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Assessment of the flood mitigation ecosystem service in a coastal wetland and potential impact of future urban development in Chile

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ABSTRACT

A worldwide increase in flooding due to climate change and population growth in exposed areas is expected, especially in coastal areas; therefore, nature-based solutions (NBS) for risk reduction are necessary to increase the resilience of cities, particularly in developing countries, which usually lack large budgets for structural measures but have natural areas such as wetlands that can be used as NBS. The flood mitigation ecosystem service of a coastal wetland in central Chile was analyzed. Using hydrological and topo-bathymetric data, two flood hazard scenarios were modeled: (i) S1 current and (ii) S2 projected, which was established based on land-use planning instruments and urban projects developed since 1954. Flood hazard maps for different return periods were obtained and indicators related to the mitigation potential of the wetland were calculated. It was proven that urban project development has intensified since 2000, mainly in the form of real estate development, with an increase in occupation of 50%, and the wetland area is projected to be further reduced by around one third, decreasing potential flood mitigation. Thus, for an extreme return period, in this case 500 years, the water volume stored by the wetland would decrease by more than 38% and the flooded area of the wetland by 30%, increasing flooding and vulnerability of the urban area, with various repercussions for surrounding neighborhoods and infrastructure. The number of people and homes affected would increase by around 6% and 8%, respectively, such that the affected land value would reach an additional US$55 million, which would be very detrimental in a city that has seen its natural spaces encroached upon by gray infrastructure. This research reaffirms the need to support the restoration and conservation of coastal wetlands under pressure from urban development in an area with a lack of green infrastructure planning.

1. Introduction

Wetlands are transition zones between terrestrial and aquatic ecosystems (Cowardin et al., 1979) that provide important benefits to society, or ecosystem services, which are usually classified as: provisioning (food cultivation, water for agricultural use), cultural (appreciation of flora and fauna, aesthetic value, tourism), or regulating (e.g., air purification, erosion protection, microclimate) (Millennium Ecosystem Assessment MEA, 2005; Bertram & Rehdanz, 2015). It is also recognized that wetlands offer important regulating services in natural hazard and flow regulation (Ming et al., 2007; Da Cruz & Lopes, 2018; Ramsar, 2018), such as maintenance of flows during low-water periods and the regulation of flood frequency and magnitude (Kadykalo & Findlay, 2016; Pattison-Williams et al., 2018).

Floods are among the most frequent and extensive hazards globally (Adhikari et al., 2010), and an increase in events worldwide due to population growth in exposed areas, economic growth, and climate change is expected (Tanoue et al., 2016). Therefore, the effort to decrease the effects of floods via mitigation is an emerging topic (Wamsler et al., 2017; VanHeemst et al., 2013; Van Coppenolle et al., 2018; Wu & Chiang, 2018). Traditionally, floods have been mitigated using gray infrastructure approaches (Frantzeskaki et al., 2019; Frantzeskaki, 2019), which have high environmental and economic costs, especially in developing countries where resources are limited and areas

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exposed to flooding have grown substantially (Rojas et al., 2017). However, during the last decade nature-based solutions (NBS) for risk reduction have gained momentum; these solutions entail the use of nature or green infrastructure to complement traditional mitigation measures as a cost-effective and comprehensive approach (Wamsler et al., 2017; Narayan et al., 2017; Van Coppenolle et al., 2018), promoting sustainable urban design and development (Espinosa et al., 2018). Thus, the protection of ecosystems such as wetlands is crucial to halting the impact of hazards in the Sendai Framework (UNISDR, 2015).

It has been recognized that there is a need for scientific studies to strengthen the protection and restoration of wetlands as NBS and to understand their role in flooding (Liu et al., 2018; Pattison-Williams et al., 2018) and runoff processes in urban environments (Yergeau, 2010). Studies in the United States related to recent coastal flooding due to hurricanes and storm surges have demonstrated that wetlands protect infrastructure (Highfield et al., 2018) and that marsh wetlands even prevented $625 million in direct damage from flooding during Hurricane Sandy (Narayan et al., 2017). Gulbin et al. (2019) stressed that wetland loss in closed watersheds in North Dakota (United States) would cause an increase in flood risk in climate change scenarios. Meanwhile, in Latin America, specifically Ecuador, Da Cruz and Lopes (2018) analyzed the benefits of water storage and peak flow behavior on restoration of these ecosystems, showing that they serve as mitigation measures that are also applicable in developing countries. Therefore, this study focuses on the ecosystem service of flood hazard regulation in a coastal wetland in central Chile.

While many studies are focused on developed countries (Tsihrintzis et al., 1998; Simonovic & Juliano, 2001; Lawrence et al., 2019; Gulbin et al., 2019, Javaheri & Babbar-Sebens, 2014; Marsooli et al., 2016; Watson et al., 2016; Narayan et al., 2017; Pattison-Williams et al., 2018), some evidence comes from developing countries in Asia and Latin America (Da Cruz & Lopes, 2018; Wagenaar et al., 2019), in which the impact of flooding is especially damaging due to the low levels of natural ecosystem protection (Tanohue et al., 2016). Most of these studies emphasize wetland restoration or the construction of artificial wetlands to recover flood-regulation attributes such as peak flow reduction, flooded area reduction, and flow velocity. In addition, they have focused on storm surges and hurricanes, with few studies on models related to river floods with a forward-looking approach to the implications of future urban planning. The above becomes relevant when discrepancies have been recognized in relation to the types of wetlands, their storage capacity, and topography when generalizing about their flow regulation capacity (Kadykalo & Findlay, 2016). There seems to be a consensus that further damage to or loss of these ecosystems will exacerbate coastal risk (Narayan et al., 2017) and that different management scenarios must be assessed (Kadykalo & Findlay, 2016).

Numerous important wetland types can be found along the global coast (estuaries-tidal flats, salt marshes, coastal deltas, mangroves, coastal lagoons). However, they are subjected to multiple stressors by urban growth, industrial zones, tourism, and port infrastructure, which have resulted in an increase in their vulnerability and a 35% decrease in their surface area worldwide in the 1970–2015 period (Ramsar, 2018; Darrah et al., 2019). There is a consensus on the function of wetlands as mitigators of flood impacts, and their loss around the world has caused concern due to the evidence of increases in flood exposure in coastal cities. This increased exposure will cause expected losses of US$52 billion by 2050 based on current projections of socioeconomic change (Hallegatte et al., 2013).

Latin America and the Caribbean (LAC) is a region of developing countries with a high degree of urbanization (79.5%), with a population that is expected to increase to 768 million by 2050 (86.2%) (United Nations, 2017; UnitedNations Department of Economic and Social Affairs Population Division, 2019); its cities also present an elevated urban growth rate in low coastal zones (Rojas et al., 2020; Martínez et al., 2020). LAC accounts for the third-greatest natural wetland surface area in the world (16%) (Davidson et al., 2018); however, it is also the region in which wetlands underwent the greatest reduction in the 1970–2015 period (around 59%) (Darrah et al., 2019). Thus, the deterioration of ecosystems in urban and peri-urban areas in LAC is a worrisome situation given its high vulnerability to extreme events (United Nations, 2017), even when there are efforts to mitigate and adapt cities to climate change (Romero-Lankao et al., 2014). For example, in Mexico residential development on wetlands increased socioeconomic losses from natural disasters (Vázquez-González, 2019); therefore, Da Cruz and Lopes (2018) emphasize the need to research the potential benefits provided by wetland conservation to reduce flooding in cities, mainly in Latin America.

Located in South America, Chile is among the countries with the greatest socio-environmental conflicts over the use, degradation, water pollution, and filling of wetlands (Smith & Romero, 2009; Arriagada et al., 2019; Novoa et al., 2020); it also has a high frequency of floods (Rojas et al., 2014), which were the second most recurring and devastating hazard in the 20th century (Camus et al., 2016). Particularly frequent are the events in the Mediterranean region of central Chile, in which 73% of the national population is concentrated. At its southern end is the Concepción Metropolitan Area (CMA), which since 1970 has lost 23% of its total wetland area (Pauchard et al., 2006). This loss has increased over time and is expected to continue due to the development of urban residential, transport, and industrial projects zoned and validated by urban planning instruments (Rojas et al., 2013). In addition, Rojas et al. (2018) indicate that a climate change-induced sea level rise of 60 cm would cause a 4% increase in flood areas, 17% of which would occur in built-up areas and 83% in floodplains and saltmarsh wetlands. Thus, this research analyzes the regulation ecosystem service amid river flooding in a coastal wetland of the CMA, considering the current provision scenario and that projected by urban planning instruments. The implications of this study are discussed in relation to (i) the role of coastal wetlands amid flood processes and (ii) urban planning in a developing country.

