Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-256, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 9 September 2016

Natural Hazards and Earth System Sciences Discussions
Open Access

Risk Factors and Perceived Restoration in a Town Destroyed by the 2010 Chile Tsunami

Carolina Martínez[1, 6], Octavio Rojas[2], Paula Villagra[3], Rafael Aránguiz[4, 6], Katia Sáez-Carrillo[5]

[1]Instituto de Geografía, Pontificia Universidad Católica de Chile, Santiago, 8320000, Chile
[2]Departamento de Planificación Territorial, Universidad de Concepción, Concepción, 4030000, Chile
[3]Instituto de Ciencias Ambientales y Evolutivas, Universidad Austral de Chile, Valdivia, 5090000, Chile
[4]Departamento de Ingeniería Civil, Universidad Católica de la Santísima Concepción, Concepción, 4030000, Chile
[5]Departamento de Estadística, Universidad de Concepción, Concepción, 4030000, Chile
[6]National Research Center for Integrated Natural Disaster Management (CIGIDEN), Santiago, 8320000, Chile

Correspondence to: Carolina Martínez (camartinezr@uc.cl)

ABSTRACT

A large earthquake and tsunami took place in February 2010, affecting a significant part of the Chilean coast (Maule earthquake (Mw = 8.8). Dichato (37° S), a small town located on Coliumo Bay, was one of the most devastated coastal places and is currently under reconstruction. Therefore, the risk factors which explain the disaster at that time as well as perceived restoration 6 years after the event were analyzed in the present paper. Numerical modeling of the 2010 Chile tsunami with four nested grids was applied to estimate the hazard. Physical, socio-economic and educational dimensions of vulnerability were analyzed for pre- and post-disaster conditions. A perceived restoration study was performed to assess the effects of reconstruction on the community and a principal component analysis was applied for post-disaster conditions.

The vulnerability factors that best explained the extent of the disaster were housing conditions, low household incomes and limited knowledge about tsunami events, which conditioned inadequate reactions to the emergency. These factors still constitute the same risks as a result of the reconstruction process, establishing that the occurrence of a similar event would result in a similar degree of disaster. For post-earthquake conditions, it was determined that all neighborhoods have the potential to be restorative environments soon after a tsunami. However, some neighborhoods are still located in areas devastated by the 2010 tsunami and present a high vulnerability to future tsunamis. Therefore, it may be stated that these areas will probably be destroyed again in case of future events.

Keywords: tsunami, natural risk, territorial planning, social resilience

1. Introduction

A tsunami is a phenomenon known for its great destructive power in a short period of time; however, the process of post-disaster reconstruction usually lasts a long time and generates significant socio-territorial transformations. A total of seven destructive tsunamis affected the coasts of Indonesia, Samoa, Chile and Japan in only the last decade: 2006, 2007, 2009, 2010 (Feb 27th and Oct 24th) and 2011. These tsunamis took the lives of 237,981 people and generated an estimated US $456 million in economic losses (Løvholt et al., 2012; Løvholt 2014 et al.). These disaster levels have been explained by a number of factors, such as ineffective early warning systems, inadequate management of information by the population, lack of coordination of emergency mechanisms and high levels of social vulnerability (Rofi et al., 2006; Løvholt et al., 2014). Although scientific research has led to significant advances in the generation and propagation mechanisms of these phenomena (Aránguiz et al., 2013; Løvholt et al., 2014), other aspects linked to social components (vulnerability and resilience) are less understood, primarily for post-disaster conditions, given social system dynamics and complexity. The latest events have shown that increased mortality may be associated with intrinsic aspects of vulnerability, which in the natural disaster context is defined as the inability of society to respond to an event, in this case a dangerous natural phenomenon (Anderson and Woodrow, 1989 in Cardona, 2001; Wilches-Chaux, 1993). Intrinsic aspects include population characteristics such as age and gender (Rofi et al., 2006), income levels and job occupations (Birkman et al., 2007), ideological and cultural factors, levels of knowledge and inadequate reactions to the emergency (Ruan and Hogben, 2007). Others, through a line of still incipient work, have established that factors associated with social capital and territorial identity foster social resilience, which would be an enabling framework to overcome the negative effects of a disturbance (Pelling, 2003).

The 2010 Chile tsunami showed the high fragility of social and institutional systems in coastal areas, as significant destruction along 600 km of coastline was observed (Quezada et al., 2010; by Fritz et al., 2011; Contreras et al., 2011; Jaramillo et al., 2012; Sobarzo et al., 2012; Bahlburg and Spiske, 2012; Martinez et al., 2012). Historical records show that these phenomena are not sporadic in the country but rather highly recurrent, causing significant devastation (Lomnitz, 1970; Monge, 1993, Lagos, 2000; Ruegg et al., 2011; Palacios, 2012).

Territorial planning in Chile, as in much of the rest of the world, has been focused primarily on interventions for mitigation (Herrmann, 2015), with policies and instruments for reconstruction (e.g., Sustainable Reconstruction Plans and Master Plans) focused on housing production rather than social reconstruction of territories (Rasse and Letelier, 2013; Martinez, 2014). On that ground, interdisciplinary approaches necessary for the reconstruction of human settlements in an integrated manner, i.e., studies which identify, assess and integrate physical, economic, social, environmental and perceptual factors, have been neglected. This complex approach has already been addressed in an international context, with the application of different study models of urban resilience to disaster (e.g., Cutter et al., 2008; Norris et al., 2008). Resilience refers to the ability of a community to adapt and recover after a disturbance without losing its character (Cutter et al., 2014; Walker and Salt, 2006). Resilience is expressed multi-dimensionally (Cutter et al., 2014); in Chile, however, physical and social dimensions are the least considered in post-disaster planning. This occurs despite the fact that the integration of these dimensions in planning can promote community recovery after a disaster, with the potential to rebuild "the place where the restoration occurs" (Allan and Bryant, 2010). A restorative experience is described as "the process of recovering psychological and social resources that have become diminished in the efforts to meet the demands of everyday life" (Hartig, 2007, p.164). After a large tsunami, the city "takes on a new meaning [and] its spaces and components are re-evaluated (by the people)" for their capacity to provide restorative experiences (Allan and Bryant, 2010). Thus, post-disaster reconstruction processes are an opportunity to effectively reduce risk and generate mechanisms of physical as well as social resilience.

In this context, we analyze tsunami inundation risks pre- and post-disaster in one of the coastal towns most affected by the earthquake and tsunami on Feb. 27, 2010, which presented an intense transformation as a result of post-disaster reconstruction. It is unknown whether this reconstruction process has reduced vulnerability and provided a restorative urban system, which enhance urban resilience, or if it has generated new risk areas. Questions were asked in relation to the neighborhoods being rebuilt in Dichato, such as: Do they have the potential to be restorative environments? Which specific sites provide restoration? Are restorative environments pre-existing areas that persist after the disaster? Or are they new sites built during reconstruction? These questions seek to determine whether the reconstruction process has favored the population's ability to adapt after a tsunami, and whether it has decreased the damage potential in the case of future events.

2. Regional setting

Dichato is a town located on Coliumo Bay (36° 33'S). It belongs to the Tomé Commune and has a population of 3,488 inhabitants dedicated largely to fishing, trade and tourism (INE, 2002).

It has an urbanized coastal plain of approximately 2 km^2, dissected by Dichato Stream, with an average height of 6m (Fig. 1). These characteristics explain the great impact of the 2010 tsunami, which had inundation heights of up to 8m, a penetration distance of 1.3 km inland and an inundation area of 0.85 km^2. The affected population was 1,817 people, with 66 people dead and 60% of total housing destroyed (Martinez et al., 2011). According to historical records, this coast had previously been affected by six destructive tsunamis, the most significant occurring in 1751 (M = 8.5), 1835 (M = 8.2) and 1960 (M = 9.5) (Lagos, 2000; Palacios, 2012).

