The generation of new tsunami risk areas due to an intentionally biased reconstruction process: Case study of Ilico after the 2010 Chile tsunami

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ABSTRACT

Tsunamis are among the most significant hazards in coastal settlements. Mitigation measures have been focused mainly on physical aspects, and few studies have addressed vulnerability and resilience in a multidimensional approach. The main objective of the present work is to assess changes in vulnerability and, consequently, risk, considering a time-space dimension. Three deterministic tsunami scenarios based on historical events were analyzed, and vulnerability analysis with an emphasis on social cohesion and community organization in pre-reconstruction (2012) and post-reconstruction (2017) conditions was carried out using physical, socioeconomic and social organization variables. The extreme scenario was found to be a 2010-like tsunami, and high levels of social trust and community cooperation were found in pre-reconstruction conditions, which decreased in post-reconstruction conditions due to the relocation of the affected population to other parts of the region. Therefore, it can be concluded that even though physical aspects are important for improving the livability of an affected place and the quality of life of its inhabitants, intentionally biased reconstruction processes (focused mainly on physical aspects) do not effectively reduce risk. Finally, it is crucial to include social capital and social resilience in public policies to implement more comprehensive and successful reconstruction processes.

1. Introduction

Advances in tsunami research have mainly focused on analyzing hazard rather than risk [1–12]. Moreover, recent studies have developed probabilistic tsunami hazard analyses at national and regional scales [13]. However, due to the increasing impacts of tsunamis in recent years, risk assessment is becoming more focused on vulnerability and resilience, highlighting the importance of communities that are well-organized and aware of tsunami risk [14]. Nevertheless, our understanding of vulnerability, which changes as a function of highly dynamic social and territorial processes, has not improved commensurately compared to our understanding of hazard. The use of vulnerability and resilience indices facilitates spatial analysis [15]. However, the evolution of vulnerability, and subsequently risk, has not yet been analyzed in a time-space dimension, especially when reconstruction processes are involved and not all aspects of recovery (physical, socioeconomic, organizational) are taken into account, as these processes could effectively decrease the risk or even generate new areas of risk [16].

According to the Hyogo and Sendai Frameworks for Disaster Reduction, the reconstruction process plays an essential role in strengthening social and urban resilience through the design of an urban fabric that considers hazard scenarios, public participation, citizen collaboration and prevention at various levels. Reconstruction is aimed at restoring sustainable living conditions for a community that has been strongly affected in physical, social, economic, institutional, cultural and ecological terms as a result of its vulnerability prior to the event [17]. Therefore, a biased reconstruction process may be defined as a process that is carried out considering only few dimensions, such that sustainable living conditions may not be completely restored. An

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example of a successful reconstruction process is that of Kobe, Japan, after the 1995 Mw 6.9 earthquake. In this case, recovery was focused on three dimensions: urban, economic and lifestyle [18]. This process is considered the basis of post-disaster recovery process research, as it resulted in the creation of recovery indicators and models [17–20]. By contrast, the reconstruction policy after the 2010 earthquake and tsunami in Chile has been intentionally focused on physical aspects such as construction of new houses and inefficient hard mitigation measures rather than restoration of living conditions. [16,21–26,108]. The results of these biased reconstruction processes highlight the need for a critical reflection on their impact and how each stage of recovery and its evolution over time must be implemented in order to ensure an effective restoration of sustainable living conditions.

The main objective of the present work is to assess the impact of a biased reconstruction process on vulnerability and, consequently, risk, considering a time-space dimension for a given deterministic tsunami scenario. To this end, changes in physical and social conditions in the fishing village of Llico over a period of 5 years (2012–2017), including post-disaster (pre-reconstruction) and post-reconstruction periods, are analyzed. This village was chosen as a study area for three main reasons: It was significantly affected by the 2010 tsunami, the village survived the emergency for a long time thanks to the community organization after the collapse of the transport network, and finally, it is located on a coastal axis characterized by peri-urbanization related to the second-largest metropolitan area in Chile (Greater Concepcion). Section 2 gives a short background on risk assessment in order to explain the approach used in this research. Section 3 presents a description of the study area, as well as records of historic tsunami events that affected the village. Section 4 contains the methodology, which describes the numerical simulations used to analyze the tsunami hazard. It then presents the dimensions and indicators to analyze the vulnerability and describe the tsunami risk assessment approach. The numerical simulation and risk assessment results are given in section 5. Section 6 presents the discussion and section 7 the main conclusions of this research.

2. Background

Many destructive earthquakes and tsunamis have affected the coast of Chile throughout its history [28–30]. In fact, two of the six largest recorded earthquakes in the world have taken place in central and southern Chile, namely, the 1960 and 2010 events. The latter caused significant destruction of urban infrastructure [31], and the tsunami was observed along 600 km of the coast. Around 500 people perished, 125 as a result of the tsunami [32]. The earthquake also generated uplift of up to 1.8 m in the Gulf of Arauco (37° S), which affected river mouths and wetlands such as the Tubul wetland, located on the southern shore of the Gulf of Arauco [33]. Due to tectonic factors and marine cycles, the coast of central Chile consists of several bays and paleo-bays that open northward, allowing tsunami energy to be focused or defocused. In addition, the most affected coastal areas are usually located on low coastal plains that interact with local drainage, enabling the tsunami to propagate farther inland; the majority of the coastal cities and towns in Chile most affected by the 2010 and 2014 tsunamis had these characteristics [16,22]. Urban sprawl has led to large clusters and metropolitan areas that assimilate rural territories along the coastal axis, such that tsunami affect not only urban areas, but also neighboring rural spaces, which quickly become urban through peri-urbanization processes [34–36,65].

The most recent literature on risk assessment presents different theoretical and methodological approaches influenced by the scientific discipline involved, generating different alternatives for analyzing natural hazards, beyond the traditional or classical framework in which risk is defined as the interaction between hazard and vulnerability [26]. In this framework, research into hazard, particularly tsunami hazard, has progressed greatly with respect to methodological aspects, especially in terms of the advance from deterministic to probabilistic models [13,37].

