RESPONSE TO THE REVIEWS

Anonymous referee #1

Referee: The application looks appealing but the manuscript must undergo substantial changes in order to be fully understood and applicable in other cases. First and perhaps the most profound concern is that I don't quite see what are the research questions the authors are trying to address and what are the novel aspects of their work besides its application in this particular site. The methodology has already been applied in many other sites so the authors should emphasize why this particular application is scientifically interesting. As it is, the study could be useful for local agencies and/or planners as part of their decision making process but cannot be regarded as an originally scientific work.

Answer: This work presents the results of the use for the first time of the PTVA models in Chile, one of the most tsunamigenic areas of the world. Furthermore, we study a real scenario in contrast with most of the published works in which modeled scenarios are presented. All the above imply a new and relevant approach when compare with previous works in other study areas around the world. Our decision of using the two latest versions of the model lies upon the extraordinary opportunity of having the real damages caused by the 2015 tsunami impact in the study area. This has allowed us validating which of the two versions results in RVI trends similar to the occurred damages. Obviously, our results will be helpful in future urban planning assessment in Chile as decision makers will know which model will have more representative results in terms of vulnerability. Nevertheless, the case study of Coquimbo – La Serena is, to our understanding, a highly valuable contribution to the tsunami risk science.

Referee: Amendments should be done to improve the introduction (some sentences are poorly structured or definitely have no meaning), the methodological aspects which are vaguely presented and on the poor discussion, including sensitivity of the results to various assumptions done with no further explanation.

Answer: Using the helpful and exhaustive revision done by the referee in the commented manuscript we will be able to improve the new version including the introduction, the methodology and the discussion both in content and form.

Referee: I doubt if this study can be replicated given the few details in many of the parts of the manuscript. This is especially true for the flooding "scenario" which is vaguely explained. It is unclear what is the (tsunami) model' setup (if there is a model, as this is not clearly explained as well), what are its assumptions and limitations and how the validation is carried out. Given that this is an actual tsunami (not a scenario, as the authors consistently mention), there are readily available records of runups and water depths, as well as numerical models in the literature that provide spatial information of the flooding and from which the authors should take advantage from.

Answer: We strongly disagree with the referee comment. In our opinion our reconstructed scenario of the tsunami flood occurring on September 16, 2015 is more easily replicated by other authors than numerical models as well as more reliable. We have used field inundation height and runup data and we have reconstructed the scenario as other authors have previously done in real tsunami cases (for example, Mas et al., 2012 – NHESS). The scenario was validated calculating the RMSE (root mean square error) that is a frequently used measure of the differences between values predicted by an interpolation and the values actually observed (our field measures). Nevertheless, we will improve the 'Tsunami inundation map' point in the methodology so it is clearer the reconstruction we have carried out.

Referee: The validation of the final results (relative vulnerability index) is not clearly explained, given that there is abundant information of damage from a MINVU.

Answer: As the MINVU dataset for the damages occurred in Coquimbo – La Serena is large, we have only used for the validation stage the MINVU final damage classification for the buildings located in Sector 2 – Baquedano, considering it was one of the most damaged by the tsunami. This classification was then compared with our RVI score results.

Referee: The authors should discuss the advantages or withdraws of the used methodology with respect to other approaches which provide much more detail (e.g. fragility curves) and are currently embedded in the common research practice. They should also discuss if the application of these methods (PTVA3 and PTVA4) to a single case is enough to generalize which one is better, as is suggested in the text, and what consequences do the modifications of these methods have on the results (are results sensitive to these modifications?, are there other ways to lump two categories into one?). It is not explained nor justified why the use these two models and disregard older versions of the PTVA or other approaches. The authors seem to be driven by one train of thought but should be a bit more sceptic with the results they obtain.

Answer: A brief discussion of the use of fragility curves in the vulnerability assessment when compare with the PTVA models will be included in the new version of the manuscript. However, we cannot justify why we discard every other single model published for tsunami building vulnerability estimation. We selected the two latest versions of the PTVA model as the version 3 has been widely used (see Vulnerability index calculation section in Methodology) and version 4 claims to improve version 3 (Dall'Osso et al., 2016).

Referee: The manuscript should also improve the poor language which I believe is due to the possibility that authors are nonnative English speakers. The authors should be specific in the use of terminology which is used in a somewhat vague way (e.g. height, runup, water depth and crest to trough amplitude or hazard, vulnerability, impact, risk). I enclose a revised manuscript in pdf format with 74 comments, most of which are related to formal aspects.

Answer: The new version of the manuscript will be reviewed by an English native speaker and all the terminology will be checked and defined in the manuscript so it is clear the way the different terms are used in the manuscript. We thank the referee for his/her comments in manuscript that will be considered to improve the new version.

Anonymous referee #2

Referee: General Comments: The paper by Fritis et al. addresses the vulnerability of coastal buildings to tsunami impact from events occurring along the Chilean coast. To this end, the authors use an existing qualitative model (the 2 latest versions of PTVA) together with the post-tsunami damage data from the 2015 Illapel event to analyse the use and validate the PTVA models in two coastal cities of Chile, Coquimbo and La Serena. The authors conclude that the PTVA3 model performs better than the PTVA4 model when comparing the obtained RVI scores with the damage data. While, the manuscript presents some interest as it contributes to a better understanding of the building damage in one of the most tsunami vulnerable coasts of the world, I find that this work seems (as mentioned by the authors in l20 of the introduction) to an exercise more than a research article. Moreover, the present version of the MS is immature and was not ready for submission. Therefore, in my opinion, the paper must undergo major revision before been accepted in NHESS journal. Overall, the manuscript needs substantial improvement and rewriting.

Answer: We strongly disagree with the comment made by referee 2 in which he/she refers to our work as an exercise. The manuscript is a study case that was possible to carry out thanks to the unique opportunity that represented the impact of a real tsunami in a coastal city as La Serena – Coquimbo. The study case is not only a good example for the use of the models in a city with a wide variety of buildings but also for the possibility of studying the real impact of a tsunami. The work includes a section in which we discuss the model results and compare them with the real damages occurred in the city, something that is not usual in the published papers as luckily tsunamis do not impact cities quite often. We will review the manuscript in order to improve the final version including all the referees' suggestions that will undoubtedly help elaborating a better paper.

Major Comments:

Referee: 1. The tittle seems too long, unclear and not reflecting the content of the MS. There is no need to mention both PTVA-3 and PTVA-4, in fact they are 2 versions of the same model (PTVA); . The authors apply a tsunami vulnerability model and attempt to validate it using filed data, which is not clear in their MS tittle. . What is the meaning of "16S"? the September 16th ? Therefore, I propose to change the title and consider the following suggestion: "Analysis and Validation of the building tsunami vulnerability model, PTVA, using the 2015 Chile post-tsunami damage data".

Answer: We thank the referee for the title suggestion and we will modify the title according to his/her recommendations.

Referee: 2. The abstract needs substantial re-writing: As example, the first sentence of the abstract (l7-8, p1) is too long and confusing, I suggest splitting it in 2, something like "Chile is highly exposed to tsunami hazard from large earthquakes often occurring along the Peru-Chile trench. However, only recently the tsunami hazard has been considered in the land-use policies of the Chilean coasts." The same applies for the other sentences in the rest of the abstract: l9-11, p1; l13-15, p1. . Also, introduce the complete expression of the acronyms like "PTVA" and "RVI", the reader must understand what it is about from the beginning. . Some numerical values are necessary to quantify the "low", "high" and "very-high" levels of RVI.

Answer: We agree with the referee that the abstract sentences are unnecessary long. We will rewrite the abstract including shorter sentences as well as including the complete expressions of the acronyms. However, we think there is no need to include numerical values to quantify the RVI levels as they are the final result of the PTVA models as mentioned by Dall'Osso et al. (2009) and Dall'Osso et al. (2016).

Referee: 3. The Introduction is poor and requires improvement: For instance, the statement "the Nazca plate subducts beneath the S America plate at a rate of 74 mm/yr" needs revision as it is only valid for the Central Chile because the Nazca plate is subducting beneath the S America plate with a convergence speed that varies from north to south. It moves approximately at 80 mm/year in the south and at about 65 mm/year in the north, relative to a fixed South America plate (DEMETZ et al.2010). Recent references on the Maule 2010, Mw=8.8; Iquique 2014, Mw=8.2; 20 and Illapel 2015 Mw= 8.4 earthquakes and tsunamis must be added (lines 18,19,20, page 1) (i.e Satake and Heidarzadeh 2017; Omira et al., 2016; Fuentes et al., 2016) . lines 26 to 28 (p1): the authors mentioned that the March 11 Tohoku-oki earthquake arrived at the Chilean coast after 21h with a max. amplitude of 2.23m. I suppose that the authors meant the tsunami instead of the earthquake. . A paragraph shortly describing other tsunami vulnerability methods, such as the Fragility Curves methods (Koshimura et al., 2009; Supasri et al., 2012) and other PTVA-similar methods (Omira et al. 2010), must be included. . My main concern is on the aim of the paper. The authors are invited to clearly state in the introduction that their work aims to apply the PTVA model on two coastal cities of the Chilean coast and validate it using post-tsunami damage data.

Answer: We thank the referee for the information about the different rates at which the Nazca plate subducts. Of course we will read the Demetz et al. (2010) paper and include the data for northern Chile. We will also include the references for the Maule, Iquique and Illapel earthquakes and tsunamis that we mention in lines 18, 19 and 20 of page 1. In line 28 it should say "… that generated a tsunami that arrived at the Chilean coasts…", we will modify the sentence in the new version of the manuscript. As suggested by the referee we will include a brief paragraph describing other methodologies for tsunami building vulnerability assessment (fragility curves and other PTVA-similar methods). We will include a final sentence in the introduction that clearly states the main objective of the work.

