximum levels obtained based on the simulation, it can be determined that as long as the configuration of the coast does not suffer sudden changes (such as bays, channels, river delta, among others); the sea level in these areas will be similar (Sánchez, 2008), as shown by the results obtained for Candelillas de la Mar and Bay of Tumaco, despite a different coastal geomorphological configuration.

The results obtained were compared with previous investigations that have been carried out (Sánchez, 2008), for the case the Morro Island, a difference in the maximum flood level was 0.5859 m, due to the fact that in past studies there was no information regarding at the mean sea level for the seaport of Tumaco.

In order to determine the highest tide line, it is necessary to determine the zero ellipsoidal height of the tide rule. For the urban area of Tumaco, a height of 13.99 m was established, by means of a process of height correction developed in the CCCP in the Integrated Coastal Zone Management Area. This height was added to the maximum flood elevations obtained to trace isolines on the raster soil model of the area under analysis. This information together with the geomorphological conditions, vegetation cover prevailing in the Colombian Pacific coastal zone, and geoprocesses, were the criteria used to determine the route of the highest tide line over the study zone (CCCP, 2013). The Figure 8 shows the high tide line defined for the zone.

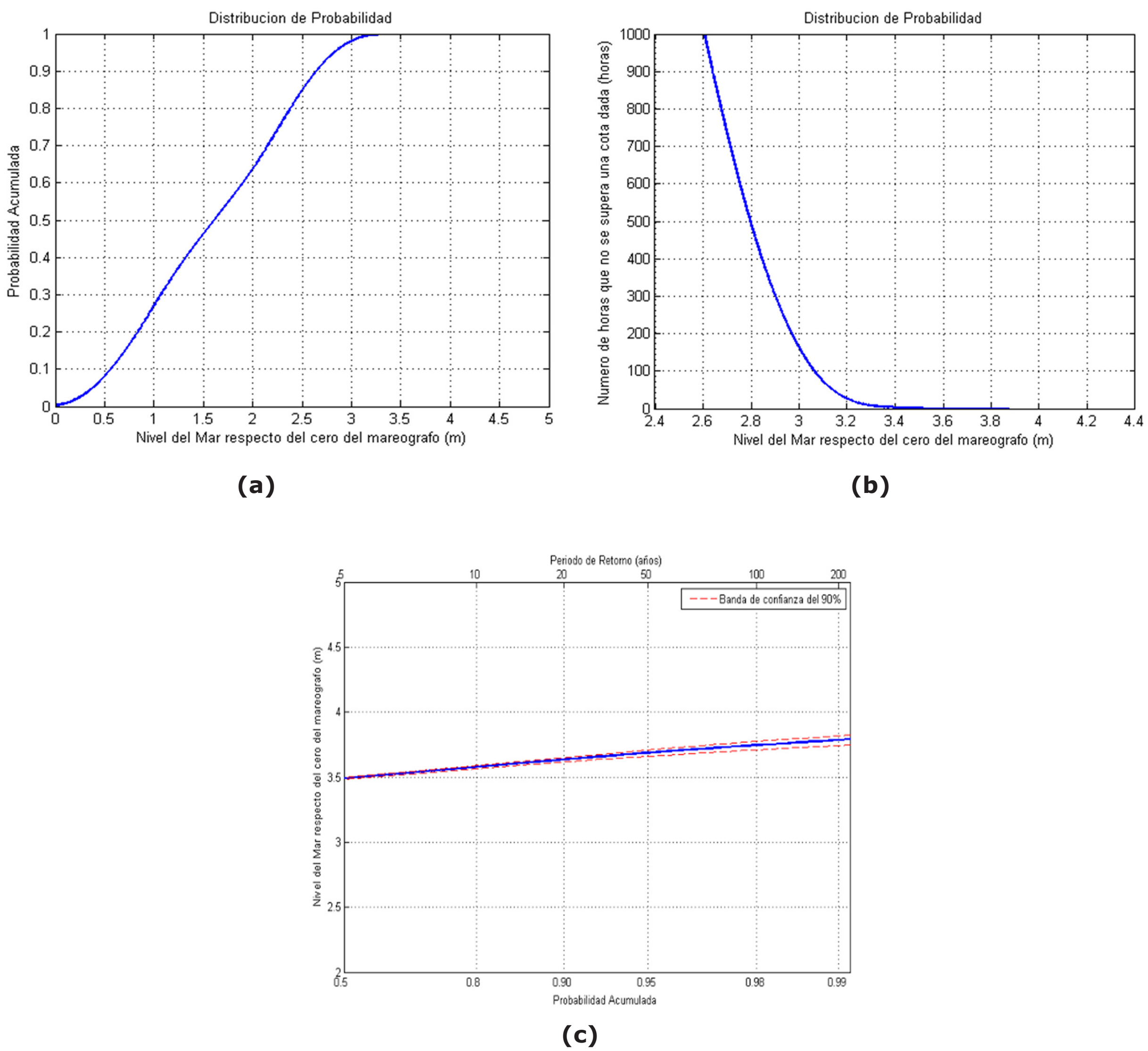


Figure 5. a) and b) Average Regime. c) Extreme regime for the selected point in Candelillas de la Mar.