3. Materials and methods

In order to give risk a value in pre- and post-disaster conditions, the equation R = H * V was used, where R = Risk, H = Hazard and V = Vulnerability (Blakie et al., 1994).

3.1 Hazard

The tsunami hazard was estimated by means of a numerical simulation considering the tsunami on February 27, 2010. The Non-hydrostatic Evolution of Ocean WAVEs NEOWAVE numerical model (Yamazaki et al., 2010, 2011) was used. This model solves linear and nonlinear shallow water equations using nested grids with different spatial resolutions. In this case, 4 nested grids were used with 120" (~3600m), 30" (~900m), 6" (~180m) and 1" (~30m) resolution. Grids 1 and 2 were built from GEBCO topo-bathymetric data, while nautical charts and detailed bathymetry in Coliumo Bay were used for Grids 3 and 4. In addition, Grid 4 used 2.5m resolution LIDAR topographic data obtained in 2009, representing the situation at the time of the 2010 tsunami. The initial tsunami condition was defined using the finite fault model proposed by Hayes (2010), with 180 sub-faults and heterogeneous slip. Figure 2 shows the 4 nested grids and the tsunami initial conditions used in the numerical simulation. The figure shows that Grid 4 takes into account the entire Coliumo Bay and not just the town of Dichato.

A Manning roughness coefficient of 0.025 was used and the total simulation time was 6 hours with output results of 1 minute. The tide level was set to the sea level at the time of the maximum inundation. To do this, preliminary numerical simulations were conducted to find the maximum tsunami wave. The tide level was estimated to be -0.25m and the grids were modified to include this tide level. Furthermore, a virtual tide gauge on the Dichato beachfront was defined to obtain arrival times of different tsunami waves. The validation of the numerical simulation was performed using the Root Mean Square Error and the parameters $K$and κ proposed by Aida (1978), cited by Suppasri et al. (2011) given in equations 1 and 2. The variable K_i is defined as $K_i = x_i/y_i$, where x_i and y_i are recorded and computed tsunami heights, respectively. The recorded tsunami heights were obtained from field survey data published by Mikami et al. (2011) and Fritz et al. (2011).

Eq (1) $$\log K = \frac{1}{n}\sum_{i=1}^{n} \log K_i$$

Eq (2) $$\log \kappa = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (\log K_i)^2 - (\log K)^2}$$

Hazard levels proposed by Walsh et al. (2005), defining flow depths of 0, 0.5 and 2.0m, were selected when obtaining tsunami inundation hazard levels (Table 1). The hazard levels generated by the current velocity were also included in the hazard analysis. The levels were selected in terms of security for human life (Table 2).

3.2 Vulnerability and environmental restoration

In order to establish which factors determined the achieved hazard level as well as the effects generated by the post-disaster reconstruction process in shaping new risk areas, the vulnerability analysis was conducted for two scenarios: pre- and post-disaster.
For total vulnerability analysis, variables selected for both scenarios were representative of physical, socio-economic and educational dimensions; however, some variables were modified according to pre/post-disaster conditions (Table 3). In the case of pre-disaster conditions, the analysis unit corresponded to census blocks with data taken from the last census (INE, 2002). Meanwhile, for post-disaster conditions, the analysis unit was the neighborhood, which, due to the destruction caused by the tsunami and the absence of census data, was defined according to similarities of the post-disaster buildings (Fig. 4). Variables were incorporated into the GIS ArcGis 10.1 to generate thematic maps and synthesis charts through map algebra.

The capacity of the neighborhoods of Dichato to provide restorative experiences post-disaster was assessed through a perceived restoration study (Hartig et al., 1997). The inhabitants assessed their neighborhoods by means of the Perceived Restorative Scale (PRS), an instrument constructed based on the Attention Restoration Theory (Kaplan and Kaplan, 1989). The neighborhoods were defined as units of study (Fig. 4). The PRS has been used to identify landscape attributes that can be restorative to people subjected to high levels of stress and mental fatigue (Hartig et al., 1997; Korpela and Hartig, 1996; Ulrich et al., 1991). Access to restorative environments is also crucial in cities prone to natural disasters, such as tsunamis. Three factors were used to evaluate the interaction of people with the neighborhood they inhabit: being away (BE-AW), which reflects the need to escape from everyday life or daily mental activities that require major concentration; fascination (FAS), which is found in environments that attract and hold our attention without any effort; and compatibility (COMP), which refers to a sense of oneness with environments that provides the capability to meet our desires and needs. Each factor was evaluated using five items which people assessed using the Likert scale 1-7, where 1 is the lowest value and 7 is the highest. Subsequently, each person was asked to describe the neighborhood areas they recalled while answering. In this way, neighborhoods with the highest and lowest restoration values were identified, as well as the specific locations that were more meaningful to the inhabitants.

Sampling and statistical analysis

For the application of pre-disaster surveys oriented at determining vulnerability and perception of the phenomenon, stratified sampling was conducted, with groups (strata) corresponding to 95 census blocks (Figure 1) (INE, 2002). Population was defined as the number of inhabitants between 15 and 59 years of age (N = 2120), with a confidence level of 95% and a sampling error margin lower than 5%; finally, 337 surveys (n) were carried out.

The determination of post-disaster vulnerability and restoration was also addressed by stratified sampling, where groups (strata) corresponded to 9 neighborhoods (Figure 3). Population was defined as heads of households (male or female) who live in the town of Dichato permanently (N = 1850). Eq (3), for finite populations, was applied to determine the sample size.

Eq (3) $$n \geq \frac{N z_{1-a/2}^{2} PQ}{z_{1-a/2}^{2} PQ + d^{2}(N-1)}$$

Where: Confidence level was 95%; Precision (5%); Proportion 90% (≈ 90% of families in the Biobio Region who experienced problems due to the 2010 earthquake and tsunami) (Larrañaga and Herrera, 2010). The minimum sampling size was estimated to be n=130. Finally, 156 surveys were carried out.

Performing a multivariate descriptive analysis, a cluster analysis and a principal component analysis were applied in order to compare results obtained from the assessed variables in the neighborhoods. The chi-squared test was used to compare proportions and a one-way analysis of variance (ANOVA) was conducted for the numerical variables. The Tukey test was applied for comparison, using a significance level of $\alpha = 0.05$.

3.3 Risk

Risk factors were integrated into a matrix (Eckert et al., 2012; Jalínek et al., 2012; Martinez et al., 2012) and three risk levels were obtained from the multiplication: high, medium and low, with scores from 1 to 9 (Table 3). Risk level is applied to analysis units, according to pre and post event conditions, in the GIS vulnerability section.

4. Results

4.1 Hazard

Fig. 3 (a) shows the inundation area obtained from the numerical simulation. Dots indicate inundation height records while asterisks indicate synthetic tide gauge location. Fig. 3 (b) shows a comparison of recorded and simulated data, where the error obtained from Eq (1) was K = 1.09 with a standard deviation from Eq (2) of κ = 0.12, which is considered acceptable (Suppasri et al., 2011). Fig. 3 (c) shows the tsunami wave form obtained from the synthetic tide gauge. It can be seen that the largest wave is not the first, but rather the third wave, which reached an inundation height of up to 7m. A fourth wave is also observed reaching up to 5m. Fig. 4 shows the area inundated by the event, which reached a maximum runup of 10m, spread through Dichato Stream.