Referee: 4. Study area: Since the work aims to study the vulnerability of coastal buildings to tsunami impact, the authors, when describing their study areas, must focus on the built environment within the tsunami prone coastal zones. I suggest to add a paragraph that carefully describes the type, structure, number of stories, etc of the buildings present within the study areas. Also, a map with these typologies will be welcome.

Answer: We agree with the referee suggestion, a paragraph describing the buildings present in the study area is needed for a better understanding however we believe the heterogeneity of the buildings and the size of the study area make impossible to elaborate a map with the referee suggestions.

Referee: 5. Methodology: I suggest to re-organize the methodology section by joining everything in two main subsections: “Field Survey”, in which the authors are invited to mention all the post-tsunami information leading to reconstruct the inundation maps and to derive the vulnerability index. Then a section on the “Vulnerability Model” and the way they applied it to the study areas.

Answer: We thank the referee for this suggestion. After thinking about this possibility we agree it will help improving the manuscript so we will reorganize the methodology under the main sections suggested.

Referee: 6. Results: All the maps must have coordinates. . Provide more quantitative description of the results. . Describe your results in each city (Coquimbo and La Serena) rather than sectors . There is an excess in the number of figures. A unique vulnerability map per site is sufficient in my opinion.

Answer: We will include the coordinates in all the map and a more extensive and quantitative description of the results in the text. Coquimbo and Serena are a conurbation without a real limit between them nowadays. We divided in sectors to facilitate the map elaboration as the area is quite long and with orientation changes. We will reduce the size of the maps in order to design a single figure that includes the vulnerability results trying to maintain their legibility.

Referee: 7. Discussion of the results: A section discussing the main results and their usefulness is missing in the paper. This must include the validation section and also a comparison of the PTVA methodology with other ones. Also, if available, a comparison with other similar studies in the region is welcome.

Answer: As suggested by this referee and referee #3 a comparison of our results with the work by Aranguiz et al. (2018) will be included. This work is the only one published assessing tsunami building vulnerability in Chile therefore, unfortunately, no other works can be considered. It is very difficult to compare the used methodologies with others without having applied them to our scenario. Only a general discussion can be included in this case.

Anonymous referee #3

Referee: This paper applied existing vulnerability models to a city in northern Chile. The authors used tsunami inundation data from the 2015 Coquimbo tsunami. The methodology considered two PTVA modes, namely PTVA-3 and PTVA-4, thus results of both methods are compared. The results of vulnerability assessment are also compared with damage data surveyed by the Ministry of Housing (MINVU). One of my major concerns is that the paper does not present new concepts or methods, it is just an application to a very specific location.

Answer: It is true that we used existing methodologies, specifically the PTVA-3 and PTVA-4 models, and applied it to a study case. However, we did adapt the model to the Chilean construction materials and in addition and more important we compared our modeled results that are normally used by decision makers with the actual damages of a real tsunami. This allowed us to assess if the buildings really had a response similar to the RVI scores obtained trends which a unique opportunity as luckily no many tsunamis affect large cities often. Even tough La Serena – Coquimbo is a very specific location, it is a great example for the validation of these models due to the wide variety of buildings (from informal settlements with light construction materials to modern tower buildings) and different inundation heights.

Referee: The authors mention in the text that "...the RVI scores cannot be used to predict which buildings will reach or exceed a given damage state.....the aim of our comparison is not to provide a damage description to a given RVI score but to verify if the low RVI scores correspond to minor building damages and viceversa.." As a novel thing here, would it be possible to propose a correlation between RVI and damage state?, Would it be possible to add other variables or wights to the model such a better correlation is obtained?

Answer: As mentioned by Dall'Osso et al. (2016) the RVI scores are not predictive but they can be used to compare the expected performance of buildings. The referee suggests the possibility of a direct correlation between the RVI scores and the damage state however this is not possible with the existing methodologies. For doing so, it would be necessary to re-weight the different variables using the real damages to develop a new model which RVI results should agree directly with the MINVU damage categories. Although, this is beyond the scope of this research we consider it is a work that can be approached in a future manuscript.

Referee: I recommend to avoid using the words PTVA in the title, thus the subject is more clear and easy to understand by a wide and general audience. In fact, the meaning of PTVA is never explained throughout the text. I recommend to write something like "The Papathoma Tsunami Vulnerability Assessment (PTVA)..." in some place in the abstract. In some places it is written PTVA but in other PVTA. Please check.

Answer: As suggested by the referee we will modify the title to avoid including the model names. In addition, we will check the manuscript for any PTVA typos.

Referee: It would be necessary to check the terms related to tsunami inundation. The international scientific community uses words such as Inundation height, Flow depth (or inundation depth) and Runup. The authors use terms such as flood height, inundation height, flood depth, water depth among others in different contexts, which is very confusing.

Answer: We will check the manuscript and modify the terms used in order to use those used by the international scientific community.

Referee: Section 3.2. It is not clear whether the "flood scenario" is a map of inundation height or flow depth. It would be necessary to explain better how the map was obtained. It is mentioned that 24 inundation height measurements were obtained during the field survey, which were combined with SERNAGEOMIN data. But the latter has 18 flow depth measurements. How did you obtained 266 points?. In addition, did you use interpolation? What variable was interpolated, inundation height or flow depth? Which method was used for interpolation?. What kind of DTM model was used? Which was the resolution?

Answer: The answers to the referee questions are included in section 3.2 however, we will rewrite this paragraph in order to make it more understandable. In this sense, the 266 points are obtained from 3 sources: (1) our field campaign that included 24 points; (2) SERNAGEOMIN data that includes 18 measures; and finally the inundation limit in which all the assigned points present a 0 m inundation height. We did interpolate the inundation height obtained from these 266 points using a kriging model in the Geostatistical tool in ArcGIS 10.3 and including a 1 m/pixel DEM as an external drift. The DEM was obtained from the Chilean Navy (SHOA).

Referee: sections 4 and 5 should be part of a section called "Results", while section 6 and 7 should be part of a "Discussion". However, the discussion should be extended.

Answer: We agree that sections 4 and 5 represent our results and sections 6 and 7 are the discussion of the results, however, we do not consider necessary to organized the manuscript in a more conventional way that include results and discussion sections specifically.

Referee: Even though the Introduction shows several papers as literature review on the development and application of PTVA models, the discussion is limited to the current results only.

Answer: Unfortunately, there aren't other similar papers in Chile with the exception of the proposal of fragility curves developed by Aranguiz et al. (2018). We will include a discussion with their results as their study area is also La Serena – Coquimbo. However, discuss and compare our results with other published papers for around the world is difficult as the tsunami scenarios as well as the urban features are completely different for one city to another.

LIST OF ALL RELEVANT CHANGES

Dear Dra. Baptista,

According to the comments and suggestions of the three referees the main changes in the manuscript are the following:

- We have reviewed the language and the tsunami terms, so they agree with the international scientific community.
- The title has been changed as suggested and a detailed revision has been carried out in the manuscript following the comments and suggestions of referee #1.
- We have reorganized the methodology and improve the description of the flood map reconstruction after flow depth field data.
- We have included a new point in the discussion comparing our approach with other methodologies (fragility curves) in the same city.
- The number of figures has been reduced from 12 to 7.
- Finally, we have changed the authors order in agreement with the amount of work during the writing and revision of the manuscript.

Analysis and validation of the PTVA tsunami building vulnerability model using the 2015 Chile post-tsunami damage data in Coquimbo and La Serena cities~~Assessing the tsunami building vulnerability PTVA-3 and PTVA-4 models after the 16S 2015 event in the cities of Coquimbo – La Serena (Chile)~~

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Abstract. Chile is highly exposed to tsunami hazard from large earthquakes often occurring along the Perú – Chile trench, ~~tsunamigenic events~~, as the one occurred in September 16, 2015.~~;~~ H~~h~~owever, only recently the tsunami hazard has been considered in ~~it has not been until recent years that~~that the land-use policies of the Chilean coast~~have begun to be considered~~. These new regulations must enforce the identification~~y~~ of the most vulnerable sectors of the Chilean coastal cities. This paper analyses and validates ~~the use of ~~the two latest versions of the Papathoma Tsunami Vulnerability Assessment (PTVA) model in the 2015 tsunami reconstructed scenario in the cities of La Serena and Coquimbo~~ and their potential use in other Chilean cities in future land-use or mitigation measures planning~~. Both models result in a similar number of very-high and high Relative Vulnerability Index (RVI) scores. However, the less vulnerable categories do not show a similar trend and the PTVA-4 model obtains a larger number of minor and average RVI scores. When compare to~~with~~ the damages caused by the tsunami, the PTVA-3 shows a more similar distribution to the actual damages than the~~that~~ obtained by the PTVA-4 model that shows a more concentrated distribution of the RVI scores. These results suggest this version of the model should be used in Chilean coastal cities in future land-use or mitigation planning.

