THE EFFECT OF A SUBMARINE CANYON ON TSUNAMI PROPAGATION IN THE GULF OF ARAUCO, CHILE

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The 2010 Chile tsunami affected the entire coast of the Biobio Region, where several bays were flooded, and seawater surged hundreds of meters into rivers. However, no inundation occurred in the 2km wide Biobio River, located at the northern entrance of the Gulf of Arauco. Likewise, minimal inundation (less than 2m) was found on the gulf's eastern coast, just south of the river mouth. The study was done by means of numerical simulation with TUNAMI code. Four (4) nested grids with 81", 27", 9" and 3" resolution were defined. Several scenarios were simulated, including the 1730, 1835, 1960 and 2010 events. The first two scenarios considered only a uniform rupture zone, while the others were defined using non-uniform initial condition. Another set of simulations were run without the presence of the island and with a modified bathymetry, so that its effect on tsunami propagation could be studied. It can be concluded that the Biobio canyon is very important in tsunami propagation in the Gulf of Arauco. There is a mitigation effect on the eastern side of the Gulf due to the refraction and dispersion generated by its presence. The change in wave direction is enhanced due to wave diffraction generated by the Santa María Island, causing the wave fronts to move in a north-south direction, preventing severe damage to the eastern side. However a direct impact of the tsunami in the southern end of the Gulf can be observed

Keywords: tsunami propagation, submarine canyon, run up, inundation height

INTRODUCTION

The Biobío canyon is a trench perpendicular to the coast which is located just front of the Biobio river mouth (-71.2S -36.8W). The sediments from the river and the wave-induced currents generated a relatively flat and low area with coastal dunes from San Pedro de la Paz to Coronel Bay (Quezada, 2000b). Figure 1 show the location and magnitude of the canyon, which is taken from a bathymetry survey of the Gulf of Arauco wich was made by the Hydrographic and Oceanographic Service of the Chilean Navy, (SHOA from his name in Spanish). It is possible to see that there are no data near the coast between the mouth of the Biobío River and the Bay of Coronel, therefore, detailed studies in this area are performed for this research.

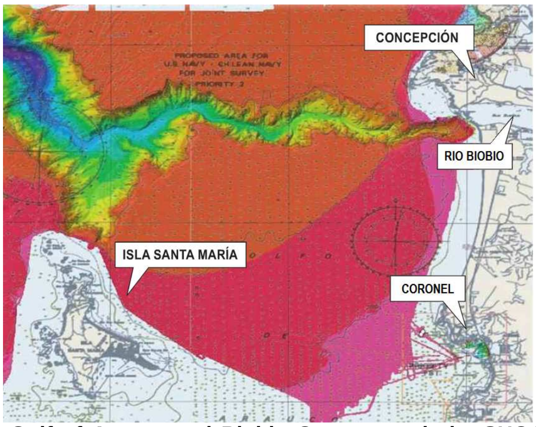

Figura 1. Bathymetry of the Gulf of Arauco and Biobio Canyon made by SHOA. The bathymetry from the nautical chart 6120 is also included (source:http://www.armada.cl, March 7th, 2011)

The post-tsunami survey did not report any inundation at the River mouth after the 2010 Chile tsunami (Vargas et al, 2011) nor into the river neither as was the case of Tirúa (Fritz et al, 2011), Lebu (Vargas et al, 2011), Tubul and Coliumo where water surged 1.8 and 2.5km, respectively (Quezada et al, 2010). In the same manner, no inundation or damage were reported for the 2011 Japan tsunami as it did again in Coliumo and Dichato, where the field survey reported an inundation height of 4m (Diario de Concepción, Ed March 14th, 2011).

On the other hand, there are no historical records which report inundation into the river during hystorical events such as the ones in 1835 and 1960. Therefore, it is interesting to investigate the effect of this submarine canyon on tsunami propagation, because the southern bank of the river is a very developed area that requires not only suitable land planning instruments but also efficient evacuation plans.

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As a first approach, the effect of a canyon can be studied using traditional ideas about the propagation of tsunamis, i.e. refraction, diffraction and reflection (Levin and Nosov, 2009) in which the bathymetry plays an important role. This analysis extends the study of Quezada (2000a), who makes a brief analysis on the influence of the islands and peninsulas arguing a mitigating effect without considering the existence of the submarine canyon.

