

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

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19 **ABSTRACT**

20

21 A large earthquake and tsunami took place in February 2010, affecting a significant part of the Chilean
22 coast (Maule earthquake, Mw = 8.8). Dichato (37° S), a small town located on Coliumo Bay, was one of
23 the most devastated coastal areas and is currently under reconstruction. Therefore, the objective of this
24 research is to analyze the risk factors that explain the disaster in 2010, as well as perceived restoration
25 six years after the event. Numerical modeling of the 2010 Chile tsunami with four nested grids was
26 applied to estimate the hazard. Physical, socio-economic and educational dimensions of vulnerability
27 were analyzed for pre- and post-disaster conditions. A perceived restoration study was performed to
28 assess the effects of reconstruction on the community. It was focused on exploring the capacity of newly
29 reconstructed neighborhoods to provide restorative experiences in case of disaster. The study was
30 undertaken using the Perceived Restorative Scale.

31

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

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

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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 the last decade alone: 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 et al., 2014). These degrees of destruction have been explained by a number of factors, such as ineffective early warning systems, inadequate information management by the population, lack of emergency mechanism coordination and high levels of social vulnerability (Rofi et al., 2006; Løvholt et al., 2014). Although scientific research has led to significant advances in the understanding of 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 occupations (Birkmann et al., 2007), ideological and cultural factors, levels of knowledge and inadequate reactions to the emergency (Ruan and Hogben, 2007). Other studies, through a line of still incipient work, have established that elements associated with social capital and territorial identity foster social resilience, which would be an enabling framework for overcoming 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; Fritz 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). Thus, 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), and is expressed multi-dimensionally (Cutter et al., 2014); in Chile, however, its psychological and social dimensions are the least considered in post-disaster planning. This is the case 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

89 "takes on a new meaning [and] its spaces and components are re-evaluated (by the people)" for their
90 capacity to provide restorative experiences (Allan and Bryant, 2010). Thus, post-disaster reconstruction
91 processes are an opportunity to effectively reduce risk and generate mechanisms of physical as well as
92 social resilience.

93

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

104

105 **2. Regional setting**

106

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

109 Dichato's urban layout is characterized by a coastal plain of approximately 2 km², dissected by Dichato
110 Stream, with an average height of 6 m (Fig. 1). These characteristics explain the great impact of the
111 2010 tsunami, which had inundation heights of up to 8 m, a penetration distance of 1.3 km inland and an
112 inundation area of 0.85 km². The affected population was 1.817 people, with 66 dead and 60% of all
113 housing destroyed (Martinez et al., 2011). According to historical records, this coast had previously been
114 affected by six destructive tsunamis, the most significant occurring in 1751 (M = 8.5), 1835 (M = 8.2)
115 and 1960 (M = 9.5) (Lagos, 2000; Palacios, 2012).

116

117 **3. Materials and methods**

118

119 In order to give risk a value in pre- and post-disaster conditions, the equation $R = H * V$ was used, where
120 $R =$ Risk, $H =$ Hazard and $V =$ Vulnerability (Blakie et al., 1994).

121

122 **3.1 Hazard**

123 The tsunami hazard was estimated by means of a numerical simulation considering the tsunami on
124 February 27, 2010. The Non-hydrostatic Evolution of Ocean WAVES (NEOWAVE) numerical model
125 (Yamazaki et al., 2009, 2011) was used. This model solves linear and nonlinear shallow water equations
126 using nested grids with different spatial resolutions. In this case, 4 nested grids were used, with
127 resolutions of 120" (~3600 m), 30" (~900 m), 6" (~180 m) and 1" (~30 m). Grids 1 and 2 were built
128 from GEBCO topo-bathymetric data, while nautical charts and detailed bathymetry in Coliumo Bay
129 were used for Grids 3 and 4. In addition, 2.5-m-resolution LIDAR topographic data obtained in 2009
130 were used for Grid 4, representing the situation at the time of the 2010 tsunami. The initial tsunami
131 condition was defined using the finite fault model proposed by Hayes (2010), with 180 sub-faults and
132 heterogeneous slip. Figure 2 shows the 4 nested grids and the tsunami initial conditions used in the

133 numerical simulation. The figure shows that Grid 4 takes into account the entire Coliumo Bay and not
134 just the town of Dichato.

135

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

146

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

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

149

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

154

155 3.2 Vulnerability

156

157 The overall vulnerability analysis was performed for two scenarios: pre- and post-disaster. This was
158 done in order to establish the variables related to the level of destruction and the effects generated by the
159 process of post-disaster reconstruction in the configuration of new risk areas. Pre-disaster vulnerability
160 was determined in 2010, while post-disaster conditions were determined using data collected in 2014.

161

162 In the case of pre-disaster conditions, the analysis unit corresponded to census blocks. Due to the
163 destruction of most of the census blocks after the tsunami, for post-disaster conditions the analysis unit
164 was the neighborhood. Neighborhood units were first defined with respect to their pre- and post-tsunami
165 existence. In this line, newly reconstructed areas and old built zones were identified. Within each of
166 these larger areas, neighborhoods were subdivided based on urban morphology characteristics such as
167 type of grid, housing and land use. Finally, main streets such as avenues were used to define the
168 boundaries of neighborhoods. Fig. 1 illustrates the location of the nine neighborhoods in Dichato.

169

170 For the overall vulnerability analysis, variables selected for both scenarios were representative of
171 physical, socio-economic and educational dimensions; however, some variables were modified
172 according to the pre- and post-disaster availability of data (Table 3). For pre-disaster conditions, the
173 variables related to the physical and socio-economic dimensions were obtained from the 2002 census
174 (INE, 2002). However, due to the destruction of the post-tsunami census blocks, the use of the census
175 was invalidated and data were collected through surveys. To this end, variables related to those of the
176 pre-disaster data collection were selected (for example, in the physical dimension the housing type
177 variable is related to the number of floors variable). The survey was also used also to collect data related

178 to the educational dimension in pre- and post-disaster scenarios, including the following variables:
179 knowledge of evacuation routes, knowledge of safe zones and participation in educational programs or
180 talks.

181

182 Three levels of vulnerability for each dimension were established (high, medium, low). The variables
183 associated with each vulnerability dimension were given equal weight in the final matrix. This was done
184 because previous studies that included the dimension of vulnerability in risk (Martínez et al., (2012);
185 Rojas et al., (2014) used similar criteria, which have been found to be representative of local conditions.
186 Variables were incorporated into the GIS using ArcGis 10.1 to generate thematic maps and summary
187 charts through map algebra.

188

189 3.3 Environmental restoration

190

191 The capacity of the neighborhoods of Dichato to provide restorative post-disaster experiences was
192 assessed through a perceived restoration study (Hartig et al., 1997). This type of study explores the
193 capacity of environments to be restorative, which is particularly crucial in cities prone to natural
194 disasters such as tsunamis. For Dichato in particular, this type of study can reveal the specific landscape
195 attributes that influence perceptions, indicating whether restorative post-tsunami experiences are based
196 on newly reconstructed neighborhoods and features or pre-existing neighborhood character. In other
197 ways, it provides information regarding whether or not post-tsunami reconstruction contributes to a
198 restorative experience, and hence to resilience.