1 Introduction

Tsunamigenic events in Chile are a consequence of the convergence boundary in which the Nazca plate subducts under the South American plate at a rate of ~~74~~ 65 mm/yr (DeMets et al., 2010). In fact, three of the ~~last ~~eight largest earthquakes (Mw> 8) occurred during the last six years around the world have occurred in Chile: Maule 2010, Mw=8.8; Iquique 2014, Mw=8.2; and Illapel 2015 Mw= 8.4 (Fuentes et al., 2016; Omira et al., 2016; Satake and Heidarzadeh, 2017). All of them were tsunamigenic. The first historical observations of earthquakes and tsunamis in the Pacific coast of South America date from the 16th century with the arrival of the Spaniards to this region, although there are more ancient descriptions of these catastrophes in Peruvian and Chilean legends (Kulikov et al., 2005). Especially relevant was the earthquake occurred on May 22, 1960 (Mw~9.5) with a rupture zone of almost 1,000 km (Smith, 2010) that triggered a large tsunami. This event~~ that~~ affected the entire Chilean coast as well as Hawaii, Japan, the Philippines, New Zealand, Australia and Alaska (SHOA, 2000). Likewise, tsunamigenic earthquakes that occur in other subduction zones of the Pacific Ocean can affect the Chilean coast. The most recent example is the earthquake that occurred on March 11, 2011 in Tōhoku, Japan (Mw = 9.0; Simons et al., 2011). The triggered tsunami waves~~ that~~ arrived at the Chilean coasts after 21 hours (Dunbar et al., 2011) with a maximum observed amplitude of 2.23 m in Arica and Talcahuano tidal gauges~~cities~~ (SHOA, 2016).

The historical record includes dozens of destructive tsunamis on the Chilean coast while the geological record confirms its recurrence in the last thousands of years (Cisternas et al., 2005; Ely et al., 2014; Cisternas et al., 2017; Kempf et al., 2017). In the Coquimbo Region one of the worst recorded tsunamis ~~recorded ~~occurred after the Vallenar earthquake of November 11, 1922 with Mw~8.3. The deformation in the ocean floor triggered a wave train that ~~reached ~~caused an inundation height ~~height ~~of 7 m on the coast of the epicentral region (Caldera-Coquimbo), and the cities of La Serena and Coquimbo were significantly damaged (Beck et al., 1998; Lomnitz, 2004). According to Bobillier (1926), the tsunami flooded Coquimbo with three waves, the third of which reached an elevation 4.6 m a.s.l. ~~However, Beck et al. (1998) and Lomnitz (2004) refer to a 7m tsunami in the same area.~~ Some zones reached 3 m water depth and horizontal inundation distances of up to 800 m (Contreras-López et al., 2016). In the same context, the water penetrated 2 km at the most low-lying places, and as a result, part of the city situated at the southern apex of the Coquimbo Bay was completely destroyed by the combined effect of water, ~~, not only by the water, but also by~~ boats and other objects washed ashore (Soloviev and Go, 1975).

Although Chile is highly exposed to these high-energy marine events, it has not been until recent years that land-use ~~planning~~ policies has begun to ~~be~~ considered tsunami risk. The new planning tools include the study of both hazard and vulnerability of the coastal cities to these extreme waves. Despite this~~an~~ incipient development of national urban policies ~~is observed~~ after the February 27, 2010 tsunami (Lunecke, 2016), tsunami impact remains a cause for economic and life losses. Among the main advances in land-use planning, the Chilean Ministry of Housing and Urban Planning (MINVU) has started to define tsunami hazards areas and, in addition, the National Emergency Office (ONEMI) has included civil protection plans for tsunamigenic events. However, to minimize the losses associated with future tsunamis, it is necessary to assess building~~s~~ vulnerability from what is estimated the probable maximum loss~~–~~ (PML)~~(Dall'Osso et al., 2009a)~~. Recently, Aránguiz et al. (~~under~~ in review) have developed fragility curves to assess tsunami damage in Coquimbo after the 2015 tsunami. This method can serve as a complement~~n adjunct~~ to the Papathoma Tsunami Vulnerability Assessment (PTVA) models although recently some authors have indicated the limitations of these vulnerability functions (Tarbotton et al., 2015; Dall'Osso et al., 2016). For example, they consider only the construction material as the attribute influencing the vulnerability to tsunami and do not ~~, like a macro level identification in the assessment tsunami damage builds because offers a binary classification ("low" or "high"). However, it does not~~ include structural details or other engineering factors whereas the ~~, which are variable in each building. On the other hand,~~ PTV~~T~~A models include a wider range of variables in the vulnerability assessment. Furthermore, most of these curves are based on local observations after actual tsunamis what difficult their application in locations different from where they were developed (Tarbotton et al., 2015; Dall'Osso et al., 2016). Other methodologies have been proposed to assess tsunami building vulnerability such as the "Building Tsunami Vulnerability (BTV)" (Omira et al., 2010) or the remote sensing based method of Mück et al. (2013). Recently, Vera San Martín et al. (in press) applied an adaptation of the PTVA and BTV methodologies to determine a Vulnerability Index for Salinas (Ecuador).

-This work evaluates the vulnerability to the tsunami ~~impact~~ for the La Serena-Coquimbo conurbation in the reconstructed flood~~scenario~~ occurred on September 16, 2015 after the tsunami generated by the Illapel earthquake (Mw 8.4). The tsunami had a maximum wave height of 4.7 m in Coquimbo (SHOA, 2016) and caused 11 fatalities (CCT-ONEMI, 2015). ~~For that, w~~We first reconstruct the flood in the cities ~~after inundation heights measured in the field~~ and ~~then,~~ we estimate the Relative Vulnerability Index (RVI) using the PTVA-3 (Dall'Osso et al., 2009a) and PTVA-4 (Dall'Osso et al., 2016) models. Finally, we validate our results by comparing them with the real damages ~~the constructions suffered~~ after the event evaluated by MINVU. The~~is~~ unique opportunity of studying a real case and validating the PTVA model results using post-tsunami damage data will help future urban planning in Chile ~~exercise allows us~~ establishing which model can be considered a better approach for those cities in which other methodologies have not been developed ~~tsunami building vulnerability assessment based on the real damages reported after a high-energy marine event~~.

2 Study area

The cities of La Serena and Coquimbo (412,586 inhabitants) are located in the Coquimbo Region (North-Central Chile), in the so-called "Norte Chico" (Fig. 1). The distance between the oceanic trench and the coast here varies between 80 and 100 km, i.e. it is smaller than in other regions of Chile, where the most typical distances range between 120 and 140 km (Fuentes et al., 2016). According to Pardo et al. (2002) and Tassara et al. (2006) ~~and Pardo et al. (2002)~~ in this zone the subduction angle of the Nazca plate is almost horizontal at depths close to 100 km. This ~~almost horizontal~~ geometry of the plate gives rise to a strongly coupled inter-plate contact, a highly compressed continental crust with back-arc seismicity and shortening of the crust, together with the absence of active ~~quaternary~~ Quaternary volcanoes in the Andes Cordillera (Jordan et al., 1983).

The Coquimbo Bay is open to the Northwest providing natural protection against the dominant southwestern swells. The submarine part of the bay shows a wide marine platform, close to 10 km, with gentle slope on the seabed.~~ In particular,~~ T~~t~~he Coquimbo Bay exposes depths that do not exceed 50 m inside the bay (Aránguiz et al., 2016). It presents a gentle topography and a more than 1~~1~~0 km long sandy beach only interrupted by the mouth areas of the Culebrón stream and Elqui River which are characterized by the existence of marshlands, much larger in the first case. This Culebrón marsh runs parallel to the coast behind the foredune and it is currently largely anthropized as ~~and~~ a high percentage of its original surface is now part of the urban area (Fig. 1).

In the Coquimbo - La Serena conurbation, the urbanization process and the coastal border occupation have caused a convergence in the coastal space of several uses causing conflicts (Hidalgo et al., 2009). At present, due to rapid growth ~~and discrepancies in the coastal sector regulations (Maureira, 1998)~~ several uses appear in the littoral such as residential, commercial, industrial and tourist as well as illegal settlements, what results in different construction types (Maureira, 1998). Besides this heterogeneity a dominant construction type can be described in the different sectors of the bay. Buildings in La Serena (North of the study area) correspond to modern reinforced concrete structures with more than 10 stories whereas in Coquimbo the predominant building type is one or two stories wood, adobe or masonry houses. In the Coquimbo Port light metal structures can be observed and finally, along the sandy beach several light wood structures corresponding to restaurants and other tourist facilities can be found.

~~In addition, there is no capacity for a complete evacuation of the coastal border in case of a tsunami especially during the summer season due to the high number of tourist (McBride et al., 2016).~~

3 Methodology

3.1 Geodatabase and field survey~~GIS Geodatabase~~

~~We developed a Geographic Information System (GIS) based geodatabase that gathers different spatial information needed for the vulnerability calculation. On the one hand, the city cartography was downloaded from the Copernicus Emergency Management Service of the European Union webpage (http://emergency.copernicus.eu) whereas the tsunami flood scenario was reconstructed after a field survey (see section 3.2).~~To reconstruct the flood a field survey was carried out the week after the occurrence of the tsunami. During the campaign, 24 flow depths or inundations depths were measured distributed across the flooded area (Fig. 2). These measures combined with those published by the National Geology and Mining Service (SERNAGEOMIN, 2015) and the inundation limit with a flow depth value of 0 allowed us to reconstruct the flow depth in the urban area. From a total number of 266 points a flow depth map was estimated using a kriging model in the Geostatistical tool in ArcGIS 10.3 and including a 1 m/pixel Digital Elevation Model as an external drift as the flow depth is topography dependent. The obtained modelled map (10 m/pixel) presents a Root Mean Square Error (RMSE) = 0.54. This field-based reconstructed tsunami flood was used to obtain the flow depth value for each assessed building along the affected area, an essential parameter for the vulnerability index calculation.

In addition, we developed a Geographic Information System (GIS) based geodatabase that gathers different spatial information needed for the calculation of the vulnerability. The cartography including a cadastre for the cities was downloaded from the Copernicus Emergency Management Service of the European Union webpage (http://emergency.copernicus.eu). We first verified in the field that the spatial information integrated in the GIS geodatabase corresponded with the reality. In those cases where it did not, the polygons, that represent single buildings, were manually modified. Information was also added on buildings under construction as well as those destroyed by the 2015 tsunami. The attributes for each polygon were collected during a third post-tsunami survey. A total of 65 out of 1,239 buildings (5.2%) were not accessible and classified as “No access”.