Regarding vulnerability, there have been advances in both conceptual and methodological aspects [38,39]. Regarding conceptual aspects, there has been an evolution from classical schemes [40–43] to a broad, multidimensional concept that combines social, economic, ethical, political and socioecological approaches [39,44,45]. In the context of vulnerability to climate change, it has been stated that this vulnerability is complemented by the recovery capacity of socioecological systems, in which it is possible to recognize certain vulnerability patterns [39,46,47]. Regarding methodology, various models have been proposed to analyze vulnerability and its integration into risk, notable examples of which are the Social Vulnerability Index SoVI® [45,48,49] and use of the analytical hierarchical process (AHP)-based approach to coastal vulnerability studies as an improvement on the existing methodologies for vulnerability assessment [50]. In the case of coastal vulnerability indices, for example, biophysical aspects linked to hazards resulting from climate change scenarios are integrated into vulnerability [50–52]. Other models integrate exposure, sensitivity and response capacity factors, in line with the ideas of Adger [39] and Gallopin [46] on the relationships between vulnerability, resilience and adaptive capacity.

Recent studies have emphasized the ability to interpret vulnerability and resilience from a multidimensional point of view. Both variables are difficult to measure [53]. Thus, territorial identity, social fabric, social cohesion and sense of belonging are key aspects to explain both disaster response and damage levels [48]. Other relevant aspects are topophilia and topophobia, which change and recover according to the perceived landscape [53–56]. Therefore, a more comprehensive analysis of these elements becomes important to prevent negative consequences of tsunami impacts, using elements deemed to increase resilience in order to acclimate communities to scenarios of global change and local adaptability. The emphasis is on the adaptive and resilience capabilities of a community, including community participation, as an important factor in reduce areas exposed to risk [14,57,58]. Even though there is a lack of methodologies for analyzing these comprehensive and dynamic concepts [53,59,60], there are important proposals that promote the use of integrated vulnerability indices in risk assessment for purposes of land-use planning [15,60,61] and adaptation to global climate change [50].

3. Study area and historical tsunamis affecting the Gulf of Arauco

3.1. Study area

Llico is a coastal village located on the southwestern shore of the Gulf of Arauco, 32 km from the city of Arauco (See Fig. 1). It was founded in the 18th century as a small town for native people (Mapuche) during the Spanish conquest period. The village is located on a coastal plain formed by Holocene deposits and bounded by a low terrace between 75- and 100-m high belonging to the Nahuelbuta Mountains [62]. The climate is Mediterranean with oceanic influence, with a long dry season and rain concentrated in winter [63]. Two streams flank the village, with related wetlands. Sea water can surge a few meters into the streams during the highest tides. In 2002, it had an estimated population of 554 inhabitants, with men accounting for 52% [64]. The main economic activity is fishing.

The 2010 Chile tsunami significantly affected the village and destroyed 157 of its 231 houses, meaning that 68% of its families lost their houses. Moreover, 90% of families experienced problems resulting from the earthquake and tsunami [109]; in fact, the socioeconomic vulnerability index increased by 16% in Llico after the 2010 event [65]. In addition, the main facilities, including 6 small restaurants, a maritime museum, the fishing pier, 7 shops and a gas station were also destroyed. Also destroyed were 21 fishing boats. In general, one of the most affected sectors was fishing, due to the destruction of small-scale fishing boats [31]. In addition, the uplift due to the earthquake affected some maritime resources such as shellfish and seaweed, resulting in 88 workers.
who had collected them losing their jobs. Moreover, due to damage to main roads and bridges, people in Llico were isolated for a long time (~2 months) before connectivity was restored.

Although Llico is considered a rural community, its house typology and building concentration give it urban characteristics [64]. The total number of houses was 231 in 2002. According to the last census, the number of houses was estimated at 375 [66].

3.2. The 2010 earthquake and tsunami

The 2010 Chile tsunami was generated by a moment magnitude Mw 8.8 earthquake. The earthquake source of this event has been studied by several authors [67–70] and the length of the rupture zone was estimated at 500 km, with a maximum slip of 15 m [70]. It is thought that this earthquake filled the seismic gap between Constitución and the Arauco Peninsula since the last major earthquake in 1835 [69, 70].

The earthquake generated significant uplift along the coast. Surveys of intertidal zones, coralline algae biomarkers and coastal infrastructure allowed the coastal uplift to be estimated. For example, Quezada et al. [71], measured up to 2 m on Santa María Island, Llico, Morguilla and Lebu. However, Vargas et al. [72] measured 2.5 m on Santa María Island, 1.3 m in Punta Lavapié and 1.7 m in Lebu. Moreover, Jaramillo et al. [73], found a mean range of 1.89–2.09 m on the Arauco Peninsula (Punta Lavapié, Llico and Lebu) and Santa María Island, while Fritz et al. [32] measured 1.6 m in Punta Lavapié, 1.9 m in Llico and 1.5 m in Tubul. It can be seen that all the measurements differ; however, they are on the same order of magnitude. Thus, the authors carried out topographic measurements in Llico using a geodetic GPS connected to the TIGO (Transportable Integrated Geodetical Observatory) station in Concepción in December 2013 (See Fig. 2-a and b) and then contrasted these data with LIDAR data obtained in 2009. The measurements were carried out at specific locations, which were also important for estimating the inundation area of the 1960 tsunami, as explained in the following sections. The average uplift in Llico was found to be 1.2 m. The use of a realistic uplift is important during validation of numerical simulations validation; otherwise, maximum inundation may be overestimated.

