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Assessing the Role of Land-Use Planning in Near Future Climate-Driven Scenarios in Chilean Coastal Cities

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Abstract: This study reviews the degree to which land-use planning addresses climate change adaptation in Chilean Low Elevated Coastal Zones (LECZ). We first select 12 of the country's most exposed coastal municipalities using a Municipal Exposure Index (MEI). Then, we conduct a content analysis of the communal regulatory plans (CRPs) using a "presumed exposure analysis", which assumes that the inventory of assets within LECZ, according to the 2017 census, is a proxy of the exposure. Then, we conduct a more refined "hazard exposure analysis" by comparing changes in flooding levels between a historical period (1985–2004) and the RCP8.5 scenario (2026–2045). Using the latter approach, we show that flooding could affect large portions of the municipalities' housing areas (3.7%), critical facilities (14.6%), and wetlands (22.7%) in the period 2026–2045. In the presumed exposure analysis, these percentages rise to 7.5%, 23.9%, and 24.9%, respectively. We find that CRPs also allow for a densification of exposed residential areas, whose density would increase by 9.2 times, on average, between the historical period and the RCP8.5 scenario. Additionally, only four municipalities define floodable zones as "risk areas". Lastly, the difficulty in updating CRPs and their antiquity −21.25 years old on average could explain their ineffectiveness in implementing climate change adaptation strategies.

Keywords: urban planning; climate change; coastal cities; coastal flooding

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1. Introduction

1.1. Climate Change and Land-Use Planning for Adaptation in Coastal Areas

In the first two decades of this century, the global surface temperature increased between 0.84 and 1.10 °C, compared to 1850–1900. This unquestionable evidence of global warming is linked to worldwide impacts such as the rise of overland precipitation, retreat of glaciers, ocean acidification, and sea level rise, the global mean of which increased in 0.15–0.25 m between 1901 and 2018 [1]. Extreme weather events have deviated from historic records in their distribution, severity, and frequency [2]. This shifting climate has the potential to severely affect coastal areas, which are vulnerable to sea level rise, floods, erosion, saltwater intrusion, and torrential rainstorms. In this respect, McGranahan et al. [3] (p. 17) point out that, while Low Elevation Coastal Zones (LECZ, defined as "the contiguous area along the coast that is less than 10 m above sea level") cover only 2% of the world's land area, they contain 10% of the global population, 13% of which live in cities. In recent years, meteorological hazards have led to large impacts on urban agglomerations within LECZ, including thousands of casualties and damage to infrastructure.

Seavitt et al. [4] underline that current approaches to risk reduction in coastal areas are moving away from traditional flood control infrastructure to adaptation strategies including habitat restoration, stormwater management, new building types, and urban planning measures. These recommendations are aligned with the New Urban Agenda from the Habitat III Conference [5], which recommends the integration of climate change adaptation and mitigation into urban development and planning processes, along with age and gender perspectives. In this respect, Seavitt et al. [4] propose a layered approach combining wave energy attenuation, coastal protection, and land-use planning. Similarly, Tsimopoulou et al. [6] draw attention to a multi-layer safety system used in Netherlands, where flood infrastructure, spatial solutions for loss reduction, and emergency management measures are considered. Macintosh [7] points out that urban planning has traditionally used three strategies to adapt to climate-driven coastal hazards: protect, accommodate, and retreat settlements. Gargiulo et al. [8] deliver a list of urban measures that could enhance adaptation, namely the use of permeable areas (e.g., wetlands) and specific building standards within coastal areas, as well as the adequate localization of activities, public services, and transport infrastructure.

Significant challenges still exist for developing adaptation strategies. For instance, Hamin and Gurran [9] found potential conflicts in achieving climate change adaptation and mitigation simultaneously in land-use plans in Australia and United States. Overall, there is consensus on the need for a change of planning principles and regulations as one of the major components of adaptive urban governance [10].

1.2. Climate Change and Land-Use Planning in Chilean Coastal Areas

The Chilean coastline extends for nearly 106,000 km [11] and, in forthcoming decades, will be affected by sea level rise [12]. The World Bank [13] states, in addition, that climate change is expected to change the frequency, intensity, and magnitude of extreme events that have historically affected the country, such as landslides and floods. According to the 2017 census, 25.6% of Chile's 17.6 million inhabitants live in one of its 106 coastal municipalities, and ~1 million reside in LECZ within such municipalities [14]. This number, corresponding to 5.7% of the Chilean population, is lower than the global and Latin American averages of 10% and 6%, respectively [3]. The country's coastal population is unevenly distributed within the sparsely inhabited Atacama Desert, large metropolitan areas in Central and South Chile, and southern Patagonia (Figure 1). Overall, Chile's coastline is 2% urban and 98% rural [15]. In recent decades, Chilean coastal areas have undergone an intense process of anthropisation, leading to a growing exposure to natural hazards, as well as the deterioration of coastal ecosystems [16].

In Chile, land-use planning is carried out by metropolitan, inter communal, and communal regulatory plans (CRPs hereafter). CRPs guide the public and private urban development at the municipal level through the classification of land (into urban, urban extension, non-developable, and rural) [17]. They also regulate building permits, urban growth limits, non-habitable areas, public spaces, road structure hierarchization, building requirements, maximum densities, and land uses [18]. Since 2001, it has been mandatory to elaborate a risk study for the design of CRPs, to define risk areas as superimposed layouts on the land zones. In such areas, certain types of constructions are limited, and additional engineering works to mitigate disasters are required. Nevertheless, these studies are often limited to the hazard assessment, excluding any sort of vulnerability analysis [19]. Moreover, CRPs approved before 2001 do not contemplate risk studies, as they were not legally requested.