199

200 To undertake this study, the nine neighborhoods of Dichato were defined as analysis units (Fig. 1).
201 People living in each of these neighborhoods assessed their environment by means of the Perceived
202 Restorative Scale (PRS), an instrument constructed based on the Attention Restoration Theory (Kaplan
203 and Kaplan, 1989). The PRS has been used to identify landscape attributes that can be restorative to
204 people subjected to high levels of stress and mental fatigue (Hartig et al., 1997; Korpela and Hartig,
205 1996; Ulrich et al., 1991). Three factors of the PRS were used to evaluate the interaction of people with
206 the neighborhood they inhabit: being away (BE-AW), which reflects the need to escape from everyday
207 life or daily mental activities that require major concentration; fascination (FAS), which is found in
208 environments that attract and hold our attention without any effort; and compatibility (COMP), which
209 refers to a sense of oneness with environments that provides the capability to meet our desires and needs.
210 A survey was developed based on previously validated PRS questionnaires, including 15 sentences that
211 refer to each of these factors (five for each). This survey was used to interview people in their homes
212 during the same time the vulnerability questionnaire (described in the previous section) was
213 administered. Each interviewee was informed about the survey takers' interest in understanding their
214 experience in their current neighborhood. Accordingly, they were asked to assess each sentence from 1
215 to 7 (Likert scale), with 1 indicating that the sentence did not apply to their neighborhood at all and 7
216 indicating that it applied to the highest degree. As an example, a sentence referring to the BE-AW factor
217 was "Being in this neighborhood is like a break from my daily routine." Another sentence, referring to
218 the FAS factor, was "There are many interesting things that catch my attention in this neighborhood." A
219 sentence referring to the COMP factor was "The activities that can be done in this neighborhood are
220 activities that I enjoy." After evaluating each of the 15 sentences, each person was asked to describe the
221 neighborhood areas they recalled during the evaluation.

222

223 Numerical data obtained using the Likert scale were organized in Excel sheets for each interviewee and
224 neighborhood, and were later used for performing an ANOVA and calculating mean and SD values for
225 each factor and neighborhood. Textual data were organized in Excel sheets as well, including the
226 frequency of mention of each site that interviewees recalled during the evaluations (expressed as a
227 percentage). The results allowed the following aspects to be identified: significant differences among
228 neighborhoods with respect to restoration capacity; neighborhoods with the highest and lowest
229 restoration values and the sites that were more meaningful for providing a restorative experience to the
230 inhabitants.

231

232 3.4 Sampling and statistical analysis

233

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

239

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

$$244 \text{ Eq (3)} \quad n \geq \frac{Nz_{1-\alpha/2}^2 PQ}{z_{1-\alpha/2}^2 PQ + d^2 (N - 1)}$$

245

246 Where: confidence level was 95%, precision (5%) and proportion 90% ($\approx 90\%$ of families in the Biobio
247 Region who experienced problems due to the 2010 earthquake and tsunami) (Larrañaga and Herrera,
248 2010). The minimum sampling size was estimated to be $n=130$. Finally, 156 surveys were carried out.

249

250 Data collected in these surveys were subjected to multivariate descriptive analysis, cluster analysis and
251 principal component analysis. Cluster analysis allowed the similarities and dissimilarities among
252 neighborhoods to be easily observed, whereas principal component analysis allowed the association of
253 the different dimensions of vulnerability with each analyzed neighborhood to be observed. The chi-
254 squared test was used to compare proportions and a one-way analysis of variance (ANOVA) was
255 conducted for the numerical variables. The Tukey test was applied for comparison, using a significance
256 level of $\alpha = 0.05$.

257

258 3.5 Risk

259

260 Risk factors were integrated into a matrix (Eckert et al., 2012; Jelínek et al., 2012; Martínez et al., 2012)
261 and three risk levels were obtained from the multiplication: high, medium and low, with scores from 1 to
262 9 (Table 4). Risk level is applied to analysis units, according to pre- and post-event conditions, in the
263 GIS vulnerability section.

264

265 4. Results

266 4.1 Hazard

268 Fig. 3 (a) shows the inundation area obtained from the numerical simulation. Dots indicate inundation
269 height measurements from field surveys (Mikami et al 2011; Fritz et al, 2011), while the asterisk
270 indicates the synthetic tide gauge location. Fig. 3 (b) shows a comparison of recorded and simulated
271 data, where the error obtained from Eq (1) was $K = 1.09$ with a standard deviation from Eq (2) of $\kappa =$
272 0.12 , which is considered acceptable (Suppasri et al., 2011). Fig. 3 (c) shows the tsunami wave form
273 obtained from the synthetic tide gauge. It can be seen that the largest wave is not the first, but rather the
274 third wave, which reached an inundation height of up to 7m. A fourth wave is also observed, reaching up
275 to 5m. Fig. 4 shows the area inundated by the event, which reached a maximum runup of 10m, spread
276 through Dichato Stream.

277

278 4.2 Pre-disaster vulnerability

279

280 In the case of physical vulnerability, 51% of census blocks reported high vulnerability levels, which
281 involved 47% of the total inundated area and 57% of the total population (Fig. 5). Vulnerability levels
282 relate to a deficiency in housing materials (e.g.: wood, fiber cement, clay and waste). In relation to
283 economic vulnerability, 73% of households reported a medium level, which involves 61% of the
284 inundated area and 67% of the total population. These vulnerability levels can be explained mainly by
285 the location of the residential areas, in which more than 75% of the inhabitants reside, where there is no
286 overcrowding but income levels are low, with approximately 44% of the population receiving monthly
287 incomes of less than \$118,000 Chilean pesos (about US \$170). In addition, 54% of the population has
288 high educational vulnerability. Low levels of schooling influence overall vulnerability as 42% of the
289 population has only a primary school education or has not completed this level and only 55% has
290 finished secondary school. It is important to note that 58% of the population indicated that the tsunami
291 was the result of the earthquake, while 42% attributed the tsunami to other causes, sometimes related to
292 religion, including global warming and the apocalypse.

293

294 4.3. Post-disaster vulnerability

295

296 For post-disaster conditions, the Reconstruction Plan applied to Dichato, known as PRBC-18, modified
297 29% of the total town area, with 15% established as a tsunami-resistant building area, not including
298 expropriation (Fig.7). Elevated houses (stilt houses) and community buildings were designed and built in
299 these areas (coastline). Twelve percent of the total area was reserved for mitigation parks, which were
300 built along the coastline and river banks, where the tsunami surged and the greatest destruction was
301 generated. Construction of the mitigation park began in 2015, with a line of trees that covered a surface
302 area 95.7 ha, with a width of more than 20 m. The fishing area accounts for 1.6% of the total town area,
303 including the construction of a fishing pier and a market in Villarrica Cove.

304

305 The post-event vulnerability measures presented variations in relation to pre-disaster levels. The
306 physical dimension presented an average level in 53% of the total area, explained by the number of
307 floors (≥ 2) and the type of dwelling. Regarding socio-economic vulnerability, the reported levels were
308 medium and high in 42% and 31% of the total area, respectively, and were associated with a low per
309 capita income level. Educational vulnerability was average in 87% of the area; however, spatial
310 differences were reported among the districts analyzed. The cluster analysis (Fig. 8a) performed for
311 post-event vulnerability dimensions identified six neighborhood groups. Four groups were represented

312 individually by neighborhoods C, E, F and A. The fifth cluster grouped analysis units D and B. Finally,
313 the sixth group was composed of units I, H and G. Only neighborhoods C, E, A, D and B were directly
314 affected by the 2010 tsunami inundation.

315 The ANOVA showed significant differences in the physical and educational vulnerability dimensions (p
316 <0.05), while the socio-economic dimension was homogeneous for all evaluated neighborhoods ($p =$
317 0.1808). The neighborhoods with the highest physical vulnerability were older sectors (I, D) and a
318 provisionally relocated sector (A). Neighborhoods directly affected by the tsunami (B, C) were grouped
319 in the medium level, as was as an unaffected sector (H). The neighborhoods found in the low level (E, F,
320 G), presented higher quality buildings. Regarding the educational dimension, the lowest vulnerability
321 corresponded to relocated sector A, which was most devastated by the 2010 tsunami. The above was
322 reinforced by a principal component (PC) analysis, which showed that the first two components
323 explained 85.5% of the total variance. Fig. 8b indicates that only sector C had a higher association with
324 socio-economic vulnerability, while the remaining 8 neighborhoods were related to the physical and
325 educational vulnerability dimensions.