4.2 Vulnerability pre-disaster

In the case of physical vulnerability, 51% of census blocks reported high vulnerability levels, which involved 47% of the total inundated area and 57% of the total population (Fig. 5). 73% of households reported average vulnerability, which involves 61% of the inundated area and 67% of the total population. These vulnerability levels can be explained mainly by the locations of the residential areas in which more than 75% of the inhabitants reside, where there is no overcrowding but income levels are low, with approximately 44% of the population receiving monthly incomes less than $118,000 Chilean pesos (about US $170). For educational vulnerability, it was determined that low levels of schooling influenced overall vulnerability because 42% of the population has only basic education or has not completed this level and only 55% has secondary education. It is important to note that 58% of the population attributed the tsunami to the results of the earthquake and 42% attributed the tsunami to divine causes, including global warming and the apocalypse. Accordingly, 54% of the population has high educational vulnerability, involving 74% of the inundated area.

After the tsunami occurred, i.e., in post-event conditions, it was determined that 72% of census blocks were affected by the tsunami, as well as 73% of the population and 70% of housing (Fig. 6).

4.3. Vulnerability and restoration post disaster

For post-disaster conditions, the Reconstruction Plan applied to Dichato, known as PRB-18, modified 29% of the total town area, with 15% established as a conditioned building area, not including expropriation (Fig.7). Elevated (Palafitte-style houses) and community buildings were designed and placed in these areas (coastline). 12% of the total area was reserved for mitigation parks, construction along the coastline and river banks, where the tsunami surged and the greatest destruction was generated. The fishing area utilized 1.6%, with the construction of a fishing pier and a market in Villarrica Cove. Mitigation park construction began in 2015, with a tree line that covered several meters of the surface.

Cluster analysis (Fig. 8a) performed for post-event vulnerability dimensions identified six neighborhood groups. Four groups were represented individually by the neighborhoods C, E, F and A. The fifth conglomerate grouped the analysis units D and B. Finally, the sixth group was composed of units I, H and G. Only neighborhoods C, E, A, D and B were directly affected by the 2010 tsunami inundation.

ANOVA showed significant differences in physical and educational vulnerability dimensions ($p < 0.05$), while the socio-economic dimension was homogeneous for all evaluated neighborhoods ($p = 0.1808$). The neighborhoods with higher physical vulnerability were older sectors (I, D) and a provisionally relocated sector (A). Neighborhoods affected directly by the tsunami (B, C) were grouped in the medium level, as well as an unaffected sector (H). The neighborhoods found in the low level (E, F, G), presented higher quality buildings. Regarding the educational dimension, the lowest vulnerability corresponded to relocated sector A, which was most devastated by the 2010 tsunami. The above was reinforced by a principal component (PC) analysis, which showed that the first two components explained 85.5% of the total variance. Fig. 7b indicates that only sector C had a higher association with socio-economic vulnerability, while the remaining 8 neighborhoods were related to physical and educational vulnerability dimensions.

Regarding feelings assessed on the possibility of a future tsunami (Table 4), 5 feelings showed no significant differences by neighborhood ($p > 0.05$): panic (19%), fear (39%), tranquility (41%), security

(19%) and indifference (3%). A significant difference (p = 0.0258) was found for the feeling of anxiety, which was higher (67%) for relocated inhabitants (A).

Safety perception in current residential areas was evaluated in terms of safe or very safe by 65% of the local population (p>0.05), considering changes made by authorities in the Master Plan for Reconstruction. The feeling of identity with the city pre-disaster was 49% (p>0.05), with a higher percentage in neighborhoods A (75%), C (59%) and D (57%), which were the most affected. Desire to change place of residence was not homogeneous among neighborhoods (p = 0.0018) and percentages ≥ 40% were obtained for sectors affected by the tsunami (A, B) and in areas not directly affected (F, G).

The Likert scale 1-7 was applied to assess 5 topics, namely, reconstruction, process quality, equipment and the role of the National Emergency Office (ONEMI). The results showed that there is no difference among neighborhoods. Positive evaluations were obtained for the reconstruction process (Mean = 5.6; SD = 1.4), associated equipment (Mean = 5.5; SD = 1.4) and quality (Mean = 6.0; SD = 1.3). The worst performance was obtained for ONEMI (Mean = 3.8; SD = 1.9).

In relation to the perceived restoration study, ANOVA analysis showed significant differences (p <0.05). The best evaluated areas were neighborhoods C (Mean = 6.1; SD = 0.8) and I (Mean = 5.8; SD = 1.0). The means reported here correspond to the three factors combined for each neighborhood. For the results of each factor, see Table 4. Neighborhood C (Villarrica) was affected by the tsunami and completely rebuilt, while neighborhood I was not modified (Pingueral). The new coastal infrastructures (25%), new anti-tsunami houses (19%) and views of the coast (16%) were mentioned the most by respondents in neighborhood C as elements that contribute to restoration. Meanwhile, in neighborhood I, views of the river (20%) and the presence of uphill streets (20%) and nearby hills (17%) were mostly mentioned as restorative elements. In contrast, neighborhoods A (Mean = 4.4; SD = 1.6) and H (Mean = 4.7; SD = 1.5) were the worst evaluated. Neighborhood A, as previously mentioned, is the relocated neighborhood most affected by the tsunami. In this case, new urban infrastructure (19%), views of the bay (19%), and the community building (19%) were found to contribute the most to restoration. Neighborhood H was not affected by the tsunami nor was it modified. In this case, the presence of nearby hills (32%), pre-existing housing (23%) and uphill streets (16%) were found to add to restorative experiences.

In addition, a cluster analysis with the three restoration factors was conducted to complement the previous results. To do this, 4 neighborhood groups were identified (Fig. 9). One group was composed of the best evaluated neighborhoods, C and I. A second group was composed of neighborhood F, which was not affected by the tsunami and a third group by neighborhoods G, E, D and B, most of which were directly affected by the tsunami. These last two groups received moderate evaluations. A fourth group was composed of neighborhoods H and A, which were the worst evaluated. Furthermore, principal component analysis results indicate that these groups are organized from right to left along PC1, explaining 75% of the variance. To the right is the group of the best evaluated neighborhoods (C and I), associated mostly with BE-AW and COMP factors, while on the left is the worst evaluated group (A and H), which does not show a clear association with restoration factors.

Vulnerability analysis for pre- and post-tsunami conditions (Fig. 10) established reduced vulnerability, however, from high to medium levels, and spatial distribution of vulnerable areas was maintained for both conditions. For pre-tsunami conditions, 90% of neighborhoods presented high vulnerability, 5.4% medium vulnerability and 4.6% low vulnerability. For post-tsunami conditions, 55% of the area presents high vulnerability and 45% medium vulnerability, while low vulnerability was not found. These findings conclude that currently the entire area is vulnerable at high and medium levels.

4. 4 Risk pre- and post-disaster

Little difference was presented between surface (0.11 km^2) and tsunami risk area spatial distribution, considering the conditions pre- and post-2010 event, with a high level of risk (≥78%) for both scenarios (Fig. 11). In case of pre-disaster, some sectors of the town had small areas with medium risk, explained by better building quality or sites without buildings. This situation changed post-disaster due to increased construction, especially public housing as part of the Reconstruction Plan. Construction quality was one of the most important variables in levels of damage experienced. According to Fig. 12, most buildings were destroyed by the tsunami due to poor quality of materials. In the area where the greatest destruction occurred (Villarrica sector or section C), initial housing was replaced by two-level, 27 m^2 palafitte-style houses made of wood, on steel columns 2m high. This type of housing was implemented as a mitigating action against the possibility of a tsunami with similar characteristics, where the steel structure will prevail while the wood can always be replaced (Fig. 12E). Not all former inhabitants returned to their neighborhood to occupy these homes, because most were elderly and could not climb stairs to enter the palafitte houses (Khew et al., 2015). Despite being owners, they opted for relocation to higher sectors of Dichato, forming a new neighborhood.