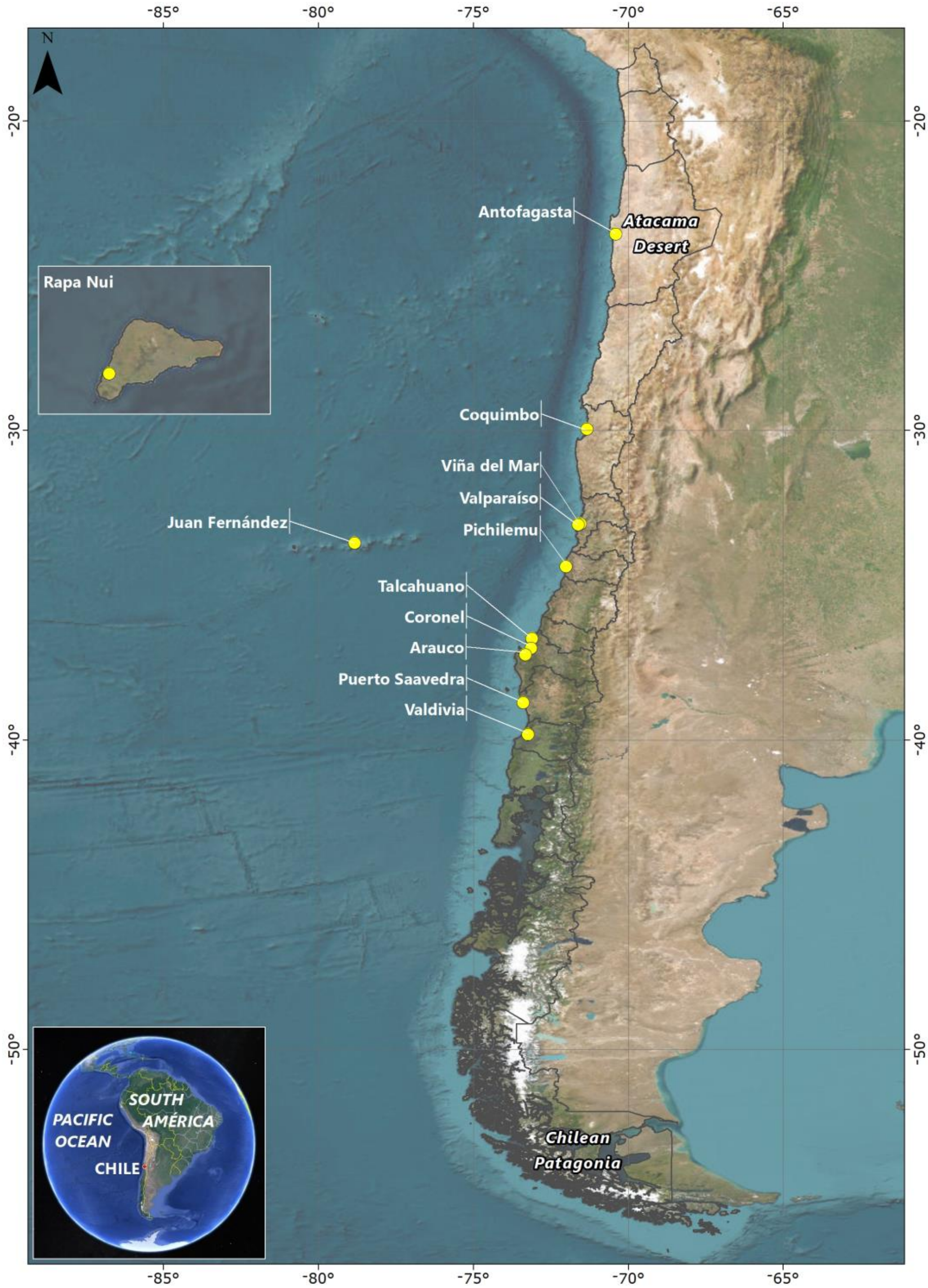


Figure 1. Location of the 12 case studies. Geographic projection system, Datum WGS 84.

Another example of planning instruments aimed to protect environmental assets and strengthen hazard adaptation is the new Urban Wetlands Act (*Ley de Humedales Urbanos N°21.202*). Since 2020, CRPs have included urban wetlands as protected areas, establishing conditions under which permits will be granted for developments in such areas. Urban wetlands are conceived as ecosystems with geomorphological and hydrological properties that interact with economic and socio-cultural processes [20]. Their ability to capture CO_2 and minimize heat waves are important to mitigate local effects of climate change [1,21]. Unfortunately, wetlands have been harmed by urbanization processes, resulting in a loss of urban wetland surface, particularly in Latin America [22,23].

Despite the inclusion of risk studies in CRPs and the Urban Wetlands Act, Chilean land-use planning does not provide a comprehensive and integrated framework capable of preserving environmental assets and reducing coastal risks [16,24]. On the contrary, urban management and planning are split across several governmental agencies, depending on how the property is defined at a particular site. According to the coastal act of 1994 (*D.S. (M) N°475*), an 80-meter wide "coastal buffer" is defined inland from the high-tide line in public properties, and no buffer is considered in private properties. The Ministry of Defense is entitled to assign leases for up to 30 years on this buffer for several uses (tourism, fishing, leisure, etc.), usually without comprehensive planning or zoning criteria [25]. The coastal buffer and the leases mentioned above are the only planning tools that take care of the first coastal front.

In this study, we assess the degree in which current CRPs cope with climate-driven flooding risks in 12 Chilean municipalities. We base our findings on a report commissioned by the Ministry of the Environment (MMA) that assessed climate change risks along national coasts [11]. The report includes an inventory of human and natural systems within the LECZ, as well as a flooding hazard analysis for a historical period (1985–2004) and a near future projection (2026–2045) associated to the Representative Concentration Pathway RCP8.5, a conservative greenhouse gas scenario (IPCC, 2014). The report identifies 12 critical coastal municipalities, in which we conduct a content analysis of the CRPs and analyze how these relate to hazard and exposure. To the best of our knowledge, this is the first study in Chile and in Latin America that addresses to what extent urban planning deals with flooding risk in various scenarios of sea level rise.

The paper is organized as follows: Section 2 describes the methodology, including the selection of examined municipalities according to their exposure, the computation of the flooding hazard, and the analysis of CRPs. Section 3 presents the results of our research, which we critically discuss in Section 4. Lastly, Section 5 provides the main conclusions and suggests paths for future investigation.

2. Methodology

2.1. Selection of Examined Municipalities according to Their Exposure

The selection of the critical municipalities along the Chilean coastal zone (Figure 1) was based on a semi-quantitative method, the details of which can be found in [11] (Table 30) and are summarized hereafter. First, the authors developed an inventory of coastal systems located in the LECZ of 106 coastal municipalities. Figure 2a depicts the conceptual model in the "presumed exposure analysis", where the inventory at each municipality was computed (note that this inventory is independent of the flood level). The area corresponding to LECZ was obtained from a digital elevation model (DEM) built from satellite data (ASTER GDEM-2, ALOS WORLD 3D, and ALOS PAL) and topographic surveys provided by the Navy Hydrographic and Oceanographic Service (SHOA). Data used for the inventory were obtained from governmental sources [11] (Table 20) and validated with fieldwork and workshops conducted in Antofagasta, Valparaíso, and Concepción.

To select the critical municipalities, a purely quantitative Municipal Exposure Index (MEI) was used in combination with expert judgement, according to the needs of the MMA. The MEI was defined as:

$$MEI = f \times \langle \underbrace{c_A A}_{\substack{\text{Exposed}\\\text{area}}} + \underbrace{c_P P}_{\substack{\text{Exposed}\\\text{population}}} + \underbrace{c_{NI}\frac{NI}{L}}_{\substack{\text{Exposed}\\\text{Infrastructure}}} + \underbrace{c_{NE}\frac{NE}{L}}_{\substack{\text{Exposed}\\\text{urban}\\\text{equipment}}} + \underbrace{c_{NA}\frac{NA}{L}}_{\substack{\text{Exposed}\\\text{economic}\\\text{activities}}} + \underbrace{c_{NN}\frac{NN}{L}}_{\substack{\text{Exposed}\\\text{natural}\\\text{systems}}} \rangle \quad (1)$$

The index included the exposed area, population, infrastructure, urban equipment, economic activities, and natural systems located within each municipality's LECZ. f is a scaling factor aimed to adjust the maximum MEI to 1; $MEI = 1$ is thus interpreted as the most exposed municipality, while $MEI \to 0$ represents a low exposed municipality. The weighting coefficients $(c_A, c_P, c_{NI}, c_{NE}, c_{NA}, c_{NN})$ were arbitrarily set to 1/6, though they could be set according to expert judgement, local needs, or disciplinary criteria. A is the percentage of the area within the municipality's LECZ, P is percentage of permanent inhabitants within the municipality's LECZ according the 2017 census, and L is the length of the coastline of each municipality. NI, NE, NA, and NN are the number of infrastructures (e.g., ports, marinas, transport network, water treatment, power plants, submarine cables), urban equipment, economic activities, and natural systems within each municipality's LECZ. Details of each of these categories are included in MMA [11] (Table 22). Five municipalities with the highest MEI values are analyzed herein. Additionally, seven municipalities were considered due to their distinct conditions (e.g., high intervention with coastal infrastructure, evidence of coastal erosion, or high degree of naturalness).