326

327 Regarding feelings assessed regarding the possibility of a future tsunami (Table 4), 5 feelings showed no
328 significant differences by neighborhood ($p>0.05$): panic (19%), fear (39%), tranquility (41%), security
329 (19%) and indifference (3%). A significant difference ($p = 0.0258$) was found for the feeling of anxiety,
330 which was higher (67%) for relocated inhabitants (A).

331

332 The overall vulnerability analysis for pre- and post-tsunami conditions indicates that vulnerability was
333 reduced from high to medium levels, and that the spatial distribution of vulnerable areas was maintained
334 for both conditions (Fig. 9). For pre-tsunami conditions, 90% of the area evaluated presented high
335 vulnerability, 5.4% medium vulnerability and 4.6% low vulnerability. For post-tsunami conditions, 55%
336 of the area presents high vulnerability levels and 45% exhibits medium vulnerability, while low
337 vulnerability was not found. These findings lead to the conclusion that the entire area has high or
338 medium levels of vulnerability.

339

340 4.4. Post-disaster environmental restoration

341

342 Safety perception in current residential areas was evaluated as safe or very safe by 65% of the local
343 population ($p>0.05$) in view of changes made by authorities in the Master Plan for Reconstruction. The
344 feeling of identity with the city pre-disaster was 49% ($p>0.05$), with higher percentages in
345 neighborhoods A (75%), C (59%) and D (57%), which were the most affected. Desire to change one's
346 place of residence was not homogeneous among neighborhoods ($p = 0.0018$) and percentages $\geq 40\%$
347 were obtained both in sectors affected by the tsunami (A, B) and those not directly affected (F, G).

348 The 1-7 Likert scale was applied to assess 5 topics, namely reconstruction, process quality, equipment
349 and the role of the National Emergency Office (ONEMI). The results showed no differences among
350 neighborhoods. Positive evaluations were obtained for the reconstruction process (Mean = 5.6; SD =
351 1.4), associated equipment (Mean = 5.5; SD = 1.4) and quality (Mean = 6.0; SD = 1.3). The worst scores
352 were obtained for ONEMI (Mean = 3.8; SD = 1.9).

353

354 In relation to the perceived restoration study, the ANOVA showed significant differences among
355 neighborhoods ($p <0.05$). The best evaluated areas were neighborhoods C (Mean = 6.1; SD = 0.8) and I
356 (Mean = 5.8; SD = 1.0). The means reported here correspond to the three factors combined for each

357 neighborhood. For the results of each factor, see Table 5. Neighborhood C (Villarrica) was affected by
358 the tsunami and completely rebuilt, while neighborhood I (Pingueral) was not modified. The new coastal
359 infrastructure (25%), new anti-tsunami houses (19%) and views of the coast (16%) were most mentioned
360 by respondents in neighborhood C as elements that contribute to restoration. Meanwhile, in
361 neighborhood I, views of the river (20%) and the presence of uphill streets (20%) and nearby hills (17%)
362 were the most mentioned as restorative elements. In contrast, neighborhoods A (Mean = 4.4; SD = 1.6)
363 and H (Mean = 4.7; SD = 1.5) were the worst evaluated. Neighborhood A, as previously mentioned, is
364 the relocated neighborhood most affected by the tsunami. In this case, new urban infrastructure (19%),
365 views of the bay (19%), and the community building (19%) were found to contribute the most to
366 restoration. Neighborhood H was neither affected by the tsunami nor modified. In this case, the presence
367 of nearby hills (32%), pre-existing housing (23%) and uphill streets (16%) were found to add to
368 restorative experiences.

369

370 4.4 Pre- and post-disaster risk

371

372 Little difference was presented between the surface area (0.11 km²) and spatial distribution of the
373 tsunami risk areas, considering the pre- and post-2010-event conditions, with a high level of risk ($\geq 78\%$)
374 for both scenarios (Fig. 10). In case of pre-disaster conditions, some sectors of the town had small areas
375 with medium risk, explained by better building quality or sites without buildings. This situation changed
376 post-disaster due to increased construction, especially public housing as part of the Reconstruction Plan.
377 As seen in Fig. 11, most buildings were destroyed by the tsunami due to poor quality of materials. In the
378 area where the greatest destruction occurred (the Villarrica sector or section C), initial housing was
379 replaced by two-level, 27-m² stilt houses made of wood, on 2-m-high steel columns. This type of
380 housing was implemented as a mitigating action against the possibility of a tsunami with similar
381 characteristics, in which the steel structure would prevail while the wood could always be replaced (Fig.
382 11E). Not all former inhabitants returned to their neighborhood to occupy these homes as most were
383 elderly and could not climb stairs to enter the stilt houses (Khew et al., 2015). Despite being owners,
384 they opted for relocation to higher sectors of Dichato, forming a new neighborhood. These homes were
385 also located in neighborhood B (or downtown), where a beachfront and boulevard have been built in
386 order to promote tourism. The only structural changes made to houses consisted of replacing steel
387 columns with reinforced concrete columns, while retaining the same overall dimensions (Fig. 11F). The
388 ground floors of these stilt houses have been transformed by the inhabitants in order to increase living
389 area (Khew et al., 2015).

390

391 Neighborhood B presented the greatest post-earthquake transformation, replacing a fish market with
392 beachfront buildings, a mitigation park and a boulevard with a striking design in order to attract tourism.
393 However, behind these buildings, a mixture of stilt houses and other types of one-story housing, made of
394 wood or masonry, were built, giving rise to new neighborhoods and post-earthquake risk areas. Other
395 areas, such as neighborhood A, went from being provisional neighborhoods to consolidated settlements
396 (e.g., El Molino) and in turn absorbed part of the relocated population. In general, new post-disaster risk
397 areas affect neighborhoods C, D, E, F, G and H up to a height of about 20 meters; however, Dichato
398 Stream extends the propagation area into more inland neighborhoods.

399

400 5. Discussion

401

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

408
409 The main factors explaining high risk levels are building quality and materials, which are highly related
410 to the degree of destruction caused by the 2010 tsunami. Many of these houses were one-story buildings
411 made of wood or lightweight materials and built in a do-it-yourself manner. Lack of infill and reinforced
412 concrete masonry (failure of brick masonry infill walls and lightly reinforced concrete columns) was a
413 damage factor, coinciding with studies by Palermo et al. (2013) in the area. According to these authors,
414 residential housing consisting of light timber frame and concrete frame construction with brick masonry
415 infill walls suffered widespread damage throughout the surveyed coastal region of Chile.

416
417 According to numerical modeling, tsunami wave heights reached between 5 and 8 m, with current
418 velocities greater than 2 m/s, which could be enough to damage house foundations and destroy coastal
419 infrastructure. In this regard, tsunami fragility curves developed by Mas et al. (2012) for Dichato from
420 field data and satellite imagery showed a 68% probability of damage at a flow depth of 2 m, mainly due
421 to building materials, predominantly wood. In this case, it was found that approximately 80% of the built
422 area of Dichato experienced damage or was completely destroyed by the 2010 tsunami.

423
424 Other important factors were the socio-economic status and education level of the population, which
425 were relevant mainly in pre-disaster conditions. In this case, 44% of the population has low incomes and
426 a widespread lack of knowledge concerning emergency plans or evacuation routes, resulting in
427 inadequate reactions. One year after the event, people still had symptoms of post-traumatic stress,
428 indicating feelings of panic, fear and sadness (Venegas, 2011). Most of this population, which consisted
429 of owners affected by the tsunami, moved to provisional neighborhoods where they remained for two
430 years without basic services. Some of these provisional houses became final settlements. The study
431 conducted in Dichato by Shahinoor and Kausel (2013) stated that risk of tsunamis is not well addressed
432 in planning and community-oriented programs and that the pre-established mechanisms for post-disaster
433 recovery are not appropriate, which is why risk is not reduced. The latter is not a specific problem of the
434 location but derives from the lack of coordination between planning instruments and risk management in
435 Chile, which is essentially reactive and not preventative (Martínez, 2014). On the other hand, Chile lacks
436 a public policy oriented at establishing criteria or a reconstruction model to implement in case of a
437 disaster, and usually gives priority to physical reconstruction rather than social reconstruction. Yet
438 physical reconstruction continues to take place in inappropriate locations and therefore, in considering
439 only spatial location, risk areas fail to be managed in a way that effectively reduces risk.