The refraction phenomenon has been studied and defined as the change in direction of a wave front due to the changes in wave celerity, which is generated by the variation of the water depth (Murata et al, 2010). The reflection is generated by the interaction of the tsunami wave with abrupt bathymetry changes or interaction with steep coastal cliffs (Murata et al, 2010). These abrupt changes and their effects on tsunamis propagation have been studied by Levin and Nosov (2009), who defined analytically the reflection and transmission coefficients for a rectangular step. In a similar manner, Goring (1979) studied the transformation of tsunamis over the continental shelf by means of a series of steps and Mofjeld et al (2000) analyzed the wave behavior with and oblique impact on an abrupt bathymetry change, which consider the critical angle of incidence.

Furthermore, the effect of submarine canyons has been studied by Jinadasa (2008) and Ioualalen et al (2007), who analyzed the effect of the 2004 tsunami in Sri Lanka and Bangladeshi Coasts, respectively. They found an amplification of the wave amplitude due to the presence of the submarine canyons. In addition, Didenkulova and Pelinovsky (2011) studied the shoaling and run-up in narrow bays and canyons, concluding that when the depth varies smoothly along the channel axis, a weak reflection provides significant shoaling effects.

The main objective of this study is to analyze the tsunami propagation over the Biobio submarine canyon in the Gulf of Arauco. Firstly, the methodology is explained, and then the results and conclusions are presented.

METHODOLOGY

The topography was built from LIDAR data with 2.5m resolution. The datum was set as the mean sea level. The bathymetry was obtained from different sources such as GEBCO with resolution 30”, Nautical charts N° 6120 and 6110, and data collected with echosounder along the coastal area between the mouth of the Biobío river and the Bay of Coronel.

The TUNAMI code was used for the numerical simulations. This code is based on the linear shallow water theory at deep water, while in shallow water it uses nonlinear shallow water theory with quadratic friction and advection of momentum, which corresponds to a vertical integration, whereas the resistance of seabed is assessed by the Manning resistance coefficient (Imamura et al, 2006).The numerical integration is performed using an orthogonal coordinate system, which proposes a scheme of four nested grids with different spatial resolution. The 4 grids are 81 ", 27", 9 "and 3" resolution, which correspond to the grids A, B, C, and D, respectively. Figure 2 shows the grids B, C and D used in the simulations. The dimensions and location of the grids were selected such that the Courant number, $Cr = \sqrt{gh_{\max}}\left(dt/dx\right)$, satisfies the condition Cr <0.7, since larger values generated numerical instabilities. In the above equation, h is the maximum water depth at each grid, dt is the time step for numerical integration and dx is the grid size in the x and y direction.

In general, accurate tsunami models require information about the slip distribution caused by the earthquake (Kundu 2007), which does not occur in a uniform manner throughout the surface of the rupture zone. These models are constructed from a seismic and tsunami wave inversion procedure (Satake and Kanamori, 1990). This work considered four events, namely 1730, 1835, 1960 and 2010. The first two events do not have enough information to build a heterogeneous rupture model; therefore, a uniform initial condition is used. For the 2010 event we used the model proposed by Delouis et al (2010), which is in good agreement with recorded arrival time and amplitude of the first wave with the tidal gauge at Talcahuano and with visual observations of the following waves (Aránguiz, 2010). The initial condition for the 1960 event is built from the rupture model proposed by Barrientos and Ward (1990). Despite this model was not contrasted with sea level measurements, it is important to mention that this rupture model was developed from more than a hundred of field observations and measurements, besides horizontal stresses calculation (Barrientos and Ward , 1990). Figure 3 shows the four initial conditions used in the analysis with their respective grid A.

The same set of simulations also considered a modified bathymetry, thus the Santa Maria Island was removed in order to analyze the direct effect of it on tsunami propagation.