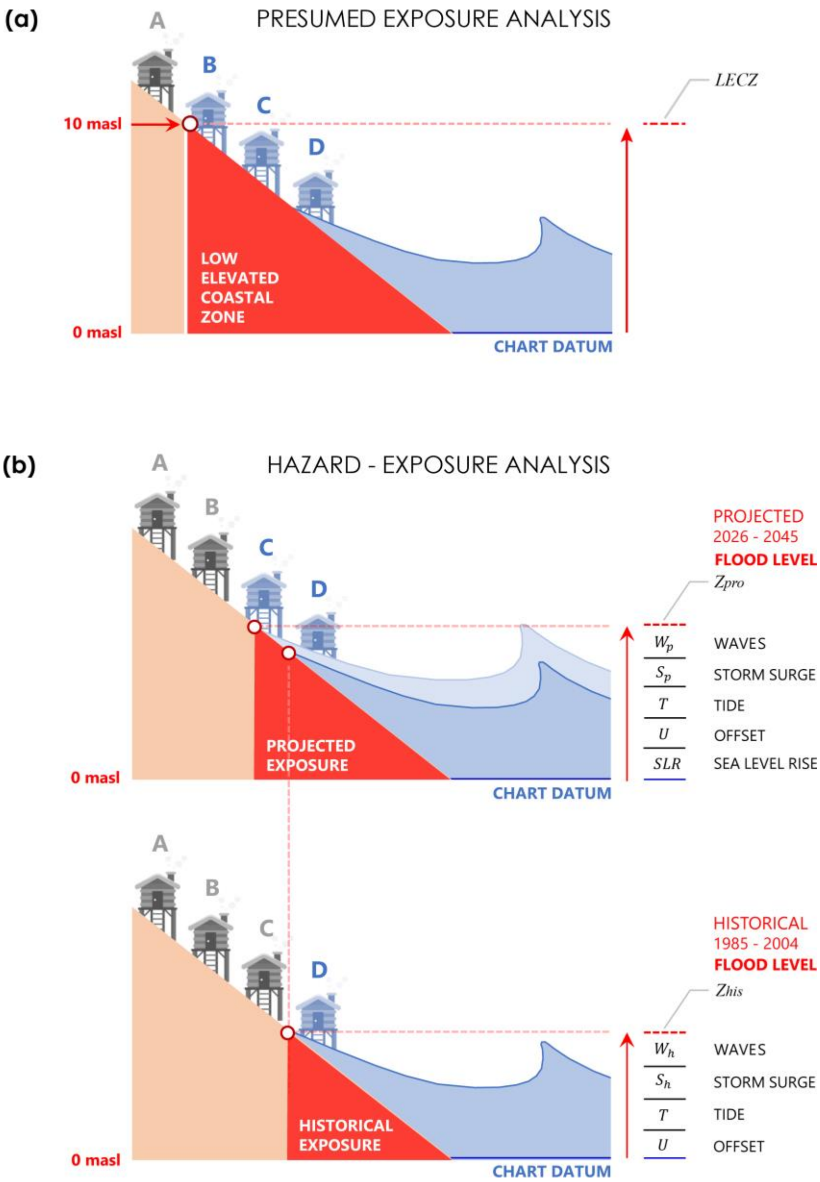


Figure 2. Conceptual models used in the study. (**a**) "Presumed exposure analysis", where the inventory at each municipality is computed within LECZ, i.e., below 10 m.a.s.l. (**b**) "Hazard exposure analysis", where the flood level for the historical period (1985–2004) and the projection (2026–2045) are depicted. Houses in light blue are counted in the corresponding inventory, while houses in gray are not. Houses represent any measure of population, infrastructure, urban equipment, economic activities, and natural systems.

2.2. Computation of the Flooding Hazard

The flooding hazard at each municipality was computed using the historical flood level (1985–2004) with respect to the lowest astronomical tide (Z_h) as a proxy. Its computation considered the contribution of waves (W_h), storm surge (S_h), the maximum yearly astronomical tide (T), and an additional offset (U), which considers the uncertainties associated to the overall modelling approach:

$$Z_h = W_h + S_h + T + U \tag{2}$$

The mid-century projection (2026–2045) of the flood level $\left(Z_p\right)$ included the projected contribution of waves (W_p), storm surge (S_p), tide, and sea level rise (SLR) between both periods and the above-mentioned offset:

$$Z_p = W_p + S_p + T + SLR + U \tag{3}$$

The choice of both the historical period and the projection was based on the availability of oceanographic variables used to force wave models (e.g., wind fields and ice coverage), which were unavailable for other periods. Figure 2b depicts the conceptual model used in the "hazard exposure analysis", where the flood level for the historical period and the projection are depicted. The contribution of waves was computed from a combination of (a) a Pacific-Wide model, (b) the transformation of wave spectra to each site, and (c) the use of an empirical formula to compute runup.

The Pacific-Wide model, implemented in WAVEWATCH III v4.18 [25] on a Pacific-wide domain, was forced by 3-hour wind data and daily ice coverage from six General Circulation Models (GCMs) available at the Coupled Model Intercomparison Project 5 [26,27]. Four GCMs (ACCESS 1.0, HadGEM2-ES, MIROC5, and MRI-CGM3) were selected based on their good performance to generate wave climate on the southeast Pacific Ocean [28], while two (EC-EARTH and CMCC) were used due to their high resolution in the Pacific Ocean. The ocean bottom was modelled with a spatial resolution of 1° using ETOPO2v2's bathymetry [29] in combination with a coastline from the GHHSGVIII database [30]. Details of the model parametrization are included in [31], and it has shown a good performance off Chile's coasts [32].

Transformation of wave spectra from deep waters to representative nodes at a depth of 20 m on each site was conducted using Snell's Law and the small amplitude wave theory, thus considering the effects of shoaling and refraction. The time series of wave height (H_s), period (T_m), and direction (θ_m) were then used to compute the wave runup using Stockdon et al. [33]. Finally, temporal medians for 20 years were computed for each GCM for both periods (W_h, W_p).

Sea level rise (SLR) between the RCP 8.5 projection and the historical period was computed from 21 GCM from CMIP5 [27] in the entire Pacific basin. The GCMs were interpolated to each study site. Storm surge was based on data by [34]. Data from 2010 were used as representative of the historical period, while data from 2040 were used for the projection. These data were interpolated to each site. The maximum yearly astronomical tide (T) was obtained from tidal charts [35] and assumed to be invariant between both periods. This assumption is consistent since the tide is bounded, periodic, and climate-independent. Finally, we assumed $U = 1$ m for both periods.

2.3. Land-Use Planning and Hazard Exposure in Significant Chilean Urban Coastal Areas

For the selected municipalities we conducted a content analysis to examine how CRPs relate to the "presumed exposure analysis" (Figure 2a) and the refined "hazard-exposure analysis" (Figure 2b). We examined five urban dimensions previously used to understand how CRPs relate to risk analysis [36], namely, population density, land uses, risk areas, location of critical facilities, and urban wetlands. We carried out this analysis using ArcMap 10.4.1 to compile, geo-reference, and post-process the information, using open-source georeferenced data collected from governmental sources (Table 1). We used WGS 84/UTM zone 19S for the continental municipalities, WGS 84/UTM zone 17S for Juan Fernández, and WGS 84/UTM zone 12S for Rapa Nui. We also reviewed the risk studies developed during the elaboration of CRPs, if applicable.

Table 1. List of sources of geo-referenced secondary data used in the land-use planning analysis.

Dimension	Variable	Description	Data Source
Population density	Existing density (people/ha)	Ratio between existing population and one hectare.	2017 Census data (https://inechile.maps.arcgis.com/apps/webappviewer/index.html?id=c2155cac57d04032bf6ca5f151cddd6d, accessed on 20 May 2022)
	Planned maximum density (people/ha)	Ratio between maximum planned population (according to CRP) and one hectare. When maximum density is not planned, it was estimated using the following urban codes: building height, floor area ratio, and building footprint.	Ministry of Housing and Urbanism official information on planning instruments (2022) (https://www.observatoriourbano.cl/; http://seguimientoipt.minvu.cl/main.php, accessed on 17 March 2022) Local municipalities websites (2022)
Land uses	Types of zones (prohibited and allowed uses in each CRP)	Land-use zoning, including: Residential Commercial Industrial Non-buildable	
Risk areas	Surface and type of risk areas (ha)	Territory identified as a flood risk area by the CRP	
Critical facilities	Number of buildings per CRP zone (#)	Primary physical structures, technical facilities, and systems that are socially, economically, or operationally essential to the functioning of a society or community, both in routine circumstances and in the extreme circumstances of an emergency [37]. Mapping of: Health buildings (public and private establishments) Education (public and private establishments) Security (firefighters, research, police) Tourism (local development, tourism, and heritage) Industry (basic and dangerous services) Government (municipal services and municipal services and external)	Chilean infrastructure for geo-spatial data (https://www.ide.cl/, accessed on 16 January 2022) MMA [11]
Urban wetlands	Urban wetland surface (ha)	Proportion of urban wetlands within LECZ	

3. Results

3.1. Selection of Examined Municipalities according to Their Exposure

The 12 critical coastal municipalities are included, from north to south, in Table 2, along with their acronym, geographical coordinates, selection criteria, and *MEI*. Flooding levels for the historical period (1985–2004) and the projection (2026–2045) are also included. The most exposed municipalities were Talcahuano, Valparaíso, Arauco, Coronel, and Puerto Saavedra. Additionally, seven municipalities were analyzed due to their distinctive conditions: Antofagasta is representative of northern cities heavily intervened with coastal infrastructure. Coquimbo shows evident signs of coastal erosion. Viña del Mar constitutes, together with Valparaíso, the largest coastal conurbation of Central Chile. Pichilemu is a worldwide-known surf hotspot and one of the few sites with low intervention of coastal infrastructure. Valdivia is characterized by its low elevation and wetlands, which were significantly enlarged by the co-seismic subsidence of the 22 May 1960 earthquake [38]. Finally, the islands of Rapa Nui and Juan Fernández were chosen due to their remoteness.