Tsunami intensity may be measured by means of several variables such as inundation height, run-up and flow depth. The inundation height is defined as the elevation reached by seawater measured relative to the sea level at the time of tsunami arrival. The run-up is also the elevation reached by seawater, but measured at the inundation limit. Therefore, the run-up is also defined as the maximum ground elevation reached by the tsunami at the inundation limit. The flow depth is the height of water column above the ground at a specific location. The 2010 tsunami presented a varied intensity along the coast. For example, Coliumo (36.54 S, 72.95 W) and Concepción bays (36.7 S 73.1 W) experienced inundation heights of 8 and 7 m, respectively [32, 74], while the eastern coast of the Gulf of Arauco, from the mouth of the Biobío River to the town of Lota, did not experience significant inundation [32, 75]. In addition, run-ups of 8.4 and 13.4 m were measured in Tubul and Llico, respectively, located on the southern shore of the Gulf of Arauco. Moreover, the maximum run-up on the Gulf of Arauco, reaching 18 m, was measured in Llico [74]. The tsunami behavior on the Gulf of Arauco can be explained by the presence of the Biobío submarine canyon and Santa María Island. The submarine canyon diffracts and refracts tsunami waves and then the change in wave direction is enhanced due to wave diffraction generated by Santa María Island,
Fig. 2. Field survey at Llico in December 2013. a) GPS Measurements at former location of primary schoole. b) GPS Measurements at eucalyptus forest and former house of Mr Fernandez. c) Interview to Ms Mendoza. d) Interview to Mr Fernandez.

Fig. 3. a) Tsunami inundation area in Llico due to the 2010 Chile tsunami. Coloured area indicates the inundation area estimated by Rojas et al. [65]. b) Estimated inundation area of 1960 tsunami based on eyewitness testimonies and ground elevation. The dashed line indicates the estimated inundation limit of 2010 tsunami defined by the National Statistics Institute [110].
causing the wavefronts to move in a north-south direction. This phenomenon prevents severe damage to the eastern side of the village; however, a direct tsunami impact on the southern end of the gulf can be observed [75].

Tsunami damage in Llico was significant, and almost all structures below a ground elevation of 4 m were destroyed. It was observed that the seawater surged up to 500 m inland. Fig. 3-a shows the estimated inundation area in Llico due to the 2010 Chile tsunami [65]. The dashed line indicates the inundation limit estimated by the National Statistics Institute (INE, for its initials in Spanish). Tsunami behavior in this area is discussed in following sections based on results of numerical simulations.

3.3. The 1960 tsunami

The 1960 earthquake has been defined as the largest earthquake ever recorded. This event had a moment magnitude of Mw = 9.5 and a rupture area that extended 1000 km from the Arauco Peninsula (37°S) to the Taitao Peninsula (46°S) [76]. In addition, significant morphological changes were observed along a width of 200 km.

The earthquake generated a destructive tsunami with an inundation height that reached up to 10 m along the Chilean Coast. By means of paleo-tsunami studies, it was concluded that the preceding event occurred 385 years earlier and that similar events had taken place every 285 years on average [77].

Table 1 shows some field measurements made by a Japanese team [78]. Like during the 2010 tsunami, the effects along the coast are varied. It can be seen that maximum run-up was observed on Mocha Island just north of the tsunami source, while close to the epicenter in Corral and Puerto Saavedra, the tsunami caused inundation heights of 8–9 m. It is noticed that the lowest values inside the Gulf of Arauco were measured on the eastern shore in Coronel and Lota (as in 2010), which means that the presence of the submarine canyon and Santa María Island have similar effects on a tsunami from southern Chile [75].

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In order to assess the possible inundation area of the 1960 tsunami in Llico, the authors carried out a field survey in December 2013. Fig. 2-c and d show two eyewitnesses interviewed during the field survey who gave valuable information about the behavior of the 1960 tsunami. Fig. 2-d shows Luis Fernandez, who is a 70-year-old man, and Fig. 2-c shows Catalina Mendoza, a woman of 89. These two witnesses have lived in the same place for more than 60 years, and experienced both the 1960 and the 2010 tsunami events. They were interviewed separately and their testimonies were consistent. Ms. Mendoza was 33 years old at the time of the 1960 tsunami; she mentioned that her house was flooded during the 2010 tsunami, but that the 1960 tsunami did not cause any flooding. However, she could see seawater inundating low wetlands close to her house, similar to what happened in 2010 (wetland around Budi Stream). She also mentioned a police station that was destroyed by the tsunami and was never rebuilt. Mr. Fernandez was 14 years old at the time of 1960 tsunami, and he remembered even more precise information regarding the inundation and tsunami behavior. He mentioned that the 1960 tsunami came from the northeast and after hitting the cliff, it was reflected and inundated the town. He remarked that this behavior was similar to what happened in 2010. He remembered that the tsunami destroyed a fish factory close to the Llico River beside the cliff, his primary school and the police station. In addition, he remembered that the tsunami inundated a warehouse and surged a few meters into the wetland around Budi Stream. Moreover, Mr. Fernandez mentioned that the inundation area of the 1960 tsunami reached the site of what is now a small eucalyptus forest, which is beside his former house (destroyed by the 2010 tsunami). All the places mentioned by the eyewitnesses were recorded by GPS so that the inundation area could be analyzed (Fig. 2-a and b). Fig. 3 shows a map of Llico with all the places mentioned by the eyewitnesses. In addition, it is possible to estimate an inundation area based only on ground elevation. Based on the eyewitness accounts, it was assumed that the tsunami run-up reached up to 3 m. A detailed analysis of the inundation area based on numerical simulations is given in following section.

3.4. The 1730 tsunami

The 1730 event has been recognized as the largest earthquake in central Chile in the last 500 years [79]. The earthquake generated severe damage in Valparaiso and Santiago, but no significant damage was reported in Concepción [28]. However, a destructive tsunami was observed along 1000 km of the coast [79,80] and Valparaíso and Concepción (formerly located in Penco) were destroyed by the flooding. Even though the magnitude of the earthquake has been defined as Mw=8.5–9.0, with a rupture length ranging from 350 to 550 km, [28,81], recent research suggests that the magnitude of that earthquake was as large as Mw 9.1–9.3 [82].