In addition to the Villarrica sector, these homes were also stationed in neighborhood B (or center), where a beach front and boulevard have been built in order to promote tourism. The only structural change made to houses consisted of replacing steel columns with reinforced concrete columns, while retaining the same overall dimensions (Fig. 12F). Currently, the ground floors of these stilt houses have been transformed by the inhabitants in order to increase living area (Khew et al., 2015). Neighborhood B presented the greatest transformation post-earthquake, replacing a fish market with beach front buildings, a mitigation park and a boulevard with a striking design in order to attract tourism. However, behind these buildings, a mixture of palafitte-style houses and other types of one-story housing, made of wood or masonry, were built, giving rise to new neighborhoods and risk areas post-earthquake.

Other areas, such as neighborhood A, went from being provisional neighborhoods to consolidated settlements (e.g. El Molino neighborhood) and received in turn a part of the relocated population.

In general, new post-disaster risk areas affect neighborhoods C, D, E, F, G and H up to a height of about 20 meters; however, Dichato Stream extends the propagation area into the neighborhood.

5. Discussion

The main results of this research found that in this urban area, with a strong reliance on natural resources (fishing) and associated tourism, high risk levels are presented for both pre- and post-disaster conditions. These conditions are not new and have already been reported for other areas in the country under the reconstruction process (Rojas et al., 2014). However, few studies exist worldwide on how coastal towns evolve in response to post-disaster reconstruction processes, generating transformations that do not contribute to risk reduction or urban resilience.

The main factors explaining high risk levels are mainly quality and materials of buildings, which are highly related to the degree of destruction caused by the 2010 tsunami. Many of these houses were one-story buildings made of wood or lightweight materials and built in a do-it-yourself manner. Lack of infill and reinforced concrete masonry (failure of brick masonry infill walls and lightly reinforced concrete columns) were a damage factor, coinciding with studies by Palermo et al. (2013) in the area. According to these authors, residential housing consisting of light timber frame and concrete frame construction with brick masonry infill walls experienced widespread damage throughout the surveyed coastal region of Chile.

According to numerical modeling, tsunami wave heights reached between 5 and 8m, with current velocities greater than 2m/s, which could be enough to damage house foundations and destroy coastal infrastructure. In this regard, tsunami fragility curves developed by Mas et al. (2012) for Dichato from field data and satellite imagery showed a 68% probability of damage at a flow depth of 2m, mainly due to building materials, predominantly wood. In this case, it was found that approximately 80% of the built area of Dichato experienced damage and was completely destroyed by the 2010 tsunami.

Other important factors were socio-economic status and educational level of the population, which were relevant mainly in pre-disaster conditions. In this case, 44% of the population has low incomes and a widespread lack of knowledge concerning emergency plans or evacuation routes, resulting in inadequate reactions. One year after the event, people still had symptoms of post-traumatic stress, indicating feelings of panic, fear and sadness (Venegas 2011). Most of this population, which consisted of owners affected by the tsunami, moved to provisional neighborhoods where they remained for two years without basic services. Some of these provisional houses became final settlements. The study conducted in Dichato by Shahinoor and Kausel (2013) stated that risk of tsunamis is not well addressed in planning and community-oriented programs and that the pre-established mechanisms for post-disaster recovery are not appropriate, which is why risk is not reduced. The latter is not a specific problem of the location but derives from the lack of coordination between planning instruments and risk management in Chile which is essentially reactive and not preventative (Martinez, 2014). On the other hand, Chile lacks a public policy oriented at establishing criteria or a reconstruction model to implement in case of a disaster, and usually gives priority to physical reconstruction rather than social reconstruction. Yet physical reconstruction continues to take place in inappropriate locations and therefore, considering only the spatial location, risk areas fail to be managed to generate effective risk reduction.

Regarding restoration results, it is interesting to find that the restoration capacity of neighborhoods varies with respect to the presence and absence of natural and built elements.

Natural elements such as the presence of hills and views of bodies of water contribute to perceived restoration. These results are in line with previous restoration studies indicating that the presence of natural elements such as water and vegetation are related to restorative environments (Korpela and Hartig, 1996, Hartig et al., 1997). However, in this case, it is not only the mere presence of these elements that is relevant, but most probably the sense of security they give to the community as well. Hills are useful for refuge in case of tsunami as well as for observation points, which are much needed to keep people informed about what happens in case of a disaster. Consequently, it is important for future planning processes to consider the potential of natural elements to restore communities post-disaster. For instance, access to these natural sites from different neighborhoods should be enhanced during the reconstruction process by, for example, including evacuation routes that lead to these areas in everyday life. The latter would contribute to adaptation post-disaster and social resilience (Pelling, 2003).

On the other hand, new elements introduced during the reconstruction process, such as the new coastal infrastructure for mitigation and the new anti-tsunami housing, characterize neighborhoods which provide restorative experiences as well (Khew et al., 2015). It is possible that these elements, although they are built features, give a certain sense of security to respondents, which could explain these results. This study did not focus on establishing relationships between perceived safety and post-disaster restoration factors; however, it is highly recommended that this possible relationship be expanded in future studies. It may be that restorative experiences post-disaster are found in new built sites that give security to the community. This would also be important to consider in the process of reconstruction, as built features of the kind described here not only play a role for mitigation, but also for community function post-disaster, contributing to social resilience (Pelling, 2003).

In this sense, vulnerability and resilience are distinct elements but superimposed in their role in natural disasters and come together in the cornerstone of sustainability (Turner, 2010). In the case of Dichato, vulnerability showed a close relationship with lack of resilience because few lessons were learned from the 2010 event and the same mistakes are still being made, with a rebuilding process almost completed which presents vulnerability conditions very similar to those that existed pre-2010 earthquake. This situation is explained by the emphasis on physical rather than social reconstruction, lack of public policies to face a rebuilding process of this magnitude despite recurring events in the country and especially by the poor consideration and assessment of risk areas in planning at a local scale, since other affected areas were repopulated in the same manner and relocated to the same risk areas (Martinez, 2014). In some neighborhoods, increased social and environmental problems, such as pollution, crime and poverty, occurred as a result of reconstruction processes (Rojas et al., 2014). The main disadvantage of these programs is that they were implemented as similar projects in 18 affected coastal towns, regardless of geographic reality and territorial identity. In addition, the programs did not distinguish between rural or urban areas. Small fishermen's coves located in coastal wetlands and small bays under semi-urbanization processes had to absorb relocated populations from affected areas, resulting in increased population densities in new risk areas and loss of cultural and territorial identity. The latter was reflected in that between 57% and 75% of the population mostly affected by the tsunami six years ago identified with Dichato pre-tsunami. In this respect, most current approaches establish that resilience is characterized by socio-ecological system responses to natural disturbances, capacity for self-organization, learning and adaptation to change (Folke, 2006; Turner, 2010). These elements present a challenge from an institutional point of view in Chile, in order to strengthen risk management and its link to organized society, so as to ensure that investments in reconstruction processes produce effective ways to reduce risks to phenomena that undoubtedly continue to occur in the country. On the other hand, reconstruction involves addressing physical, social and environmental territory components to facilitate the development of post-disaster resilience, for which the country must change its approach to natural disaster management, moving towards sustainability of its cities and coastal towns.