Table 2. Municipalities analyzed in this study. The selection criteria used on their selection and the Municipal Exposure Index (MEI) are included. The hazard is expressed as the flood elevation for the historical period 1985–2004 (Z_h) and the RCP8.5 projection (Z_{pro}). The year each CRP was enacted and explicit mentions of climate change (C.C.) and tsunamis on each CRP's risk study are also included. For the islands, there was not enough information in freely available sources to compute the MEI.

Municipality	Acronym	Lon W	Lat S	Selection Criteria	MEI	Z_{his} (m)	Z_{pro} (m)	CRP Enacted	CRP Mentions C.C.	CRP Mentions Tsunami
Antofagasta	ANTO	70°23′	23°39′	Typical northern city	0.19	4.67	4.88	2002	No	Yes
Coquimbo	COQU	71°17′	29°56′	Evident erosion	0.31	4.67	4.89	2019	No	Yes
Viña del Mar	VIÑA	71°33′	33°00′	Conurbation	0.55	4.74	4.97	2002	No	No
Valparaíso	VALP	71°35′	33°02′	High MEI	0.93	4.74	4.97	2005	No	No
Pichilemu	PICH	72°00′	34°23′	Low intervention	0.30	4.82	5.04	2005	No	No
Talcahuano	TALC	73°07′	36°43′	High MEI	1.00	4.92	5.14	2006	No	No
Coronel	CORO	73°08′	37°01′	High MEI	0.61	4.90	5.12	2013	No	Yes
Arauco	ARAU	73°18′	37°14′	High MEI	0.69	4.87	5.09	2014	Yes	Yes
Puerto Saavedra	SAAV	73°23′	38°47′	High MEI	0.61	4.79	5.01	1964	No	No
Valdivia	VALD	73°14′	39°49′	Low elevation	0.39	4.78	5.01	1995	No	No
Rapa Nui	RAPA	109°20′	27°06′	Remote island	-	4.68	4.90	1971	No	No
Juan Fernández	JFER	78°49′	33°38′	Remote island	-	4.75	4.97	2013	No	Yes

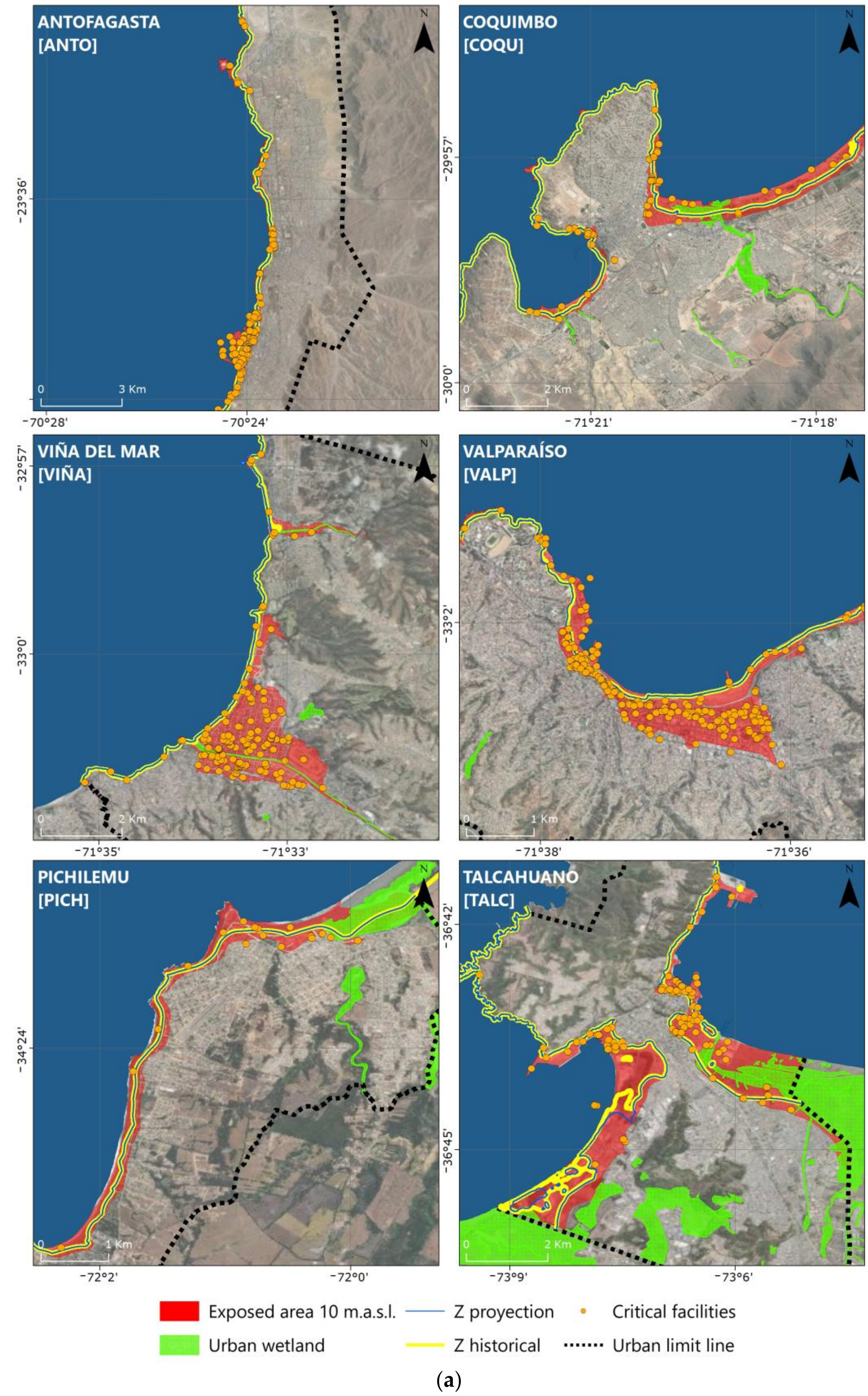
3.2. Land-Use Planning Analysis Based on Presumed Exposure Data (LECZ)

Table 3 shows that the municipalities can be classified into large cities with more than 200,000 inhabitants in North and Central Chile (Antofagasta, Coquimbo, Viña del Mar, Valparaíso), small island towns with less than 10,000 inhabitants (Rapa Nui, Juan Fernández), and intermediate cities in Central and South Chile (Pichilemu, Talcahuano, Coronel, Arauco, Puerto Saavedra, Valdivia). The exposed territories within the LECZ of the 12 selected municipalities comprise 21.6% (92.2 km^2) of the total urban areas, where about 7.5% (101,419 inhabitants) of the total population live. LECZ include 23.9% of the critical facilities (861), including 169 educational, 10 governmental, 571 tourism and industry, and 66 security facilities. Additionally, 24.9% of the wetlands' area is contained in LECZ. The top-exposed municipalities in terms of population are Rapa Nui, Juan Fernández, and Viña del Mar, where 23.8%, 16.7%, and 14.3% of their inhabitants reside in 9.7%, 2.6%, and 4.6% of their urban areas in LECZ, respectively. On the contrary, Antofagasta, Valparaíso, Pichilemu, Talcahuano, Coronel, and Puerto Saavedra present less than 5.0% of the exposed population within LECZ. The percentage of exposed population tends to be lower or slightly higher than the percentage of exposed urban area, except in the island cities, Rapa Nui and Juan Fernández, where inhabitants concentrate on the coastline. The cities of Viña del Mar, Talcahuano, Valdivia, and Juan Fernández have high percentages (>40%) of critical facilities within LECZ, followed by Coquimbo (32.5%) and Pichilemu (23.4%). Other cities have smaller percentage of critical facilities. Valparaíso (58.8%), Viña del Mar (47.1%), Arauco (40.8%), and Puerto Saavedra (40.5%) are the municipalities with the highest percentages of the exposed wetlands areas in LECZ, cities which also have high percentages in exposed areas and population (Figure 3).