440
441 A limitation in this research was that not all of the variables used for post-disaster conditions were
442 similar to those used for pre-disaster conditions, for which there were census data at census block level.
443 Even so, the results were concordant with the observed reality and the behavior of the variables
444 coincides with other studies carried out in affected locations (Martínez, 2014, Rojas et al., 2014). The
445 lack of standardized open-access geospatial databases prior to the disaster makes it difficult to manage
446 risk, overcome the emergency and begin the reconstruction process. In the case of Chile, this has been

447 critical, limiting the monitoring of post-disaster socio-territorial changes as since 2002 there has been no
448 update to the national census, which only recently has been planned for 2017. In addition, the lack of
449 coordination among various ministries in the country causes replication of information, which in turn is
450 collected according to various criteria or standards, and to which access is not easy. These aspects limit
451 continuity in risk studies. Given the high social cost of these and other threats, debate on this matter has
452 recently begun in the country.

453

454 Regarding restoration results, it is interesting to find that the restoration capacity of neighborhoods
455 varies with respect to the presence and absence of natural and built elements. Natural elements such as
456 the presence of hills and views of bodies of water contribute to perceived restoration. These results are in
457 line with previous restoration studies indicating that the presence of natural elements such as water and
458 vegetation are related to restorative environments (Korpela and Hartig, 1996, Hartig et al., 1997).
459 However, in this case, it is not only the mere presence of these elements that is relevant, but most
460 probably the sense of security they give to the community as well. Hills are useful for refuge in case of
461 tsunami as well as for observation points, which are much needed to keep people informed about what is
462 happening in the event of a disaster. Consequently, it is important for future planning processes to
463 consider the potential of natural elements to remain in place after a disaster in order to restore
464 communities post-disaster. For instance, access to these natural sites from different neighborhoods
465 should be enhanced during the reconstruction process by, for example, including evacuation routes that
466 lead to these areas for recreation purposes in everyday life. The latter would contribute to post-disaster
467 adaptation and social resilience (Pelling, 2003).

468

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

479

480 In this sense, vulnerability and resilience are distinct elements but superimposed in their role in natural
481 disasters and brought together in the cornerstone of sustainability (Turner, 2010). In the case of Dichato,
482 vulnerability exhibited a close relationship to lack of resilience because few lessons were learned from
483 the 2010 event and the same mistakes are still being made, with a nearly completed rebuilding process
484 that presents vulnerability conditions very similar to those that existed prior to the 2010 earthquake. This
485 situation is explained by the emphasis on physical rather than social reconstruction, the lack of public
486 policies to face a rebuilding process of this magnitude despite recurring events in the country and,
487 especially, by the poor consideration and assessment of risk areas in planning at a local scale, since other
488 affected areas were repopulated in the same manner and relocated to the same risk areas (Martinez,
489 2014). In some neighborhoods, increased social and environmental problems such as pollution, crime
490 and poverty occurred as a result of reconstruction processes (Rojas et al., 2014). The main disadvantage
491 of these programs is that they were implemented as similar projects in 18 affected coastal towns,

492 regardless of geographic reality and territorial identity. In addition, the programs did not distinguish
493 between rural or urban areas. Small fishermen's coves located in coastal wetlands and small bays that
494 underwent semi-urbanization processes had to absorb relocated populations from affected areas,
495 resulting in increased population densities in new risk areas and loss of cultural and territorial identity.
496 The latter was reflected in that between 57% and 75% of the population most affected by the tsunami six
497 years ago identified with Dichato prior to the tsunami. In this respect, most current approaches establish
498 that resilience is characterized by socio-ecological system responses to natural disturbances, capacity for
499 self-organization, learning and adaptation to change (Folke, 2006; Turner, 2010). These elements present
500 a challenge from an institutional point of view in Chile, as risk management and its link to organized
501 society must be strengthened to ensure that investments in reconstruction processes effectively reduce
502 risks associated with phenomena that will undoubtedly continue to occur in the country. In addition,
503 reconstruction involves addressing physical, social and environmental territory components to facilitate
504 the development of post-disaster resilience, meaning that the country must change its approach to natural
505 disaster management, moving towards sustainability of its cities and coastal towns.

506

507 **6. Conclusions**

508

509 The vulnerability factors that best explained the extent of the 2010 tsunami disaster were housing
510 materials, low incomes and poor knowledge about such phenomena, which conditioned inadequate
511 reactions at the time of emergency. The current town configuration, resulting from reconstruction
512 process in the six years after the event, has generated new risk areas that occupy the same locations as in
513 pre-event conditions, meaning that risk is not reduced. For post-earthquake conditions, it was determined
514 that all neighborhoods have the potential to be restorative environments after a tsunami, but with
515 different intensities, depending on the type of natural and built features they have kept and incorporated
516 during the reconstruction process. However, risk analysis indicates that neighborhoods with greater post-
517 disaster restoration ability remain in the same areas devastated by the 2010 tsunami and will likely be
518 destroyed again in a future event, a situation that forces us to reflect on how to plan coastal zone land
519 use and manage risk in the country. Finally, the methods used in this investigation, in which cluster
520 analysis, principal component analysis and a GIS platform are integrated, prove highly beneficial in an
521 interdisciplinary approach such as this, where the selection criterion of the variables is fitted to the
522 knowledge of the place and the variables are validated as a function of the local reality, which facilitates
523 their adaptation to other geographical areas of interest.

