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Bibliometric Analysis of Urban Coastal Development: Strategies for Climate-Resilient Timber Housing

Andrés García-Ruiz [1], Manuel Díez-Minguito [2], Konstantin Verichev [1] and Manuel Carpio [3,4,*]

[1] Instituto de Obras Civiles, Universidad Austral de Chile, General Lagos 2060, Valdivia 5090000, Chile; andres.garcia@uach.cl (A.G.-R.); konstantin.verichev@uach.cl (K.V.)
[2] Andalusian Institute for Earth System Research, University of Granada, 18006 Granada, Spain; mdiezm@ugr.es
[3] Department of Construction Engineering and Management, School of Engineering, Pontificia Universidad Católica de Chile, Avenida Vicuña Mackenna 4860, Santiago 7820436, Chile
[4] Centro Nacional de Excelencia para la Industria de la Madera (CENAMAD), Pontificia Universidad Católica de Chile, Santiago 8320000, Chile
* Correspondence: manuel.carpio@uc.cl

Abstract: Urban development in coastal areas has become increasingly important due to the climate crisis and its effects on sea level rise and extreme events, which increased the vulnerability of coastal zones. Therefore, it is important to analyze possible sustainable development techniques in urban planning and residential housing construction based on low-carbon footprint materials such as timber. These techniques should be capable of mitigating the effects of flooding and uncontrolled rises in coastal areas, as well as identifying normative and economic differences in their application in the Chilean context. For this purpose, a bibliometric analysis of 3882 articles selected from the Web of Science database between 1987 and 2022 was conducted, allowing us to identify a range of possible solutions to be developed in the study area. This includes evaluating their potential for normative application and a cost analysis of these solutions. In this regard, housing solutions such as amphibious houses and houses on stilts are two types of flood-resistant homes that are gaining popularity worldwide. Following the technical–economic analysis, it was observed that the solution on stilts can be up to 50% more cost-effective to implement in Chile. However, both options offer a promising solution to minimize the risks of coastal flooding and should be taken into account in the urban planning of coastal areas.

Keywords: urban development; coastal areas; timber; flooding; resilient buildings

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1. Introduction

Urbanization is a community process that favors socio-economic development but also generates environmental conflicts. The urban growth of cities has been the most important human activity in the development of irreversible environmental and ecosystem changes on a global scale in recent decades. This has influenced the social and ecological interaction of our societies with the environment [1,2]. In recent years, the literature has explored the motivations and mechanisms of urbanization [3–5]. Studies related to urban occupation in coastal regions are of great interest, as about 40% of the population lives in coastal areas [6,7]. Certain research identified that urban development is clearly influenced by environmental, geophysical, institutional and socioeconomic conditions throughout the world [8]. In addition, urban centers become focal points for the expansion of neighboring communities, which occupy a larger territory. This is especially significant in coastal areas, which have a terrestrial as well as an intertidal and marine area of influence [9], where a population increase of 20% is expected over the next three decades. In the case of areas of coastal influence (Figure 1) (e.g., coasts, estuaries and wetlands), they have historically been inhabited by humans due to the accessibility to various elements that provided basic needs for human communities [6,9]. At present, the areas of coastal influence favor industrial fishing and tourism development [10–12]. Human community development has been modifying coasts in multiple forms. Many of these changes are permanent, arising as a result of the many activities that take place in the coastal zone, which are carried out by coastal managers and engineers.