Table 3. Computation of exposed systems for the municipalities under study. Values are computed within the LECZ (Z = 10 m.a.s.l.). Population data correspond to the 2017 census. (Detailed information can be found in Supplementary Table S1).

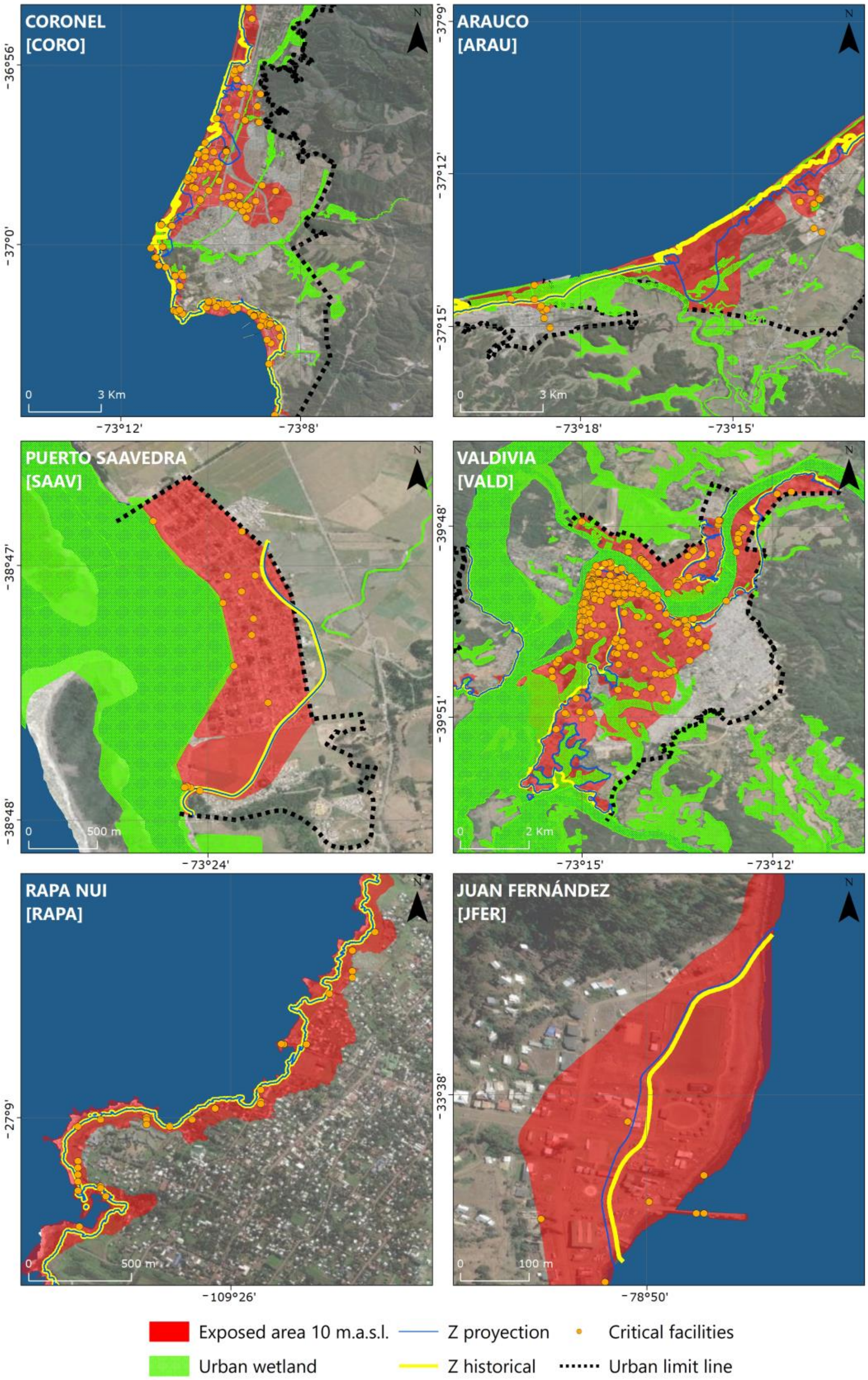
Parameters	Unit	ANTO	COQU	VIÑA	VALP	PICH	TALC	CORO	ARAU	SAAV	VALD	RAPA	JFER	Sum
Total population	inhab	361,873	227,730	334,248	296,655	16,394	151,749	116,262	36,257	12,450	166,080	7750	926	1,728,374
Exposed population	inhab	9,409	14,347	47,797	2,077	771	5463	1744	1885	149	15,778	1845	155	101,419
Total urban area	km^2	453.73	69.50	92.23	32.42	23.09	48.57	55.00	44.17	1.61	49.50	4.62	4.84	879.28
Exposed urban area	km^2	8.7	4.2	4.3	2.3	4.1	9.5	16.3	15.0	1.2	26.0	0.5	0.1	92.2

Parameters	Unit	ANTO	COQU	VIÑA	VALP	PICH	TALC	CORO	ARAU	SAAV	VALD	RAPA	JFER	Mean
Exposed population	%	2.6	6.3	14.3	0.7	4.7	3.6	1.5	5.2	1.2	9.5	23.8	16.7	7.5
Exposed urban area	%	1.9	6.0	4.6	7.1	18.0	19.5	29.6	33.9	73.1	52.6	9.7	2.6	21.6
Exposed critical facilities	%	18.1	32.5	40.6	5.1	23.4	40.1	9.3	4.0	9.1	40.4	17.2	46.7	23.9
Exposed wetlands area	%	7.1	26.8	47.1	0.0	35.9	33.3	8.9	40.8	40.5	58.8	0.0	0.0	24.9
Densification potential (Densification potential = max CRP density/existing density) (The densification potential was calculated concerning the accumulated density of each zone incorporated in the CRP, both for the existing density and the CRP density)	-	7.3	1.4	3.3	4.4	3.0	11.3	6.3	2.5	6.4	0.7	1.1	8.7	4.7
Floodable area defined as risky in CRP	%	0.0	100.0	0.0	0.0	0.0	0.0	95.4	57.0	0.0	0.0	0.0	100.0	29.4



(**a**)

Figure 3. *Cont*.

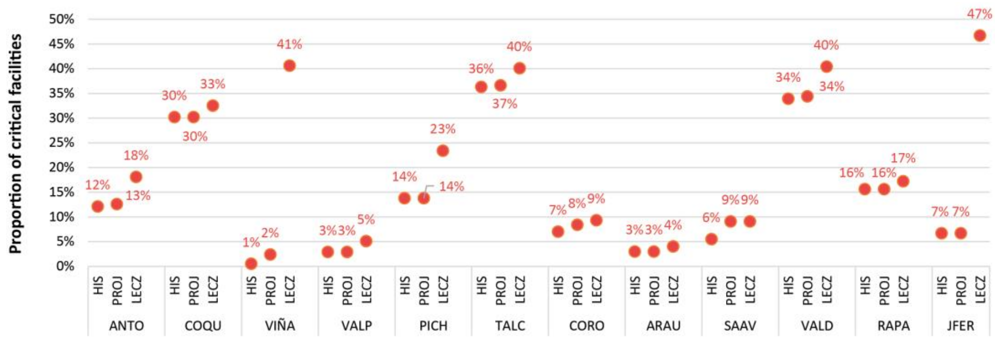


(**b**)

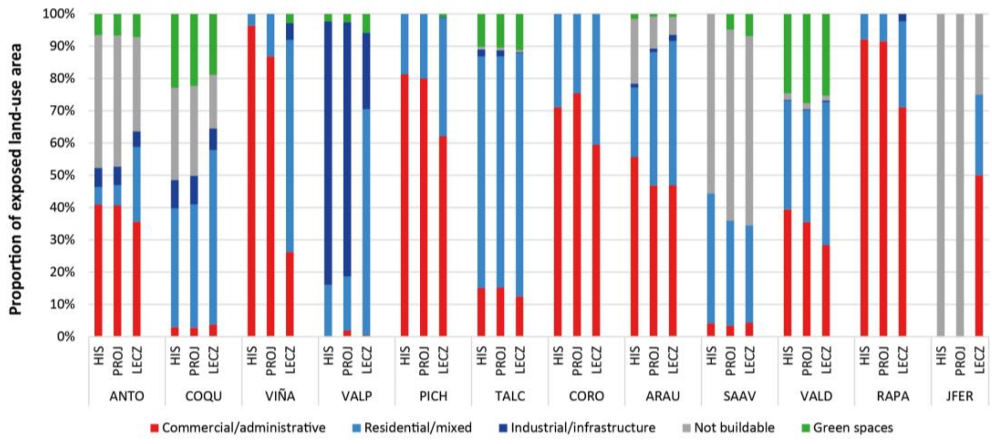
Figure 3. (**a**) Case studies of Antofagasta, Coquimbo, Viña del Mar, Valparaíso, Pichilemu, and Talcahuano. Geographic projection system, Datum WGS 84. (**b**) Case studies of Coronel, Arauco, Puerto Saavedra, Valdivia, Rapa Nui, and Juan Fernández. Geographic projection system, Datum WGS 84.