2. Methodology

2.1. Study area

The Rocuant-Andalién coastal wetland (36° 44′S 73° 03′ W) is located in the Concepción Metropolitan Area (hereafter "CMA") (Fig. 1) and forms part of the estuary of the Andalién River (715 km^2), which empties into the Pacific Ocean. The wetland is located on fluvio-deltaic deposits of the Quaternary, which originate in the paleo-fluvial system of the Biobío River and the current system of the Andalién River (Munizaga, 2015; Rojas et al., 2017). According to the definition of CONAMA (2008), Rocuant-Andalién is an estuarine intertidal and permanent salt marsh wetland. Due to its position in the CMA and strategic location, it is subjected to multiple stressors resulting from industrial activities and increasing urban land use characterized by urban sprawl (Rojas et al., 2013).

Indeed, Rojas et al. (2019), based on vegetation changes over the last 10 years (2004–2014), found a 10% reduction in the surface area of the wetland. Existing urban planning instruments, such as the Concepción Metropolitan Master Plan (PRMC, its acronym in Spanish), project that only 32% of the current surface area will be maintained in an area of natural value, while the rest will be dedicated to various residential, transport, and industrial land uses, among others. If this PRMC is completed in the coming years, it will result in an increase in urban and industrial zones from 725 ha to 1975 ha around and on the wetland.

This situation is not new; in fact, since 1943, 65.3% of the growth of the city of Concepción has taken place in areas geomorphologically exposed to river floods such as sand plains, sand dune plains, and wetlands. This growth has led to an increase in the magnitude of flooding and, therefore, a 150% increase in neighborhoods affected by flooding between 1961 and 2011 (Rojas et al., 2017). As indicated by Rojas et al.

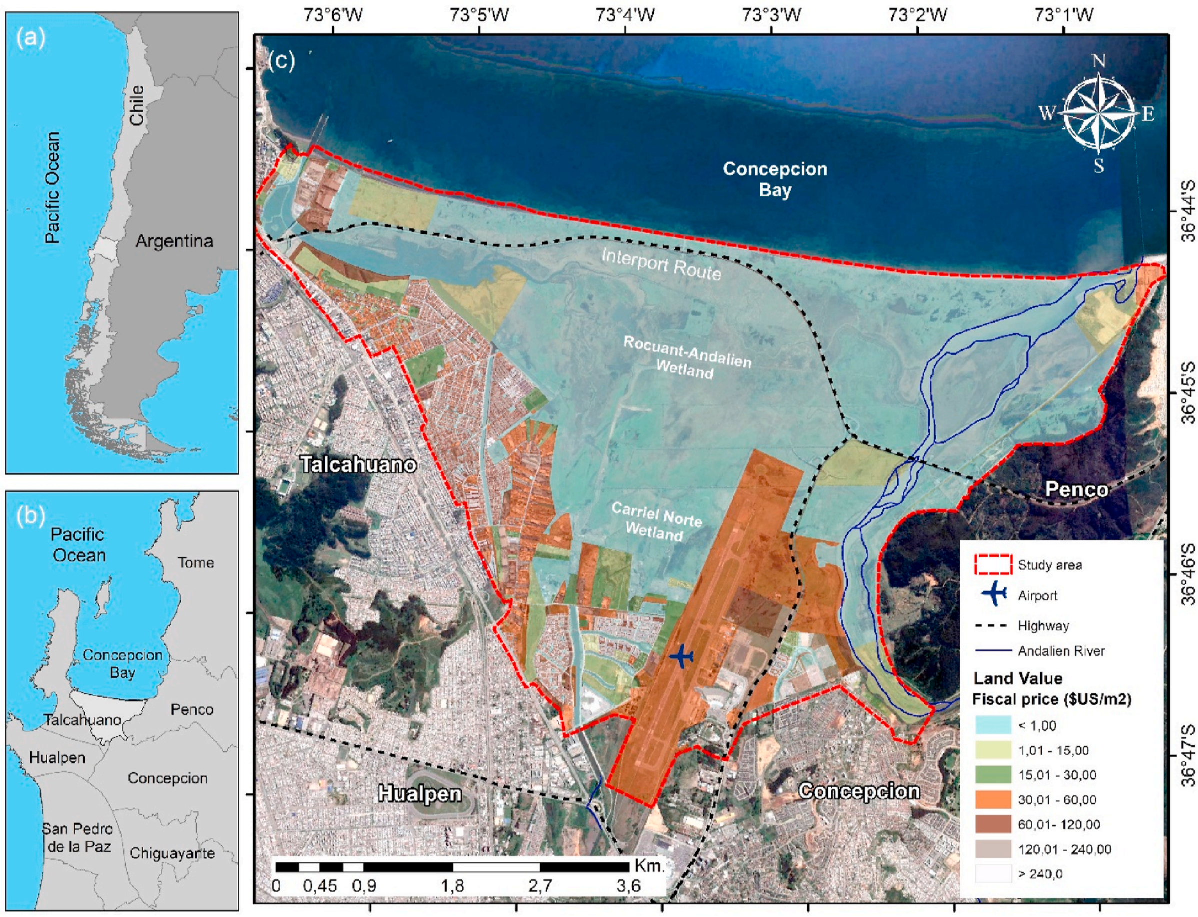

Fig. 1. Study area: (a) Chile location, (b) CMA context in Biobio Region, (c) Rocuant-Andalién Coastal Wetland, includes assessed value of land in the wetland and adjacent urban area in US$ per m2.

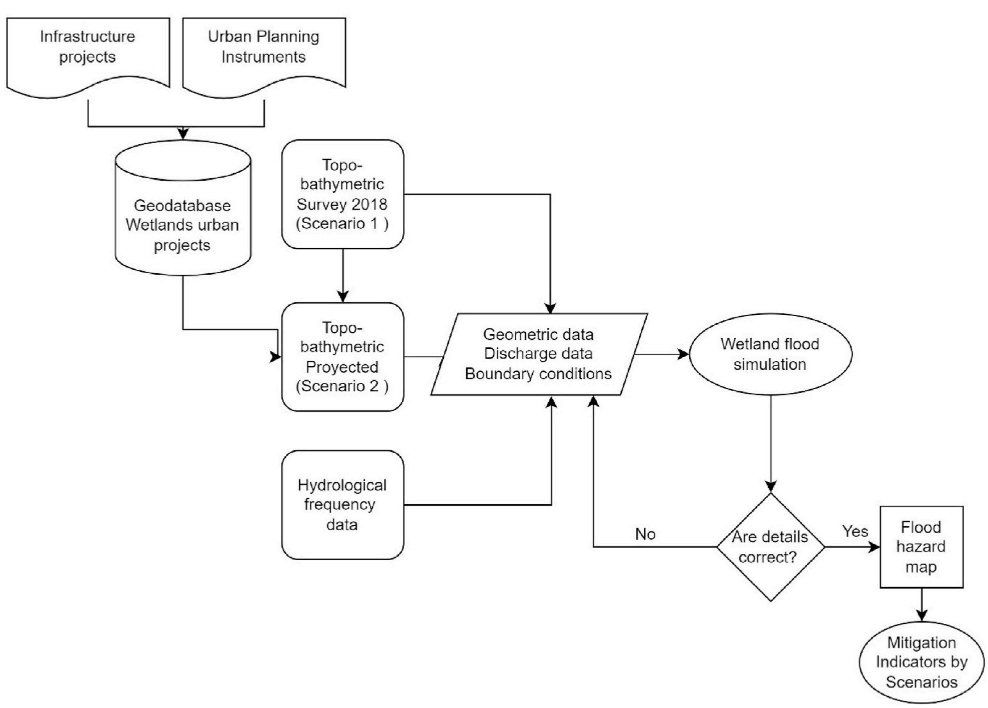

Fig. 2. Methodological scheme adopted in this study.

(2018), in this period 21 river floods were recorded in the austral winter (May–August), with a duration of between 1 and 4 days. The largest-magnitude events occurred in June 1974, August 2002, and July 2006; the last event was the most destructive, with maximum discharges reaching 634 m^3/s, a value associated with a flood return period of T = 100 years. After the 2006 event, flood management based on structural mitigation was implemented, mainly widening and channeling, with little environmental consideration for the affected ecosystems (Rojas et al., 2017).