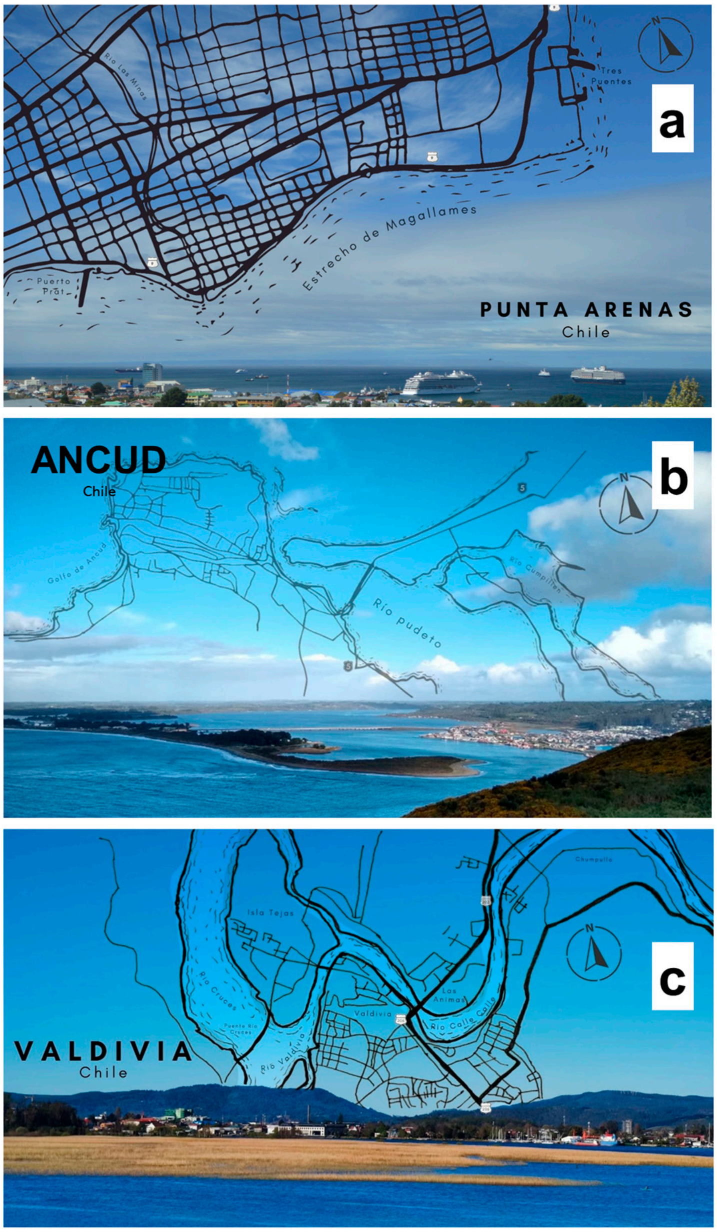

Figure 1. Example of coastal types considered in this work are (**a**) ocean–sea, (**b**) estuary, and (**c**) wetland.

The process of adapting to climate change, and in particular, to rising sea levels, requires strategic and adaptive planning and the forecasting of coastal urban development and the type of architecture for the projected building [13,14]. Therefore, it is essential to know the scientific evolution patterns associated with land use management in coastal cities (LUM-CC) (Figure 1), which will serve as a guide for the Architecture, Engineering and Construction (AEC) industry in the design of public policies and adaptation strategies, since the latter has a fundamental role in reducing the vulnerability of housing built on the coast.

Urban resilience can help address the challenges of climate change in cities by focusing on transforming the political and economic structures that perpetuate the vulnerability of urban communities. This involves putting people and their power at the center of decision-making and addressing the social and economic inequalities that make some communities more vulnerable than others [15]. Some aspects that improve urban resilience correspond to investment in infrastructure, including the construction of roads, bridges and other infrastructure that can withstand extreme events. On the other hand, developing early warning systems helps people to prepare for and respond to extreme weather phenomena. It is also essential to promote sustainable development, which helps to reduce the vulnerability of people and communities to climate change [13]. In this context, the type of residential architecture can help mitigate the risk to communities due to climate change [16]. In Chile, a study was developed to determine the risk of climate change impacts on its coasts, highlighting mainly the risk of flooding in residential areas near the coast [17]. The study concludes that for the entire national territory, a rise of (0.15–0.18 $\pm$ 0.1 m) of the Mean Sea Level (MSL) is expected in the 2026–2045 projection. In addition, an increase of 0.65 $\pm$ 0.3 m of the MSL is projected for the end of the century. Based on this, the study defines Valdivia as a critical commune due to the high number of inhabitants living below 10 m.a.s.l., in addition to the high amount of infrastructure, coastal infrastructure and equipment present below the mentioned elevation. The city of Valdivia presents 20.17% of its exposed area, with a coastline length of 437 km. In response to this need, the main objective of this work is to analyze the global state of knowledge in LUM-CC, identifying trends and key concepts to define sustainable adaptation measures and whether this is possible to realize with the use of timber. This, as a renewable material, offers significant environmental benefits by reducing the carbon footprint of buildings [18]. In addition, its versatility and durability make it an excellent choice for construction. By promoting the use of timber, we are contributing to a more sustainable and healthy future for generations to come [19].

The above, together with a technical–economic analysis for residential housing at risk of coastal flooding in southern Chile, and specifically for the city of Valdivia, will allow us to provide constructive and sustainable alternatives.

2. Materials and Methods

A bibliometric analysis will be carried out to establish the state of knowledge and the trends of scientific development in the last decades. We will then use the gaps in knowledge to develop technical applications in building solutions adaptive to the new climatic reality.

For the literature review, the Web of Science (WoS) databases were used. As shown in Figure 2, the methodology of this work considers two macro groups of analysis associated with coastal cities: "Management plan" and "Land use". The thematic search criteria were developed according to the following: (i) collect scientific articles from WoS databases in knowledge between 1987 and 2022 associated with LUM-CC; (ii) realize a quantitative review using bibliometric analysis and scientific mapping to find trends; and (iii) analyze the results obtained from the bibliometric analysis in order to identify topics of increasing interest.

Scientific mapping shows the structural and dynamic components of scientific work through graphical maps. These graphs represent a given field of knowledge and/or its specialties of individual documents and authors and how they relate to each other.

For the development of scientific mapping, an open-source software, SciMAT (Science Mapping Analysis Software Tool) Version v1.1.04, will be used to aggregate procedures, algorithms and measurements to evaluate each step of the overall scientific mapping workflow [20,21]. SciMAT applies bibliometric measures as important as the h-index [22], g-index [23] and hg-index [24], which describe the productive level of the development of the researcher and report on the number of articles defined. SciMAT was successfully applied in many areas, such as management [25,26], urbanism [27,28], construction [29,30] and health [31,32].