The 12 case studies comprise 336 CRP land-use zones fully or partially located within LECZ. Of these, 333 (99.1%) contain at least one critical facility. CRPs risk areas account for 29.4% of the analyzed LECZ and are only considered in four municipalities. In such cases, CRPs tend to fully cover (100% in Coquimbo and Coronel) or partially comprise the LECZ (95.4% in Juan Fernández and 57% in Arauco). It is noticeable that 8 of the 12 case studies' CRPs do not identify risk areas in LECZ. The average densification potential defined by CRPs is 4.7 times that in the LECZ. For the land-use zones within LECZ, the CRPs' average accepted maximum population density is 341.5 (inhab/ha), which is roughly 3.3 times the cities' average population density in those areas (104.2 inhab/ha), according to the 2017 census. Remarkable cases include Talcahuano, which, according to its planning scheme, could increase its current LECZ population 11.3 times, and to a lesser extent, Juan Fernández (8.7), Antofagasta (7.3), Puerto Saavedra (6.4), and Coronel (6.3). Lower-than-average densification potentials are found in Pichilemu, Rapa Nui, and Juan Fernández.

As observed in Figure 4, there is a significant diversity among existing critical facilities and exposed land-use areas as defined by CRPs. The former varies from 4% in Arauco to 47% in Juan Fernández (Figure 4a). In terms of land-use areas defined by CRPs, 54.8% of the total examined LECZ (156 CRP zones) includes residential and mixed uses. This percentage increases significantly in Viña del Mar (78.8%), Valparaíso (63.6%), and Talcahuano (67.8%). Furthermore, 35.5% of LECZ is allotted to commercial and administrative land uses, while 10.5% of the total surface (23 zones) is allocated to green spaces. New buildings are not allowed in only 4.7% of total LECZ areas (40 zones). In Puerto Saavedra, 57.1% of the LECZ is not buildable, while Antofagasta and Juan Fernández also have significant percentages of non-building surface. Finally, Viña del Mar, Valparaíso, Coronel, and Rapa Nui do not have this restriction in their CRPs.



(**a**)



(**b**)

Figure 4. Proportion of exposed (**a**) critical facilities and (**b**) land-use zones located within LECZs (below 10 m.a.s.l.) at each municipality.

Figure 5 shows the densification potential in hazard exposure and presumed exposure analyses. As observed, all CRPs allow for densification in exposed areas, especially in Talcahuano, Coronel, and Arauco, where there are significant changes (up to five times) in the LECZ between existing and potential densities. In Talcahuano, the densification potential between the areas defined by the presumed exposure and the hazard exposure analyses areas is similar (an increase of roughly 260%). This means that the city's CRP does not recognize, in terms of allowed population density, a spatial variability with respect to the coastline. Further, Figure 5 shows an important range in the densification potential across the 12 municipalities, ranging from Coronel with 500% to Rapa Nui with less than 10%.

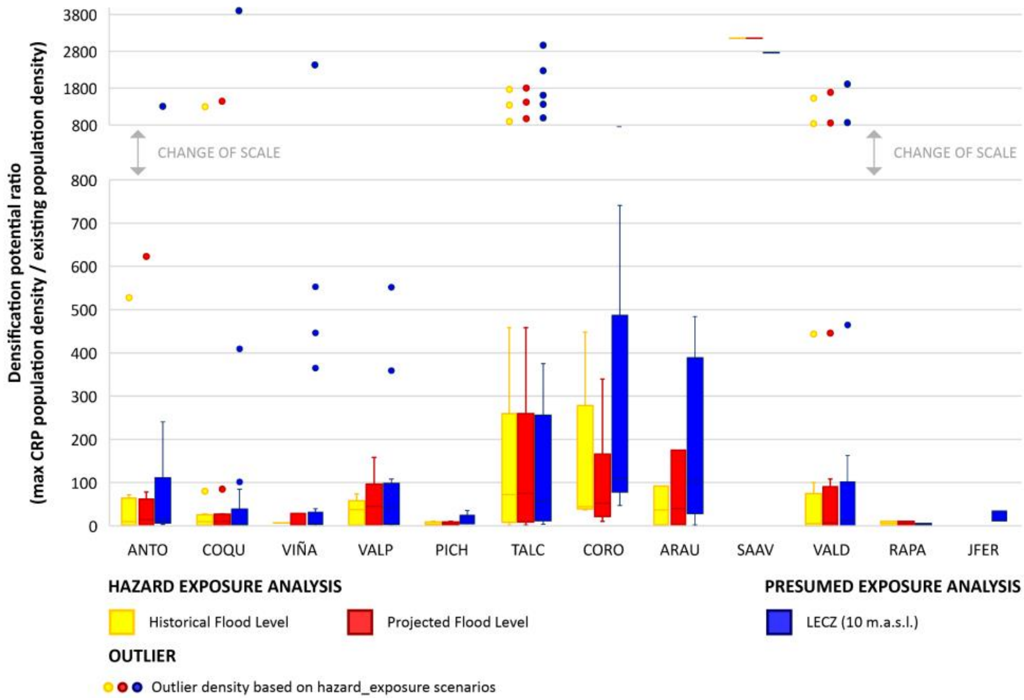


Figure 5. Densification potential and risk areas in the three examined hazard exposure scenarios. The points represent atypical values of allowed densities, much higher than the existing density and outside the average values. (Detailed information can be found in Supplementary Table S2).

3.3. Land-Use Planning Analysis Based on Hazard Exposure Data (Historical and Projected)

Table 4 shows that, except for floodable areas defined as risky in CRPs, changes in indicators between the historical and projected hazard scenarios significantly vary within cases. For instance, while northern municipalities tend to show relatively small growths in the percentage of exposed urban areas (below 6%), southern towns would increase this indicator up to 109% (Arauco). These changes in the exposed urban areas do not directly correlate with the percentage of exposed population: while in Arauco there is no increment, in Valparaíso (which has a +6% increment on its exposed urban area) the increase is 33%. Despite these values, the overall population exposure to flooding hazards is low, with the exception of the island municipalities of Rapa Nui and Juan Fernández, which could reach up to 11.9% and 6.8%, respectively, in the 2026–2045 scenario.

Table 4. Computation of the exposed urban features under flood hazard for the studied municipalities. Values are computed in areas between the mean sea level and the flooding levels for the historical period Z_{his}(1985–2004) and for the RCP8.5 projection Z_{pro} (2026–2045), referred as His and Pro, respectively. The ratio between the projected and historical values (Δ) is also included.