2.2. Methods

To analyze the role of the Rocuant-Andalién wetland as a river flood mitigator, an integrated method was used. The method consisted of the compilation and systematization in a database of spatial data on urban projects executed and proposed for the wetland and adjacent urban area. Subsequently, a high-resolution topo-bathymetric survey for current and projected conditions according to the urban projects was generated, allowing two flood hazard scenarios to be obtained for different return periods, from which indicators related to the mitigation potential of the wetland were determined. Fig. 2 presents a flow chart that summarizes the development of the methodology.

2.2.1. Urban projects (1954–2018)

An assessment of the temporal evolution of urban projects by decade between 1954 and 2018 was carried out. Investments in current (Scenario 1- S1) and expected urban projects allowed by planning instruments such as real estate development (Scenario 2- S2), industrial development, and road infrastructure on the wetland or in the adjacent urban zone were identified. They were classified in terms of their dates of presentation and execution, responsible party, geographic location, project description, project type, surface area affected, investment amount, and environmental considerations. To this end, official sources presented to the Environmental Assessment Service (SEA, its acronym in Spanish), consisting of environmental impact declarations or assessments, were reviewed. In addition, an in-person search of the archives of the Environmental, Municipal Works, and Production Development departments of the municipalities of Concepción, Talcahuano, and Penco was carried out.

The projects were placed spatially using ArcGIS 9.3 (ESRI, 2009) with the WGS_1984_UTM_Zone 18S coordinate system. In environmental terms, for each housing or industrial complex construction process, the following information was obtained: fill height, soil classification and suitability, presence of flora and fauna, possible synergies between construction processes, and declarations of natural hazards. The obtained soil fill data were integrated into the flood simulations as topographic variables.

2.2.2. Scenarios, input data, simulation, and indicators

A hydraulic simulation of the extent and effects of river floods in the wetland was carried out for five return periods (T5, T50, T100, T200 and T500), considering two scenarios: current (Scenario 1- S1) and projected (Scenario 2- S1). The main variation in the two scenarios consisted of the topographic criterion associated with the urban sprawl and construction fills in the wetland surface in zones validated by metropolitan territorial planning instruments (IPT in Spanish), mainly the PRMC. The socio-economic conditions related to the effects (population, housing, and land value) were kept constant in both scenarios (Table 1).

The input data for the flood hazard model scenarios included geometric data and peak flows. The geometric data consisted of high-resolution (topography and bathymetry) data used to model the two flood scenarios. The current topographic conditions (Scenario 1- S1) were obtained from a 1-m-resolution LIDAR (Light Detection and Ranging) flight, although the flight took place before the structural mitigation measures in the river (widening, channeling, and levees) were implemented. Therefore, a field campaign consisting of a topo-bathymetric survey in a zodiac boat using the dual-frequency Echologger ECS D24S and supported by a TRIMBLE R-4 dual-frequency GPS and linked to geodetic points was carried out. The altitude model data was referenced to the mean sea level (MSL). Finally, a DEM (Digital Elevation Model) updated to 2018 in raster format, with a resolution of 0.77 m, representative of the current conditions, was obtained.

To obtain the topography for Scenario 2 (future conditions of urbanization allowed by the PRMC, corresponding to a wetland loss scenario, two activities were carried out. First, information from urban projects regarding the average heights of the historical fills in the study area, by building height range, was integrated; thus, the values for projected fills in not yet built-up areas were obtained (Table 2). Once this data was obtained, the topography for 2018 (Scenario 1) was modified according to the estimated fills and future urbanization developments established in the PRMC (2003), by height range (Fig. 3).

In the case of the flow data, peak flows for five return periods (T) (Table 3), defined in Arrau Ingeniería (2012) and applied by Rojas et al. (2017), were used. They were obtained via frequency analysis of mean daily peak flows and instantaneous peak flows. These values which were subsequently contrasted with hydrometeorological methods, precipitation-runoff transformation methodologies, and the unit hydrograph technique.

To obtain the flood and depth maps, hydraulic modeling was carried out using the 1D software HEC-RAS 5.0.4 (Brunner, 2010), for which it was necessary to determine the cross sections. They were obtained using HECgeo-RAS 4.3.1 extension in ArcGIS 9.3 (3D Analyst Toolset). Thus, 56 cross sections in the flood plains and Andalién River were generated, with an average distance between sections of 103 m and a variable width of 409–8473 m, which allowed the last 6 km of the river to its mouth to be covered.

In the Andalién River, the mouth of which is on the ocean, it has been shown that there is a tidal influence on flooding processes (Rojas et al., 2018). Therefore, a boundary condition of 1.9 m (tidal height), corresponding to high tide (astronomical tide), without considering the meteorological effects, was defined. For Manning's roughness coefficient (n), values calibrated by Rojas et al. (2018), obtained via field visits and georeferenced photos of the channel and floodplain, were used. The application of this methodology allowed ten flood hazard maps to be obtained in raster format, five for each scenario (S1 or S2). Each map was reclassified according to flow height into three intensities (high, medium, low), adapting the methodology proposed by the Nicaraguan Institute of Territorial Studies (INETER) and the Swiss Agency for Development and Cooperation (COSUDE) (INETER &

Table 1
Criteria used for the flood scenarios.

Criterion/scenario	Scenario 1- S1	Scenario 2-S2
Condition	Current	Projected
Wetland area	767 ha	271 ha
Topo-bathymetry	Updated 2018	Updated PRMC
Boundary condition (tidal height)	1.9 m	1.9 m
Population and housing	2017 national census	2017 national census
Land value	2018 tax appraisal	2018 tax appraisal

Source: authors.

Table 2
Current height ranges and projected meters of fill for Scenario 2, according to the Concepción Metropolitan Master Plan (PRMC).

Current height range (m)	Estimated height by urbanization (m)
−0.5–0	2.5
0–0.5	2.0
0.5–1.0	1.5
1.0–1.5	1.0
1.5–2.0	0.5
>2.0	0.3

Source: Authors.

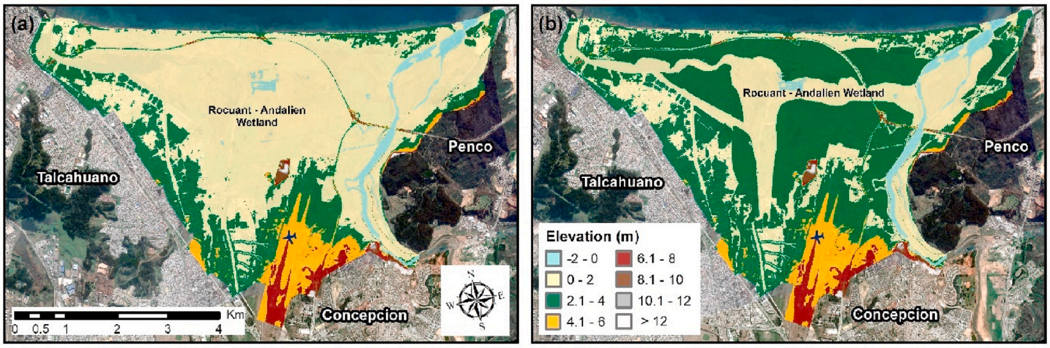

Fig. 3. Rocuant-Andalién Wetland topo-bathymetric data. (a) Current conditions from 2018 (current scenario), (b) estimated conditions due to urbanization (projected scenario S2). A comparison of images A and B shows a loss of wetland surface (−496 ha) (in green) in scenario S2.

Table 3
Estimated peak flows by return period (T).

Return period	Estimated peak flow (m^3/s)
T5	266
T50	565
T100	634
T200	704
T500	828

Source: Rojas et al., 2017.

COSUDE, 2005).

Finally, indicators were used to quantify the flood mitigation potential of the wetland, which was obtained for each return period in the two scenarios. Two physical-natural indicators related to flood dynamics were calculated: flooded surface area (ha/T) and storage volume (m3/T). In the case of flooded area by return period, the indicator was obtained by considering the zones affected by a water column height of over 0.1 m. The storage volume of the wetland was obtained with the Spatial Analyst raster calculator.