The historical sequence of large earthquakes in central Chile (1575, 1647, 1730, 1822, 1906 and 1985) indicates a constant recurrence interval of ~85 years [28]. However, Carvajal et al. [82] suggest that all the earthquakes had different sizes and characteristics and not all of the accumulated seismic energy had been released. In fact, based on the observed effects, it is believed that the 1822 and 1906 events ruptured the deepest portion of the subduction zone. In addition, the earthquake of 1985 released only part of the total energy budget since 1730 [82]. Therefore, a large earthquake with shallow slip, and subsequently large tsunami, may occur in the near future. Thus, although there is no evidence of the 1730 event affecting the southern shore of Gulf of Arauco, it is important to analyze possible effects in Llico of a tsunami generated by a large earthquake in central Chile.

4. Tsunami risk assessment in llico

This chapter describes the methodology used to assess the tsunami risk in Llico. First, the methodology for estimating the tsunami hazard, which includes the numerical setup and tsunami initial conditions, is described. Then the methodology for assessing the vulnerability is presented. Three types of vulnerability were considered: physical, socio-economic, and organizational.

4.1. Tsunami hazard analysis

4.1.1. Numerical setup

In order to simulate the tsunami inundation due to the 2010, 1960 and 1730 events, the NEOWAVE (Non-hydrostatic Evolution of Ocean WAVES) model was used for tsunami numerical simulation. NEOWAVE is a staggered finite-difference model that solves the nonlinear shallow water equation and uses a vertical velocity term to account for weakly dispersive waves. A detailed description of the model can be found in Yamazaki et al. [83,84]. This model has already been used in numerical simulations of the 2010 tsunami in the Gulf of Arauco [85]. In addition, Martinez et al. [16,33] used the model to simulate the 2010 tsunami in Tubul and Dichato. Aranguiz et al. [107] simulated the 2015 Coquimbo
tsunami and defined a Manning roughness coefficient of $n = 0.025$. Recently, Aránguiz et al. [86] simulated the 2011 Tohoku tsunami and validated the event with DART buoys and the Talcahuano tide gauge. A validation of the 2010 tsunami in the southern shore of the Gulf of Arauco is presented in the Supplementary Material.

Five levels of nested grids were set up to model the tsunami from generation in the source region to inundation in Llico. Fig. 4 shows the nested grids for modeling the 1730, 1960 and 2010 tsunamis in Llico. Grid 1 is the southeast Pacific Ocean at 2-arcmin (~3600 m) to cover tsunami generation and tsunami propagation to the Gulf of Arauco. An open boundary condition is applied to radiate the tsunami away from Grid 1. Grid 2 at 30-arcsec (~900 m) describes wave transformation over the continental shelf and slope along the Chilean coast and Grid 3 at 6-arcsec (~180 m) is used to model tsunami propagation inside the Gulf of Arauco, while Grid 4 at 1-arcsec (~30 m) is defined to model the tsunami on the southern shore of the gulf. Grid 5 (~10 m) is used to model inundation and tide gauges in the village of Llico. Grids 1 and 2 are generated from GEBCO 08 (https://www.gebco.net/data_and_products/gridded_bathymetry_data/) and Grids 3, 4 and 5 are built from nautical charts and detailed bathymetries at Llico. The topography of the higher-resolution grids is obtained from 2.5-m-resolution LIDAR data. Table 2 shows the geographical coordinates, resolution and time steps of simulation grids. Because the LIDAR data were obtained in 2009, some corrections were applied so that the uplift coincided with the measured values. It is important to mention that the uplift correction was applied only to the case of the 2010 tsunami, while the topography during 1960 tsunamis remained the same. Nevertheless, in the latter case, the topography around the coastal road and pier was edited because they were built in 2005. In the case of the 2010 tsunami, an uplift of 1.2 m covers an elapsed time of 6 h for the 2010 event and 8 h for the 1730 and 1960 tsunamis in order to be sure that maximum tsunami amplitudes are captured during the simulations. The output time intervals were set at 1 min.

### 4.1.2. Tsunami initial conditions for each event

A kinematic sea bottom deformation was used to generate the tsunami initial condition. The planar fault model of Okada [87] was used to obtain the floor displacement given the fault parameters such as length (L), width (W), slip (D), focal depth (h), strike ($\theta$), dip ($\lambda$) and rake ($\phi$).

Fig. 5 shows the tsunami initial condition of the 1730 event. This source model, proposed by Carvajal et al. [82]; corresponds to an event of magnitude Mw 9.2. The right side of Fig. 5 shows the initial condition for the 2010 tsunami. The finite fault model of 180 subfaults proposed by Hayes [67] was used; it was validated by Yamazaki and Cheung [85] using DART buoys 32,412, 51,406 and 32,411 and 43,412. In addition, Martínez et al. [33] and Martínez et al. [16] validated this fault model with inundation height measurements in Tubul and Dichtato, respectively.