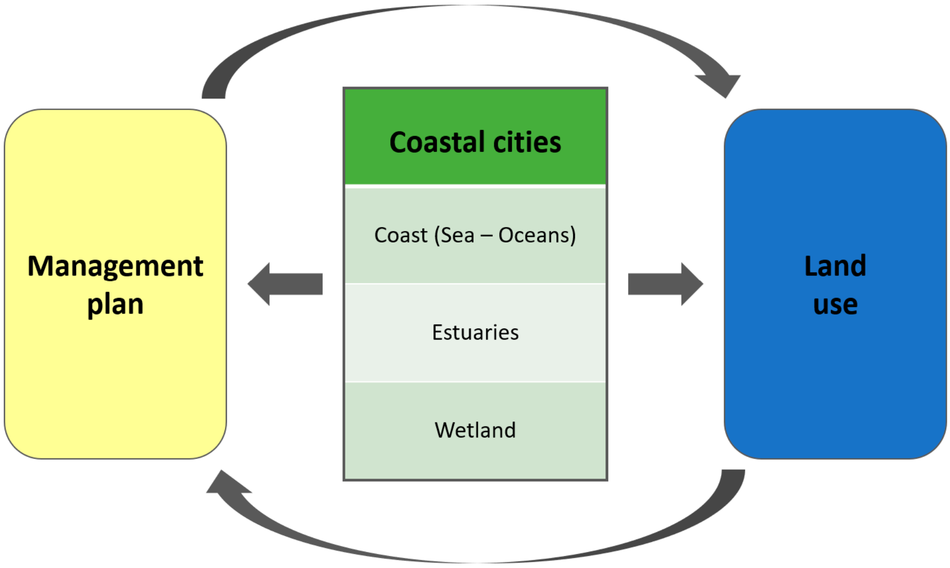

Figure 2. Relationship between the two search macro groups and coastline types.

2.1. Bibliometric Analysis

The bibliometric performance analysis corresponds to a statistical review of bibliometric indicators, such as the number of citations and their published papers (h-index) and the geographical distribution of the most cited papers and authors [33].

The literature search was carried out by identifying the relevant literature associated with the matrix concept LUM-CC (Figure 3), using specific criteria, which avoids any possibility of bias, indicated by Thomé et al. [34] and updated by Díaz-López et al. [29].

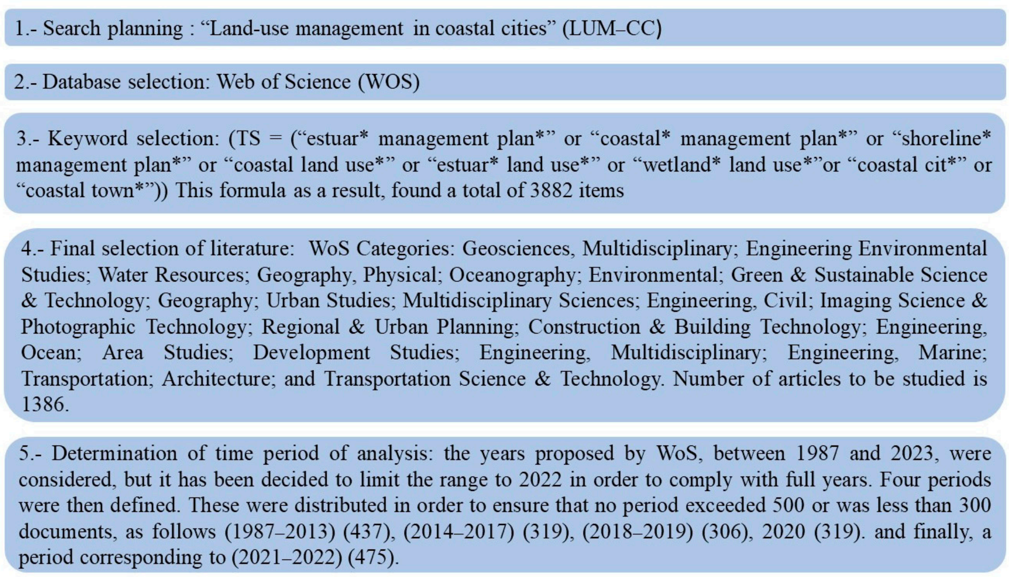

Figure 3. Diagram of selection of research papers. The "*" is used to indicate that the word is singular or plural.

The analysis of scientific maps corresponds to a graphical representation of the temporal evolution of a given field of knowledge and its authors [30], which in this case was developed using SciMAT software. This software performs bibliometric analysis of the content of papers based on scientific mapping using the methodology of Cobo et al., 2012 [20]; this software is a free and open-source scientific mapping tool. These features allow any user to analyze the conceptual, intellectual, and social evolution of a scientific field, as well as to define the importance of the works in the context of different time periods and the link between keywords. SciMAT after bibliometric analysis, generates flowcharts (Figure 4) [29].