To assess the potential for damage from the events, three socioeconomic indicators were used: flooded population (N°/T), flooded homes (N°/T), and the value of flooded land ($US/T). The inhabitant and housing exposure indicators were developed in accordance with data from the 2017 Population and Housing Census (INE, 2017, p. 95). For the land value affected by flooding, tax appraisals of the properties recorded by the Internal Revenue Service of Chile from the first semester of 2018 were digitized in ArcGis 9.3. The information was expressed in raster format (1 m^2) for representation (0.77 m^2) and impact calculation. The socioeconomic indicators were assumed to be constant over time.

3. Results

3.1. Urban project and hazard considerations

In the 1954–2018 period there was a total of 26 investment urban projects in the municipalities adjacent to the wetland, of which 84.6% were executed, while 3.8% are underway and 11.5% are pending execution. The projects are mainly real estate developments (64%) and industrial and logistical infrastructure (16%), with other project types accounting for no more than 20% (municipal, educational, gas pipeline, and road infrastructure). Construction on the wetland was carried out on soil classified as fine sand and organic silt with high or very high moisture in the subsoil (SM, ML or *S*P-SM, according to the USCS classification); indeed, the presence of a shallow water table or ponds was declared. In order to build this infrastructure, fills and 80–95% compactions were carried out.

The number of projects varied by decade. The first projects, entered into the environmental impact system or municipal works offices, were registered in 1954. From 1954 to 1999 only 4 projects were identified, the first of which was a 2.7 ha residential development proposed in 1954 and executed starting in 1962; the company declared the presence of coastal lagoon on a building site, with unhealthy conditions, in reference to the wetland. The main project in this period was the Talcahuano Industrial Park, which was developed in the 1980s and consisted of more than 300 industrial lots. The number of projects increased in the 2000s and 2010s, with total of 23 projects, primarily homes and road and port infrastructure.

Project reports mention studies for the safety and stability of populations; however, they do not incorporate criteria to assess synergy among developments on the wetland. In addition, the presence of flora and fauna was indicated, without identification of species. Regarding the identification of risks presented by the building companies, pluvial flooding, erosion, mass wasting, and processes that would not affect the development of the project are mentioned. River flood processes were scarcely mentioned and/or studied, despite the existence of flood zones found in this study, the results of which are consistent with the high recurrence of these events in the 1960–2010 period shown by Rojas et al. (2017), who determined that 21 river floods had occurred.

It bears mentioning that 80% of the projects entered into the environmental impact assessment system were evaluated through a declaration of environmental impact, a process in Chile that simplifies approval as it requires fewer specific environmental studies. The main future project that would reduce the surface area of the Rocuant-Andalién wetland is the *Biobío Plataforma Logística* (logistical port infrastructure), with a total surface area of 900 ha, on what the project calls the "most important and central soil reserve of the urban system," in reference to the wetland (Biobío Plataforma Logística, 2008). This public-private management project is consistent with PRMC zoning, which includes the approved and projected future development of the industrial and port zone. The study area is subdivided into 12 zones that include: services, activities, distribution and logistical support, airport services, a collection center, business and commercial centers, a tourism park, and an ecological protection zone, which would reduce the wetland to 32% of its current area (Rojas et al., 2019). This scenario was considered for the model of the flood mitigation ecosystem service.

3.2. Coastal flood mitigation indicators

The socioeconomic and physico-natural indicators related to the flood mitigation function of the Rocuant-Andalién wetland were analyzed. The physico-natural indicators presented a generalized decrease due to the possible increase in fill in wetland zones for urban developments. The flooded areas (Fig. 4a) in current conditions (Scenario 1) varied between 1810 ha (T = 5) and 2079 ha (T = 500), while in projected conditions (Scenario 2) the areas varied between 737 ha (T = 5) and 1760 ha (T = 500), demonstrating a decrease of between 30.5%

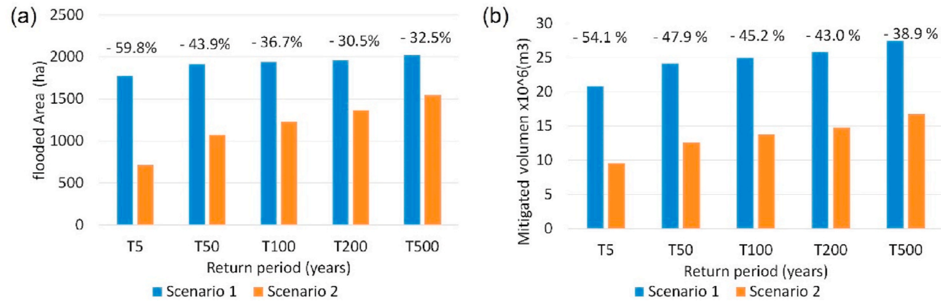

Fig. 4. (a) Total flooded area (b) and total storage area by return period. Percentages express the difference between current (Scenario 1) and projected conditions (Scenario 2).

and 59.8%. Nonetheless, an examination of behavior by scenario for extreme return periods (T = 5 and T = 500) showed that in Scenario 1 the variation in flooded areas was 269 ha (15%), while in Scenario 2 the increase was 1023 ha (139%), which would demonstrate a greater contrast between the most and least frequent events with respect to current flooding behavior. A similar situation occurred with the water storage volume of the wetland; the indicator decreased in the projected period by between 54.1% (T = 5) and 38.9% (T = 500) (Fig. 4b).

Fig. 5 shows the visual comparison of surface areas and hazard levels (high, medium, and low) between the current (a and b) and projected scenarios (a' and b') for return periods related to the most frequent and smallest-magnitude floods (T = 5) versus the least frequent and largest-magnitude floods (T = 500). In general, a decrease in flooded zones between the two conditions (a-a'/b-b') was reported. It was also observed that the decrease was concentrated in the current Rocuant-Andalién sectors, located north of Carriel Sur Airport and east of the Talcahuano urban area, which are associated with an increase in filling works in the marsh.

The global flood hazard analysis indicated that the low (0.1–0.5 m) and medium levels (0.5–1 m) increased in Scenario 2 for return periods of 100, 200, and 500 years, while affected surfaces with depths of ≥1 m (high hazard) decreased, a result of the fills that will take place as part of expected urbanization. This projection does not apply in the current urban zone, where for T = 5 an increase of 35 ha of high hazard area would be expected, which is related to the loss of storage volume in the wetland. For an extreme event of T = 500, equivalent to the flood of 2006 (Rojas et al., 2017), it was found that the affected areas with depths of up to 1 m accounted for 557 ha in current conditions, decreasing the wetland area while increasing the flooded area to 1036 ha.

In addition, the socioeconomic indicators (Fig. 6) present negative behaviors with a tendency to increase the effects of disasters in the projected scenario. Fig. 6-a shows the variation in affected inhabitants in the largest-magnitude projected scenarios (T = 50 a T = 500). As can be observed, the flooded population was greater (2.9%–7.1%) compared to that under the current topo-bathymetric conditions of the marsh. Only for the return period of 5 years was a decrease of 1130 affected inhabitants observed (−4.6%). The behavior of the affected housing indicator was similar; on average an increase of 586 flood-affected homes is expected (T = 50 a T = 500) (Fig. 6-b). However, these projections could be even greater due to the increase in urbanized zones projected by territorial planning instruments, in which residential use will be permitted, which will increase the number of homes and inhabitants relative to the baseline year of the 2017 census.

Regarding the estimation of the value of land affected by flooding (land price), between T = 100 and T = 500 years an average increase of US$44 million between scenarios 2 and 1 was observed. In contrast, for T = 5 and T = 50 years, the trend was the opposite, with the affected land value decreasing by US$28 million, with the greatest difference observed when T = 5 years (Fig. 7). These estimates are directly related to land use and tax appraisals; for example, in areas with recent housing developments (since 1990), tax appraisals varied between US$145–575/$m^2$, while industrial areas presented appraisals between US$35–142/$m^2$. The lowest land values, below US$1/$m^2$, were recorded in the wetland zone. The PRMC (2003) zoning allows the urbanization of the wetland zone, which would result in an increase in land values along with a potential increase in costs associated with flooding events in terms of infrastructure, goods, and people.

4. Discussion

Wetlands in Latin America are disappearing (Darrah et al., 2019), and our study area is no exception. The results show a progressive increase in urban development on the Rocuant-Andalién coastal wetland, one of the biggest wetland areas in Chile. The increase is consistent with the surface area loss reported by Rojas et al. (2019), who indicate that between 2004 and 2014 alone urban areas increased by 28%, while in the future an increase of 238% is expected in accordance with planning instruments. Urbanization pressure by residential, transport, and industrial land uses is undoubtedly among the main reasons for current surface area loss (64% of projects), while in the future road infrastructure development will contribute more to wetland loss. It is expected that urban growth will continue, as the current urban planning policy protects only 1/3 of the wetland (Rojas et al., 2019), which will affect the provision of ecosystem services, especially flood mitigation, as urban development will continue on the floodplain (Rojas et al., 2017) without regard for the value of green infrastructure.