524

525

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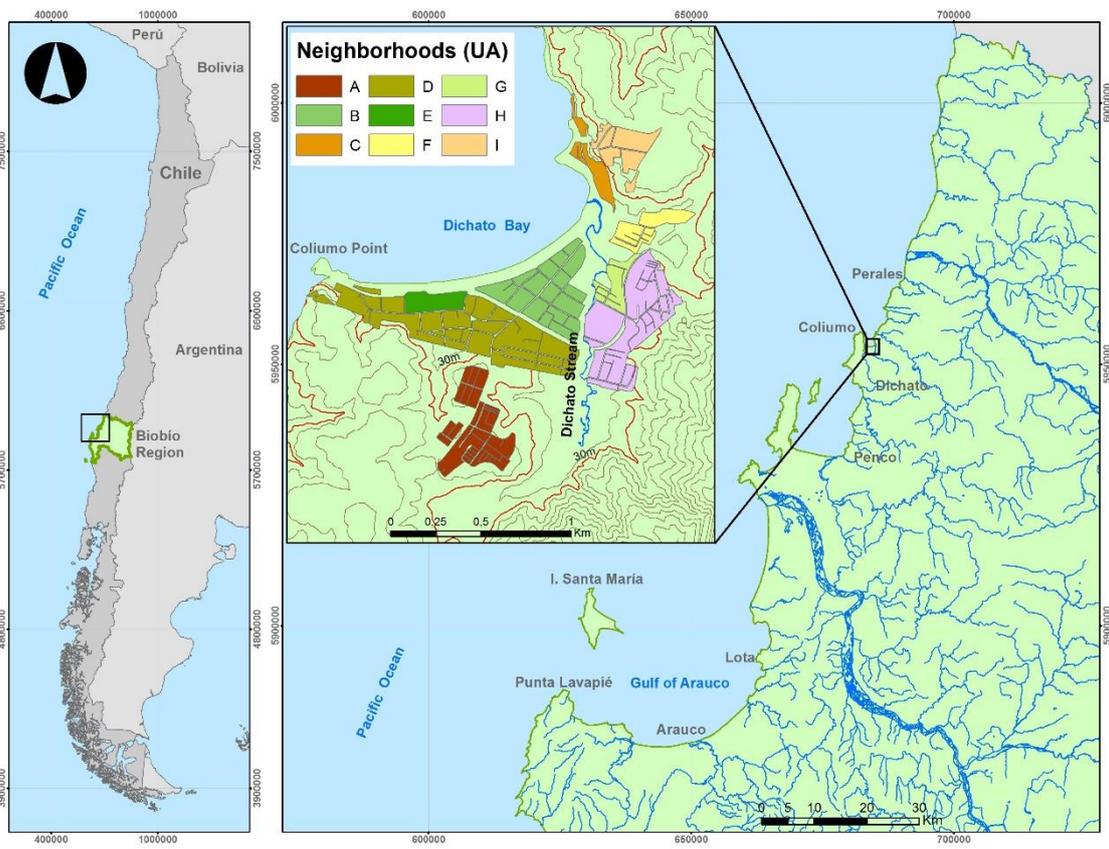
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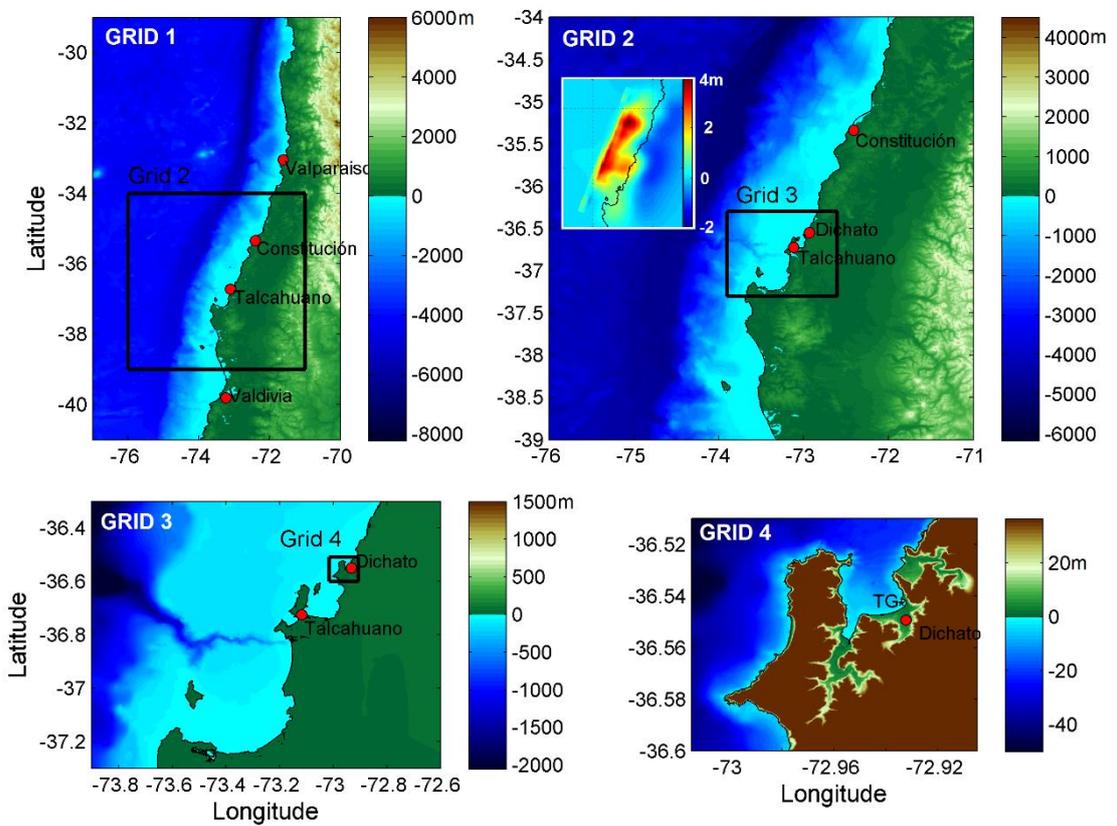
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746 Fig. 1 Geographical context of the study area. Dichato is located on Coliumo Bay (36° S). The letters
 747 (A-I) identify different neighborhoods analyzed in the post-disaster period.

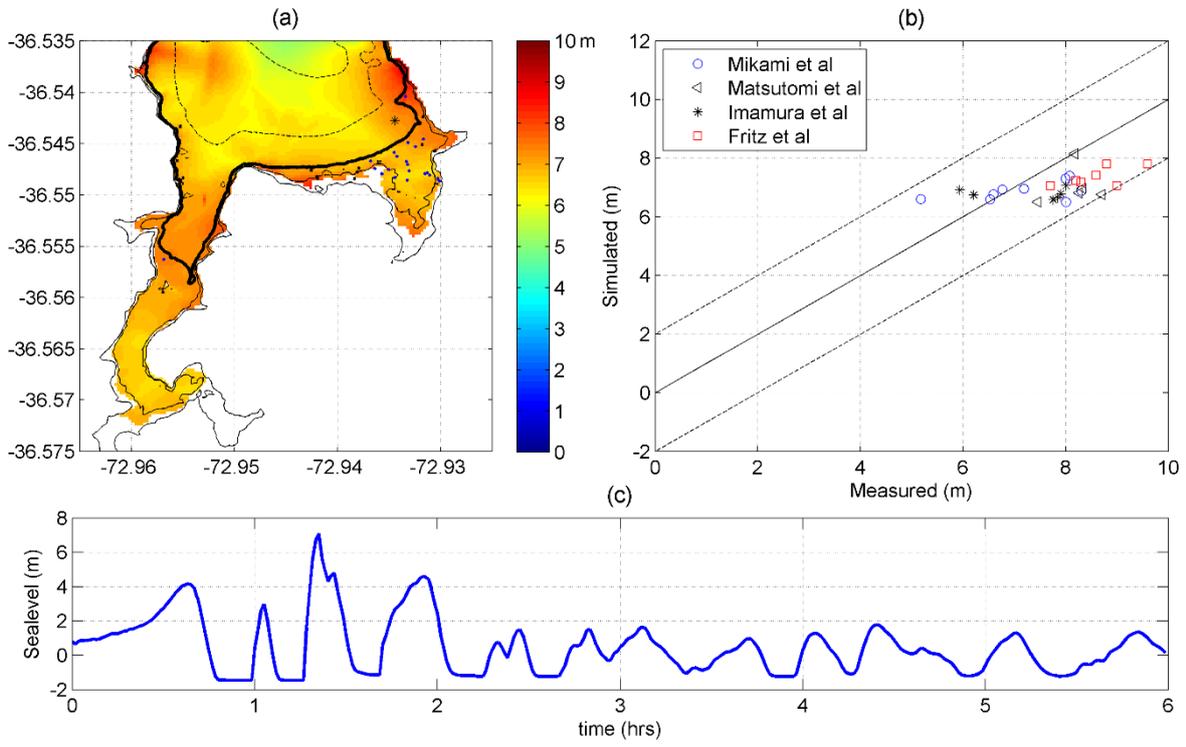


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 751 Fig. 2. Nested computational grids. The inset in Grid 2 shows the tsunami initial condition (Hayes,
 752 2010). TG in grid 4 indicates the location of the virtual tide gauge.