6. Conclusions

The vulnerability factors that best explained the extent of the 2010 tsunami disaster were housing materials, low incomes and poor knowledge about these phenomena, which conditioned an inadequate reaction at the time of emergency. The current town configuration, resulting from reconstruction process in the six years after the event, has generated new risk areas which occupy the same locations as pre-event conditions, so risk is not reduced. For post-earthquake conditions, it was determined that all neighborhoods have the potential to be restorative environments after a tsunami, but with different intensities, depending on the type of natural and built features they have kept and included during the reconstruction process. However, risk analysis indicates that neighborhoods with greater restoration ability post-disaster remain in the same areas devastated by the 2010 tsunami and will likely be destroyed again in a future event, a situation that forces us to reflect on how to plan coastal area occupation and manage risk in the country.

Acknowledgements

Grants funding from FONDECYT N°1151367, 11140424, 1150137 y FONDAP N°15110017 from the National Scientific and Technological Research Commission (CONICYT), Chile.

References

Allan, P., and Bryant, M.: The critical role of open space in earthquake recovery: A case study, 2010 NZSEE Conference. Paper Number 34, 1-10, 2010.

Aránguiz, R., Shibayama, T., and Yamazaki, Y.: Tsunamis from the Arica-Tocopilla source region and their effects on ports of Central Chile. Natural Hazards, 71 (1), 175-202, DOI 10.1007/s11069-013-0906-5, 2013.

Bahlburg, H., and Spiske, M.: Sedimentology of tsunami inflow and backflow deposits: key differences revealed in a modern example. Sedimentology, 59 (3), 1063-1086, 2012.

Birkman, J., Fernando, N., Hettige, S., and Amarasinghe, S.: Vulnerability assessment of social groups. In: Birkman, J., Fernando, N., Hettige S, Amarasinghe, S., Jayasingam, T., Paranagama, D., Nandana, M., Nabi, M., Voigt, S., Grote, U., Engel, S., Schraven and Wolferts, B. (eds) Rapid vulnerability assessment in Sri Lanka: post-tsunami study of two cities: Galle and Batticaloa. UNU Institute for Environment and Human Security, Bonn, pp 25-78, 2007.

Blaikie, P., Cannon, T., Davis, I., and Wisner, B.: At Risk: Natural Hazards, People's Vulnerability and Disasters. Routledge, London, 1994.

Cutter,S., Barnes, L., Berry, M., Burton, C., Evans, E., Tate, E., and Webb, J.: A place-based model for a understanding community resilience. Global Environmental Change, 18, 598-606, 2008.

Cutter, S., Ash, K., and Emrich, C.: The geographies of community disaster resilience. Global Environmental Change, 29, 65-77, 2014.

Folke, C.: Resilience: The emergence of a perspective for social–ecological systems analyses. Global Environmental Change, 16, 253–267, 2006.

Fritz, H., Petroff, C., Catalan, P., Cienfuegos, R., Winckler, P., Kalligeris, N., Weiss, R., Barrientos, S., Meneses, G., Valderas-Bermejo ,C., Ebelig, C., Papadopoulos, A., Contreras, M., Almar, R., Dominguez, J., and Synolakys, C.: Field Survey on the 27 February 2010 Chilean Tsunami. Pure and Applied Geophysics, 168, 1989-2010, 2011.

González-Riancho, P., Aguirre-Ayerbe, I., and Aniel-Quiroga, I.: Tsunami evacuation modelling as a tool for risk reduction: application to the coastal area of El Salvador. Natural Hazards and Earth System Science, 13, 3249-3270, doi: 10.5194/nhess-13-3249-2013, 2013.

Hartig, T.: Three steps to understanding restorative environments as health resources. Open Space People Space. C. W. Thomposon and P. Travlou, London, pp 163-180, 2007.

Hartig, T., Korpela, K., Evans, G., and Gärling, T. A Measure of Restorative Quality in Environments. Scandinavian Housing & Planning Research, 14, 175-194, 1997.

Jaramillo, E., Dugan, J., Hubbard, D., Melnick, D., Manzano, M., Duarte, C., Campos, C., Sánchez, R.: Ecological Implications of Extreme Events: Footprints of the 2010 Earthquake along the Chilean Coast. PLoS ONE 7: e35348, 2012.

Jelínek, R., Krausmann, E., González, M., Álvarez-Gómez, J., Birk-Mann, J., and Welle, T.: Approaches for tsunami risk assessment and application to the city of Cádiz, Spain. Natural Hazards 60 (2):273-293, 2012.

Kaplan, R., and Kaplan, S.: The experience of nature: a psychological perspective. Cambridge: Cambridge University Press, 1989.

Khew, J., Pawel, M., Dyah, F., SanCarlos, R., Gu, J., Esteban, M., Aránguiz, R., and Akiyama. T.: Assessment of social perception on the contribution of hard-infrastructure for tsunami mitigation to coastal community resilience after the 2010 tsunami: Greater Concepcion area, Chile. International Journal of Disaster Risk Reduction, 13, 324-333, 2015.

Korpela, K., and Hartig, T.: Restorative qualities of favorite places. Journal of Environmental Psychology, 16, 221-233, 1996.

Koshimura, S.: Vulnerability estimation in Banda Aceh using the tsunami numerical model and the post-tsunami survey data. In: Proceedings of 4th International Workshop on Remote Sensing for post-disaster response, 2006.

Lagos, M.: Tsunamis de origen cercano a las costas de Chile. Revista de Geografía Norte Grande, 27, 93-102, 2000.

Lomnitz, C.: Major earthquakes and tsunamis in Chile during the period 1535 to 1955. Soderdruck aus der Geologischen Rundschau Band, 59, 938-690, 1970.

Løvholt, F., Setiadi, N., Birkmann, J., Harbitz, C., Bach, C., Fernando, N., Kaiser, G., and Nadim, F.: Tsunami risk reduction – are we better prepared today than in 2004? International Journal of Disaster Risk Reduction, 10, 127-142, 2014.

Løvholt, F., Glimsdal, S., Harbitz, C., Zamora, N., Nadim, F., and Peduzzi, P.: Tsunami hazard and exposure on the global scale. Earth-Sci Rev, 110, 58–73, 2012.

Martínez, C.: Factores de vulnerabilidad y Reconstrucción post terremoto en tres localidades costeras chilenas: ¿generación de nuevas áreas de riesgo? Bulletin de l'Institut Français d'Études Andines, 43, (3), 529-558, 2014.

Martínez, C., Rojas, O., Jaque, E., Quezada, J., Vásquez, D., Belmonte, A.: Efectos territoriales del tsunami del 27 de Febrero de 2010 en la costa de la Región del Bio-Bío. Revista Geográfica de América Central, Número Especial EGAL, Costa Rica, 1-16, 2011.

Mas, E., Koshimura, S., Suppasri, A., Matsuoka, M., Matsuyama, M., Yoshii, T., Jiménez, C., Yamazaki, F., and Imamura, F.: Developing Tsunami fragility curves using remote sensing and survey data of the 2010 Chilean Tsunami in Dichato. Nat. Hazards Earth Syst. Sci., 12, 689–2697, 2012.

Monge, J.: Estudios de riesgo de tsunami en costas chilenas. Jornadas Chilenas de Sismología e Ingeniería Antisísmica 2, 3-22, 1993.

Norris, F., Stevens, S., Pfefferbaum, B., Wyche, K., and Pfefferbaum, R.: Community resilience as a metaphor, theory, set of capacities and strategy for disaster readiness. Community Psychology, 41, (1-2), 127–50, 2008.

Palermo, D., Nistor, I., Saatcioglu, M., and Ghobarah, A.: Impact and damage to structures during the 27 February 2010 Chile tsunami. Can. J. Civ. Eng., 40, 750–758. 2013.

Pelling, M.: The Vulnerability of Cities: Natural Disasters and Social Resilience. London: Earthscan, 2003.

Prerna, R., Srinivasa, Kumar, T., Mahendra, R., and Mohanty, P.: Assessment of Tsunami Hazard Vulnerability along the coastal environs of Andaman Islands. Natural Hazards, 75, 701–726, 2015.