As shown, nature-based solutions (NBS) can significantly reduce the risk of flooding and its impact on infrastructure and society, and measuring the economic value of NBS can help mainstream them (Lallemant et al., 2021). However, in our case study the potential protection the area provides against flooding is neither considered nor quantified in land valuation or urban planning, as the value of the protection provided natural ecosystems is underestimated. As observed in Fig. 1, the Rocuant-Andalién wetland zone presents the lowest land value per m^2 in comparison to adjacent built-up areas, that is, 1 dollar per square meter. The disregard for the value of the protection offered would explain the degradation of the wetland and the exclusion of NBS from risk management, despite it having been clearly shown by Vázquez-Gónzalez et al. (2019) that wetlands have an important monetary value as they mitigate flooding and must be considered in land-use decisions, especially for their value for climate change resilience (Watson et al., 2016).

In coastal Latin American cities wetland loss is influenced by urbanization processes (Rojas et al., 2020), although the Chilean case is particular because the real estate market is a determining agent in land-use decisions and locations, beyond the criteria related to socio-ecological planning or the ecosystem services of the territory, which could be connected to the increased vulnerability of settlements and infrastructure in terms of their ability to respond to certain natural hazards (Camus et al., 2016). According to Da Cruz and Lopes (2018), in Latin America the gap among decision making, scientific research, and the participation of citizens who value these ecosystems must also be

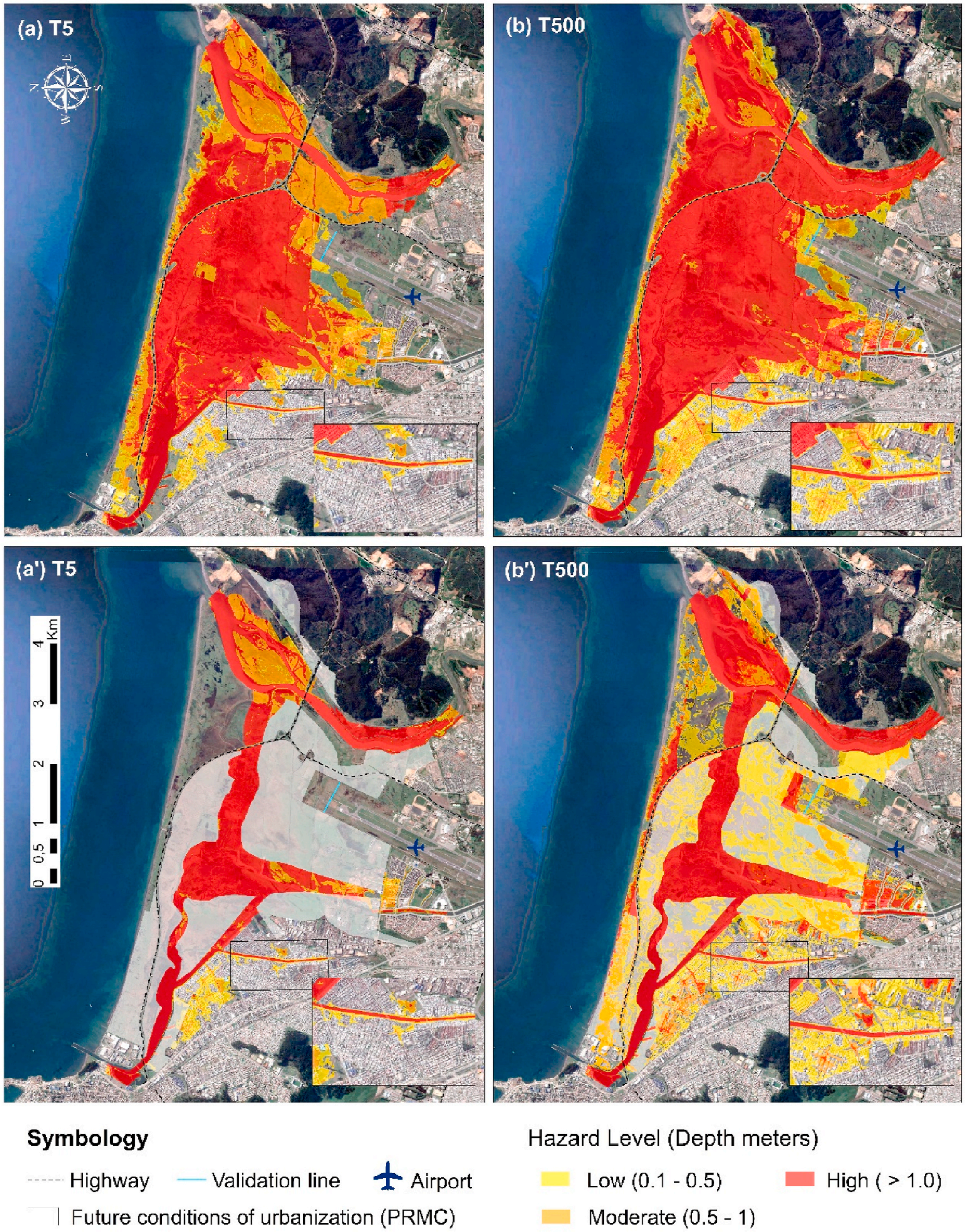

Fig. 5. River floods hazard maps of the Rocuant-Andalién wetland (CMA) for T = 5 and T = 500 years. On top, (a) and (b) show flood area with current topographical conditions; on the bottom, (a') and ('b) show flood zones with a smaller wetland surface due to conditions resulting from projected urbanization.

considered (Banwell et al., 2020).

By contrast, Reed et al. (2018) state that planners around the world increasingly value the conservation and restoration of coastal ecosystems for their provision of ecosystem services. The incorporation of parks and riparian vegetation into flood risk management is also deemed advisable (Browder et al., 2019). There are regional differences between developed and developing countries in this area. Juarez and Kibler (2016) indicate that developed countries favor limits on land use in floodable areas, while in developing countries, where urban governance is weak, it is likely that such measures will be unsuccessful; therefore, territorial actions must be carried out in accordance with sustainability criteria given the ecological fragility of wetlands.

An opportunity to promote NBS arose in Chile in January 2020, when the Urban Wetland Protection Law was enacted. The law aims to regulate the rational use of wetlands in urban planning instruments, incorporating minimal sustainability criteria that will allow them to maintain their surface and groundwater regimes, among others, prohibiting them from being built-up indiscriminately (De Urresti, 2019). This law was passed due to the environmental impact assessment system (SEIA, its acronym in Spanish) and urban planning having no effect on

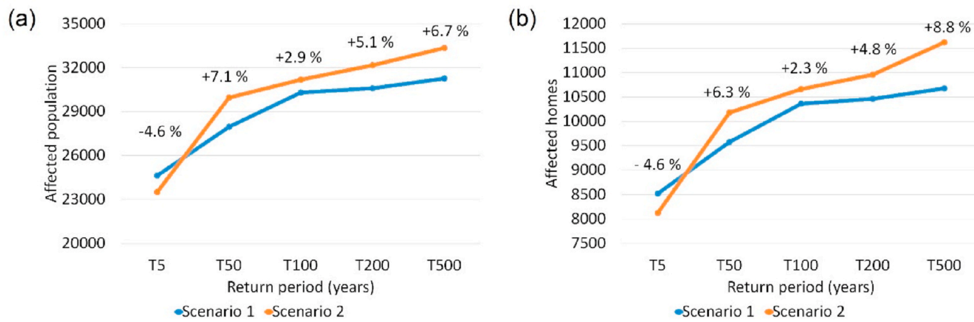

Fig. 6. (a) Total flooded inhabitants (b) Total flooded homes. Percentages express difference between current conditions (Scenario 1) and projection (scenario 2).