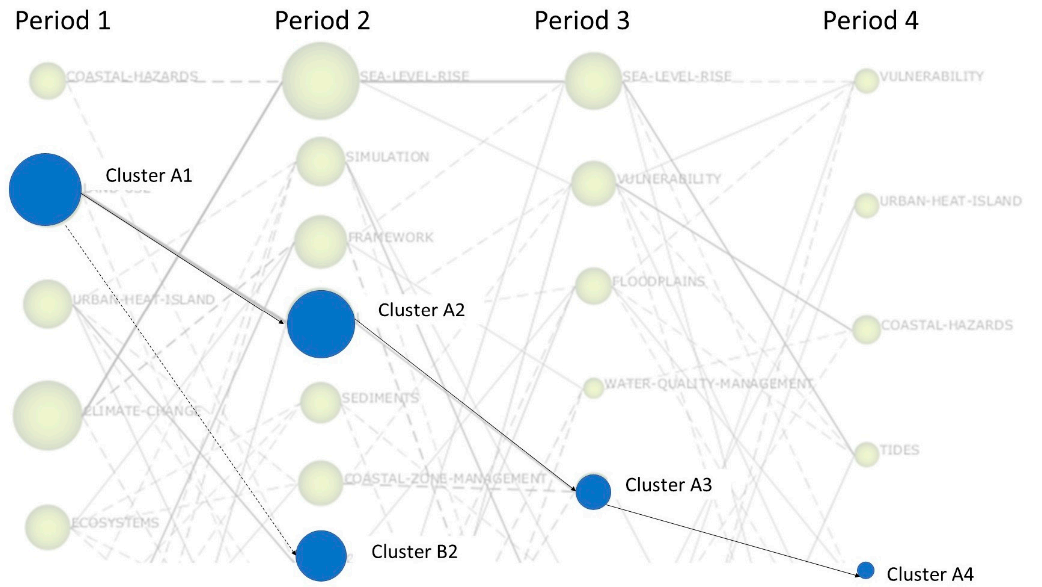

Figure 4. Evolution map. Solid lines indicate that related topics share a keyword; a dotted line shows that topics share words that are not the topic name. The size of the line is related to the inclusion rate.

The thematic evolution map (Figure 4) shows the development of the topics and the relationship between them from one period to another (i to i + 1). The circles represent the different groups, where the size of each group is directly proportional to the number of publications. Solid lines indicate that related topics share a keyword; a dotted line shows that topics share words that are not the topic name. Finally, the size of the line is related to the inclusion rate [35].

2.2. Building Solutions for Urban–Residential Infrastructure against Flooding

After the bibliometric analysis, the incorporation of solutions in buildings to increase resilience to floods in the short term, during and after the event, is estimated. A conscious design of buildings in flood zones includes the choice of building typologies or the integration of material technologies to improve their performance against flood vulnerability [36].

According to the U.S. Federal Emergency Management Agency and the Building Design Council of Canada, for a home to be less vulnerable to coastal flooding, it must have certain characteristics [37,38]. Some of the main features are as follows: (i) the dwelling should be constructed at an adequate height to prevent floodwater from entering the house. The height of the dwelling should be greater than the height of the expected flood level. (ii) The design of the dwelling should be adequate to resist the effects of water and wind. Windows and doors should be wind-resistant and have a watertight sealing system to prevent water from entering the house. (iii) Building materials should be water- and wind-resistant. Traditional materials, such as brick, stone, and concrete, are more resistant than more modern materials, such as plaster or plasterboard. (iv) The house should have an adequate drainage system that allows water to flow away from the house. This may include drainage channels, pumping systems, or elevated ground. (v) The location of the dwelling is important to avoid coastal flooding. The home should be built on an elevated area or on a hill to prevent water from pooling around the house.

Proposed Resilient Building Solutions in Chile

To determine a typical house, the average size of social housing in Chile is established, which varies according to the housing program and the region of the country. According to data from the Ministry of Housing and Urbanism (MINVU) of Chile, the average size of a social housing unit built under the Social and Territorial Integration Program (PIST) is approximately 50 m^2 (Figure 5).

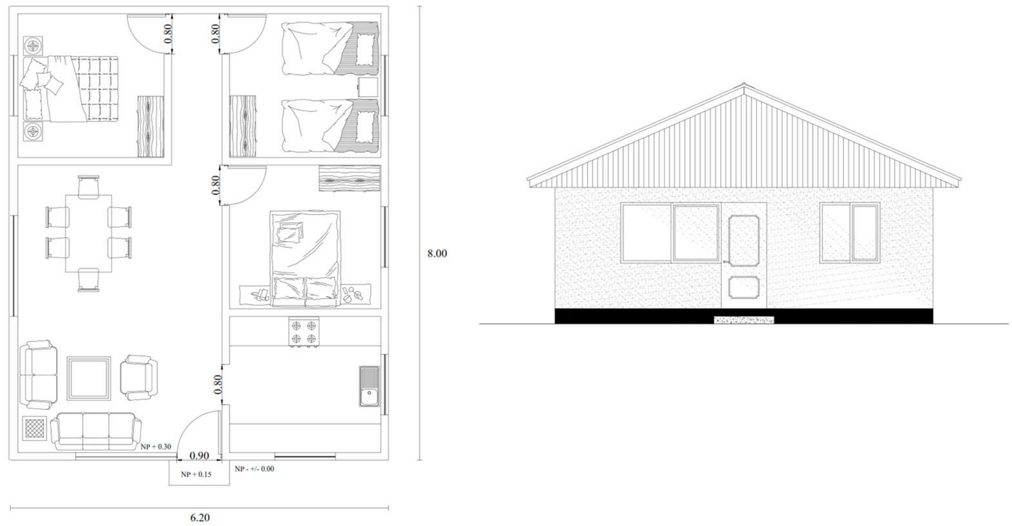

Figure 5. Two-Dimensional plans and elevation of the proposed house.