Fig. 6 shows the tsunami initial conditions considered for the 1960 tsunami according to three different rupture models. The first model (Fig. 6-a) is that proposed by Fuji and Satake [88]. It consists of 27 subfaults with variable slip and a moment magnitude Mw 9.2. The second model (Fig. 6-b) is the Planar Fault Model (PFM) proposed by Barrientos and Ward [76]. This model assumed a rupture size of L = 850 m, W = 130 m and an average slip of 17 m, while the other parameters are strike, dip and rake angles of 7°, 20° and 105°, respectively. It is important to consider that the 1960 event consisted of a sequence of 3 large shocks over 33 h; therefore, the earthquake rupture models reproduced the vertical deformation generated by all of them independently of the initiation time [89]. Consequently, the tsunami source model could differ from the earthquake model because the main shock was the most important in the generation of the 1960 tsunami. Thus, Aránguiz [89] proposed a 5-segment rupture model, which was based on the Finite Fault Model (FFM) proposed by Barrientos and Ward [76]; but it considered only the two main events on May 22nd. Numerical simulation of the 5-segment model showed that maximum tsunami amplitudes are in agreement with tsunami records in Talcahuano (3 m), Tiriúa (4–5 m), Corral (10 m) and Ancud (5–6 m), see Table 1. The results were contrasted with numerical simulations of the PFM given by Barrientos and Ward [76]. In general, the maximum tsunami amplitudes in Tiriúa, Corral and Ancud are similar. However, the 5-segment model fits the Talcahuano tide gauge better for both arrival time and maximum tsunami amplitude [89]. Fig. 6-c shows the initial conditions of the 1960 tsunami given by the 5-segment model of Aránguiz [89]. The three previously mentioned tsunami scenarios of the 1960 event were validated by Hayes [67]; it was validated by Yamazaki and Cheung [85] using DART buoys 32,412, 51,406 and 32,411 and 43,412. In addition, Martínez et al. [33] and Martínez et al. [16] validated this fault model with inundation height measurements in Tubul and Dichtato, respectively.

![Grids 1-5](image_url)

**Fig. 4.** 5 levels of nested grids used in tsunami numerical simulations.

| Grid | Longitude | Latitude | Resolution | Time step (s) |
|------|-----------|----------|------------|---------------|
| 1    | -80°–70° | -50°–29° | 120° (~3.7 km) | 1 |
| 2    | -74.5°–71.7° | -38°–35° | 30° (~900 m) | 0.5 |
| 3    | -73.75°–72.85° | -37.3°–36.5° | 6° (~185 m) | 0.25 |
| 4    | -73.63°–73.5° | -37.26°–37.12° | 1° (~30.8 m) | 0.125 |
| 5    | -73.59°–73.54° | -37.21°–37.185° | 1/3 (~10.2 m) | 0.125 |

Table 2: Coordinates, resolution and time steps of simulation grids.
simulated to find the best model for representing the historical inundation in Llico.

The results of the numerical simulations allowed the extreme tsunami scenario to be defined in order to make the hazard maps and then carry out the risk assessment. To this end, two tsunami intensity measures were defined, namely, inundation depth and flow velocity. In addition, three hazard levels were defined for each intensity measure. The hazard levels for inundation depth and flow velocity are defined based on the effect on people [90–92], as shown in Tables 3 and 4, respectively.

### 4.2. Vulnerability assessment

Since the village of Llico is in a rural area, the plot was the smallest unit of analysis in the spatial vulnerability assessment. Field surveys proportional to the population size in each plot were conducted, examining three main variables of vulnerability: physical, socioeconomic and organizational [59,60,93,94]. The vulnerability of the village was analyzed under two conditions: pre-reconstruction (2012) and post-reconstruction (2017).

For the pre-reconstruction condition (2012), the sample size was determined based on the following elements: population (356 households), which was estimated from the Master Plan for Reconstruction of Llico (PRBC-18 for its initials in Spanish, https://www.preventionweb.net/files/28726_plandereconstruccinminvu.pdf), confidence interval of

| Range       | Descriptor         | Hazard Level |
|-------------|--------------------|--------------|
| 0–0.5 m     | Knee-high or less  | Low          |
| 0.5–2 m     | Knee-high to head-high | Medium    |
| >2 m        | More than head-high | High        |

Table 3: Inundation depth (modified from Ref. [90] and [91]).

| Range       | Descriptor       | Hazard Level     |
|-------------|------------------|------------------|
| 1.0–1.35 m/s| Very low and low danger (speed at which it would be difficult to stand) | Low |
| >1.35 m/s   | Danger for most  | Medium           |
| >5.0 m/s    | Danger for all, >5.0 m/s very dangerous | High |

Table 4: Flow velocity (modified from [92]).
Table 5

Variables for each type of vulnerability.

| Variable                          | Weight | Source                                |
|-----------------------------------|--------|---------------------------------------|
| I. Physical                       |        |                                       |
| Housing type                      |        |                                       |
| House or apartment                | 1      | Ministry of Housing and Urban Planning |
| Tenement or wooden shack          | 2      |                                       |
| Hut or shanty                     | 3      |                                       |
| Housing material                  |        |                                       |
| Concrete, brick                   | 1      | Ministry of Housing and Urban Planning |
| Wood, structural panels           | 2      |                                       |
| Fiber cement, adobe or mud        | 3      |                                       |
| Housing quality and resistance    |        |                                       |
| Very resistant                    | 1      | Ministry of Housing and Urban Planning |
| Moderately resistant              | 2      |                                       |
| Minimally resistant               | 3      |                                       |
| Proximity to coast                |        |                                       |
| Not floodable (over 25 m safe level) | 1   | Modified from [123] |
| Intermediate (between extreme event flood level and 25 m) | 2 | |
| Floodable (below the historical flood level) | 3 | |
| II. Socioeconomic                 |        |                                       |
| Income level                      |        |                                       |
| 1st and 2nd quintiles (< US$ 380) | 1      | MIDEPLAN [112]                        |
| 3rd and 4th quintiles (US$ 381–840) | 2   |                                       |
| 5th quintile (>US$ 840)           | 3      |                                       |
| Economic activity                 |        |                                       |
| Tertiary (in the village)         | 1      | Authors                               |
| Tertiary and secondary (outside the village) | 2 | |
| Primary (fishing-related activities) | 3 | |
| Houses with crowding              |        |                                       |
| 1 to 2.5 people per bedroom       | 1      | Ministry of Housing and Urban Planning |
| 2.5 to 3.5 people per bedroom     | 2      |                                       |
| >3.5 people per bedroom           | 3      |                                       |
| III. Organizational               |        |                                       |
| Social trust                      |        |                                       |
| Great social trust                | 1      | Authors                               |
| Little social trust               | 2      |                                       |
| No social trust                   | 3      |                                       |
| Community cooperation             |        |                                       |
| Great cooperation among neighbors | 1      | Authors                               |
| Little cooperation among neighbors| 2      |                                       |
| No cooperation among neighbors    | 3      |                                       |
| Participation in organizations    |        |                                       |
| High                              | 1      | Authors                               |
| Occasional                       | 2      |                                       |
| Low                               | 3      |                                       |