Quezada, J., Jaque, E., Belmonte, A., Fernández, A., Vásquez, D., and Martínez, C.: Movimientos cosísmicos verticales y cambios geomorfológicos generados durante el terremoto Mw=8,8 del 27 de Febrero de 2010 en el centro-sur de Chile. Revista Geográfica del Sur, 1, (2), 11-45, 2010.

Martínez, C., Rojas, O., Aránguiz, R., Belmonte, A., Quezada, J., Altamirano, A., and Flores, P.: Riesgo de tsunami en Caleta Tubul, Región del Bio-Bío: escenarios extremos y transformaciones territoriales post-terremoto. Revista de Geografía Norte Grande 53: 85-106, 2012.

Ruan, X., and Hogben, P.:Topophilia and topophobia: reflections on twentieth century human habitats. Abingdon, Oxon: Routledge, 2007.

Ruegg, J., Olcay, Y., and Lazo, D.: Co, post and pre-seismic displacements associated with 1995 July 30 Mw=8.1 Antofagasta, Chile, earthquake as constrained by InSAR and GPS observations. Seismological Research Letters, 72, 673-678, 2011.

Sobarzo, M., Garcés-Vargas, L., Tassara, A., and Quiñones, R.: Observing sea level and current anomalies driven by a megathrust slope-shelf tsunami: The event on February27, 2010 in central Chile. Continental Shelf Research, 49, 44–55, 2012.

Suppasri, A., Koshimura, S., and Imamura, F.: Developing tsunami fragility curves based on satellite remote sensing and the numerical modeling of the 2004 Indian Ocean tsunami in Thailand. Nat. Hazards Earth Syst. Sci., 11, 173–189, 2011.

Turner II, I.: Vulnerability and resilience: Coalescing or paralleling approaches for sustainability science? Global Environmental Change, 20, 570–576, 2010.

Reese, S., Cousins, W., Power, W., Palmer, N., Tejakusuma, I., and Nugrahadi, S.: Tsunami vulnerability of buildings and people in South Java – field observations after the July 2006 Java tsunami. Nat Hazards Earth System Science, 7, 573-89, 2007.

Rofi, A., Doocy, S., and Robinson, C.: Tsunami mortality and displacement in Aceh province, Indonesia. Disasters, 30, (3), 340–50, 2006.

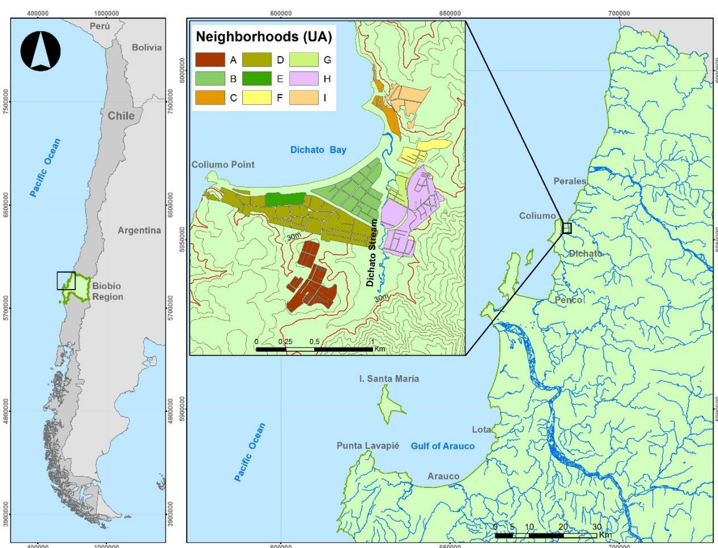
Shahinoor, M., and Kausel, T.: Coastal Community Resilience to Tsunami: A Study on Planning Capacity and Social Capacity, Dichato, Chile. IOSR Journal of Humanities and Social Science (IOSR-JHSS), 12, (6), 55-63, 2013.

Venegas, J.: Análisis de vulnerabilidad por tsunami en la localidad de Dichato, Región del Biobío, Chile. Tesis para optar al título de Geógrafo. Universidad de Concepción, Facultad de Arquitectura, Urbanismo y Geografía, Depto. de Geografía, 2012.

Walker, B., and Salt, D.: Resilience thinking: sustaining ecosystems and people in a changing world. Washington, Island Press, 2006.

Walsh, T., Titov, V., Venturato, A., Mofjeld, H., González, F.: Tsunami Hazard Map of the Anacortes – Whidbey Island Area. Washington: Modeled Tsunami Inundation from a Cascadia Subduction Zone Earthquake. Washington Division of Geology and Earth Resources and NOAA TIME Center PMEL. Open File Report 2005-1, scale 1:62.500, 2005.

Fig. 1 Geographical context of the study area. Dichato is located on Coliumo Bay (36° S). The letters (A-I) identify different neighborhoods analyzed in the post-disaster period.



Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-256, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 9 September 2016

Natural Hazards and Earth System Sciences
Open Access
Discussions

Fig. 2. Nested computational grids. The inset in Grid 2 shows the tsunami initial condition. TG in grid 4 indicates the location of the virtual tide gauge

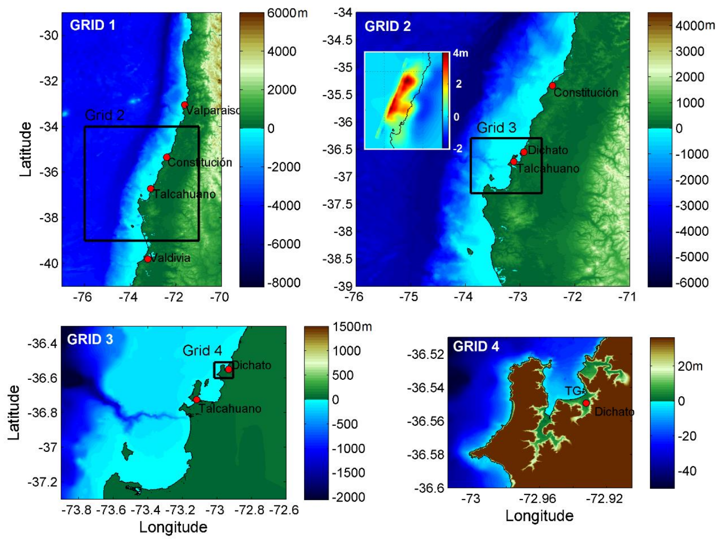


Fig. 3. (a) Inundation area obtained in the numerical simulation. (B) Comparison of measured and simulated data. (C) Tide gauge on Dichato beachfront.