3.2 Vulnerability model ~~Tsunami inundation map~~

From the different methods published for building vulnerability calculation we chose the PTVA as it has been proved to be a suitable model in the estimation of tsunami vulnerability across different coastal urban centres around the world. The first and second versions of the model were applied in the Gulf of Corinth, Greece (Papathoma and Dominey-Howes, 2003) and Seaside, Oregon, USA (Dominey-Howes et al., 2010) respectively. After improvements to the model, its third version was tested on the coast of New South Wales, Australia (Dall'Osso et al., 2009b) and has been widely used to assess the vulnerability of several coastal localities such as the Aeolian Islands (Italy; Dall'Osso et al., 2010); Figueira da Foz (Portugal; Barros et al., 2013); Setúbal (Portugal; Santos et al., 2014); the south of the Boso Peninsula (Japan; Voulgaris and Murayama, 2014); the southwest Atlantic coast of Spain (Abad et al., 2014); Naples (Italy; Alberico et al., 2015) and Chabahar Bay (Iran; Madani et al., 2016). Lately, a fourth version of the model has been tested at Botany Bay, Sydney (Australia; Dall'Osso et al., 2016). We select the two latest versions of the PTVA model as version 3 has been widely used and according to their authors version 4 is an improvement to the model (Dall’Osso et al., 2016).~~To reconstruct the flood scenario a field survey was carried out the week after the occurrence of the tsunami. During the campaign, 24 inundation heights were measured distributed across the flooded area (Fig. 2). These measures combined with those published by the National Geology and Mining Service (SERNAGEOMIN, 2015) and the inundation limit allowed us to model the inundation height in the urban area (a total number of 266 points). The map was estimated using the Geostatistical tool in ArcGIS 10.3 and including a 1 m/pixel Digital Elevation Model as an external drift as the flood height is topography dependent. The obtained modelled map (10 m/pixel) presents a RMSE = 0.54. This field-based reconstructed scenario was used to obtain the flood depth value for each assessed building along the affected area, an essential parameter for the vulnerability index calculation.~~

~~3.3 Vulnerability index calculation~~

~~We first verified that the spatial information integrated in the GIS geodatabase corresponded with the reality. In those cases where it did not, the polygons were manually modified. Information was also added on buildings under construction as well as those destroyed by the 2015 tsunami. The attributes for each polygon were collected during a field campaign. A total of 65 out of 1,239 buildings (5.2%) were not accessible and classified as “No access”.~~

~~From the different methods published for building vulnerability calculation we chose the PTVA as it has been proved to be a dynamic model in the estimation of tsunami vulnerability across different coastal urban centres around the world. The first and second versions of the model were applied in the Gulf of Corinth, Greece (Papathoma and Dominey-Howes, 2003) and Seaside, Oregon, USA (Dominey-Howes et al., 2010) respectively. After improvements to the model, its third version was tested on the coast of New South Wales, Australia (Dall'Osso et al., 2009b) and has been widely used to assess the vulnerability of several coastal localities such as the Aeolian Islands (Italy; Dall'Osso et al., 2010); Figueira da Foz (Portugal; Barros et al., 2013); Setúbal (Portugal; Santos et al., 2014); the south of the Boso Peninsula (Japan; Voulgaris and Murayama, 2014); the southwest Atlantic coast of Spain (Abad et al., 2014); Naples (Italy; Alberico et al., 2015) and Chabahar Bay (Iran; Madani et al., 2016). Lately, a fourth version of the model has been tested at Botany Bay, Sydney (Australia; Dall'Osso et al., 2016).~~

3.3.1 The PTVA-3 model

The RVI calculation depends on the Structural Vulnerability (SV) and the Vulnerability to Water intrusion (WV) (Fig. 3). WV is calculated by the relation between the number of inundated levels and the total number of levels, while the SV calculation considers the attributes of the building structure (Building Vulnerability; Bv), the building flow~~od~~ depth (Exposure; Ex) and its protection level (Prot) (Fig. 3).

The Bv calculation considers 6 different attributes (Fig. 3; Table 1). The material attribute (m) was modified and adapted to the constructions methods of Northern Chile (Table 2). Concrete or cinder blocks is included as a construction material and adobe substitutes the original single brick as this construction style is no used in Chile according to the building code. The Prot calculation includes 4 attributes (Fig. 3; Table 1) while the Exposure parameter (Ex) is classified from the flow~~od~~ or inundation depth map values (Table 3).

3.3.2 The PTVA-4 model

In the PTVA-4 model, the RVI calculation depends on the same parameters as in the PTVA-3 model, i.e. SV and WV (Fig. 3). ~~WV is obtained through the same approach as the PTVA-3 but in this model the parameter accounts for buildings with raised ground floor that will only be inundated if the water depth above the terrain level exceeds the elevation of the ground floor.~~ On the other hand, the attribute Movable Objects (mo) is now included in the parameter Surr (previous Prot) instead of in BV so all the attributes that consider the building surroundings are now in only one parameter (Figure 3; Table 4). The other modified attribute is Shape and Orientation (so) that was renamed as Shape of Building Footprint (sh) and ~~his~~ its values are described in Table 4 and Fig. 3. In addition, in this model, as in the PTVA-3 model, the attribute Material (m) was modified and adapted to the constructions of ~~northern~~ Northern Chile (Table 2). Finally, the Ex parameter is calculated using the~~calculation is the~~ ratio between the ~~water~~ flow depth impacting the building (WD) and the maximum effective water depth in the study area (WD max). ~~After all procedure,~~ Dall'Osso et al. (2016) suggest that for a better displaying of the RVI results in the case of the PTVA-4 model a more sophisticated technique should be used. We used technique based on the Jenks' Natural Breaks Algorithm (Jenks, 1977), obtaining the final scaling for the RVI classification.

3.4 Model validation

The vulnerability results obtained in the PTVA-3 and PTVA-4 models were compared with the real damages caused by the tsunami to validate both models with a real event on the ~~northern~~ Northern coast of Chile. We used the information provided by MINVU, a total of 484 analysis that correspond to a technical evaluation for the residential houses located in the area hit by the tsunami focused on Baquedano (sector 2) in Coquimbo (Fig. 1). This information was integrated in the geodatabase and compare with our RVI results (Table 5). The building damage classification used by MINVU consists of 4 categories that range from minor damage to non-reparable whereas the RVI obtained from the PTVA models involves 5 categories. To facilitate the comparison of both scales, we have unified the high and very high RVI scores. The expected RVI for each building can then be correlated with its degree of damage described after the tsunami impact. In this sense, Dall'Osso et al. (2016) specify that the RVI scores cannot be used to predict which buildings will reach or exceed a given damage state but to relatively compare the expected performance of each building. Therefore, the aim of our comparison is not to provide a damage description to a given RVI score but to verify if the low RVI scores correspond to minor building damages and vice versa.

4 The September 16, 2015 tsunami

The epicentre of the Illapel earthquake (September 16, 2015) was located at 71.741°W and 31.637°S at a depth of 23.3 km (http://www.sismologia.cl), where the rupture velocities reached 1.5-2.0 km/s (Heidarzadeh et al., 2016). The Illapel earthquake occurred between two lower coupling zones (LCZs): a small zone near 32°S, and a larger one in the north, near 30.5°S in front of La Serena. This seismic event occurred near the northern end of the rupture zone of the 1730 megaearthquake with magnitude Mw ~ 9.0 that probably controls the seismic cycle of central Chile (Ruiz et al., 2016). Considering two earthquakes of magnitude Mw ~8.0 that occurred previously (1943 and 1880; Beck et al., 1998), Nishenko (1985) suggested that the Illapel zone was a seismic gap.

Because of the inter-plate event, a transoceanic tsunami of moderate height was generated, causing damages along the Chilean coasts, especially in the Coquimbo Region. Aránguiz et al. (2016) indicates the tsunami run ~~-~~up varied between 4 and 6 m in places close to the origin region, even with maximum of 10.8 m. Moreover, local bathymetry and topography promoted the tsunami to cause greater damage in some urbanized coastal locations. The tide gauge record shows that the earthquake occurred shortly after the low tide at the epicentre (Fig. 2a)~~, which means that the highest observed wave of the tsunami arrived during high tide~~. The arrival time at Coquimbo was 23 minutes after the earthquake, with 1.1 m of tsunami amplitude. The maximum tsunami amplitude (4.68 m) was measured with the fourth wave.

The Coquimbo Region was the most affected by the tsunami. Authors such as Tomita et al. (2016) indicates that the tsunami was diffracted and refracted by the Coquimbo Peninsula, and then converged~~s~~ to the inner southwestern corner of Coquimbo Bay~~, located behind the peninsula~~. In the bay, the maximum ~~vertical~~ run up was 14 m in the Baquedano sector (Fig. 1) whereas towards the north the run up only reached~~s~~ <0.5 m and according to our reconstruction, the waves penetrated inland more than 950 m in the Elqui mouth and almost 700 m in Culebrón stream mouth, while in Coquimbo port and Serena they only reached 100-200 m and ca. 30 m respectively (Fig. 2b and 2c).

Both the earthquake and the tsunami caused ~~11~~ 12 fatalities, 12 injuries ~~while 1 person remain missing~~ and a total of 118,812 people affected in Coquimbo Region (CCT-ONEMI, 2015). The most significant effects are recorded in the denominated “Zero Zone” located in the sector of Baquedano and Coquimbo Port. In this place, the tsunami hit hard affecting the port structure, the local market, the fishing creek, commerce and a large number of private homes. In addition, ~~and~~ 17 boats were dragging from the sea. After the tsunami event, MINVU elaborated an inventory~~generated a cadastre~~ where 1,921 houses are included with non-repairable damages and 5,364 houses resulted with various types of damages.