Figure 2. Grids B, C and D with 27", 9" and 3" spatial resolution, respectively, which were used in the numerical simulations

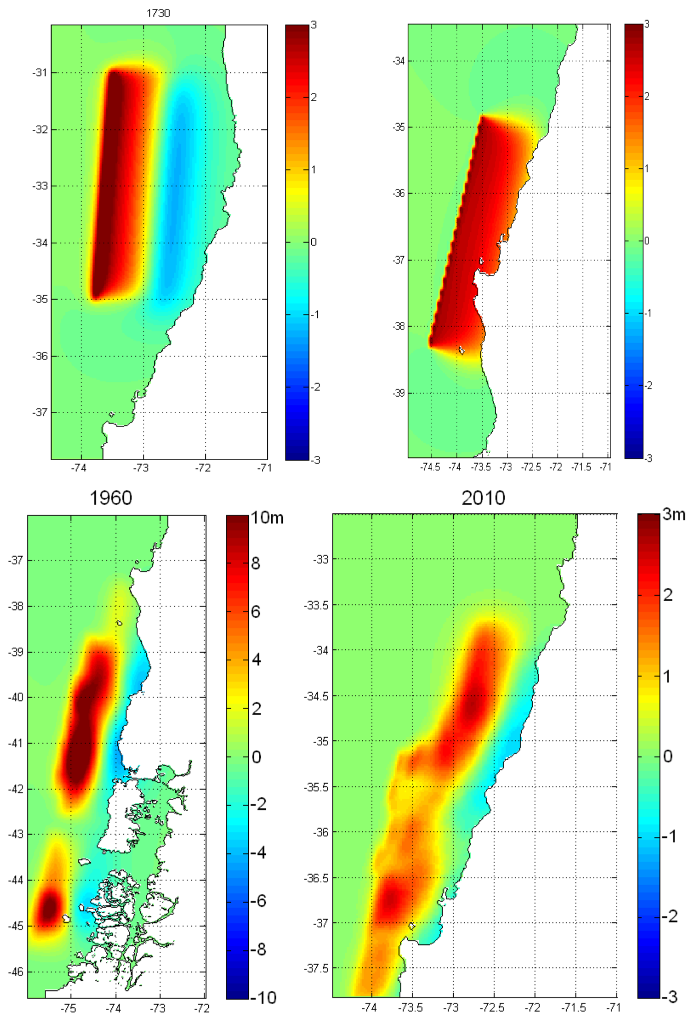

Figure 3. Initial condition of the four historical tsunami events considered in the analysis, 1730, 1835, 1960 and 2010.

RESULTS AND DISCUSSION

Figures 4 and 5 show the snapshot of the first tsunami wave corresponding to the 1960 and 2010 events, respectively. The colored surface indicates the sea surface elevation, where blue indicates a decrease and red an increase of sea surface elevation with respect to the mean sea level. For better understanding, thick lines in green, blue and back are included to indicate equal surface elevation of 0.5, 1.0, and 1.5m, respectively. In addition, the bathymetry was included as thin black lines every 200m in order to better identify the influence of bathymetry on tsunami wave propagation.

Figure 4 shows that the first wave enters the Gulf of Arauco and Biobío Canyon 40 minutes after the 1960 earthquake. It is possible to see that the 0.5m contour line of the sea's surface demonstrates a refraction effect due to deceleration of the wave front over the continental shelf and the higher celerity over the canyon. A similar situation is observed at 45 and 50 min with the 1.0m contour line, moreover, higher wave amplitude is observed at both side of the canyon due to shoaling effect, which is also observed at time 61min. It is important to notice the contour lines at the southern side of the canyon move perpendicular to the coast in a north-south direction, which result in a direct impact to the southern end of the Gulf, as observed at time 66 min.