On the other hand, different construction solutions (Figure 6) were assigned for the walls based on the materials and constructions most commonly used for timber housing in the studied city. These materials and constructions were obtained from the title work "A data analysis of the Chilean housing stock and the development of modelling archetypes" [39]. Constructive solutions for walls in dwellings where the main structural material was timber were considered. The most representative solutions include a plasterboard, glass wool and Smart panel exterior cladding, as well as a plasterboard, expanded polystyrene and fiber cement siding exterior cladding.

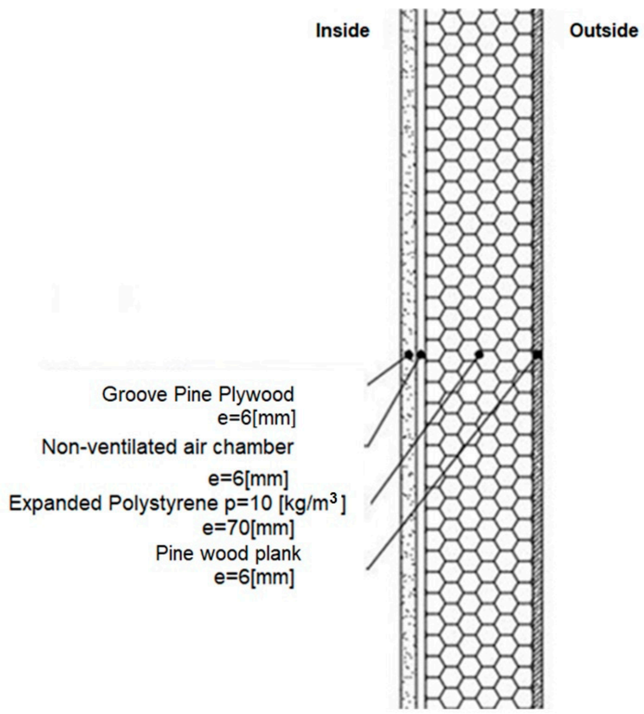

Figure 6. Construction solutions for perimeter walls.

In the case of the roofs, Figure 7 shows the scantlings of Conventional Solution 1 (SC1), which corresponds to a structural system of 2″ × 6″ pine timber for roof beams, with an OSB 11.1 [mm] bracing plate and asphalt shingles, with expanded polystyrene (EPS) insulation of variable thickness according to the thermal requirements of the area (Figure 6).

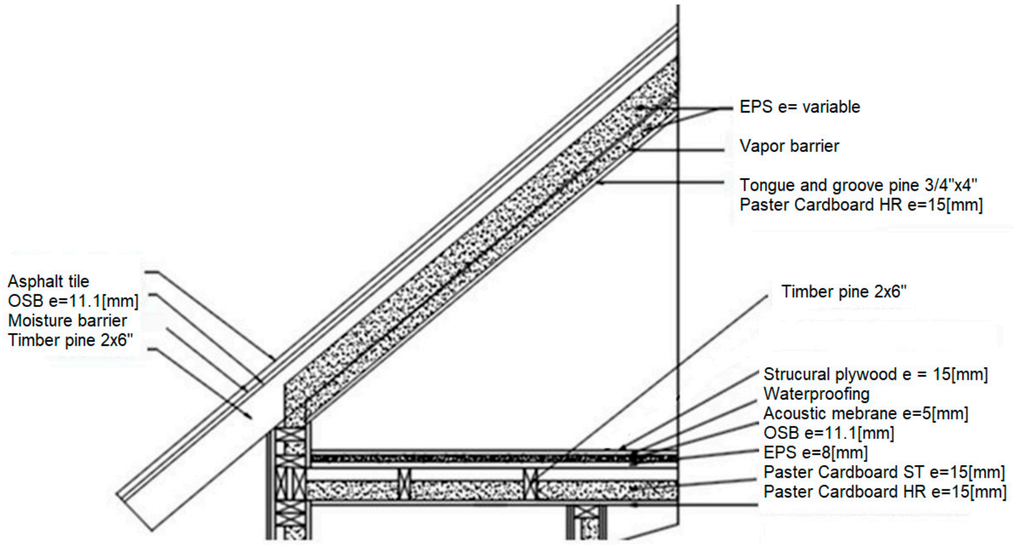

Figure 7. Construction solutions for roofing.

The structure of a floor of a house with timber supports consists of the following components:

- Beams: These are the horizontal supports that support the framing. They are usually made of timber or steel and are 60 cm to 120 cm apart.
- Truss: These are the horizontal beams that support the floor. They are made of impregnated timber and are 40 cm apart.
- Subfloor board: This is the layer of timber that is placed perpendicular to the joists and serves as a base for the finish floor. It will be made of 18 mm plywood.
- Finish Floor: This is the top layer of flooring that provides the walking surface; it will be 1 × 4″ boards. In addition, a 2 cm mortar veneer is recommended for leveling.

The framing, joists, and slab are nailed or screwed together. The subfloor is nailed or screwed to the framing, and the finish floor is nailed or glued to the subfloor (Figure 8).