5 Vulnerability assessment

~~5.1 Sector 1 – Coquimbo Port~~

Coquimbo Port is in the southwestern sector of the Coquimbo Bay (Fig. 1 and 5). The analysis of this sector considers 136 buildings that represent 10.98% of the total reconstructed flood ~~scenario~~ that reaches here flow~~od~~ depths higher than 2 m (Fig. 2 and 4a). Although it does not present a natural barrier, the buildings in this sector (mostly 1 and 2 stories) are protected by a 3 – 5 m ~~height~~ vertical seawall.

Very high or high RVI occur along the coastline and represent the most important category in the PTVA-4 model (33.83%) while they only represent 23.53% in the PTVA-3 model (Fig. 5a and 5b and Table 6). In this first building row, both the waves and movable objects available in the port would impact the buildings (as it happened in 2016; Fig. 4b), which are mainly constructed with light materials (Fig. 4a). On the other hand, some isolated constructions are moderately vulnerable to a tsunami impact, regardless their distance from the coast, due to attributes such as the construction material, the preservation status or the foundations (Fig. 5a and 5b).

For flow~~od~~ depths ranging from 1 to 2 m, the PTVA-3 model results vary according to the location of the buildings. Most of builds located in second or third row get moderate or average vulnerability when compare with constructions in the first row that score high or average RVI. For PTVA-4 model, a high-moderate RVI is predominant in these flow~~od~~ depths interval. However, in both models, the buildings with minor RVI are affected by flow~~od~~ depths smaller than 1 m. Finally, our results indicate that the model PTVA-4 obtains the largest number of buildings with High and Very high RVI scores (Table 6).

~~5.2 Sector 2 – Baquedano~~

Sector 2, located south in the Coquimbo Bay, is partially protected by a small marshland (Fig. 1 and 5~~6~~) that has been included in the model as a natural barrier (nb=0.5). On the other hand, the non-existence of a seawall in the area together with the low topographic elevation cause that the tsunami floods this area with depths up to 4 m (Fig. 5c and 5d~~6~~) affecting a total of 475 buildings (38.34%) (Table 6).

Baquedano is the historical centre of Coquimbo and its residential houses are more than 100 years old. The sector presents a wide variety of building materials from ~~grey~~ concrete block masonry to tin plate, red brick or adobe. First row buildings present RVI scores ranging from minor to very high as the southern ones are protected by marshes bodies that retain the energy propagated by the tsunami wave. In addition, some building features included in the Bv parameter, such as the number of stories and the foundations, help ~~to decrease~~decreasing the RVI scores. Although partially protected by the~~a~~ marshland, the area is exposed to flood depths > 3 m that result in a very high and high RVI score percentage (7.78% and 11.15% for the PTVA-3 and PTVA-4 models respectively) (Table 6). The most vulnerable buildings in the sector are one or two stories high (Fig. 4c, 4d and 4e) and they are located in the first three building rows. In most cases, buildings with an average or minor RVI correspond to different types of buildings with flood depths < 1m, moderately protected by natural or anthropogenic barriers and/ or reinforced concrete story buildings with more than 5 floors and deep foundations (Fig. 4f), regardless of their location with respect to the coastline (Fig. 5c and 5d~~6~~). Most of the buildings (63.16 %) obtain an average RVI score using the PTVA-4 model whereas using the PTVA-3 model only 30.53 % obtained this classification. In the later, most of the buildings are classified as moderate vulnerability (Fig. 5c~~6~~).

~~5.3 Sector 3 – La Cantera~~

La Cantera, located southeast of the Coquimbo Bay (Fig. 1 and ~~7~~5) presents, as Sector 2 did, a moderate extension of marshland, i.e. a natural barrier, and no seawall protection, with an overall low topographic elevation. The flood scenario shows ~~water~~ flow depths that range from 0 to 3 m although in the urbanized area depths only reach up to 2 m. Most of the constructions in the sector are detached or bungalow houses isolated and separated several hundred of meters one from another. This circumstance increases the potential damage of the tsunami and movable objects impacts and therefore their vulnerability (Fig. 4g).

A total of 125 buildings have been considered in the sector (10.09% of the total analysis; Table 6). For both PTVA models, buildings with flow~~od~~ depths ranging from 1 to 2 m due to their characteristics (small number of stories, poor ground floor hydrodynamics and/or average depth foundation) and the effect to direct exposure to the tsunami waves and movable objects obtain an average RVI score. On the other hand, most of the buildings with flow~~od~~ depths < 1 m obtained RVI scores that range from minor to moderate using both models. In summary, in this sector the flood area reaches 350 m of ~~–~~inland penetration and most of the affected polygons present a moderate RVI (Table 6) however, the PTVA-3 model indicates an average - moderate RVI (83.2%) whereas the PTVA-4 model shows a moderate – minor RVI classification (73.6%) (Fig. 5e and 5f~~7~~).

~~5.4 Sector 4 – Caleta Peñuelas~~

Caleta Peñuelas location, between Coquimbo and La Serena, results in almost all its urbanized area affected by the tsunami flood (Fig. 1 and ~~8~~5). This sector analysis contemplates 26.31% of the total evaluated buildings (326 buildings) (Table 6). In this area, most of the houses are one or two-story buildings (322 houses / 98.77% of buildings total) and according to the tsunami scenario they would be affected by flow~~od~~ depths <1m. In addition, the buildings are generally constructed using lightweight materials such as wood, aluminium or simple brick, with average or shallow foundations. The ground floor hydrodynamics can be generally described as not open plan (Fig. 4h), what causes the building structure to directly receive the tsunami wave. The polygons located between the road and the Pacific Ocean (Fig. 5g and 5h~~8~~) are directly constructed in the beach and correspond to restaurants and other facilities that results in average RVI scores in both models mainly due to the low flood depths. Landward, the main group of buildings shows a predominant moderate and minor RVI scores for the PTVA-3 and 4 respectively (Table 6).

~~5.5 Sector 5 – La Pampa~~

The coastal border of La Pampa is one of the residential and touristic sectors in La Serena (Fig. 1) that according to the reconstructed scenario is very little affected. The flow~~od~~ depths in the sector are < 1m and constrain to a narrow area next to the coastline. The urban development in this sector is mainly characterized by reinforced concrete story buildings with more than 5 floors and deep foundations (23.02 %). The other buildings features are quite heterogeneous including different construction materials, shallower foundations, and less floors being then, more vulnerable. A total of 120 buildings have been analysed in this sector (9.68% of the total). The results obtained (Fig. 5i and 5j~~9~~) classify the area as a relatively safe sector under the 2015 tsunami scenario, with most of the obtained RVI scores being minor in both models (Table 6). This last model obtains the largest number of minor RVI score as most of the polygons correspond to more than 5 stories buildings.

~~5.6 Sector 6 – La Serena~~

The last sector, La Serena, considers 4.6% of the studied polygons, i.e. 57 (Table 6). The flow~~od~~ depth in this area is <1 m with the smallest affected area. As in Sector 5, buildings in La Serena correspond to reinforced concrete structures with more than 5 floors. The RVI assessment shows that La Serena, is a sector with moderate - minor RVI scores for this tsunami scenario (89.48% and 98.25% for the PTVA-3 and PTVA-4 models, respectively) (Table 6). These circumstances are associated with the flood depth in the sector but mainly with the type of constructions (Fig. 5k and 5l~~10~~).

6 Discussion

6.1 PTVA-3 vs. PTVA-4 results

The distribution of the final RVI scores in the cities of La Serena – Coquimbo allow us to compare~~comparing~~ the vulnerability ~~assessment~~scores. Fig. ~~11a~~ 6a shows the distribution of the flow~~od~~ depth impacting each building according to the field-based reconstructed scenario. The maximum value is 3.49 m however, most of the buildings were flooded less than 0.5 m. In general, both models show a spatial distribution with the highest RVI scores located closer to the shoreline and average to minor vulnerabilities in the inland buildings. Similar spatial patterns of the RVI scores have been described by different authors under different tsunami scenarios, geomorphologic settings and/or diverse urban features (Alberico et al., 2015; Dall'Osso et al., 2016).

Dall'Osso et al. (2016) exposed that the Ex, Bv, Prot parameters are better distributed using the PTVA-4 model than with the PTVA-3 due to the difference in the re-scaling procedure adopted by the models. Therefore, according to them the newest model RVI scores should be more representative. Fig. ~~11b~~ 6b shows the distribution of the final RVI scores obtained with the PTVA-3 and PTVA-4 models. To compare both models we used for the PTVA-4 model the Jenks' Natural Breaks Algorithm (Jenks, 1977) classifying the RVI scores in 5 categories. For the very high and high RVI, both models show a similar number of buildings although the total number in these categories is small and only represents < 10% of the total analysed buildings. The less vulnerable categories do not show a clear tendency. While the number of buildings with minor and average RVI scores in the PTVA-4 is higher this pattern is inverted for the moderate category. In this sense, according to the PTVA-4 model RVI results, the largest number of buildings will be classified as minor and average vulnerability what should be a better reflection of the expected scenario then the PTVA-3 model results (Dall'Osso et al., 2016).