4.3. Risk assessment

Following a traditional approach, the final risk is computed from equation (1) [98]:

\[ R = V \times A \] (1)

In which \( R \) is the risk, \( A \) is the hazard as a function of the inundation depth levels (Table 3) and \( V \) is the vulnerability. The latter was computed using the Weighted Overlay method by integrating the three types of vulnerability with a specific weight of 33% each. \( A \) and \( V \) were analyzed and combined by means of a matrix [90,99], and three levels of risk were defined: high (6–9), medium (3–4), and low (1–2). Scores from 1 to 9 were assigned to risk levels using a SIGARCGis 9.3 platform, which provided the final risk zoning (Table 6).

5. Results

Fig. 7-a shows the maximum inundation heights (left) and maximum velocities (right) due to the 2010 tsunami considering an uplift of 1.2 m. The contour lines every 2.5 m from 0 to 10 m are also shown in the figure. In addition, three important points are plotted: the chapel (1), Ms. Mendoza’s house (2) and the eucalyptus forest (3). As recorded during field surveys, the simulation inundated up to the chapel (1) and flooded Ms. Mendoza’s house (2). Moreover, the wetland around Budi Stream was completely inundated, as mentioned by Ms. Mendoza, despite the surveyed inundation area (dashed line) not recording this inundation. A possible explanation for this omission is that the field survey focused on damaged houses and debris, and the wetland is an empty area where no damage could be observed. However, the inundation area published by INE [110] (See Fig. 3) clearly indicates that the wetland was inundated. Thus, the results of the numerical simulations with a 10-m grid resolution are in good agreement with field observations.

Table 6

| Hazard/Vulnerability | High (3) | Medium (2) | Low (1) |
|----------------------|----------|------------|--------|
| High (3)             | 9        | 6          | 3      |
| Medium (2)           | 6        | 4          | 2      |
| Low (1)              | 3        | 2          | 1      |
Fig. 7. Results of tsunami numerical simulations. Left column: maximum inundation height. Right column: Maximum Flow velocity. a) Inundation area due to the 2010 Chile tsunami considering an uplift of 120 cm. b) Inundation area due to 1730 tsunami with the Carvajal et al. [82] model. c) Inundation area due to the 1960 tsunami with the Fujii & Satake [88] model. d) Inundation area due to the 1960 tsunami with the planar fault model of Barrientos and Ward [76]. e) Inundation area due to 1960 event with the 5-segment model given by Aranguiz [89]. Reference points are shown in the left column: (1) Chapel, (2) Ms. Mendoza's house, (3) eucalyptus forest.
Fig. 7-b shows the modeled inundation heights and velocities due to the 1730 tsunami in central Chile. The reference points are also plotted to allow a comparison with the 2010 event. It is possible to observe that the inundation area is similar to the area generated by the 2010 tsunami, although the inundation heights and velocities are smaller. Therefore, an earthquake of magnitude Mw 9.0 off the coast of Valparaiso could generate a significant tsunami in Llico. Similarly, Fig. 7-c to e show the modeled inundation heights and flow velocities of the 1960 tsunami. It can be observed that the Fujii & Satake [88] model (Fig. 7-c) and the planar fault model of Barrientos and Ward [76] (Fig. 7-d) show larger inundation areas, similar to that of the 2010 tsunami. In fact, the simulation shows the flood reaching the chapel (1) and Ms. Mendoza’s house (2); however, the field survey indicated that the 1960 tsunami did not flood Ms. Mendoza’s house. According to Mr. Fernandez, the 1960 tsunami inundated up to the eucalyptus forest (3), and the wetland around Budi Stream was also flooded. Therefore the 5-segment model (Fig. 7-e) proves to be the best approximation of tsunami inundation due to the 1960 event.

Based on analysis of Fig. 7, the extreme tsunami scenario was defined as the 2010 inundation area. This event generated the largest inundation area and the largest inundation heights. The hazard maps as a function of inundation depth and flow velocity according to Tables 3 and 4 are shown in Fig. 8. Regarding the inundation depth, it was found that 68% of the inundation area is under a medium level of hazard, mainly the parts located close to the coastline. It is noticeable that Budi Stream facilitated the tsunami surge in the village. Twenty-nine percent of the inundation area was found to be under a medium level of hazard, while only 2.7% of the area was found to be under low level of hazard.

With respect to vulnerability, the analysis of pre-reconstruction conditions (2012) showed that housing type and material are important variables in tsunami damage levels in Llico. Sixty-nine percent of the structures were classified as presenting medium vulnerability and 29% of them high. Meanwhile, 99.4% of the structures were classified as presenting low or medium levels of housing quality and resistance (Table 5). Fig. 9 shows typical houses in Llico prior to the 2010 tsunami, which were made of timber and corrugated metal roof sheets. In addition, 91.5% of the houses were found to be located below a ground elevation of 15 m, i.e. floodable, according to Table 5. Therefore, in terms of physical vulnerability, 65% and 21% of the houses were classified as medium and high, respectively. In a similar manner, the questionnaire analysis showed that household incomes were low; in fact, 78% were classified as high vulnerability and 21% as medium. It was found that economic activity is highly dependent on fishing, as 91% of householders (324) are fishermen. Meanwhile, the level of overcrowding was found to be low in 65% of all houses. An analysis of the previously mentioned socio-economic variables together reveals a medium level of socio-economic vulnerability. Regarding organizational vulnerability, it was found that social trust among neighbors was high among 79% of householders. In addition, 78% of the householders indicated that at least one family member always or frequently participates in community activities, while 22% indicate occasional participation. However, 64% of householders indicated that they always or frequently participate in activities of local organizations, while 36% do not participate. Therefore, when these variables are analyzed together, it is possible to define low organizational vulnerability in 77% of houses. Finally, overall vulnerability tends to be low.