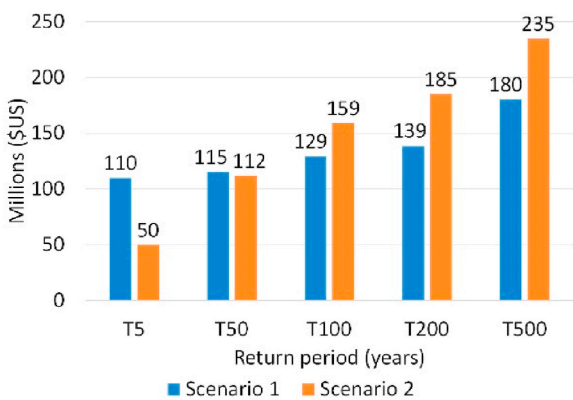

Fig. 7. Value of flood-affected land in million USD for different return periods and scenarios.

the conservation of these spaces in the face of urban expansion (Rojas, 2019, pp. 42–50). Indeed, the review of projects showed a lack of consideration of the impacts of flood hazards and the synergistic effects of the projects. Thus, the law will require every project that would affect a wetland to be submitted to the SEIA, and in terms of urban planning, the law requires that all wetlands located partly or totally within urban limits be zoned as areas of natural value (Rojas, 2019, pp. 42–50). It is hoped that this regulatory change will influence the sustainability of urban wetlands and flood mitigation in cities and increase the risk mitigation benefits of NBS.

In this regard, it is recognized that one of the greatest future challenges in Chile lies in the issue of climate change adaptation linked to land-use projections (Camus et al., 2016). Such considerations were already present in pre-Hispanic times, during which wetlands were respected. For example, the Mapuche-Huilliche people located their settlements according to the distribution of wetlands and river and sea systems (Alfaro et al., 2017). This situation possibly changed with the Hispanic occupation and worsened in recent decades, particularly since 2000, with a slight halt due to the earthquake and tsunami of 2010 (Aránguiz et al., 2020; Rojas et al., 2013).

Our results provide evidence that the Rocuant-Andalién wetland contributes to decreasing the impact of recurring floods on homes and people in the CMA; indeed, its value was recently associated with the tsunami mitigation ecosystem service (Rojas et al., 2019). The disaster regulation service was the ecosystem service most valued by the inhabitants of the city of Talcahuano in a study on perception (Coello, 2017). Our management scenarios with a high degree of urbanization and remnant wetland zones amounting to 32% of the current wetland surface area presented a decrease in storage volume, which increased flooded area significantly in the urban zone. The wetland currently has an area of 767 ha, making it the largest in the CMA. According to Narayan et al. (2017), the disaster reduction capacity of a wetland depends on its area, such that large wetlands are associated with greater reduction potential, and therefore the reduction in surface area would have a negative effect regarding the damage produced by moderate and large floods, as has been demonstrated with respect to the studied wetland. Thus, estimating the value of the land affected by flooding offers an economic basis for stakeholders to understand in monetary terms the benefits of natural ecosystems in coastal areas.

Many researchers propose the idea of restoring or recovering wetlands to mitigate flooding (Pattison-Williams et al., 2018), increasing their surface areas (Simonovic & Juliano, 2001) and storage capacities (Da Cruz & Lopes, 2018). This would allow flood frequency (Simonovic & Juliano, 2001), maximum velocity (Javaheri & Babbar-Sebens, 2014), maximum flows, and flood areas to be reduced (Da Cruz & Lopes, 2018). However, in the case of the CMA and LAC, where there is still a wealth of important wetlands, it is necessary to halt the advance of urban projects with limited environmental criteria to minimize the cost of future disasters. In this regard, Wagenaar et al. (2019) stated that stopping the use of wetlands would save between US$100 million and US$3 billion in future floods in the Colombo metropolitan area, even concluding that the benefit of their conservation is greater than that of structural measures.

This study is among the first to link the hazards zones of flooding due to river overflow using a 1D model in coastal wetlands of a metropolitan area, with projections of the provision of the flood mitigation ecosystem service with alternative urbanization scenarios in Latin America. However, it is possible to further delve into certain variables that appear relevant in other studies: from a natural perspective, focusing on variables such as wetland depth (Javaheri & Babbar-Sebens, 2014) or the influence of submerged and emergent vegetation on flow dynamics during floods (Marsooli et al., 2016); or from a hydraulic perspective, with the incorporation of 2D or 3D hydraulic models that would improve the demarcation of flood zones (Da Cruz & Lopes, 2018). Similarly, the exposed population estimates could be made more precise by incorporating models of population and housing changes in future urban areas.

5. Conclusions

The development of urban infrastructure and residential areas is one of the main causes of wetland reduction in Latin America and in particular the Concepción Metropolitan Area (Chile) (CMA) since 1954. These urban projects, mainly residential developments (64%) and industrial, logistical, and transport infrastructure (16%), have intensified since 2000, protected by planning instruments that do not incorporate ecological planning criteria related to green infrastructure and in which neither disaster-regulation ecosystem services nor opportunities to use wetlands as nature-based solutions were considered with respect to land use. Regrettably, the urbanization model allows the surface area of the wetland to be reduced, causing fragmentation and degradation of the ecosystem and diminishing its ability to mitigate river floods. Three changes are necessary: first, the environmental impact assessment system must consider the synergistic effects of the urban projects using sustainability criteria, second, urban governance must improve by recognizing the importance of these ecosystems to society as a whole, and, third, flood mitigation capacity must be considered in land value estimates.

It is shown that a decrease in the surface area of the wetland will cause a generalized decrease in river flood mitigation for four return periods (T50, T100, T200, T500). In the extreme return period (T = 500) the volume stored by the wetland decreased by 38.9%, with an increase in the flood area in the urban zone of up to 24%, which would cause increases in affected people and homes of 6.7% and 8.8%, respectively, while the affected land value would increase to an additional US$55 million. These figures could be even greater as the estimates are based on the 2017 census and 2018 tax appraisals, which will increase as the wetland is urbanized. The research results could support restoration and conservation of wetlands under pressure from urban development, mainly in Latin America and the Caribbean and other developing regions, where vulnerability to extreme hydroclimatic events is high and nature-based solutions for risk reduction are still little considered.

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Author statement

Octavio Rojas: Conceptualization, Investigation, Funding acquisition, writing - original draft, Writing - review & editing. Evelyn Soto: Methodology, Software, Visualization. Carolina Rojas: Funding acquisition, Writing - review & editing. J. Javier López: Supervision, Writing - review & editing, Supervision.

References

Adhikari, P., Hong, Y., Douglas, K. R., Kirschbaum, D. B., Gourley, J., Adler, R., & Brakenridge, G. (2010). A digitized global flood inventory (1998–2008): Compilation and preliminary results. *Natural Hazards, 55*(2), 405–422. https://doi.org/10.1007/s11069-010-9537-2

Alfaro, A., Urbina, L., Araya, S., & Alvarado, M. (2017). Asentamientos Humanos en torno a los humedales de ciudad de Valdivia en tiempos prehispánicos e históricos coloniales. *Chungará, 49*(3), 359–377 (In Spanish).

Aránguiz, R., Martínez, C., Rojas, O., Hoffmann, C., & López, P. (2020). The generation of new tsunami risk areas due to an intentionally biased reconstruction process: Case study of llico after the 2010 Chile tsunami. *International Journal of Disaster Risk Reduction, 50*(June). https://doi.org/10.1016/j.ijdrr.2020.101727

Arriagada, L., Rojas, O., Arumí, J. L., Munizaga, J., Rojas, C., Farias, L., & Vega, C. (2019). A new method to evaluate the vulnerability of watersheds facing several stressors: A case study in mediterranean Chile. *The Science of the Total Environment, 651*(April), 1517–1533. https://doi.org/10.1016/j.scitotenv.2018.09.237

Banwell, N., Gesche, A. S., Rojas, O., & Hostettler, S. (2020). Barriers to the implementation of international agreements on the ground: Climate change and resilience building in the Araucanía Region of Chile. *International Journal of Disaster Risk Reduction, 50*, Article 101703. https://doi.org/10.1016/j.ijdrr.2020.101703

Bertram, C., & Rehdanz, K. (2015). Preferences for cultural urban ecosystem services: Comparing attitudes, perception, and use. *Ecosystem Services, 12*, 187–199. https://doi.org/10.1016/j.ecoser.2014.12.011

Browder, G., Ozment, S., Bescos, I. R., Gartner, T., & Lange, G. M. (2019). *Integrating green and gray: Creating next generation infrastructure*. World Bank & World Resources Institute. *Technical report* https://openknowledge.worldbank.org/handle/10986/31430.

Brunner, G. W. (2010). *HEC-RAS, river analysis system hydraulic reference manual*. Davis, CA, USA: US Army Corps of Engineers Hydrologic Engineering Center.