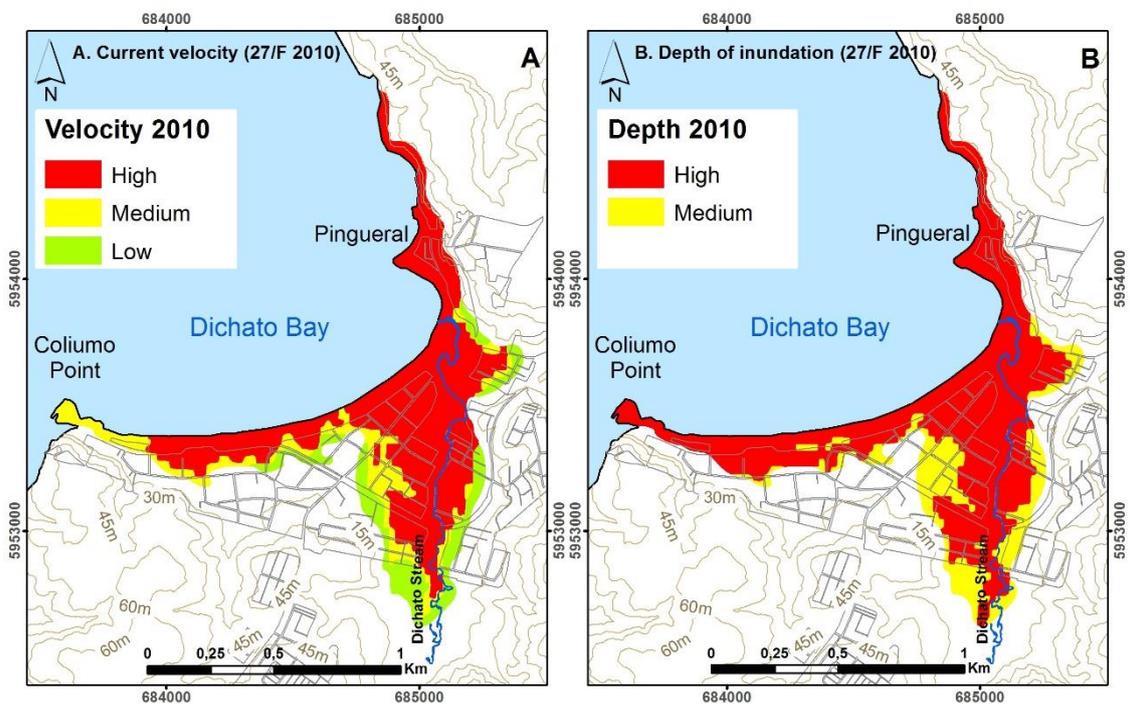
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761 Fig. 3. (a) Inundation area obtained in the numerical simulation. (B) Comparison of measured and
 762 simulated data. (C) Tide gauge on Dichato beachfront. The solid line represents the measurement equal
 763 to the simulation, while the dotted lines show the measurement ± 2 m. The simulation shows results in
 764 a range of ± 2 m with respect to the measured data.
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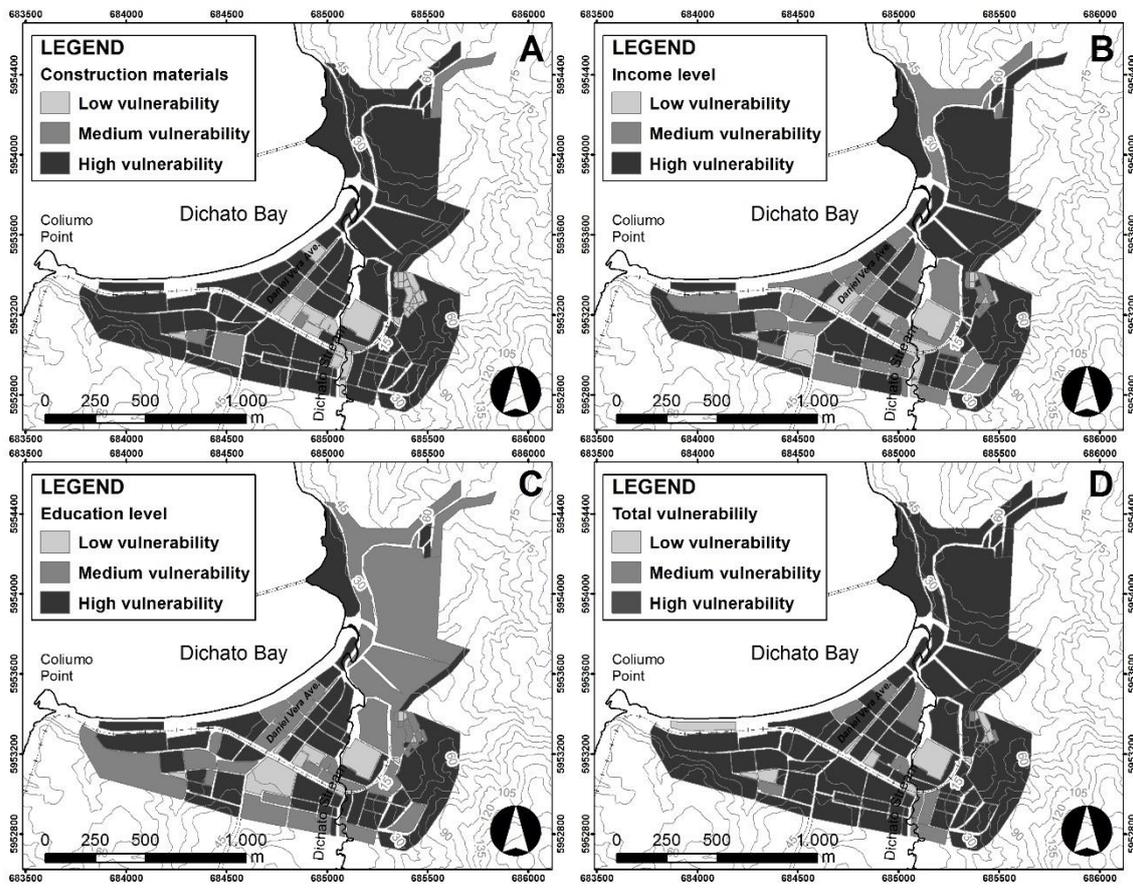
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Fig. 4. Tsunami hazard maps. A) Current Velocity. B) Flow depth



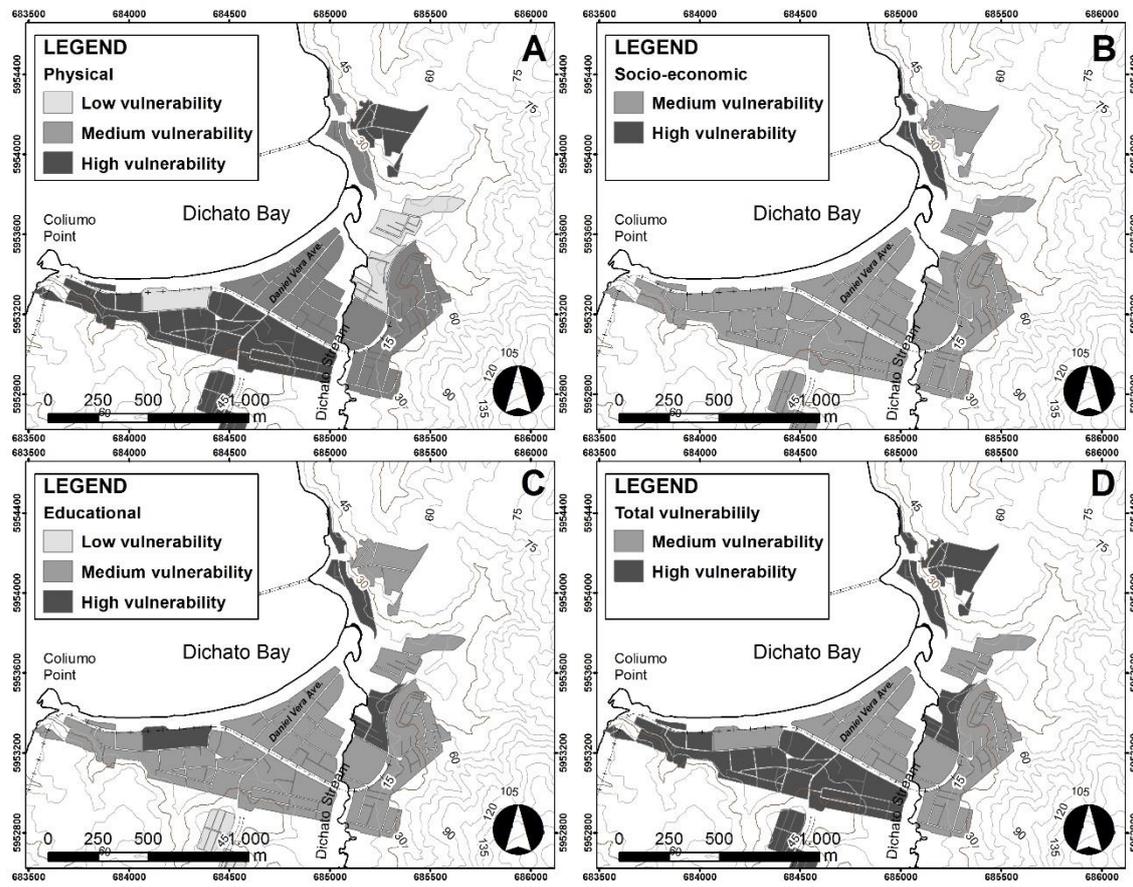
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Fig. 5. Pre-event tsunami vulnerability of the town of Dichato