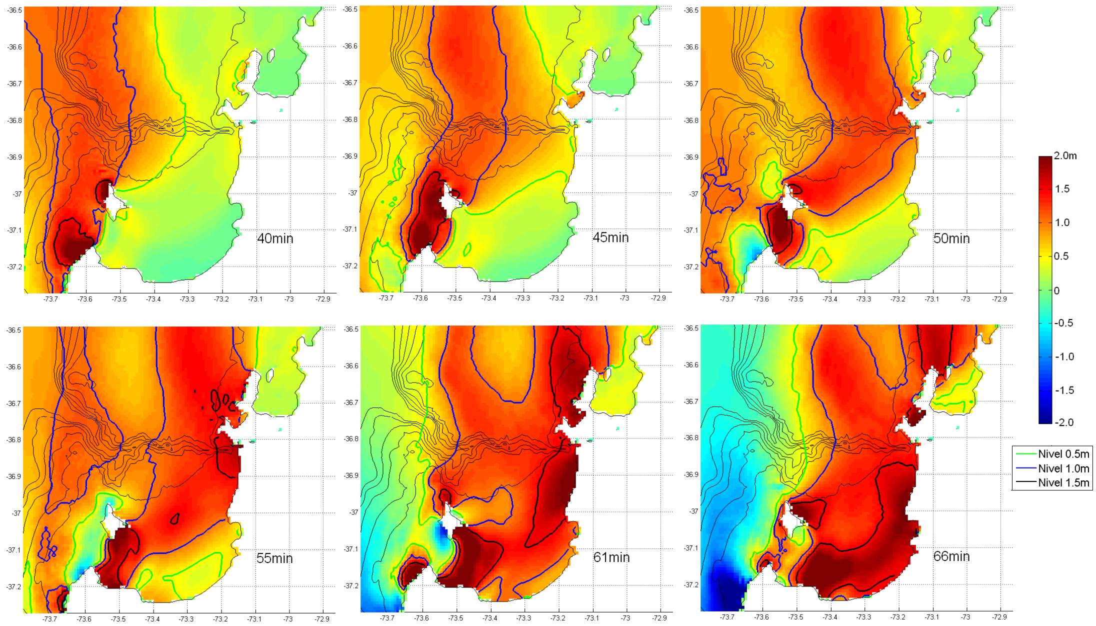

Figura 4. Snapshot of surface elevation for the 1960 Chile tsunami. The thin black lines represent the bathymetry, while the thick lines show equal surface elevation.

Now, Figure 5 shows a similar behavior of the 2010 event. 4 min after the earthquake the first tsunami wave is just over the submarine canyon, and no significant effect can be observed. However, at time 8 min the wave front experienced refraction and shoaling due to the shallower water at both side of the canyon and sea surface elevation higher than 1.5m are observed. The refraction can be observed clearly at time 12min, where the wave front propagates divergently from the canyon. In addition, as observed in the previous case, contour lines show a north-south propagation direction along the coastal zone, as seen at times 12 and 16min. Wave concentration are produced at both sides of the river mouth due to the presence of the canyon and shoaling effects.

Figure 6 show a wave front propagating in the Gulf of Arauco considering two cases: the left hand side shows the real bathymetry, while the right hand side corresponds to a modified bathymetry in which the island has been removed. This case corresponds to the 2010 Chile tsunami. It can be observed that the island's most important effect is a delay in the arrival time, and an enhancement on wave direction change due to wave diffraction.