Parameters	Unit	Period	ANTO	COQU	VIÑA	VALP	PICH	TALC	CORO	ARAU	SAAV	VALD	RAPA	JFER	Mean
Exposed urban area	km^2	Pro	6.1	2.5	0.4	0.6	2.4	7.6	5.7	8.3	1.1	18.4	0.2	0.1	4.5
		His	5.9	2.4	0.3	0.6	2.3	6.7	3.7	4.0	0.8	16.1	0.2	0.0	3.6
		Δ	3%	4%	33%	0%	4%	13%	54%	108%	38%	14%	0%	Inf	
Exposed urban area	%	Pro	1.3	3.6	0.4	1.8	10.4	15.7	10.4	18.8	65.5	37.3	3.3	1.0	14.1
		His	1.3	3.5	0.4	1.7	10.0	13.7	6.8	9.0	52.5	32.5	3.3	0.9	11.3
		Δ	0%	3%	0%	6%	4%	15%	53%	109%	25%	15%	0%	11%	
Exposed population	%	Pro	2.2	2.9	0.1	0.4	3.7	3.3	1.2	4.4	0.6	6.8	11.9	6.8	3.7
		His	2.0	2.7	0.1	0.3	3.6	3.2	1.0	4.4	0.6	5.9	8.6	5.4	3.2
		Δ	10%	7%	0%	33%	3%	3%	20%	0%	0%	15%	38%	26%	
Floodable area defined as risky in CRPs	%	Pro	0.0	100.0	0.0	0.0	0.0	0.0	100.0	54.4	0.0	0.0	0.0	100	29.5
		His	0.0	100.0	0.0	0.0	0.0	0.0	100.0	51.9	0.0	0.0	0.0	100	29.3
		Δ	0%	0%	0%	0%	0%	0%	0%	5%	0%	0%	0%	0%	
Exposed critical facilities	%	Pro	12.6	30.2	2.4	2.9	13.8	36.6	8.4	3.0	9.1	34.4	15.6	6.7	14.6
		His	12.1	30.2	0.5	2.9	13.8	36.3	7.0	3.0	5.5	33.9	15.6	6.7	14.0
		Δ	4%	0%	380%	0%	0%	1%	20%	0%	65%	1%	0%	0%	
Exposed wetlands area	%	Pro	7.5	20.3	8.0	0	21.7	26.4	5.1	27.5	94.2	61.5	0.0	0.0	22.7
		His	7.5	19.3	6.1	0	20.9	24.6	1.5	20.5	94.2	58.2	0.0	0.0	21.1
		Δ	0%	5%	31%	0%	4%	7%	240%	34%	0%	6%	0%	0%	
Densification Potential (The densification potential was calculated concerning the accumulated density of each zone incorporated in the CRP, both for the existing density and the CRP density)	%	Pro	7.0	1.9	2.1	8.8	1.4	13.4	7.6	8.4	58.2	0.8	0.8	0.0	9.2
		His	6.4	1.9	7.1	5.5	1.2	12.8	6.7	6.2	58.2	0.5	1.4	0.0	9.0
		Δ	9%	0%	−70%	60%	17%	5%	13%	35%	0%	60%	−43%	0%	

Floodable areas defined as risky in CRPs show little to no change between the historical and projected scenarios. Nevertheless, clear differences are found among case studies: three municipalities (Coquimbo, Coronel, and Juan Fernández) define 100% of their flood areas as "risky", while Arauco assigns this category to 52–54% of its area. In contrast, the other examined towns do not use this classification, even in cases like Puerto Saavedra and Valdivia, where 65.5% and 37.3% of their urban areas are exposed to flood hazard in the 2026–2045 projection, respectively.

As for exposed critical facilities, changes between the 1985–2004 and the 2026–2045 periods are minor, except by Viña del Mar (+380%), Puerto Saavedra (+65%), and Coronel (+20%). It is remarkable that, compared with the presumed exposure analysis, Coquimbo, Talcahuano, and Valdivia maintain significant percentages (~30%, 36%, and 34%, respectively) of their critical facilities exposed to hazards.

The exposure of wetlands to flooding show no significant changes between the historical and projected scenarios, except by the cases of Coronel (+240%), Arauco (+34%), and Viña del Mar (+31%). Of these, Arauco is where the percentage of exposed wetland areas is higher, accounting for 27.5% of its area for the 2026–2045 projection. The other two cases showing high ratios of exposed wetlands for the future scenario are Puerto Saavedra (94.2%) and Valdivia (61.5%).

Overall, the CRPs under scrutiny multiply several times (a mean of 9.2) the population densities in areas prone to flooding in the projected scenario, with extreme cases like Puerto Saavedra, where the current density could be augmented 58.2 times. At the same time, the densification potential shows a decrease between the historical and the projected periods in Viña del Mar (−70%) and Rapa Nui (−43%). This fact responds to higher planned densities located along the coastline, decreasing towards the more elevated inlands.

4. Discussion

4.1. Relation between Presumed Exposure and Hazard Exposure Analysis

In comparison with other countries, Chile has a low percentage of areas and population in the LECZ [14]. The insular municipalities of Rapa Nui and Juan Fernández present the highest percentages of exposed population to flooding within LECZ (23.8% and 16.7%, respectively). Juan Fernández also presents a high percentage of exposed critical facilities (46.7%). On the contrary, Antofagasta and Valparaíso present low percentages of exposed population of 2.6% and 0.7%, respectively, due to different reasons. In Antofagasta this fact may respond to a low percentage of zones with an allowed residential use within the CRP (28.2%) and a high percentage of non-buildable areas (23.1%). In Valparaíso, the residential use is extensively permitted (63.6% of the CRP's zones), and non-buildable areas are not prescribed within the LECZ; at the same time, the city's low-lying zones are undergoing a significant depopulation process, with a current population density of 49.6 inhab/ha, roughly half of the city average [39].

Small changes of +4.68% on average for the 12 municipalities are expected in the projected flood levels for the 2026–2045 timespan, in comparison to 1985–2004. These moderate variations, however, might be sufficient to provoke significant impact in these cities. For instance, the increment in the flooding level could lead to an average rise of 25% in the percentage of exposed urban areas across the examined cities, when comparing these two timespans. In turn, the exposed population increases by 16% on average between the historical and projected periods.

In terms of critical facilities, municipalities that have a high concentration in LECZ, such as Coquimbo (33%), Talcahuano (40%), and Valdivia (40%), have a low change in the projected and historical periods (Δ = 0.67% on average), maintaining a high proportion of critical facilities in analyzed areas and concentrating a growing proportion of residential and commercial/administrative land uses. On the other hand, Viña del Mar, with 41% of critical facilities within LECZ, has a low presence of critical facilities for the historical and projected periods, concentrating mainly on commercial/administrative land uses.

4.2. Perspectives on Local Urban Planning under Risk and Climate Change

Our findings also show that Chile's current CRPs do not appropriately deal with the growing risks associated with climate-driven floods, particularly regarding the potential exposure of population, critical facilities, and wetlands. This may be partly explained by the oldness of some of these instruments (Table 2). Indeed, four of the CRPs were enacted in the 2010s (Coquimbo, Coronel, Arauco, and Juan Fernández); five in the 2000s (Antofagasta, Viña del Mar, Valparaíso, Talcahuano, and Pichilemu); and three have more than 25 years, including Valdivia (1995), Rapa Nui (1971), and Puerto Saavedra (1964); the latter was a response to the 1960 Chile earthquake, which devastated the city. Since the approval of most of these CRPs, there have been significant changes in the legal and political frame of urban planning, the patterns of urban and territorial development, and the climate context. While it is mandatory to Chilean municipalities to update their CRPs every 10 years, the country's mean is 14 years, coastal cities have planning schemes that are 17 years old on average [36], and the mean age of the analyzed CRPs is 22.5 years.

Land-use planning is a technically assisted political action [40]. Diverse and sometimes conflicting interests tend to slow down the planning process, particularly when it comes to the regulation of private land, as is the case of the CRPs [41]. Additionally, a series of "conflicts of rationalities" within the state apparatus come together in the planning process [42]. These conflicts derive from contradictory actions between public organisms, such as those we detected in the municipalities analyzed herein. While central agencies consider urban planning a key aspect to deal with risk and climate change, for instance, through the National Policy for Urban Development [43], local governments are not able to place resilience at the center of the planning process due to technical or financial capacities constrains to update planning instruments. Instead, they undertake unstable and renegotiated resolutions [44] by interrupting the planning process due to private investors or community pressures.

Despite the consensus on the need for a paradigm shift towards risk-sensitive land-use planning [10], the occurrence or recent tsunamis in Chile [45] and the evidence of climate-driven impacts on coastal cities, no clear evidence of risk-based decisions was detected in the analyzed cases. In our neoliberal context, planning is incremental. This implies that policy makers decide by weighing the marginal advantages of a limited number of alternatives and moving ahead through successive approximations rather than long-term objectives [40] (p. 347). In the design process of Chilean CRPs, the impact of climate change in coastal areas is sometimes mentioned in risk studies but not necessarily required to define risk areas in CRPs. The partial exception among the analyzed municipalities is Arauco, whose CRP (2014) explicitly includes the flooding hazard due to rainfall, without any specific translation into guidelines or parameters.