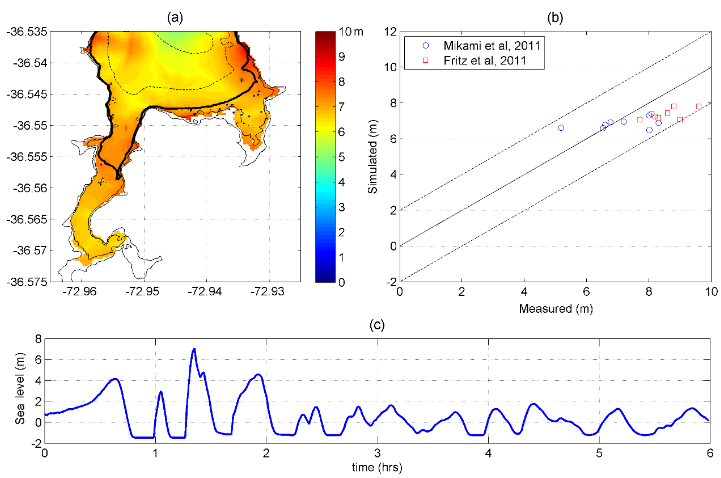


Fig. 4. Tsunami hazard maps. A) Current Velocity. B) Flow depth

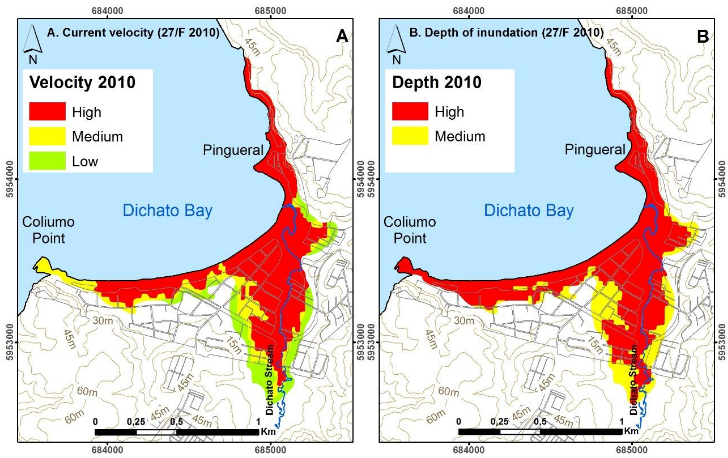


Fig. 5. Pre-event Tsunami vulnerability of the town of Dichato

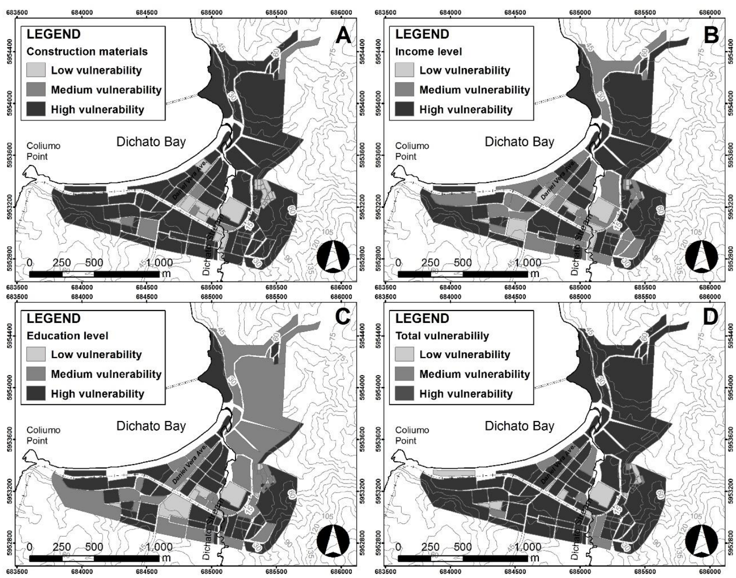


Fig. 6. Post-event Tsunami vulnerability of the town of Dichato

Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-256, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 9 September 2016

Natural Hazards and Earth System Sciences
Open Access
Discussions

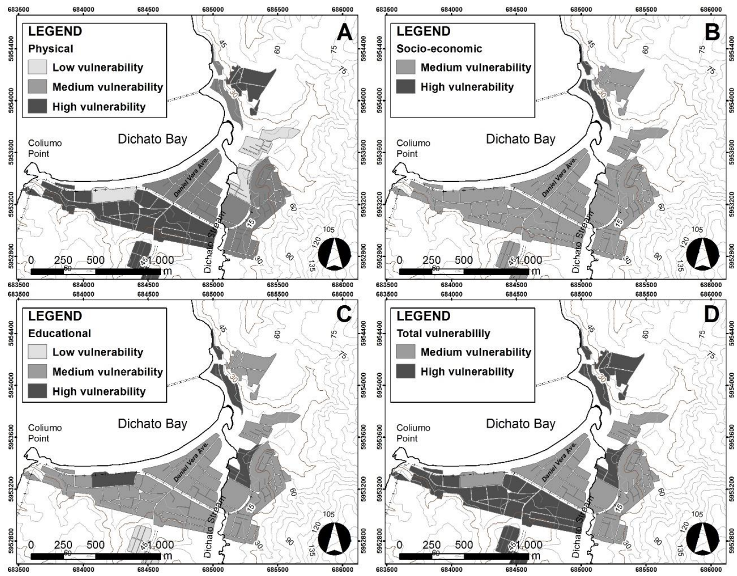


Fig.7. Master Plan for Dichato Reconstruction

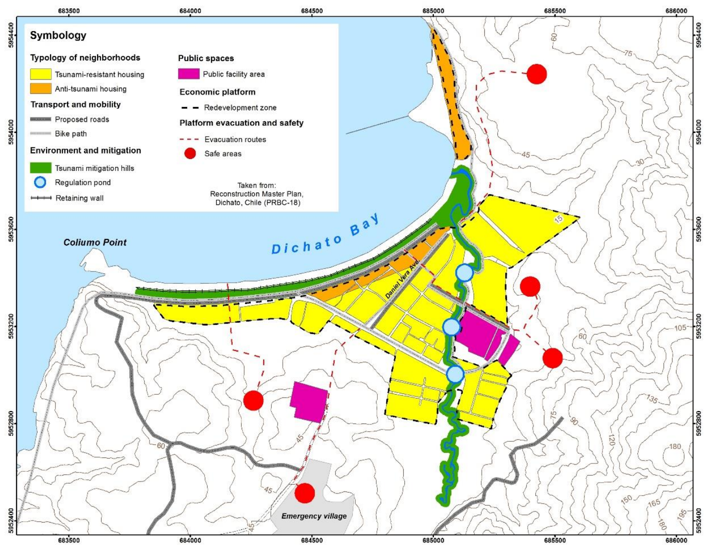


Fig. 8.a) Cluster Analysis and 8.b) principal components for different dimensions of vulnerability by neighborhood. PHY-V (Physical vulnerability), SECO-V (Socio-economic Vulnerability), EDU-V (Educational vulnerability).

Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-256, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 9 September 2016

Natural Hazards and Earth System Sciences
Open Access
Discussions

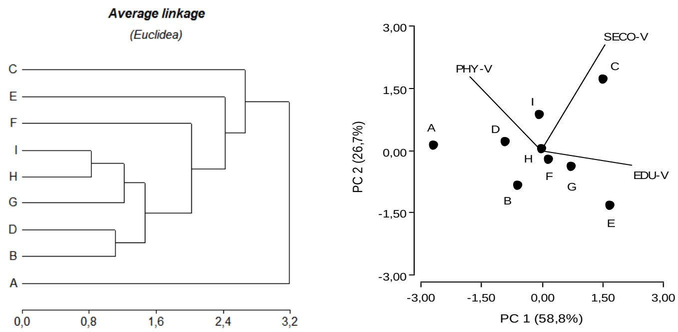


Fig. 9 a) Cluster Analysis and b) principal components for different dimensions of environmental restoration. FAS (Fascination), BE-AW (Being away), COMP (compatibility).