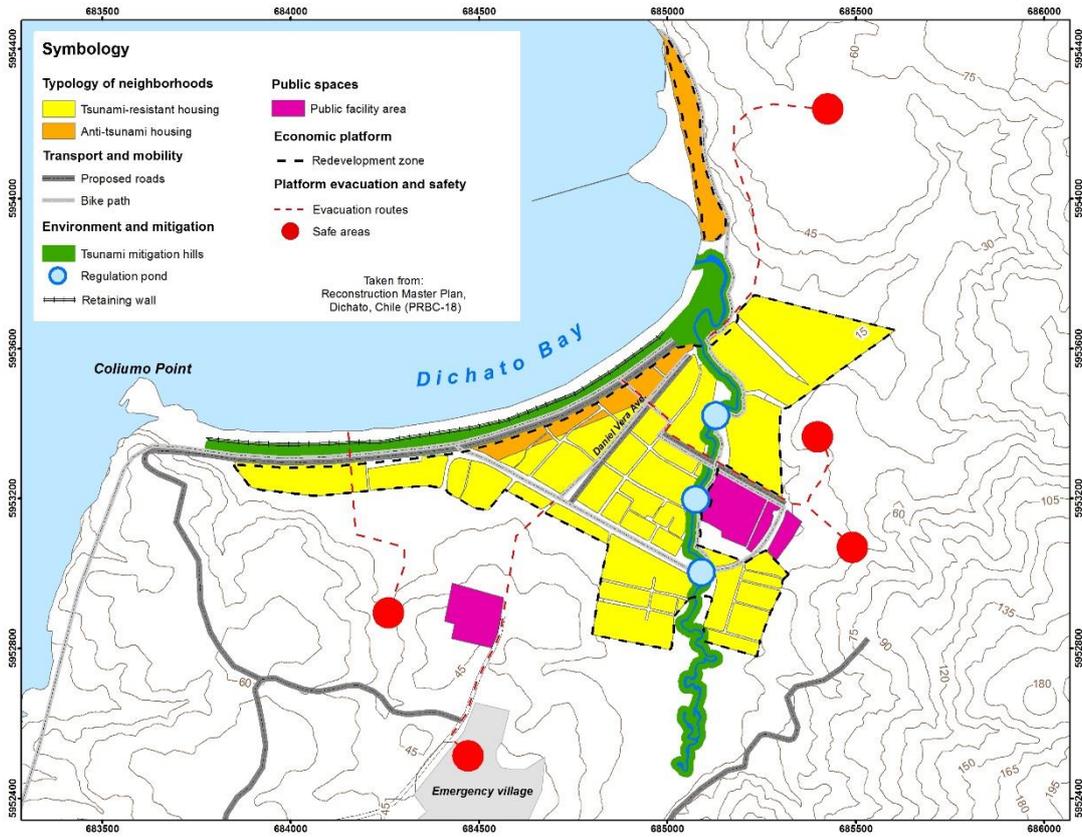
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Fig. 6. Post-event Tsunami vulnerability of the town of Dichato



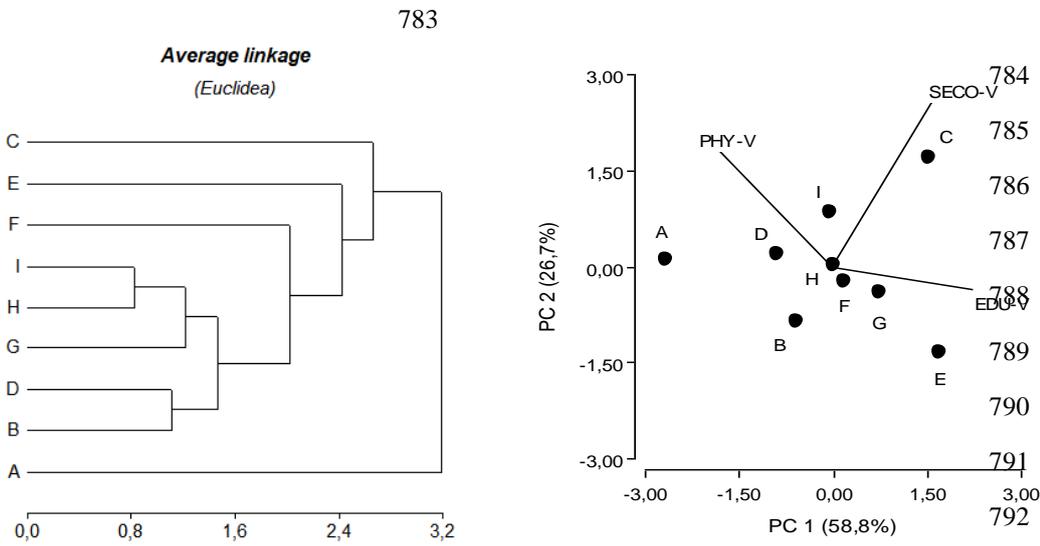
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Fig.7. Master Plan for Reconstruction for Dichato