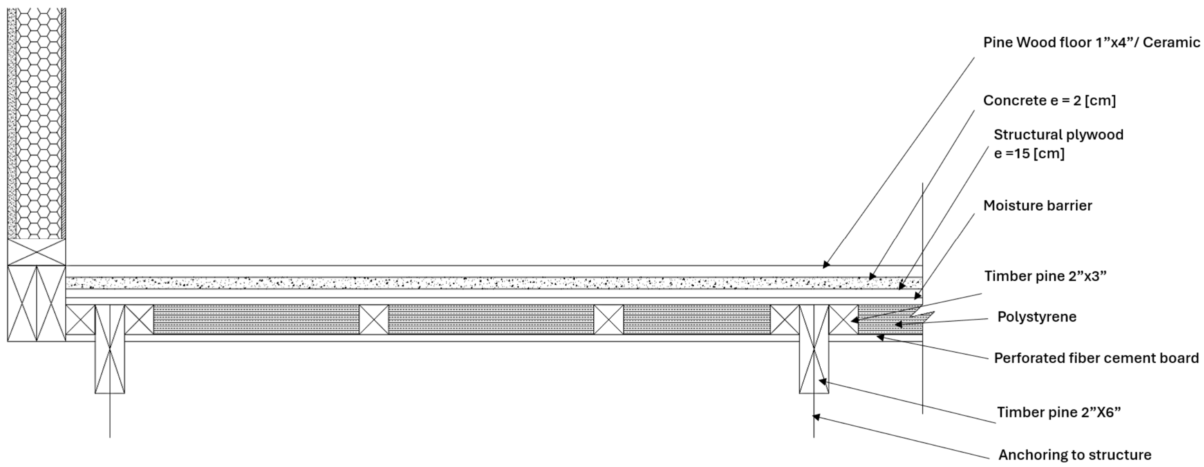

Figure 8. Construction solutions for floor.

2.3. Technical–Economic Analysis

Once the construction methods proposed by the bibliometric analysis and the respective structural design are established., an economic analysis of unit prices is performed, which is a tool used in the construction industry to break down and calculate the cost of each component or unit of a project. It consists of identifying and quantifying the materials, labor and equipment required to complete each activity or element of the project [40]. This type of analysis helps to determine the total cost of a project and is useful for decision-making in project management, so it will be used to establish which of the alternatives is the most economical in the Chilean market. Prices were obtained through an analysis of the construction materials market in the Región de los Ríos of Chile in October 2023, and prices will be presented in USD as of 20 October, according to the official peso/dollar exchange rate reported by the Central Bank of Chile, 1 USD = 941.82 CLP.

3. Results and Discussion

The method of systematic literature research and bibliometric analysis described above was applied to perform an exhaustive analysis of the research field LUM-CC, results that are reflected in the following sections, and how they influence the development of alternatives for the implementation of urban resilience to climate change.

3.1. Bibliometric Analysis

Figure 9 shows the annual distribution of the 1386 publications on the topic under study between 1987 and 2008. It is worth noting that since 2015, when the 2030—Agenda for Sustainable Development agreement was signed [41], there has been a substantial increase in scientific production (100). Between 2019 and 2022, the scientific production was the highest, with more than 5% of the articles analyzed, consolidating the LUM-CC theme due to the interest in climate change, sea level rise and the increasing number of people living in coastal cities [6,9,13,14].

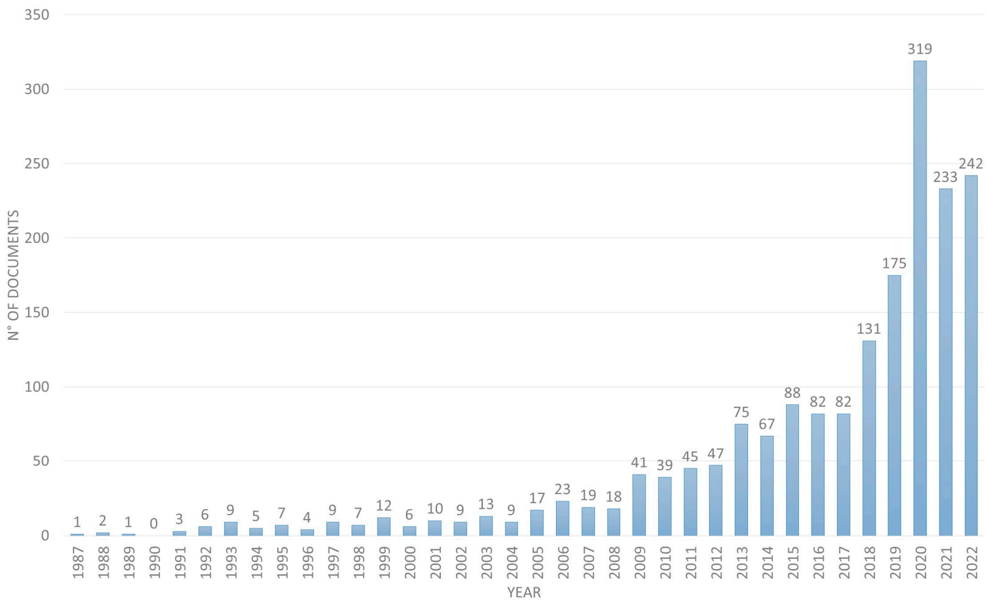

Figure 9. Time distribution of published studies by year.