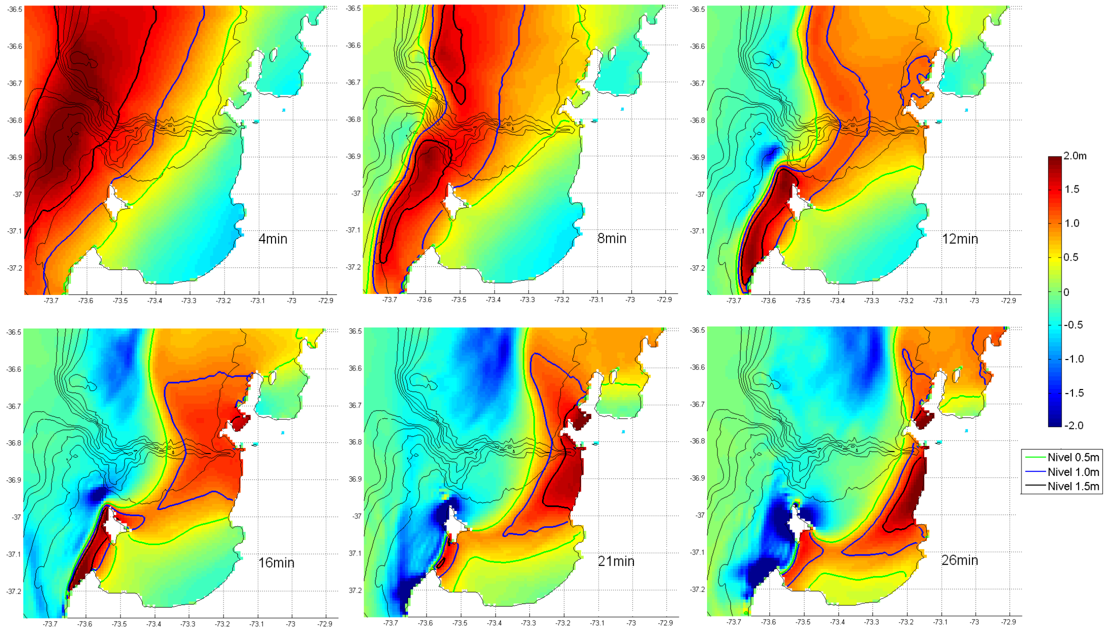

Figura 5. Snapshot of surface elevation for the 2010 Chile tsunami. The thin black lines represent the bathymetry, while the thick lines show equal surface elevation.

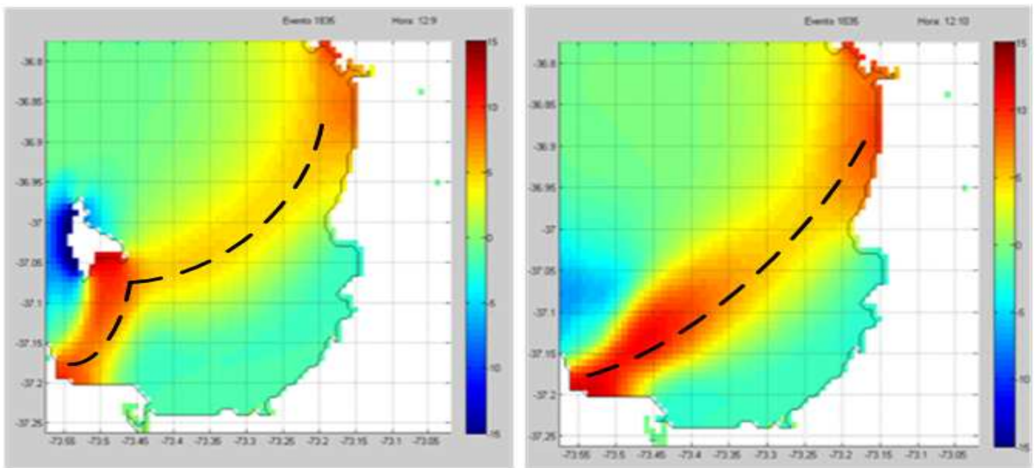

Figure 6. Wave front propagating in the Gulf of Arauco for the 2010 Chile tsunami. Left: real bathymetry which includes the Santa Maria Island, right: Modified bathymetry without the island.

In contrast to what was concluded by Jinadasa (2008) in Sri Lanka and Ioualalen et al (2007) in Bangladesh, the Biobio submarine canyon seems to be a tsunami natural barrier for the river mouth. They observed that submarine canyons could amplify tsunami wave amplitudes and increase inundation heights. On that ground, it is important to analyze the geometry of those canyons and bathymetry around them. For the case of Sri Lanka, the canyons are about 20km long and 5km wide, straight and perpendicular to the coast, which is also mostly straight. The submarine canyon in front of the Bangladeshi coast runs in a NE direction and starts at around 25km south of the coast along the continental shelf. The length of the canyon is in the order of 140km, with maximum depth of 1200m and 20km in width. In this case is also important to take into account that the shape of the Bay of Bengal and the wide continental shelf could propagates edge waves which are important in tsunami behavior [Yamazaki, et 2010] and could cause tsunami wave amplification. Also, the nature of the sediments in the area (often made of mud) could have had an important influence in the propagation and dissipation of the tsunami wave, though this effect is currently poorly understood. Thus, the results for the case of Bangladesh should be viewed with caution. The length of the Biobio canyon is in the order of 120km and can be divided into several segments which give a zigzag shape. Figure 9 shows the three above mentioned canyons, and for the purposes of comparison they are shown in the same scale. Therefore, successive change in directions of the Biobio canyon in several segments might be limiting the concentration of tsunami wave and favoring the refraction phenomenon.