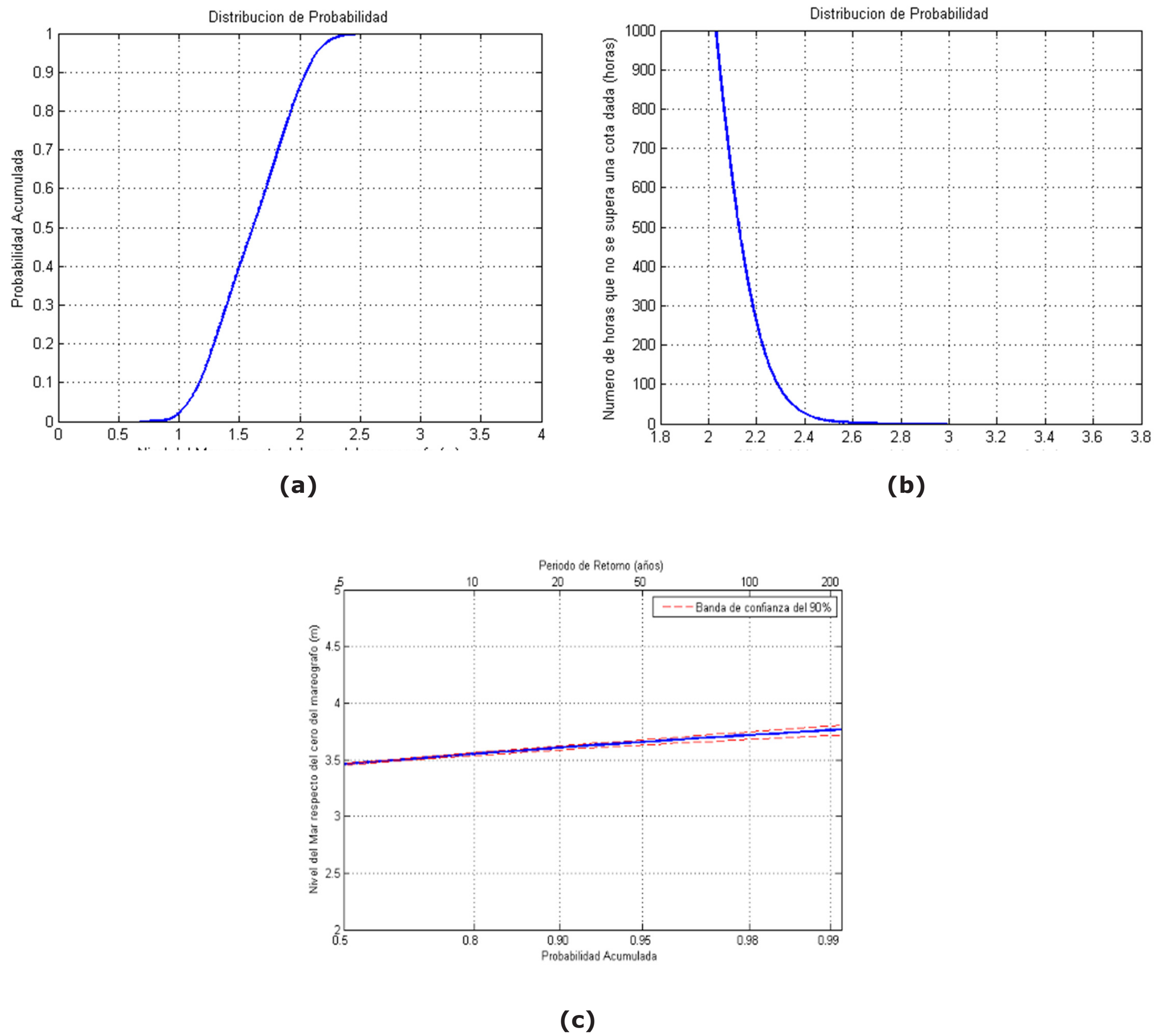


Figure 6. a) and b) Average regime. c) Extreme regime for the selected point in Cabo Manglares.