3.2. Scientific Mapping Analysis

A SciMAT setup was carried out for bibliometric analysis and scientific mapping, in which the word was selected as the unit of analysis, co-occurrence analysis was selected as a tool to construct the networks, the equivalence index was selected as a measure of similarity to normalize the networks, and the k-means clustering algorithm was selected to detect topics. The documents were analyzed according to their year of publication, the journals used, the authors and the number of citations. The results obtained are presented below.

3.2.1. Overly Chart and Thematic Evolution Map for LUM-CC

For the thematic evolution map (Figure 10), the keywords are different in number and lexicography in each of the subperiods: Period 1 (P1): 1987–2013, Period 2 (P2): 2014–2017, Period 3 (P3): 2018–2019, Period 4 (P4): 2020 and Period 5 (P5): 2021–2022 (Figure 6). It can be observed how the clusters associated with LUM-CC have evolved using different keywords to explain the subject matter of the works in each period. For example, in P1, there is the "land-use" cluster, which remains unchanged in the second and third periods (continuous line) and even incorporates the "wetlands" cluster theme in P2, showing its intrinsic relationship with the land-use themes to finally evolve to the "flood" cluster in P4 and P5, which in turn incorporated the "sea-level-rise" cluster theme, generating a relationship of the matrix themes in this period.

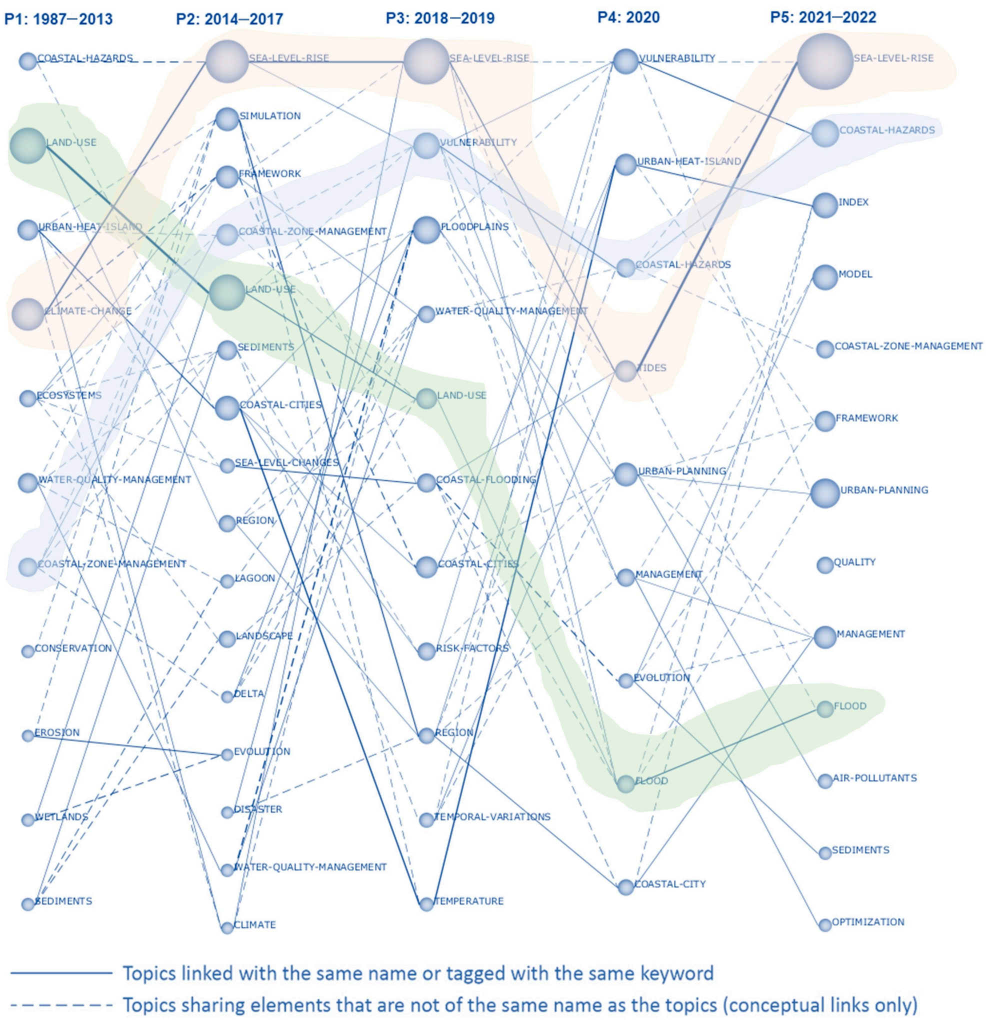

Figure 10. Map of the thematic evolution of research by period.

Considering the "climate-change" cluster, it evolves to "sea-level-rise", a theme that is maintained for P2 and P3, until it joins the "tides" cluster, which in turn returns to the central theme of "sea-level-rise" in P5. On the other hand, the evolution of the P1 cluster "coastal-zone-management" is maintained with this same keyword in P2, then this theme shares a conceptual link with "climate-change" and evolves towards "vulnerability", then to "coastal hazard" and, finally, it continues in "coastal-hazard" in P5.

3.2.2. Research Papers according to Type of Coastline

This section is devoted to analyzing the studies according to the shoreline types to which they refer, as represented in Figure 1: (a) ocean and sea, (b) estuaries, and (c) wetlands. The main studies in each section and the most representative clusters provided by SciMat for these keywords will be presented.