Figure 7. Comparison of submarine canyons in Sri Lanka (left) Bangladesh (center) and Biobio (right)

The above described behavior is mainly due to the refraction of the wave front, however, the reflection-transmission phenomenon due to different segments of the canyon must be considered as well. Figure 8 show the Biobío canyon with its three main segments with contour lines every 200m. The arrows indicate the direction of an incident tsunami wave (I) for both cases, one from the SW and the other from the NW. The reflected (R) and transmitted (T) are also indicated in the figure. Therefore, if a tsunami wave approaches the canyon from the SW, firstly it experiences refraction in the vicinity of Santa Maria Island, and then part of the wave front is reflected and part is transmitted due to the steep walls of the canyon. However, the direction of the transmitted wave is more perpendicular than the incident wave, thus the wave diverges from the canyon. This phenomenon can be clearly seen in Figure 4 at time 45min. In a similar manner, the wave front experiences reflection-transmission phenomenon when it interacts with the second segment. In this case, the transmitted wave changes its direction away from the canyon segment but in the opposite direction to the previous case, as shown in the same Figure 4, but at time 50min. In the case of an incident wave from the NW, the transmitted wave experiences the same previously described behavior, as shown in Figure 5 at times 8 and 12 min.

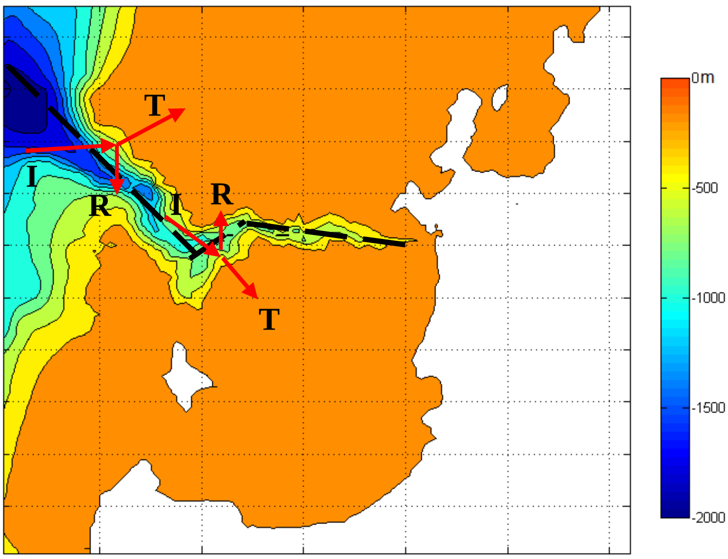

Figure 8. Bathymetry of the Biobio canyon with contour lines every 200m. The dashed lines represents the main segments of the canyon and the red arrows shows incident (I), reflected (R) and transmitted (T) tsunami waves.

One of the most important feature which can be observed from the previous analysis, is that the wave front enters the Gulf of Arauco in the same direction, regardless the origin of the tsunami. The main reason to such behavior is the wave refraction due to the canyon and the wave diffraction due to the island. These effects generate a north-south propagation direction of the tsunami wave along the coastline just south of the river mouth, which explains the low run-up (<2m) during the 2010 Chile tsunami (Quezada et al, 2010). However, this propagation direction result in a direct impact to the southern end of the Gulf, where the towns of Arauco, Llico and Tubul experienced large run ups of 4.2, 8.4, 13.4m, respectively (Fritz et al, 2011).

Now, figure 9 show the inundation area and maximum inundation heights at the river mouth corresponding to 6 hours of simulation. In order to show the location of the canyon, contour lines every 50m water depth are also shown in the figure. It is possible to see that higher inundation height occur at the sides of the river mouth and not at the river mouth itself. Therefore, there is no significant seawater surge into the river and the inundation height is rather slow, which is in good agreement with the arguments of Quezada (2000a). In addition, the coastal zone south of the river mouth does not experience large inundation either, which is mainly due to the north-south propagation direction of tsunami waves and the presence of dunes along the coast.