6.2 PTVA model vs. fragility curves

Very recently, Aránguiz et al. (in revision) analysed the buildings response to the 2015 tsunami in the most damaged area of Coquimbo (Sector 2 in our study). They developed a tsunami fragility curve in the basis of field survey data and numerical modelling simulations without considering reinforced concrete or light structures. The authors only differentiated two damage categories and establish a single fragility curve that indicates that for a 2 m flow depth a 20% damage probability exist, i.e. 20% of the buildings will present high structural damages or will collapse. According to this curve the 100% damage probability occur at 4 m flow depth. Unfortunately, this study does not include the analysis of all the buildings in the sector and only differentiate two damage categories (repairable and non-repairable). Therefore, their results show a bias and a coarser and binary approach to the vulnerability whereas the PTVA approach provides more categorized results. Even though a simpler differentiation in two categories might be useful for emergency preparedness, more accurate damage results help identifying areas that require structural or non-structural mitigation measures or evacuation routes and thus represent a better tool for land use planning and disaster management.

6.3~~7~~ Tsunami vulnerability model validation

As pointed out by Dall'Osso et al. (2016) the PTVA-3 and PTVA-4 models provide a RVI score that can be used to compare the expected performance of buildings. We have compared the two models results with the real damages occurred after the ~~16S~~ 2015 event, which was used for the flood scenario, in Sector 2 (Fig. ~~12~~7). This sector has its own architectonical characteristics ~~(see 5.2)~~ and was flooded with high flow~~od~~ depths and therefore~~, it is not representative for the whole study area. Nevertheless,~~ it can be used as a good example to check both models as it presents different flow~~od~~ depths and RVI scores in all the categories. After the tsunami, MINVU assessed a total of 190 buildings in this sector what represents only 40% of the total buildings we assessed ~~tsunami building vulnerability assessment for the sector~~ in this study (Table 6).
We have compared the RVI trends with the MINVU data trend (Fig. ~~12~~7), the curves show a unimodal distribution with the maximum located at range 3 in the PTVA models and in range 2 in the actual damages. The latter presents dispersed values along the range-axis without any of the categories being more significant than the others. On the other hand, the PTVA-3 RVI values ~~distribution~~ reveals a normal distribution with a better-defined maximum and a negative asymmetry resulting in smaller RVI scores. Finally, the RVI scores obtained in PTVA-4 show a well-defined peak that is, most of the values are concentrated in one range. Although PTVA-4 model shows better accuracy according to Dall'Osso et al., (2016), our data suggest a larger imbalance in the trend respect to the PTVA-3 model when compare to the actual performance of buildings trend. In any case, clear differences exist among both models and the real damages in the scenario.

8. Conclusions

This paper analyses and validates the use of the two latest versions of the PTVA model (PTVA-3 and PTVA-4) in a real case scenario, the September 16,~~S~~ 2015 event in the cities of La Serena and Coquimbo. Results of both ~~PTVA-3 and PTVA-4~~ models show that in the reconstructed scenario the most vulnerable areas are sectors 1 and 2 (Coquimbo Port and Baquedano) what agrees with the most damaged areas after the 2015 tsunami. Both models result in a similar number of very high and high RVI scores although these categories only represent <10% of the total analysed buildings whereas the less vulnerable categories do not show a similar trend and PTVA-~~.~~4 model obtains a larger number of minor and average RVI scores that should be a better reflection of the expected buildings performance. However, when compare with the actual damages occurred after the 2015 tsunami in the Baquedano sector, the PTVA-3 RVI scores show a normal distribution that is more similar to the actual damages distribution trend than that obtained by the PTVA-4 model that shows a more concentrated distribution of the RVI scores. Even though the Chilean construction regulation is severe, historical buildings are still vulnerable to tsunami impacts and therefore, future tsunami mitigation measures should focus on these areas.

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Table 1. Attributes and their values influencing the structural vulnerability of a building (Bv) and its level of protection (Prot) in PTVA-3 model (Dall'Osso et al., 2009a).

	-1	**-0,5**	**0**	**+0,25**	**+0,5**	**+0,75**	**+1**
s	> 5 stories	4 stories	3 stories		2 stories		1 story
g	Open plan	Open plan and windows	50% open plan		Not open plan, but many windows		Not open plan
f	Deep pile foundation		Average depth foundation				Shallow foundation
so	Poor hydrodynamic shape		Average hydrodynamic shape				High hydrodynamic shape
mo			Minimum risk of being damaged by movable objects	Moderate risk of being damaged by movable objects	Average risk of being damaged by movable objects	High risk of being damaged by movable objects	Extreme risk of being damaged by movable objects
pc	Excellent	Good	Average		Poor		Very poor
Prot_br			>10th	7-8-9-10th	4-5-6th	2nd-3rd	1st
Prot_nb			Very high protection	High protection	Average protection	Moderate protection	No protection
Prot_sw			Vertical and >5m	Vertical and 3 to 5m	Vertical and 1.5 to 3m	Vertical and 0 to 1.5m or sloped and 1.5 to 3m	Sloped and 0 to 1.5m or no seawall
Prot_w			Height of the wall is from 80% to 100% of the water depth	Height of the wall is from 60% to 80% of the water depth	Height of the wall is from 40% to 60% of the water depth	Height of the wall is from 20% to 40% of the water depth	Height of the wall is from 0% to 20% of the water depth

Table 2. Original parameter (m) (Dall'Osso et al., 2009a) and modified according to the constructions of northern Chile.

	-1	-0,5	0	+0,25	+0,5	+0,75	+1
m (original)	Reinforced concrete		Double brick		Single brick		Wood
m (modified)	Reinforced concrete	~~Gray~~ Concrete block	Red brick		Adobe		Wood and/or metal

Table 3. Numeric values assigned to the Ex parameter.

16S Flow~~ed~~ Depth (m.a.s.l)	Ex
0-1	1
1-2	2
2-3	3
3-4	4

Table 4. Attributes and their values influencing the structural vulnerability of a building (Bv) and its surroundings characteristics (Surr) in PTVA-4 model (Dall'Osso et al., 2016).

	-1	-0,5	0	+0,5	+1
s	More than 5 stories	4 stories	3 stories	2 stories	1 story
g	Completely open plan (e.g. no walls, only columns)	About 75 % open plan	About 50 % open plan	About 25 % open plan	Completely closed plan, no or very few openings at ground floor
f	Deep pile foundation		Average depth foundation		Shallow foundation
sh	Round-like or triangular	Squared or almost squared	Rectangular	Lengthened rectangular	Complex (L, T or X shaped buildings, or other complex geometries)
pc	Very good	Good	Average	Poor	Very poor
br	>10th	7-8-9-10th	4-5-6th	2nd-3rd	1st
nb	Very high protection	High protection	Average protection	Moderate protection	No protection
sw	Vertical and >5m	Vertical and 3 to 5m	Vertical and 1.5 to 3m	Vertical and 0 to 1.5m or sloped and 1.5 to 3m	Sloped and 0 to 1.5m or no seawall
w	Height of the wall is from 80% to 100% of the water depth	Height of the wall is from 60% to 80% of the water depth	Height of the wall is from 40% to 60% of the water depth	Height of the wall is from 20% to 40% of the water depth	Height of the wall is from 0% to 20% of the water depth
mo	Very low risk from movable objects		Average risk from movable objects		Very high risk from movable objects

Table 5. Established ranges for RVI and actual damage comparison.

Range	RVI	MINVU Damage	Description
1	Minor	Minor repairable	Affected house with nonstructural damages in terminations.
2	Moderate	Moderate repairable	Affected house with moderate damages although still repairable that do not impede the habitability of the house.
3	Average	Major repairable	Affected house with major damages that do not impede the habitability of the house.
4	High and very high	Non-Repairable	Affected house with non-repairable damages that prevent its habitability.
-	No access	Without residents and/or without damage	-

Table 6. Number of analyzed polygon in each sector and the obtained RVI score for PTVA-3 and PTVA-4 models.

Sector	Scenario	Very high	High	Average	Moderate	Minor	No access	Total
Coquimbo Port	16S_PTVA-3	10 (7.35%)	22 (16.18%)	37 (27.21%)	39 (28.67%)	26 (19.12%)	2 (1.47%)	136
	16S_PTVA-4	7 (5.15%)	39 (28.68%)	58 (42.65%)	10 (7.35%)	20 (14.70)	2 (1.47%)	
Baquedano	16S_PTVA-3	9 (1.89%)	28 (5.89%)	145 (30.53%)	197 (41.47%)	86 (18.11%)	10 (2.11%)	475
	16S_PTVA-4	8 (1.68%)	45 (9.47%)	300 (63.16%)	43 (9.05%)	69 (14.53%)	10 (2.11%)	
La Cantera	16S_PTVA-3	0 0%	0 0%	52 (41.60%)	52 (41.60%)	19 (15.20%)	2 (1.60%)	125
	16S_PTVA-4	0 0%	0 0%	31 (24.80%)	52 (41.60%)	40 (32.00%)	2 (1.60%)	
Caleta Peñuelas	16S_PTVA-3	0 0%	0 0%	59 (18.10%)	137 (42.03%)	82 (25.15%)	48 (14.72%)	326
	16S_PTVA-4	0 0%	0 0%	26 (7.98%)	78 (23.93%)	174 (53.37%)	48 (14.72%)	
La Pampa	16S_PTVA-3	0 0%	0 0%	21 (17.5%)	41 (34.17%)	56 (46.67%)	2 (1.67%)	120
	16S_PTVA-4	0 0%	0 0%	3 (2.5%)	37 (30.83%)	78 (65.00%)	2 (1.67%)	
La Serena	16S_PTVA-3	0 0%	0 0%	5 (8.77%)	38 (66.67%)	13 (22.81%)	1 (1.75%)	57
	16S_PTVA-4	0 0%	0 0%	0 0%	15 (26.32%)	41 (71.93%)	1 (1.75%)	
Total	16S_PTVA-3	19 (1.53%)	50 (4.04%)	319 (25.75%)	504 (40.68%)	282 (22.76%)	65 (5.25%)	1,239
	16S_PTVA-4	15 (1.21%)	84 (6.78%)	418 (33.74%)	235 (18.97%)	422 (34.06%)	65 (5.25%)	