When the post-reconstruction condition (2017) is analyzed, it was determined that high physical vulnerability decreased from 21% to 2% in post-reconstruction conditions [96], which is explained by the relocation of destroyed homes to zones outside the inundation area, as well as improved building quality and types. Forty-three percent of all homes have one story and are built according to technical standards. In a similar manner, the degree of socioeconomic vulnerability changed from high to medium due to current low or nonexistent crowding levels in homes, as well as an increase in jobs linked to the tertiary sector, in tourism and food services, for instance. Nonetheless, income levels have remained low. It was found that organizational vulnerability worsened from a low to medium due to lower levels of social trust and community cooperation than in pre-reconstruction conditions. Participation in social organizations decreased in post-reconstruction conditions, as 56% of heads of household always or occasionally participate, while 43% do not participate (high vulnerability). The main organizations in which
the community participates are related to religion (church), with an average participation frequency of once a week, and unions, whether the Fishermen’s, Seaweed Collectors’ or Women’s Union, with a participation frequency from once a month to every six months. Also noteworthy, but of secondary importance, are neighborhood organizations, senior groups, indigenous community groups and athletic organizations. Social trust decreased (50% of survey respondents do not trust their neighbors), as the respondents indicated that the people who have come to live in Llico in housing provided by the Reconstruction Plan are not local and do not share the territorial identity. These people are not part of everyday social networks or those familiar to members of the community, which causes a change or rupture in established social networks and in turn the internal cohesion of the community based on these social networks or connections, weakening the main source of social capital. Another reason indicated by the respondents is that the neighbors felt that participation in the reconstruction process was limited to union members, who did not always look out for the interests of all the inhabitants of the village.

The vast majority of respondents (78%) state that there is cooperation among members of the community, while 21.5% state that there is not much community cooperation. Although in this case it is not significant, the decrease in community cooperation weakens the ability of community members to organize and carry out a collective action with a common objective, which proves to be a fundamental element for facing and adapting in a post-disaster context. It bears mentioning that the reductions in social trust and to a lesser extent community cooperation were not reflected in aspects such as participation in local organizations, which, while not greater, did not decrease (vulnerability levels remained similar to those in 2012). Fig. 10 shows the final vulnerability maps for both pre-reconstruction (2012) and post-reconstruction conditions (2017). It can be seen that vulnerability did not change in the 5-year time window, despite the implemented mitigation measures. In addition, new areas presented the same level of vulnerability.

It can be observed that tsunami risk areas did not change.
significantly after the reconstruction process, as seen in Fig. 11. It was found that 15.24% of homes, especially those located closest to the coast, presented high risk, while the remaining 82.5% presented low risk. It is important to note that 60% of the village population is located in high-risk areas, which corresponds to the 80% (13.7 ha) of the flooded area, while the medium-risk area is only 16.9% (see Fig. 12).

6. Discussion

The hazard analysis was based on the classical approach of the “worst-case” scenario event, which is a typical practice in Chile [113]. However, since uniform slip distribution may underestimate the hazard [114–116], the current tsunami sources considered heterogeneous slip distribution and geometry of the subduction zone. The results of this investigation established that a deterministic near-field tsunami scenario like the 2010 event is the worst-case scenario, larger than those of 1960 or 1730. However, an event like 1730 in central Chile would generate a tsunami of similar characteristics. That event is particularly interesting because a similar event could take place in the near future. The recurrence of such events may be determined by means of historical records [117], paleotsunami records [77] or Guternberg-Richter law [120]. For instance, the recurrence of a 1960-like tsunami in southern Chile was found to be ~300 years on average [77], while the recurrence of a large earthquake in central Chile was found to be in the range of 200–600 years [121]. An improvement in tsunami hazard analysis would be the implementation of stochastic tsunami scenarios [114]. However, few studies have implemented this approach in Chile, mainly in the northern segment [115,122]; thus, further research is needed.

Vulnerability and risk in Llico are highly dependent on building type and location, income levels and the type of economic activity of the inhabitants (fishing). After the 2010 event, already low income levels decreased due to the general destruction of fishing tools. In addition, these effects were exacerbated by geomorphological changes caused by coastal uplift (1.2 m), making sea products unavailable in a large portion of the places from which they had been extracted [71,95,100]. The economic profile of the population was in turn reflected in self-built houses made of precarious materials that to a large degree explained the level of destruction of the 2010 tsunami, which affected 60% of the built-up area and destroyed 68% of the homes in the village [100]. These effects were also seen in other coves in the region, such as Tubul [33,65].

Prior to reconstruction, organizational vulnerability in Llico was found to be low and overall vulnerability was medium, despite the precarious conditions of housing materials, the location of housing in high-hazard areas and low income levels. This is mainly due to high levels of social trust (75% of homes) and community cooperation (78% of homes) in pre-reconstruction conditions (2012), which is partly explained by the high degree of geographic isolation of this rural coastal village. In fact, Llico was isolated during the emergency and received no humanitarian aid due to damage to road infrastructure; therefore, it used its social capital to ensure its survival as a community. After the tsunami, there were conditions within the social fabric that strengthened the feeling of solidarity among residents, enabling them to endure the lack of aid much longer than neighboring communities. Thus, the inhabitants understood that joint action was a valid path that would lead them to solutions to unfavorable situations. It is undoubtable that an organized community not only more easily finds institutional spaces for participation, but is also better equipped to open new spaces if necessary and is typically able to act in a more unified and effective manner to achieve goals than a group of disorganized inhabitants without common goals [101]. Mitigation measures aimed at taking advantage of high

Fig. 11. Tsunami risk maps of Llico for the pre-reconstruction (2012) condition (left) and post-reconstruction (2017) condition (right).