Camus, P., Arenas, F., Lagos, M., & Romero, A. (2016). Visión histórica de la respuesta a las amenazas naturales en Chile y oportunidades de gestión del riesgo de desastre. *Revista de Geografía, Norte Grande, 20*(64), 9–20. https://doi.org/10.4067/s0718-34022016000200002

Coello, E. (2017). *Percepción socio-espacial de los Servicios Ecosistémicos del Humedal Costero Rocuant-Andalién, Región del Biobío. Tesis para optar al título de Geógrafo* (p. 95). Universidad de Concepción (In Spanish).

CONAMA. (2008). *Catastro de los humedales urbanos del área metropolitana de Concepción, Región del Biobío, como base para la planificación del manejo ecosistémico* (p. 28). Gobierno de Chile (In Spanish).

Cowardin, L. M., Carter, V., Golet, F. C., & Lahore, E. T. (1979). *Classification of wetlands and deepwater habitats of the United States* (p. 124). Washington, DC: U.S. Fish and Wildlife Service. https://www.fws.gov/wetlands/Documents/Classification-of-Wetlands-and-Deepwater-Habitats-of-the-United-States.pdf.

Da Cruz, R., & Lopes, O. (2018). Incorporating wetlands in hydrologic and hydraulic models for flood zone delineation: An application to Durán, Ecuador. *International Journal of Disaster Risk Reduction, 28*, 375–383. https://doi.org/10.1016/j.ijdrr.2018.03.023. April 2017.

Darrah, S. E., Shennan-Farpón, Y., Loh, J., Davidson, N. C., Finlayson, C. M., Gardner, R. C., & Walpole, M. J. (2019). Improvements to the Wetland Extent Trends (WET) index as a tool for monitoring natural and human-made wetlands. *Ecological Indicators, 99*(December 2018), 294–298. https://doi.org/10.1016/j.ecolind.2018.12.032

Davidson, N. C., Fluet-Chouinard, E., & Finlayson, C. M. (2018). Global extent and distribution of wetlands: Trends and issues. *Marine and Freshwater Research, 69*, 620–627. https://doi.org/10.1071/MF17019

De Urresti, A. (2019). *Historia de una ley pionera y ciudadana de protección ambiental. Vicepresidencia del Senado de Chile*. Ediciones Centro de Extensión del Senado, Ediciones Universitarias de Valparaíso, Pontificia Universidad Católica de Valparaíso (In Spanish).

Espinosa, P., Horacio, J., Ollero, A., Meulder, B., De Jaque, E., & Muñoz, M. D. (2018). When urban design meets fluvial geomorphology: A case study in Chile. In M. Thornbush, & C. Allen (Eds.), *Urban geomorphology* (pp. 149–174). https://doi.org/10.1016/B978-0-12-811951-8/00009-6

ESRI. (2009). *ArcGIS 9.3*. Redlands, CA, USA: ESRI.

Frantzeskaki, N. (2019). Seven lessons for planning nature-based solutions in cities. *Environmental Science & Policy, 93*(January), 101–111. https://doi.org/10.1016/j.envsci.2018.12.033

Frantzeskaki, N., McPhearson, T., Collier, M. J., Kendal, D., Bulkeley, H., Dumitru, A., & Pintér, L. (2019). Nature-based solutions for urban climate change adaptation: Linking science, policy, and practice communities for evidence-based decision-making. *BioScience, 69*(6), 455–466. https://doi.org/10.1093/biosci/biz042

Gulbin, S., Kirilenko, A. P., Kharel, G., & Zhang, X. (2019). Wetland loss impact on long term flood risks in a closed watershed. *Environmental Science & Policy, 94*(January), 112–122. https://doi.org/10.1016/j.envsci.2018.12.032

Hallegatte, S., Green, C., Nicholls, R. J., & Corfee-morlot, J. (2013). Future flood losses in major coastal cities. *Nature Climate Change, 3*(9), 802–806. https://doi.org/10.1038/nclimate1979

Highfield, W. E., Brody, S. D., & Shepard, C. (2018). The effects of estuarine wetlands on flood losses associated with storm surge. *Ocean & Coastal Management, 157*, 50–55. https://doi.org/10.1016/j.ocecoaman.2018.02.017. July 2017.

INE Instituto Nacional de Estadísticas. (2017). *Síntesis de Resultados censo 2017* (in Spanish) https://www.censo2017.cl/descargas/home/sintesis-de-resultados- censo2017.pdf.

INETER & COSUDE. (2005). *Inundaciones Fluviales, Mapas de amenazas. Proyecto Metodologías para el análisis y manejo de los riesgos naturales (MET-ALARN). Agencia Suiza para el Desarrollo y Cooperación COSUDE e Instituto Nicaraguense de Estudios Territoriales INETER*. Managua, Nicaragua : s.n., 2005. (In Spanish).

Ingeniería, A. (2012). *Estudio de Factibilidad y Diseño Definitivo de las Obras de Regulación y Retención de Sedimentos en Río Andalién, Región del Bío–Bío*. Santiago, Chile: Dirección de Obras Hidráulicas Gobierno de Chile, 2012. (In Spanish).

Javaheri, A., & Babbar-Sebens, M. (2014). On comparison of peak flow reductions, flood inundation maps, and velocity maps in evaluating effects of restored wetlands on channel flooding. *Ecological Engineering, 73*, 132–145. https://doi.org/10.1016/j.ecoleng.2014.09.021

Juarez, A. M., & Kibler, K. M. (2016). Integrated flood management in developing countries: Balancing flood risk, sustainable livelihoods, and ecosystem services. *International Journal of River Basin Management, 14*(1), 19–31. https://doi.org/10.1080/15715124.2015.1068180

Kadykalo, A. N., & Findlay, C. S. (2016). The flow regulation services of wetlands. *Ecosystem Services, 20*, 91–103. https://doi.org/10.1016/j.ecoser.2016.06.005

Lallemant, D., Hamel, P., Balbi, M., Ning Lim, T., Schmitt, R., & Win, S. (2021). Nature-based solutions for flood risk reduction: A probabilistic modeling framework. *One Earth, 4*(9), 1310–1321. https://doi.org/10.1016/j.oneear.2021.08.010

Lawrence, C. B., Pindilli, E. J., & Hogan, D. M. (2019). Valuation of the flood attenuation ecosystem service in Difficult Run, VA, USA. *Journal of Environmental Management, 231*, 1056–1064. https://doi.org/10.1016/j.jenvman.2018.10.023

Liu, Z., Zhao, L., Xu, T., Bu, F., Liu, X., & Zhou, D. (2018). Quantification of potential flood inundation areas in the marsh wetland of Honghe National Natural Reserve, Northeast China. *Ecohydrology and Hydrobiology, 18*(4), 355–364. https://doi.org/10.1016/j.ecohyd.2018.10.005

Marsooli, R., Orton, P. M., Georgas, N., & Blumberg, A. F. (2016). Three-dimensional hydrodynamic modeling of coastal flood mitigation by wetlands. *Coastal Engineering, 111*, 83–94. https://doi.org/10.1016/j.coastaleng.2016.01.012

Martínez, C., López, P., Rojas, C., Qüense, J., Hidalgo, R., & Arenas, F. (2020). A sustainability index for anthropized and urbanized coasts: The case of Concón Bay, central Chile. *Applied Geography, 116*, 1–14. https://doi.org/10.1016/j.apgeog.2020.102166

Millennium Ecosystem Assessment MEA. (2005). *Ecosystems and human well-being: Synthesis*. Washington, DC: Island Press. ISBN 1569735972.

Ming, J., Xian-guo, L., Lin-shu, X., Li-juan, C., & Shouzheng, T. (2007). Flood mitigation benefit of wetland soil - a case study in Momoge National Nature Reserve in China. *Ecological Economics, 61*(2–3), 217–223. https://doi.org/10.1016/j.ecolecon.2006.10.019

Munizaga, J. (2015). *Cambios en la superficie del humedal Andalién-Rocuant (2004- 2014). Tesis de pregrado para optar al título de Geógrafo* (p. 122). Universidad de Concepción Concepción. pp. (In Spanish).