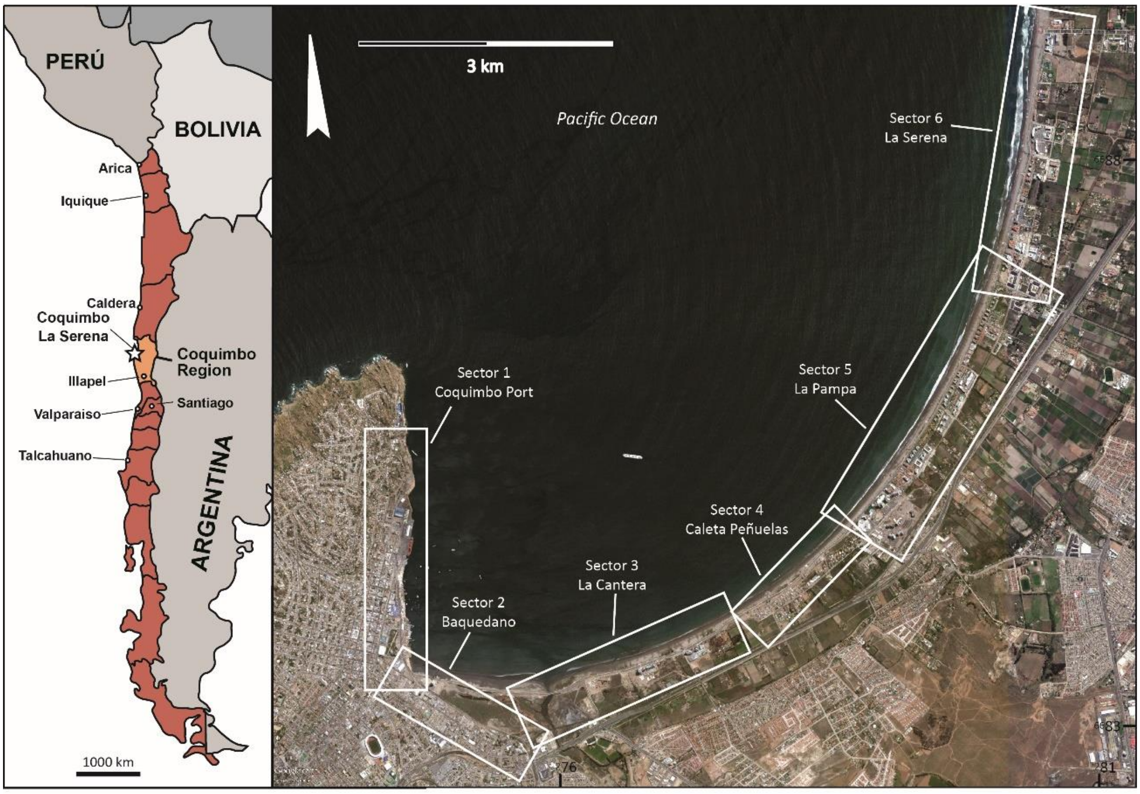

Figure 1: Location of the study area and the analysed sectors in the Coquimbo Bay (image courtesy of Google Earth).

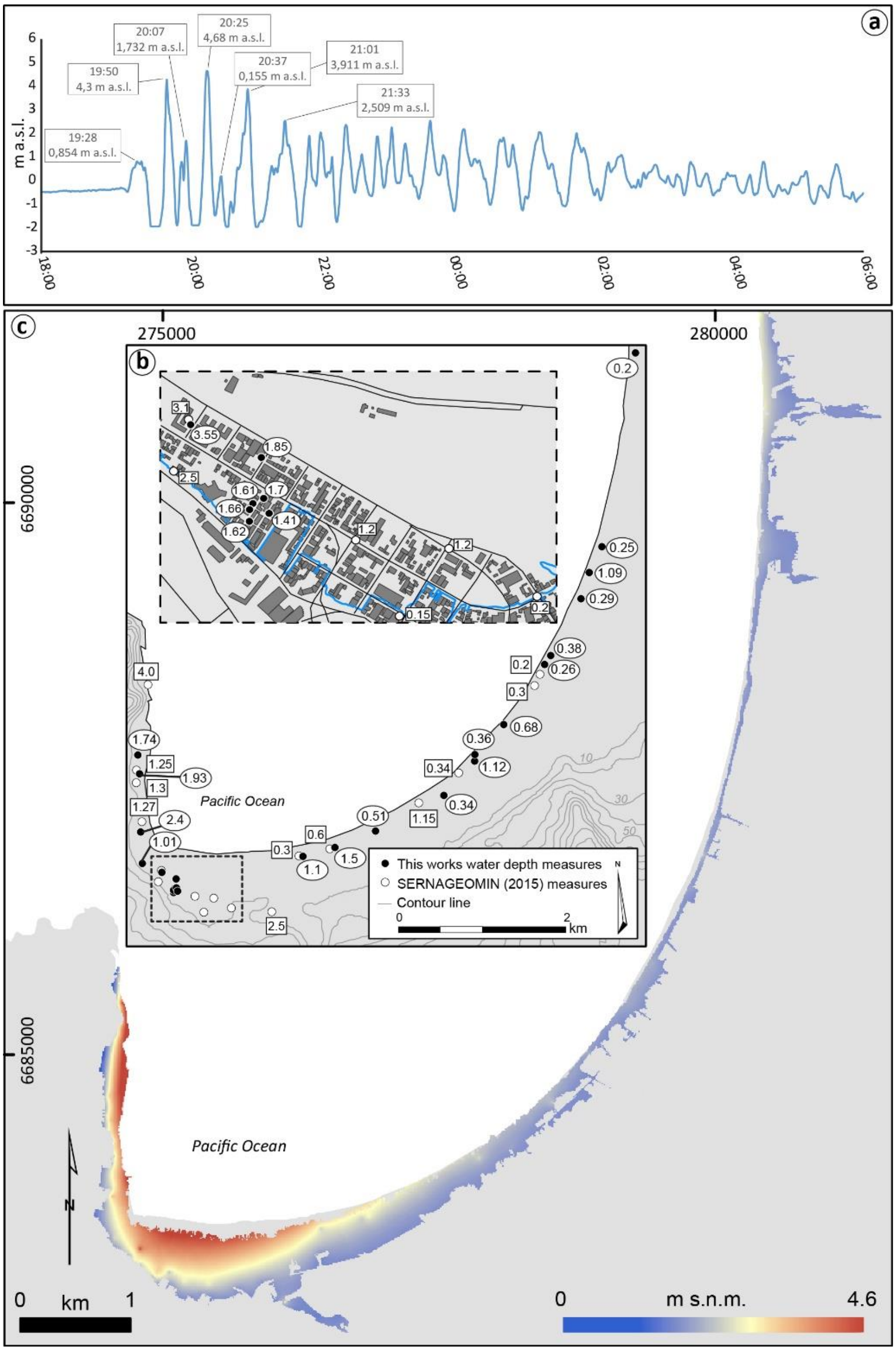

Figure 2: a) Coquimbo tide gauge measurements (SHOA); b) Flow~~od~~ depth measurements along Coquimbo and La Serena; the blue line marks the limit of the flood; c) reconstructed tsunami inundation map and flow~~od~~ depths from the data collected in the field.