Fig. 12. Comparison for pre-reconstruction and post-reconstruction conditions of area distribution for low, medium and high a) Vulnerability, b) Risk.
levels of trust and cooperation among neighbors are fundamental to reducing vulnerability amid the latent hazard that these societies live with [57,58].

Eight years later and with a reconstruction process mainly focused on physical and socioeconomic aspects, physical and socioeconomic vulnerability were actually reduced. In fact, some positive socio-territorial changes due to the intentionally biased reconstruction process have been determined: 1) The Reconstruction Plan (PRBC-18), through the relocation of homes to places above the historical flood level and building of homes with more resistant materials, has decreased physical vulnerability; 2) The creation of new sources of tourism-related employment has decreased socioeconomic vulnerability despite low reported incomes (diversification of economic activities). This is also promoted by the Reconstruction Plan, which indirectly eradicates crowding in houses. However, the arrival of outsiders in the village of Llico generated mistrust along the local population, decreasing community cooperation and affecting social networks and bonds. This process weakened the main source of social capital and in turn increased organizational vulnerability, resulting in the loss of the community’s most valuable asset for coping with a disaster. International experiences indicate that relocation can greatly affect people’s lives, especially when they are dependent on natural resources. In addition, relocation may destroy the bonds of existing communities if it is not carried out in a well-planned manner. Therefore, this process must involve measures to compensate people for the loss of their livelihoods and maintain local communities [102]. It is also important to consider that in the post-disaster period, creative and sustainable economic recovery takes maximum advantage of the existing resources of people and businesses to transform disadvantages caused by disasters into opportunities [103].

The results found in this investigation establish that reconstruction processes must focus not only on physical aspects, which, although important for improving the livability of an affected place and the quality of life of its inhabitants, do not change or reduce risk. When the social fabric – in terms collaboration networks and social trust – is weakened, the clearest path to coping with an emergency and rebuilding society without losing territorial identity is eliminated. The social fabric may be recovered by getting people to meet each other; however, to the authors’ knowledge, no specific activities have been implemented in Llico since reconstruction began and further research is needed. In the same vein, international literature has established that the recovery process must involve not only the reconstruction of buildings and restoration of infrastructure, but must also address the interactions among various groups and institutions in order to rebuild lives and livelihoods, as well as restoring cultural assets and ecological conditions [124]. In a study carried out by Valenzuela et al. [27]; a comparison of the reconstruction processes in Kirikiri (After 2011 Japan tsunami) and Dichato (After 2010 Chile tsunami) established that the two countries followed different recovery strategies. While the former chose a reconstruction in stages, the latter focused on the recovery of physical structures, based on a cost-benefit analysis and with little community participation. In the case of Fukushima (2011 Japan earthquake and tsunami), reconstruction required adaptation and innovation on the part of the local population, with innovative industrial reconstruction processes led by residents and local businesses that have been pioneering. In the cases of Indonesia and Sri Lanka, the reconstruction process following the 2004 Indian Ocean tsunami, the “Building Back Better” concept was applied to urban reconstruction, housing relocation and organizational restructuring (Davis et al., 2015 en [102]). According to this concept, disaster risk reduction is an optimal combination of structural and non-structural measures in the reconstruction process that includes physical restoration, revitalization of livelihoods and the economy and the restoration of the local culture and environment [102]. As a result of these experiences, in Japan it was decided that protection against tsunamis would not rely solely on coastal defenses and that the emphasis should always be on preserving human life [104]. Investigations on coastal cities in Chile after the 2010 earthquake and tsunami showed that reconstruction processes applied by the government were uncoordinated and characterized by pro-business urban planning and a centralist territorial planning approach in terms of both resources and policy [23].

Reconstruction processes remain incomplete and ineffective when the recovery is focused only on aspects of infrastructure recovery, disconnected from spatial planning that would allow the urban fabric to be recovered or community bonds among inhabitants to be strengthened. There is an urgent need in Chile to include social capital and social resilience as crucial elements in public policies to grapple with reconstruction processes, as these phenomena are part of its geographic reality and will continue to occur. In addition, assessment of recovery processes after an event must be based on specific indicators to guarantee objectivity and comparability (Shohei 2007 in Ref. [17]). This is a great challenge in Chile and further research is necessary to face future disasters. Understanding these characteristics allows a better approximation of the resilient elements of the society exposed to a disaster, leading to fewer negative consequences due to an intentionally biased reconstruction process. Vulnerability within human groups is also linked to gender-, age- and poverty-related social inequalities [45,105], aspects not included in this investigation that are challenges for future studies. Thus, vulnerability transcends exposure or mere estimation of damage, as it is linked to access to opportunities and social exclusion and therefore problems not resulting from human development [106], which must be considered in public policies and territorial planning in order to effectively reduce disaster risk.

7. Conclusions

In the present research, we assessed the impact of a biased reconstruction process on vulnerability and, consequently, risk, considering a period of five years for a given deterministic tsunami scenario. It was found that a 2010-like tsunami is the most conservative tsunami scenario. However, a 1730-like tsunami generated off Valparaiso could also be a significant hazard. It was observed that the intentionally biased reconstruction process did not generate any change in vulnerability. Instead, new areas proved to have the same level of vulnerability. Although the post-reconstruction socio-territorial changes reduced physical and socioeconomic vulnerability, some measures weakened elements of social capital and increased organizational vulnerability. Therefore, it is possible to conclude that even though physical aspects are important for improving the livability of an affected place and the quality of life of its inhabitants, biased reconstruction processes (focused mainly on physical aspects) do not effectively reduce risk. Finally, it is extremely important to include social capital and social resilience as crucial elements in public policies to implement more comprehensive and successful reconstruction processes in developing countries that may be affected by many natural hazards such as earthquakes, tsunamis, river floods, volcanic eruptions and storm surges.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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