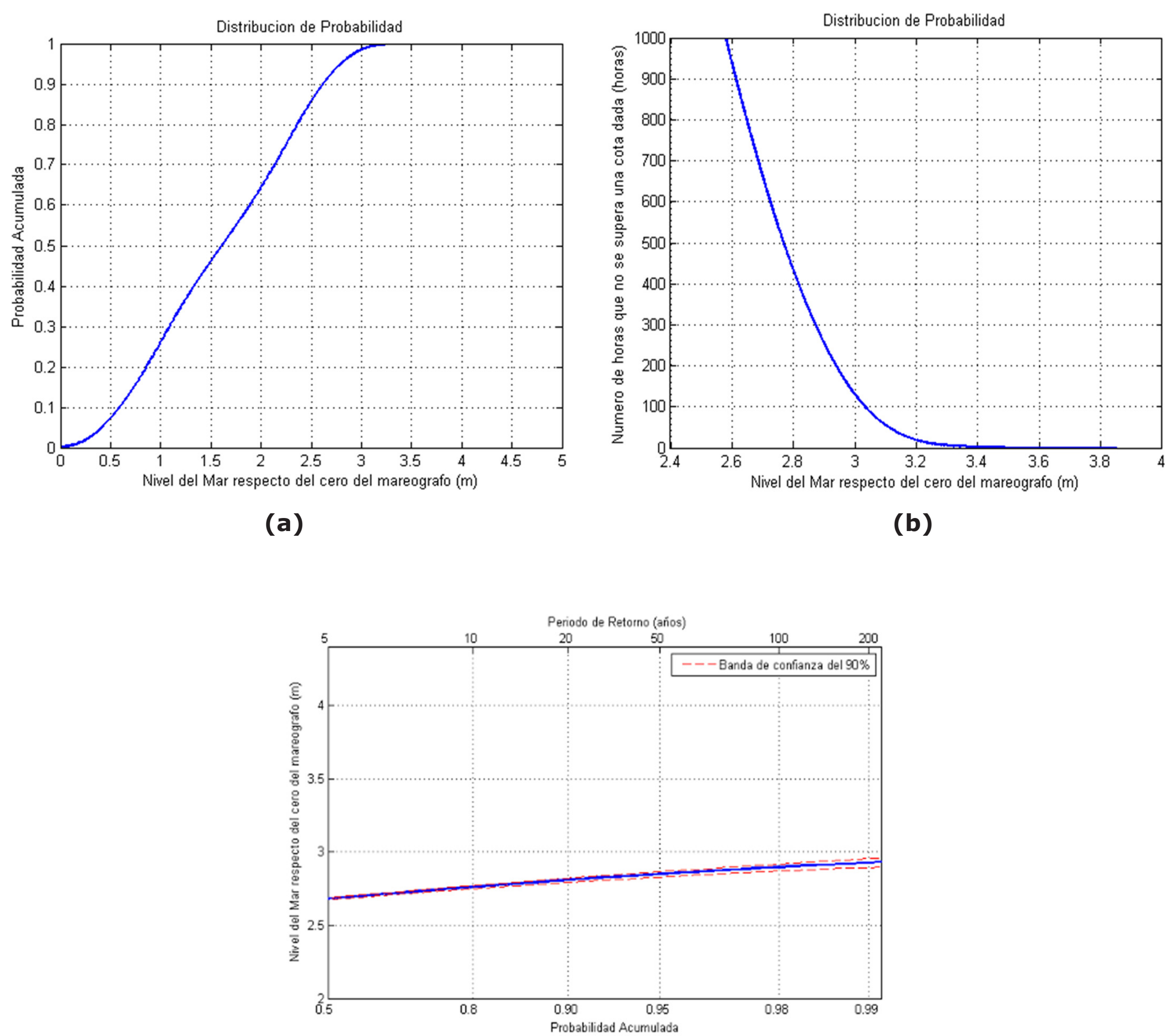
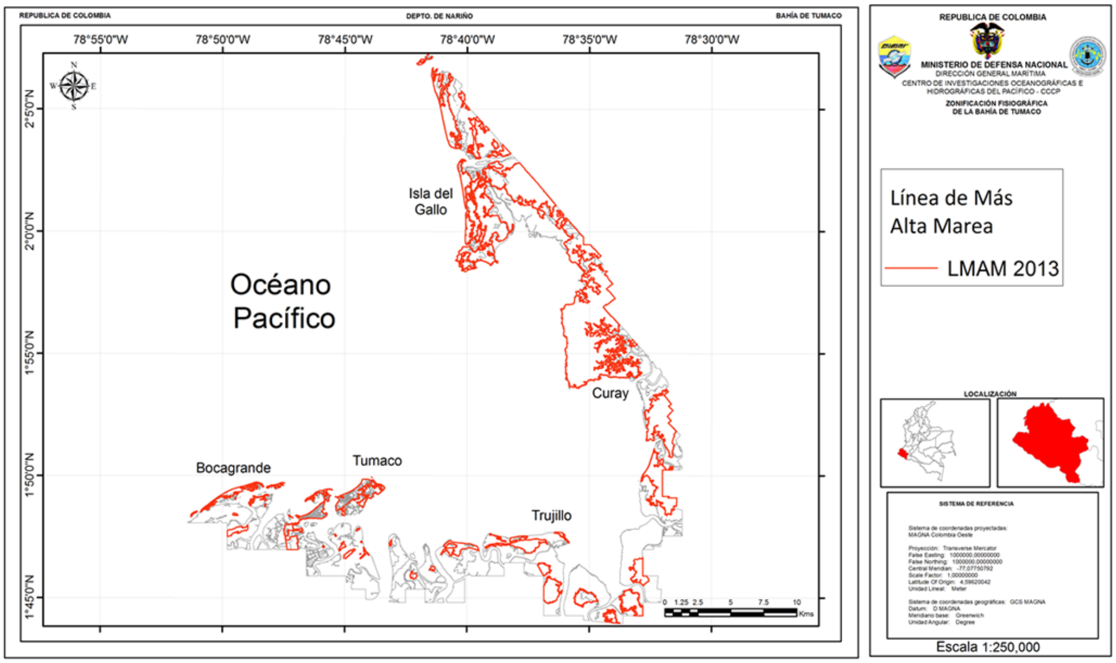