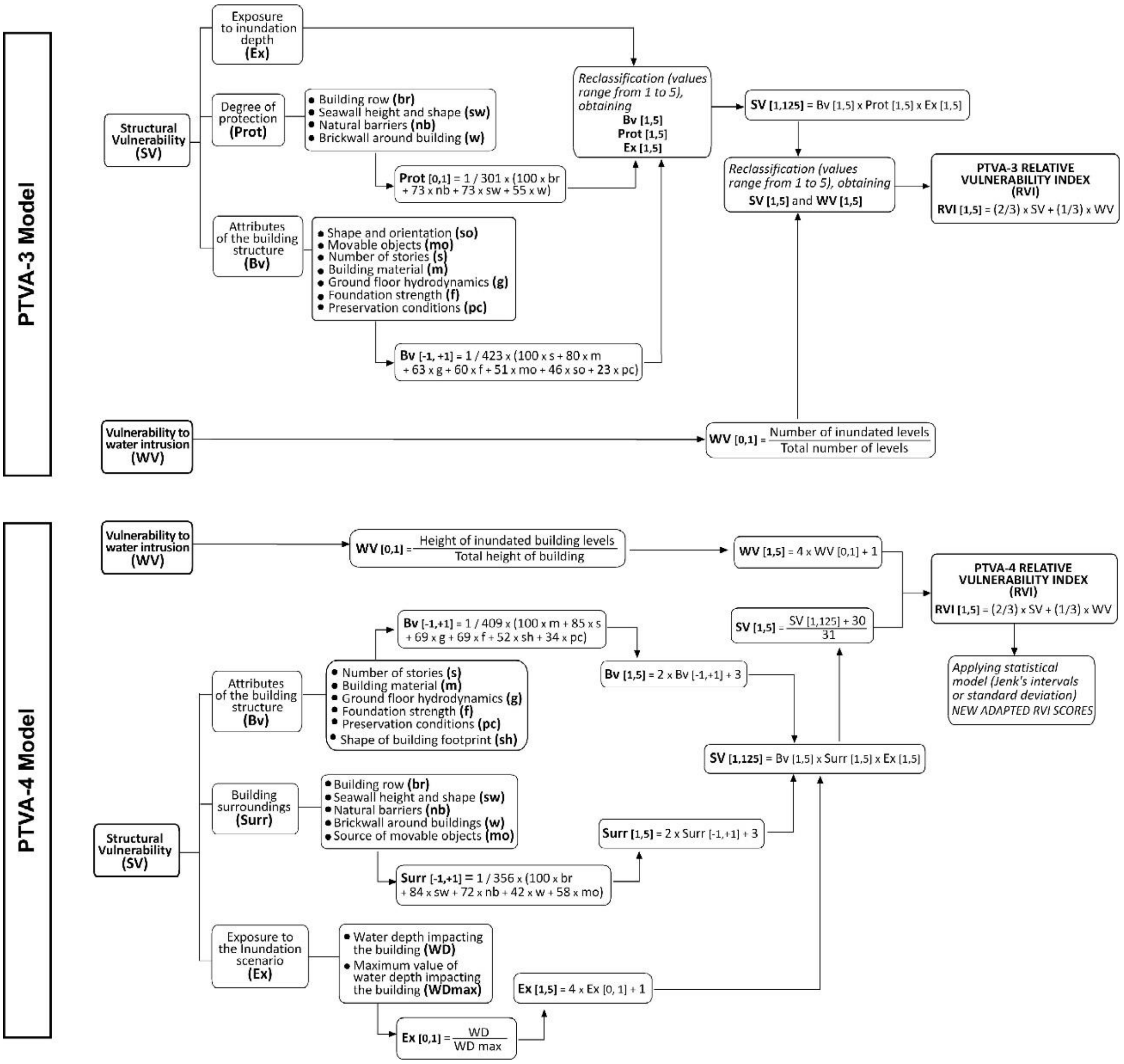

Figure 3: PTVA-3 and PTVA-4 models.

Figure 4: a) Building with average RVI score in the first coastline with flow depths~~od heights~~ of 1.9 m after the 2015 tsunami in Coquimbo Port (sector 1); b) Movable objects impacting residential buildings after the 2015 tsunami; c) High vulnerability building with more than 50% of its infrastructure flooded; d) High vulnerability building with its damaged infrastructure after the 2015 tsunami; e) Very high vulnerability building that resulted in non-repairable damage after the 2015 tsunami; f) Modern buildings with minor vulnerability RVI score; g) Very high vulnerability building highly affected by the tsunami in La Cantera sector; h) Not open plan ground floor.

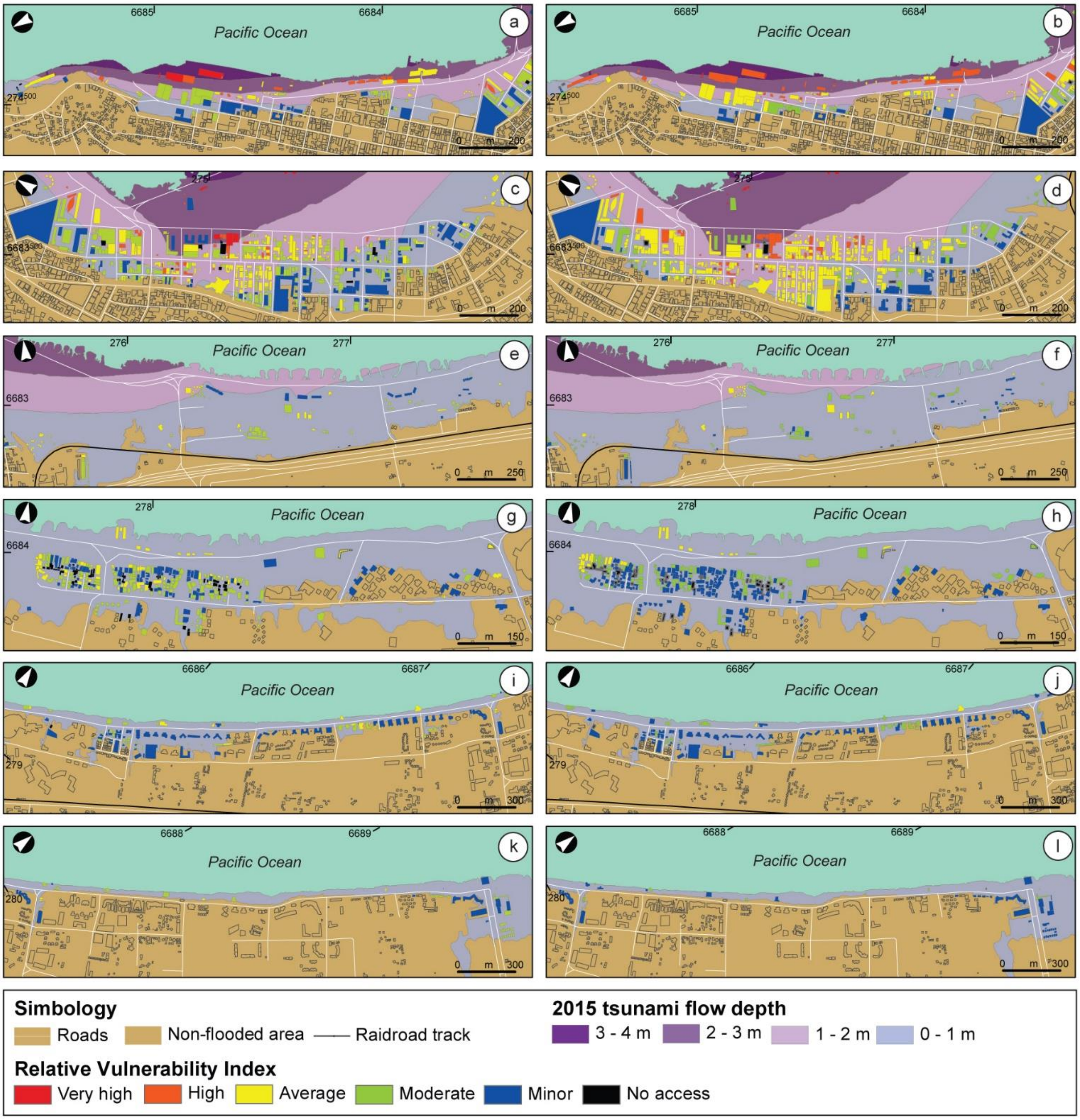

Figure 5: Relative Vulnerability Index for: a) Sector 1 - Coquimbo Port~~: a)~~ PTVA-3 model; b)~~-~~ Sector 1 - Coquimbo Port PTVA-4 model; c) ~~.~~

~~Figure 6: Relative Vulnerability Index for S~~Sector 2 - Baquedano~~: a)~~ PTVA-3 model; ~~and~~ d) Sector 2 – Baquedano PTVA-4 model; e) ~~.~~

~~Figure 7: Relative Vulnerability Index for~~ Sector 3 - La Cantera~~: a)~~ PTVA-3 model; f) Sector 3 - La Cantera ~~and d)~~ PTVA-4 model; g) ~~.~~

~~Figure 8: Relative Vulnerability Index for S~~Sector 4 - Caleta Peñuelas~~: a)~~ PTVA-3 model; h) Sector 4 - Caleta Peñuelas~~and d)~~ PTVA-4 model; ~~.~~

~~Figure~~i) ~~9: Relative Vulnerability Index for~~ Sector 5 - La Pampa~~: a)~~ PTVA-3 model; j) Sector 5 - La Pampa ~~and d)~~ PTVA-4 model; k) ~~.~~

~~Figure~~ 2~~20: Relative Vulnerability Index for~~ Sector 6 - La Serena~~: a)~~ PTVA-3 model; and l~~d~~) Sector 6 - La Serena PTVA-4 model.

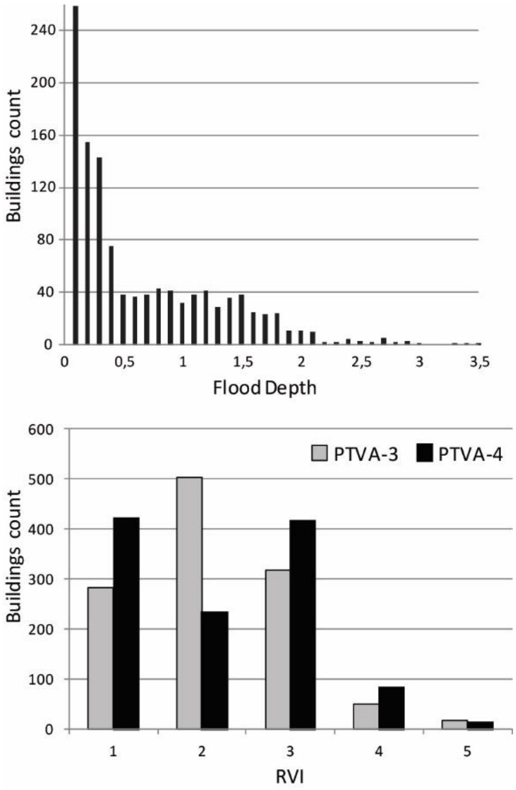

Figure 6~~31~~: a) Number of buildings exposed to the different water depth (WD) ranges in Coquimbo Bay in the reconstructed 2015 tsunami scenario; b) RVI scores obtained for the total 1,239 buildings analyzed after the PTVA-3 and PTVA-4 models.

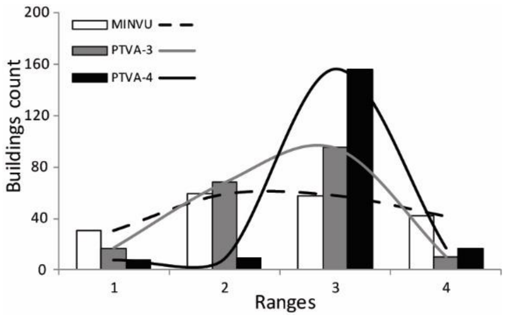

Figure 7~~42~~: Number of buildings in the different established ranges.