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



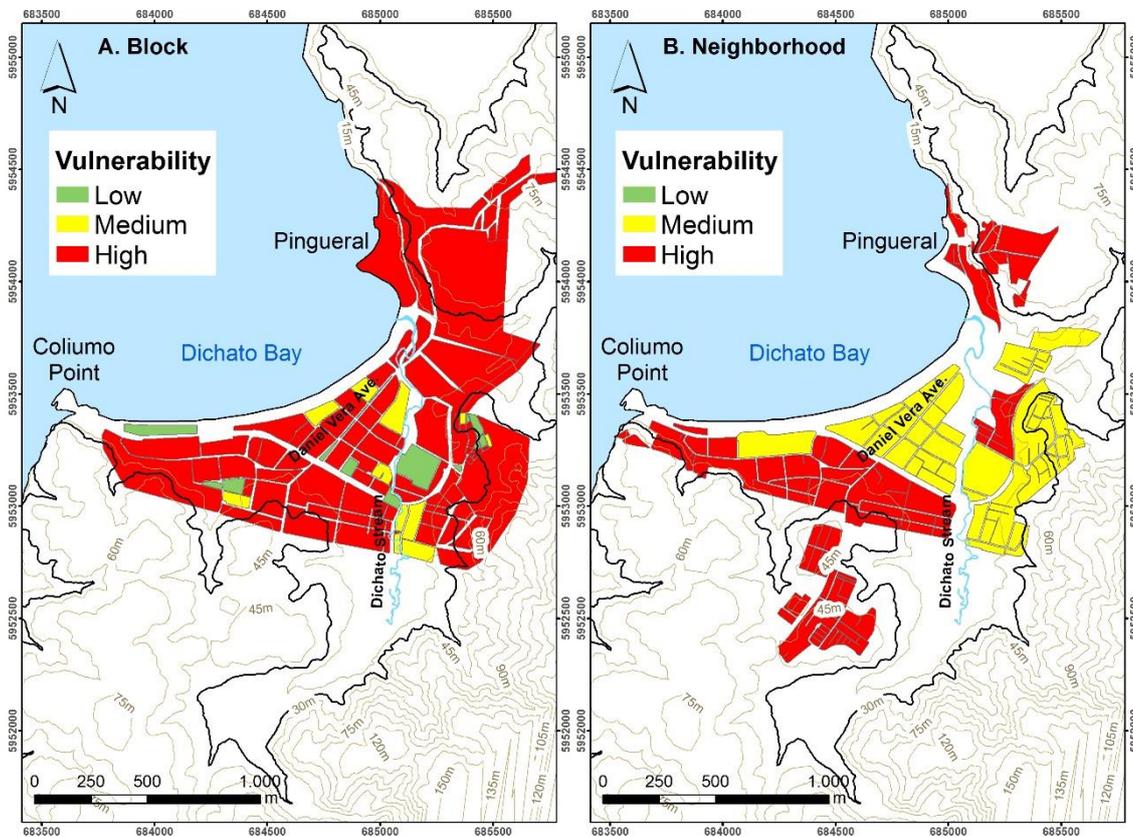
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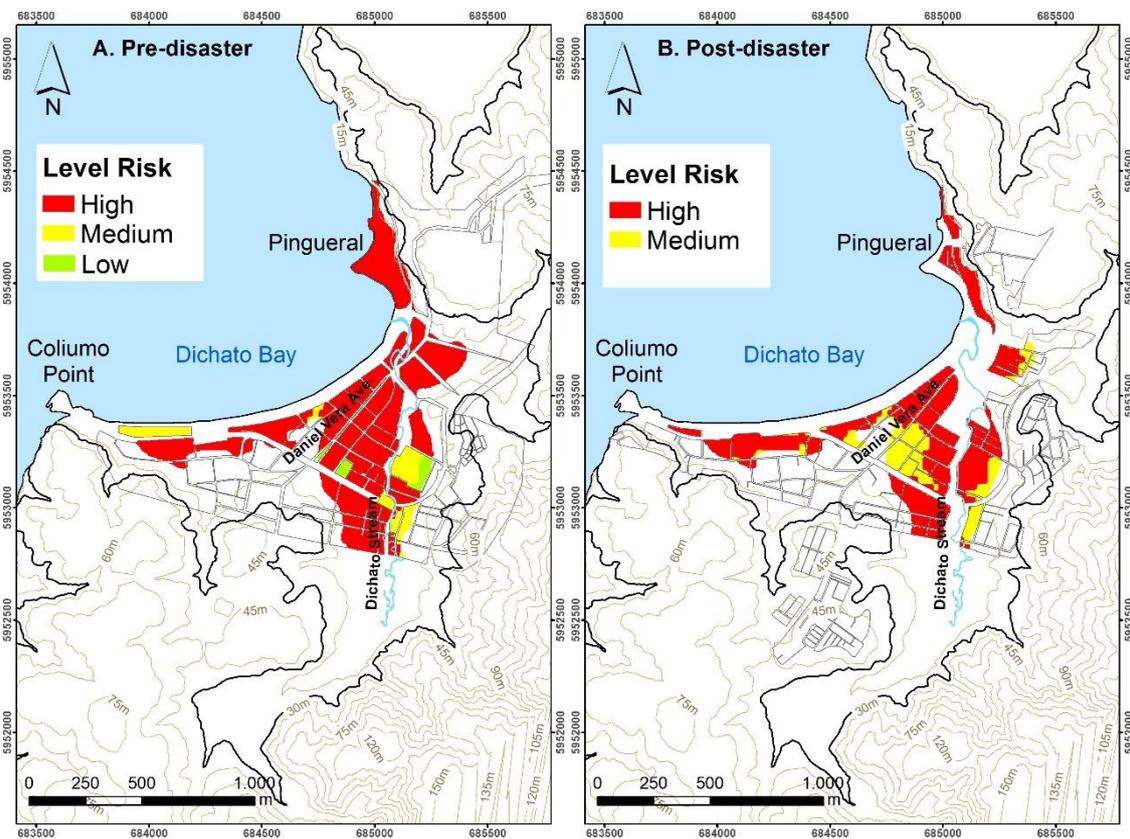
Fig.9. Pre- and post-tsunami vulnerability, Dichato



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Fig. 10. Tsunami risk areas for pre-event conditions



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Fig. 11. Pre-disaster (A, B, C and D) and post-disaster (E and F) housing in Dichato.

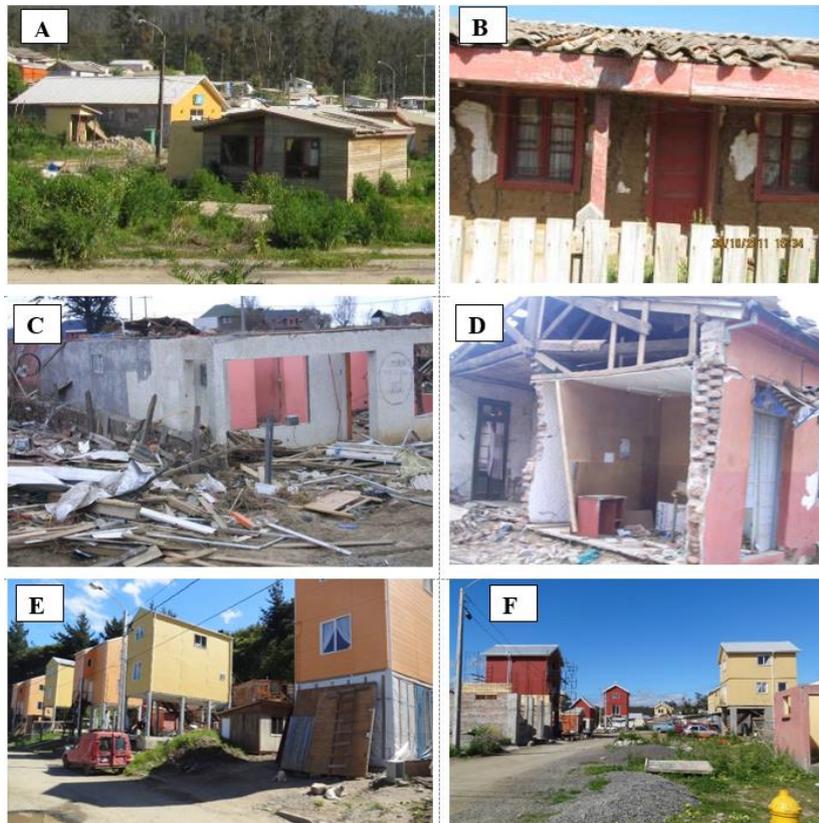


Table 1. Hazard level according to flow depth

Inundation depth		
Range	Description	Hazard Level
0 -.5 m	Knee-high or lower	Low
.5 – 2 m	Knee-high to head-high	Medium
> 2 m	More than head-high	High

Reference: modified after 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 after 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

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Table 4. 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)

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821 Table 5. Results with significant analyzed variable differences by neighborhood. Indications are as
822 follows: T_S (Total sample), Stat (statistic), df (degrees of freedom), p (p-value), FAS (Fascination) BE-
823 AW (being away), COMP (Compatibility), PHY-V (Physical vulnerability), SECO-V (Socio-economic
824 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

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