Figure 7. a) and b) Average regime. c) Extreme regime for the selected point in the Island of El Morro.



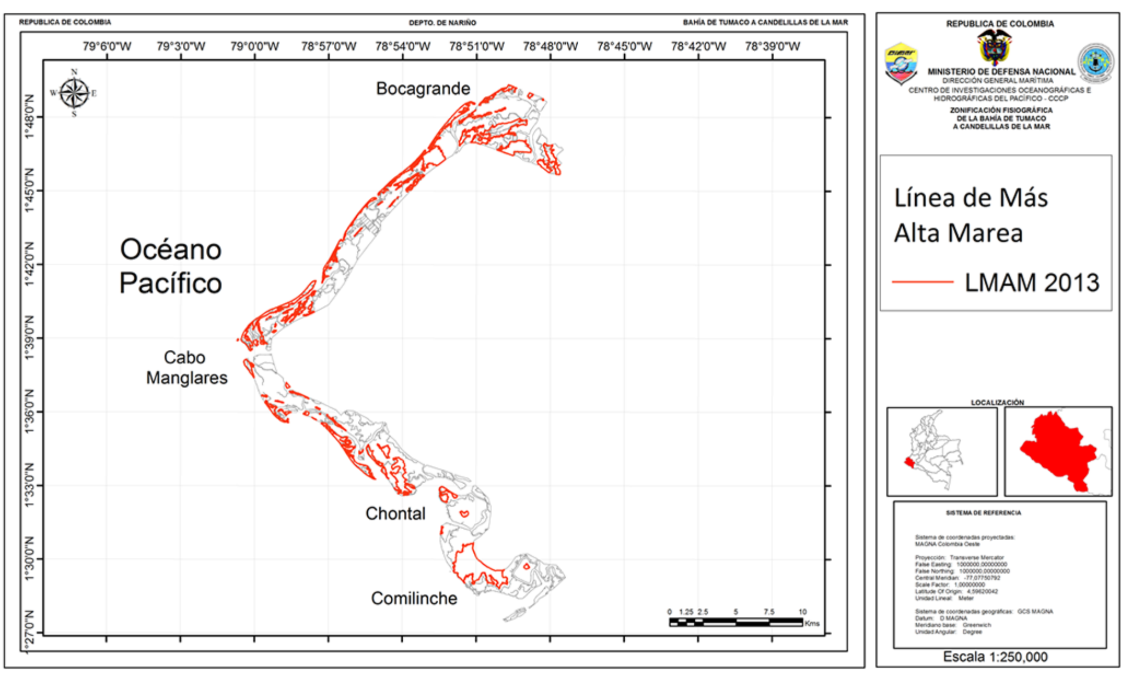


Figure 8. High tide line for the study area between Candelillas de la Mar and Salahondita, Nariño.

Conclusions

From the results obtained from the mean sea level regime, it can be concluded that the maximum flood levels for Candelillas de la Mar, Cabo Manglares and Morro Island are 3.0709, 2.2995 and 3.04874 respectively, with a probability of not exceeding 99 %, which was taken as a reference for the limit of the High Tide Line.

Maximum sea level heights of the simulated series present a low correlation due to the lack of detailed bathymetry in the area. They were also taken into account for the layout of the high tide line in the area since its layout is also delimited by vegetation cover and changes in the topography.

The high correlation that is shown between the simulated waves in the different points of interest both in the south of the Nariño Pacific and other places, concerning the observed tide in the tide gauges corroborate a very similar behavior, as long as there is no abrupt change in the geomorphological configuration of the coasts.

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