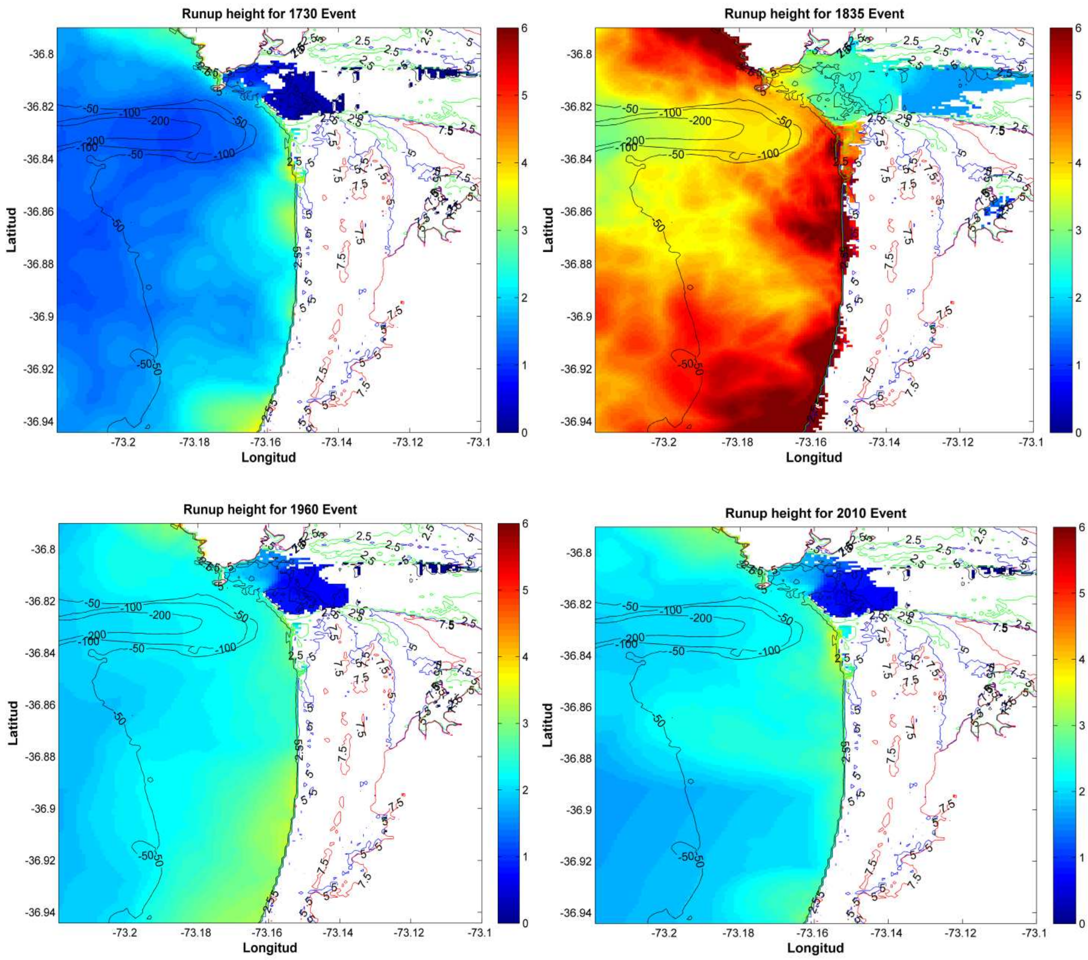

Figure 9. Inundation area and inundation height corresponding to the four analyzed events: 1730, 1835, 1960 and 2010 tsunami. Contour lines every 50m show the bathymetry and every 2.5m the topography.

CONCLUSIONS

It can be concluded that the Biobio canyon is very important in tsunami propagation in the Gulf of Arauco, thus there is a mitigation effect on the eastern side of the Gulf due to the refraction and dispersion generated by its zigzag shape. The change in wave direction is enhanced due to wave diffraction generated by the Santa María Island, causing the wave fronts to move in a north-south direction, preventing severe damage to the eastern side. However a direct impact of the tsunami in the southern end of the Gulf can be observed.

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