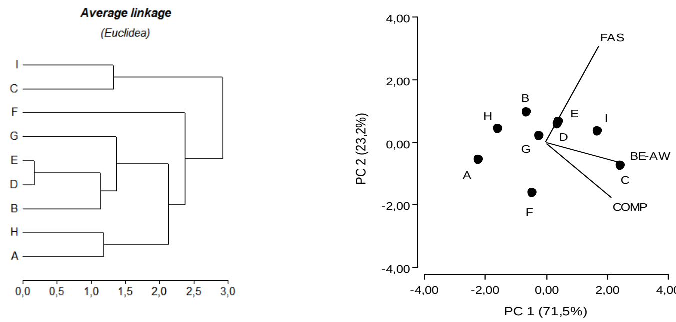
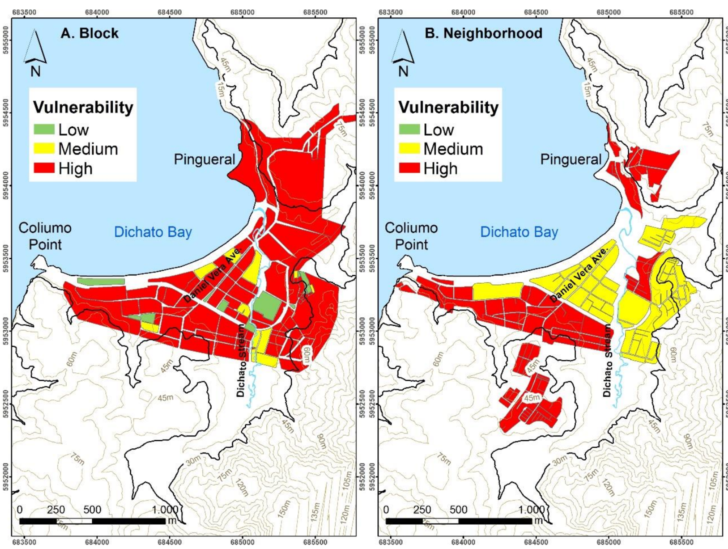


Fig.10. Pre- and post-tsunami vulnerability, Dichato



Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-256, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 9 September 2016

Fig. 11. Tsunami risk areas for pre-event conditions

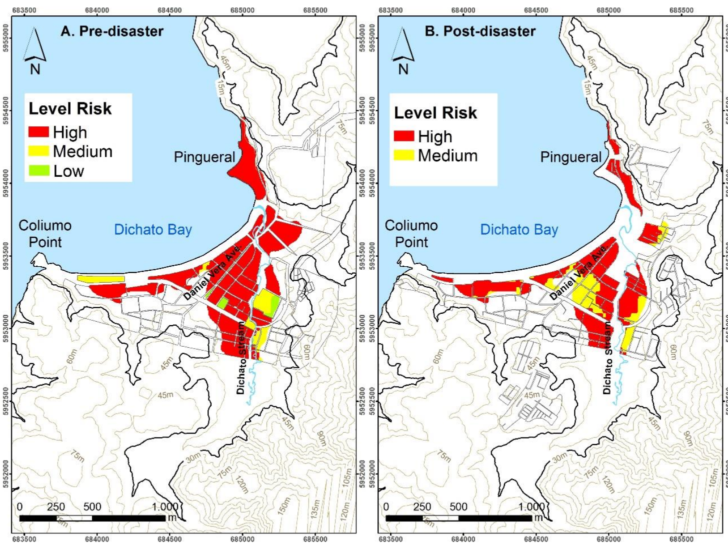


Fig. 12. Pre-disaster (A, B, C and D) and post-disaster (E and F) housing in Dichato.

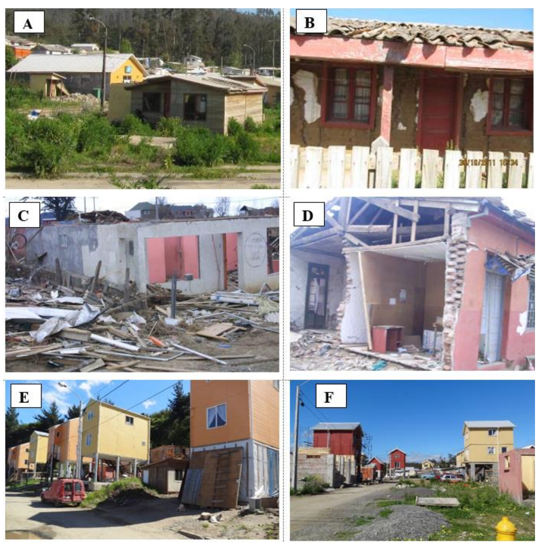


Table 1. Hazard level according to flow depth

Depth of inundation		
Range	Description	Hazard Level
0 -.5 m	Knee-high or less	Low
.5 – 2 m	Knee-high to head-high	Medium
> 2 m	More than head-high	High

Reference: modified Walsh et al. 2005.

Table 2. Hazard level according to flow current velocity

Current velocity		
Range	Descriptor	Hazard Level
.1 – 1.35	Very low and low hazard (speed at which it would be difficult to stand)	Low
1.35 – 2 m/s	Hazard for most	Medium

> 2 m/s	Hazard for all, > 5.0 m/s very hazardous	High

Reference: modified Jalínek et al. 2012 and González-Riancho et al. 2013

Table 3. Variables associated with each dimension of vulnerability pre- and post-2010 tsunami.

Physical dimension			Socio-economic dimension			Educational dimension		
Variable	Pre	Post	Variable	Pre	Post	Variable	Pre	Post
Housing type	X	X	Population density	X		Level of knowledge of the phenomenon	X	X
Housing material	X	X	Overcrowding level	X		Knowledge of tsunami warning systems	X	
Number of houses	X		Socio - economic welfare of households (IBS)	X		Reaction to the event	X	
Number of floors		X	Education level		X	Knowledge of evacuation routes		X
			Labor activity		X	Knowledge of safe zones		X
			Per-capita income		X	Participation in educational programs or lectures		X

Table 3. Inundation by tsunami risk matrix, town of Dichato

X		Hazard		
Vulnerability	Level	Low (1)	Medium (2)	High (3)
	Low (1)	L 1 X 1 =1	L 1 X 2 =1	M 1 X 3 =3
	Medium (2)	L 2 X 1 =2	M 2 X 2 =4	H 2 X 3=6
	High (3)	M 3 X 1 =3	H 3 X 2 =6	H 3 X 3 =9

Risk ranges: Low (1-2), Medium (3-4), High (6-9)

Table 4. Results with significant analyzed variable differences by neighborhood. Indications are as follows: T_S (Total sample), Stat (statistic), df (degrees of freedom), p (p-value), FAS (Fascination) BE-AW (being away), COMP (Compatibility), PHY-V (Physical vulnerability), SECO-V (Socio-economic vulnerability) EDU-V (Educative vulnerability). Standard deviation in parentheses.

	T_S	A	B	C	D	E	F	G	H	I	Est	df	p
N (n)	1710 (172)	155 (12)	258 (21)	24 (17)	325 (28)	163 (19)	142 (19)	66 (13)	382 (28)	195 (15)			
% of respondents	10%	8%	8%	71%	9%	12%	13%	20%	7%	8%			
Anxiety	30%	67%	43%	24%	29%	37%	32%	31%	14%	7%	17.440[a]	8	.0258
Desires location change (yes)	36%	42%	43%	18%	32%	37%	58%	54%	39%	0%	17.577[a]	8	.0246
BE-AW	5.6 (1.3)	4.7	5.4	6.5	5.7	5.8	5.7	5.1	4.9	6.1	3.58		.0007
FAS	4.4 (1.7)	3.3	4.7	4.8	4.8	4.9	3.2	4.6	4.1	5.2	3.38		.0013
COMP	5.6 (1.2)	5.2	5.1	6.5	5.5	5.5	5.7	5.8	5.1	6.0	3.34		0.0015
SECO-V	6.7 (1.6)	6.1	6.2	7.8	6.6	6.5	6.9	6.7	6.6	6.9	1.45		.1808
PHY-V	8.8 (2.0)	11.0	8.6	8.8	9.5	6.9	7.4	8.2	9.2	9.9	51.2		<.0001
EDU-V	7.0 (0.8)	6.6	7.0	7.2	6.8	7.5	6.7	7.2	7.1	7.1	17.9		.0221