Due to the slow updating of CRPs and the absence of flood zones, not-buildable zones, and risk areas, urban planning at the local level has not been able to prevent the residential growth in lowlands, allowing for their future densification. The most critical cases are Talcahuano (2006), Valdivia (1995), and Viña del Mar (2002), where flood zones with very high densities are not defined as risk areas in their CRPs. In the presumed exposure analysis (LECZ), the planned density in Talcahuano is 11.3 times higher than the existing one, and in Viña del Mar it is 3.3 times higher (up to 1,150 inhab/ha), as shown in Figure 5. In these three cities, around 40% of the critical facilities are within the LECZ (Figure 4).

A significant share of the examined population densities in the case studies' exposed areas could be explained by the attraction to critical facilities (also allowed by the planning schemes), which contribute to consolidate LECZ as urban centralities. In this respect, Benavides [42] show that, since colonial times, particularly after the independence in 1810, the occupation of the Chilean coast has been driven especially by military and port activities located as close as possible to the shoreline, leading to urban structures with a strong inertia to change. This high degree of exposure might lead to future disasters impacting both local and national economies. Our results show, like other cases in the developing world, a lack of capacity to translate the concept of resilience into planning [46].

Despite the inherent limitations of CRPs (for instance, they do not have the power to enforce relocation of housing and facilities), they could potentially promote adaptation to climate change in LECZ. As mentioned above, they can define risk areas where new projects should conduct a risk study stating required mitigation actions. CRPs can also restrict densities. Additionally, CRPs may define urban growth zones in low-risk areas and admit developments in medium-risk areas, requiring public or collective works as adaptation measures above private mitigating endeavors.

CRPs can also ensure adequate levels of land permeability through a series of measures (e.g., delimitation of urban wetlands, green areas, squares, parks, public places, setbacks from the sidewalk, and neighboring properties' requirements) and by defining percentages of land occupation for buildings and permeable land in the unbuilt area of public and private properties. CRPs may also restrict residential use at the street level: through sectional plans detailing CRP zoning codes, local governments can require new buildings to use certain materials and architectural parameters (e.g., height of the first floor with respect to street level, height of doors and windows, forms of access to buildings, or design parameters for front gardens and public spaces). In addition, the Chilean legislation encourages CRPs to establish incentives in zoning codes for private developers to implement sustainable measures. For example, a CRP could have a maximum height standard (e.g., five stories) and award two extra stories if the building incorporates a higher percentage of the permeable area than the minimum required by the zoning code.

Since 2020, with the new system of contributions to public space (Law 21.284), contributions in money or land have been required for all new buildings that increase occupancy density. The monetary contributions are used to finance a portfolio of projects included in an Investment Plan for Mobility and Public Space Infrastructures, which must be consistent with the CRP. These contributions also constitute an opportunity to finance adaptation measures for highly exposed urban areas to flood risk. Now, to implement these measures, CRPs should be updated and approved promptly.

4.3. Limitations of Land-Use Planning Analysis

The main limitation of this study was related to the quality and resolution of the input data used for our analysis. For instance, in some case studies, our computation of the sea level rise had a more detailed resolution than the digital elevation model used to calculate the potential flood areas. Additionally, for developing our inventory of human and natural assets in floodable zones, we had to rely on governmental sources that, despite being official and comprehensive, may lack updating and accuracy in some areas.

4.4. Limitations on th Estimation of the Flood Hazard

The hazard was calculated by summing the tide, storm surge, waves, and sea level rise for the historical period and the projection from various GCMs (e.g., an additive model in which all variables are assumed independent), thus disregarding the temporal sequence of each variable and the nearshore effects waves experience due to non-uniform bathymetries (i.e., diffraction, reflection, and breaking). Our approach provides a single flood level for each municipality, therefore neglecting local effects along irregular coastlines. Local estimates of wave climate could be improved using spectral methods [47], which would require high-resolution bathymetries that are not readily available in some of the studied municipalities, such as Pichilemu and Puerto Saavedra [48].

Additionally, data characterizing the storm surge and tides did not strictly coincide with both the historical period (1985–2004) and the RCP 8.5 projection (2026–2045). Fortunately, tides are periodic and bounded, thus using one particular year (2022) is a reasonable approximation to characterize this variable. Additionally, the choice to use data from 2010 for the historical period and 2040 for the projection to characterize storm surge was grounded on the fact that no other dataset was readily available while conducting the calculations. Nevertheless, as the storm surge is minor due to the steep bathymetry characterizing the Chilean coast and the small fetch of wind generation zones, we believe that using these data should not significantly alter the results of this study.

We also neglected coseismic changes in the elevation shaped by the subduction of the Nazca Plate beneath South America, which could alter the calculation of the flood hazards and exposure. For example, the M9.5 1960 Valdivia earthquake, the largest ever recorded [49], produced a coseismic subsidence of −2.7 m and −1.4 m in Valdivia and Puerto Saavedra, respectively [38], values which are significantly larger than the other variables used to compute flooding levels. The smaller but still important M8.8 2010 Maule earthquake produced coseismic uplifts of +0.75 m and +0.8 m in Talcahuano and Arauco, respectively [50], which are nevertheless still relevant. Though the relatively low probability of occurrence of these events [51] within the analyzed projection (2026–2045) is minor, they should not be disregarded a priori. Along this line, efforts to combine both coseismic seafloor changes and coastal flooding to compute wave overtopping [31] or to explain the role of such changes in shoreline erosion along the Chilean coasts [52] have already been achieved (note that, similarly to the flood level used herein, wave overtopping and shoreline erosion also depend on the tide, storm surge, waves, and sea level rise). The complex interaction between climate-driven changes in oceanographic variables and those associated to the tectonic nature of subduction zones should be addressed in future studies following, for example, the novel approaches of Sepulveda et al. [53,54] in combination with projections of urban growth of cities.

5. Conclusions

In this paper, we examined the degree to which land-use planning addresses climate change adaptation in 12 Chilean municipalities using two approaches: a "presumed exposure analysis", which assumes that the inventory of assets within LECZ (according to the 2017 census) is a proxy of the exposure, and a more refined "hazard exposure analysis", which compares changes in exposure for flooding levels between a historical period (1985–2004) and the RCP8.5 scenario (2026–2045). The presumed exposure analysis of CRPs, which computes an exposure index regardless of the flooding level, could be useful in countries where only census data are readily available, and climate-driven flooding hazard scenarios have not been developed. On the contrary, the much more refined hazard exposure analysis is well-suited for countries where both census data and flooding hazard projections are readily available.

We computed the exposure for both approaches using a digital elevation model and the corresponding inventory of the human and natural systems obtained from several sources. From this inventory, we conducted a content analysis of the communal regulatory plans (CRPs), aiming to identify to what extent these instruments deal with flooding in various scenarios of sea level rise. We believe this is the first study of this kind in Chile and in Latin America.

We showed that, on average, 14.1% of the territory of the 12 municipalities analyzed could be exposed to flood hazards in the 2026–2045 period. While this might lead to a minor impact on housing conditions where, on average, 3.7% of the population live, larger effects could be expected on critical facilities and on urban wetlands, as 14.6% and 22.7% of these systems would be prone to flooding, respectively. In the presumed exposure analysis, these percentages rise to 21.6% (territory), 7.5% (population), 23.9% (critical facilities), and 24.9% (urban wetlands). In addition to these figures, CRPs allow for the future densifications of residential areas (increasing 9.2 times, on average, the current population density for the 2026–2045 projection). Moreover, only four municipalities define floodable zones as "risk areas", a definition that is mandatory to ask developers for mitigation measures in new projects.

The incapacity of the examined CRPs for delivering adaptation strategies for climate change could be related to their antiquity and difficulty in being modified (they are 21.25 years old on average, including two cases from 1964 and 1971). Additionally, the challenges for changing coastal development patterns originated in colonial times. However, CRPs in Chile still do have some capacity to promote adaptation to climate change in coastal areas. Among their available tools, there are mandatory risk studies, restriction of densities, promotion of land permeability, land-use controls, and detailed guidelines for building (sectional plans).

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15043718/s1, Table S1: Computation of exposed systems for the municipalities under study; Table S2: Calculation of the potential densification ratio, based on the CRP areas allowed for residential land use within the LECZ, the RCP 8.5 projection and the historical period 1985–2004.

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Conflicts of Interest: The authors declare no conflict of interest.

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