Narayan, S., Beck, M. W., Wilson, P., Thomas, C. J., Shepard, C. C., Reguero, B. G., & Trespalacios, D. (2017). The value of coastal wetlands for flood damage reduction in the northeastern USA. *Scientific Reports*, (August), 1–12. https://doi.org/10.1038/s41598-017-09269-z

Novoa, V., Rojas, O., Ahumada-rudolph, R., Katia, S., Fierro, P., & Rojas, C. (2020). Coastal wetlands: Ecosystems affected by urbanization? *Water, 12*, 1–19. https://doi.org/10.3390/w12030698

Pattison-Williams, J. K., Pomeroy, J. W., Badiou, P., & Gabor, S. (2018). Wetlands, flood control and ecosystem services in the Smith Creek drainage basin: A case study in Saskatchewan, Canada. *Ecological Economics, 147*, 36–47. https://doi.org/10.1016/j.ecolecon.2017.12.026. June 2017.

Pauchard, A., Aguayo, M., Peña, E., & Urrutia, R. (2006). Multiple effects of urbanization on the biodiversity of developing countries: The case of a fast-growing metropolitan area (Concepción, Chile). *Biological Conservation, 127*(3), 272–281. https://doi.org/10.1016/j.biocon.2005.05.015

Ramsar. (2018). Global wetland outlook: State of the world's wetlands and their services to people. In *Ramsar convention secretariat*. Retrieved from https://static1.squarespace.com/static/5b256c78e17ba335ea89fe1f/t/5b9ffd2e0e2e7277f629eb8f/1537211739585/RAMSAR+GWO_ENGLISH_WEB.pdf.

Reed, D., van Wesenbeeck, B., Herman, P. M. J., & Meselhe, E. (2018). Tidal flat-wetland systems as flood defenses: Understanding biogeomorphic controls. *Estuarine, Coastal and Shelf Science, 213*, 269–282. https://doi.org/10.1016/j.ecss.2018.08.017

Rojas, C. (2019). *Humedales Urbanos en Chile: Impacto en políticas públicas y el Desarrollo Sostenible. En: Alfonso De Urresti Senado de Chile.* Vicepresidencia del Senado, Ediciones Centro de Extensión del Senado, Ediciones Universitarias de Valparaíso, Pontificia Universidad Católica de Valparaíso. Humedales Urbanos Historia de una ley pionera y ciudadana de protección ambiental (In Spanish).

Rojas, C., Aldana-Dominguez, J., Munizaga, J., Moschella, P., Martínez, C., & Stamm, C. (2020). Urban wetland trends in three Latin American cities during the latest decades (2002): Concón (Chile), Barranquilla (Colombia) and Lima (Perú). *Wetlands Science & Practice, N°37*(N°4), 283–293.

Rojas, O., Mardones, M., Arumí, J., & Aguayo, M. (2014). Una revisión de inundaciones fluviales en Chile, período 1574-2012: Causas, recurrencia y efectos geográficos. *Revista de Geografía, Norte Grande, 57*, 177–192.

Rojas, O., Mardones, M., Martínez, C., Flores, L., Sáez, K., & Araneda, A. (2018). Flooding in central Chile: Implications of tides and sea level increase in the 21st century. *Sustainability, 10*(12). https://doi.org/10.3390/su10124335

Rojas, O., Mardones, M., Rojas, C., Martínez, C., & Flores, L. (2017). Urban growth and flood disasters in the coastal river basin of South-Central Chile (1943-2011). *Sustainability, 9*(2). https://doi.org/10.3390/su9020195

Rojas, C., Munizaga, J., Rojas, O., Martínez, C., & Pino, J. (2019). Land Use Policy Urban development versus wetland loss in a coastal Latin American city: Lessons for sustainable land use planning. *Land Use Policy, 80*(September 2018), 47–56. https://doi.org/10.1016/j.landusepol.2018.09.036

Rojas, C., Pino, J., Basnou, C., & Vivanco, M. (2013). Assessing land-use and -cover changes in relation to geographic factors and urban planning in the metropolitan area of Concepción (Chile). Implications for biodiversity conservation. *Applied Geography, 39*, 93–103. https://doi.org/10.1016/j.apgeog.2012.12.007

Romero-Lankao, P., Hughes, S., Qin, H., Hardoy, J., Rosas-Huerta, A., Borquez, R., & Lampis, A. (2014). Scale, urban risk and adaptation capacity in neighborhoods of Latin American cities. *Habitat International, 42*, 224–235. https://doi.org/10.1016/j.habitatint.2013.12.008

Simonovic, S. P., & Juliano, K. M. (2001). The role of wetlands during low frequency flooding events in the red river basin. *Canadian Water Resources Journal, 3*(26), 377–397. https://doi.org/10.4296/cwrj2603377

Smith, R., & Romero, H. (2009). Efectos del Crecimiento urbano del Área Metropolitana de Concepción sobre los humedales de Rocuant-Andalién, Los Batros y Lenga. *Revista de Geografía, Norte Grande, 43*, 81–93. https://doi.org/10.4067/S0718-34022009000200005

Tanoue, M., Hirabayashi, Y., & Ikeuchi, H. (2016). Global-scale river flood vulnerability in the last 50 years. *Scientific Reports*, (6), 1–9. https://doi.org/10.1038/srep36021

Tsihrintzis, V. A., John, D. L., & Tremblay, P. J. (1998). Hydrodynamic modeling of wetlands for flood detention. *Water Resources Management*, (12), 251–269.

UNISDR (United Nations International Strategy for Disaster Reduction). (2015). *Sendai framework for disaster risk reduction 2015–2030*. http://www.wcdrr.org/uploads/Sendai_Framework_for_Disaster_Risk_Reduction_2015-2030.pdf. (Accessed April 2015).

United Nations. (2017). *Habitat III regional report - Latin America and the caribbean - sustainable cities with equality* (p. 104).

United Nations, Department of Economic and Social Affairs, Population Division. (2019). *World population prospects 2019: Highlights* (p. 40). ST/ESA/SER.A/423.

Van Coppenolle, R., Schwarz, C., & Temmerman, S. (2018). Contribution of mangroves and salt marshes to nature-based mitigation of coastal flood risks in major deltas of the world. *Estuaries and Coasts, 41*(6), 1699–1711. https://doi.org/10.1007/s12237-018-0394-7

Van Heemst, C., Willems, J., Weller, A., van Verseveld, H., Caamaño, D., & Aránguiz, R. (2013). Flood defence alternatives for the lower Bío Bío River, Chile. *Obras y Proyectos*, (14), 22–33. https://doi.org/10.4067/s0718-28132013000200002

Vázquez-González, C., Moreno-Casasola, P., Peralta, L. A., Monroy, R., & Espejel, I. (2019). The value of coastal wetland flood prevention lost to urbanization on the coastal plain of the Gulf of Mexico: An analysis of flood damage by hurricane impacts. *International Journal of Disaster Risk Reduction, 37*(November 2018), Article 101180. https://doi.org/10.1016/j.ijdrr.2019.101180

Wagenaar, D. J., Dahm, R. J., Diermanse, F. L. M., Dias, W. P. S., Dissanayake, D. M. S. S., Vajja, H. P., & Bouwer, L. M. (2019). Evaluating adaptation measures for reducing flood risk: A case study in the city of Colombo, Sri Lanka. *International Journal of Disaster Risk Reduction, 37*. https://doi.org/10.1016/j.ijdrr.2019.101162

Wamsler, C., Pauleit, S., Zölch, T., Schetke, S., & Mascharenas, A. (2017). Mainstreaming nature-based solutions for climate change adaptation in urban governance and planning. In N. Kabisch, A. Bonn, H. Korn, & J. Stadler (Eds.), *Nature-based Solutions to climate Change in urban areas: Linkages of science, Society and policy (theory and practice of urban sustainability transitions)*. Springer. https://doi.org/10.1007/978-3-319-56091-5_15.

Watson, K. B., Ricketts, T., Galford, G., Polasky, S., & O'Niel-Dunne, J. (2016). Quantifying flood mitigation services: The economic value of Otter Creek wetlands and floodplains to Middlebury, VT. *Ecological Economics, 130*, 16–24. https://doi.org/10.1016/j.ecolecon.2016.05.015

Wu, C. L., & Chiang, Y. C. (2018). A geodesign framework procedure for developing flood resilient city. *Habitat International, 75*(May), 78–89. https://doi.org/10.1016/j.habitatint.2018.04.009

Yergeau, S. (2010). *Development and application of a coupled SWMM-MODFLOW model for an urban wetland*. New Brunswick: UMI Dissertations Publishing. https://doi.org/10.7282/T3J1039P. Retrieved from.