Focusing on the "sea and ocean" cluster analysis, it can be seen that there is a direct relationship between both keywords, which in turn are related to the topic of "prediction", which goes along with what was established in the previous section, presenting the importance of forecasting future coastal climate events, such as sea-level rise, and flood risks in coastal cities [42–45]. SciMat presents the relationship between the sea and land-use, which is reflected in how sea level change makes it necessary to predict the effects it will have on land-use planning in coastal cities [46].

The relationship between the driving theme and the concepts of "sediment" and "water", which in turn are interrelated, is relevant to account for the relationship between sediment transport and accumulation (both natural and artificial) in coastal waters [47].

Regarding the estuarine environment, SciMat shows an intrinsic relationship with wetlands, which is to be expected because of the ecosystem relationships that exist between them [48]. A connection between "management" and "water" was observed in terms of the impact that urban planning adjoining estuaries can have on water quality [49]. It is also linked to the keyword "impact", which points to the urban environment and how it causes changes in the estuarine food chain [50].

Research papers related to wetlands SciMat show the growing problem of wetland loss through the concept of "land reclamation" since land use "management" needs to be improved all over the world [51]. The relationship of wetlands to climate change largely coincides with the work discussed above in Section 3.2.2 [49,50,52]; in addition, a noteworthy work is described in [53], showing the effects of climate change and the state of vulnerability of these habitats to human interventions.

To better understand the temporal evolution of the work, scope and application on each type of coastal area described in this section, Table 1 is presented, showing the knowledge explored by researchers in each of the periods, the research methods used and the scientific debates and conclusions obtained over the years, such as that coastal development requires coordinated efforts from scientists, engineers and government officials, and that multifactorial assessment techniques should be used to consider social, economic and environmental factors in land planning decisions.

Table 1. Summary of major studies by periods and types of coastlines.

Type of Coast	Period	Major Studies	Analysis Tools	Main Conclusions
open ocean	P1	Concern about the economic, environmental and social consequences of climate change [42,54,55].	-Time series analysis. -Local urban database.	Vulnerability indexes against coastal hazard.
	P2 and P3	It is observed that the effects of climate change begin to become latent through the rise in sea level [14,44,45], and as the danger of flooding in coastal cities.	-Data analysis. -Projections new climate scenario. -Numerical models.	The need for joint scientific, technical, but mainly governmental efforts to assess coastal development [56]. Integrating ecological and social engineering.
	P4 and P5	There is mainly an idea of the need for adaptation, indicating that we must assume our new climatic reality [57].	-Analysis of effects of climate forcing on coastal cities. -Satellite mapping.	Deliver new protection tools, not just barriers and/or retaining walls, but updated building codes and nature-based measures that will be more effective in reducing flooding on a longer time scale.

Table 1. *Cont.*

Type of Coast	Period	Major Studies	Analysis Tools	Main Conclusions
Estuaries	P1	Human actions affecting the estuarine environment, construction materials and urban development [49,58,59].	-Satellite visualization. -Analysis of data recorded.	Develop estuarine management planning strategies to integrate urban development through integrated coastal zone management.
	P2	Focus on monitoring both urban expansion [60] and flood risks due to sea-level rise [61,62].	-Satellite visualization. -Multi-criteria analysis [63]. -Hydrodynamic Models [63].	Apply multifactorial assessment techniques for the integration of social, economic and environmental criteria governing land planning.
	P3, P4 and P5	Studies currently assess the flood risk of cities located on rivers close to the sea [64,65] and the use of effective tools to protect cities from flood hazards [66], in addition to resilient housing [36].	-Analysis of data recorded. -Analysis GIS. -Coastal bathymetric measurements.	Improving the integration of field parameters to obtain more realistic simulations. Generate proposals for active mitigation and adaptation, such as the use of mobile barriers and mechanical pumping equipment, which, combined and located closer to the sea, improve effectiveness. and propose different construction solutions for floating, amphibious or pile dwellings.
Wetlands	P1	The influence of climate change on the rise inMSL will affect coastal erosion, water salinization and wetland deterioration [43,46].	-Time series observation. -Local urban data.	The need for proactive adaptation plans, which evaluate (1) protecting, (2) accommodating or (3) removing infrastructure [53].
	P2 and P3	There is a concern about how the urban expansion of cities reduces the surface of wetlands [67,68].	-Analysis GIS. -Numerical models.	Implement intelligent management strategies to help solve the coastal erosion problem, considering a multi-criteria decision analysis to identify the most desirable management regimes [69].
	P4 and P5	Concerns about the risk of flooding of wetlands due to the rise in MSL are reopened [57]. In addition to the effects of pollution derived from human activities on these habitats [70]	-Evaluating satellite images.	Include coastal infrastructure adaptation measures, evaluating economic and social factors and considering soft strategies.

3.2.3. Evolution of Wetland Research

By evaluating the classification of published research articles by coastal type, it was found that urban planning in estuarine and wetland coastal zones accounts for 11.9% and 8.9% of all papers, respectively, while research in marine and oceanic coastal zones accounts for 79.2%. This gives us an idea that research on the effects and future conditions in coastal wetland zones is not yet consolidated and evolving over time. Furthermore, this shoreline type (wetlands) was chosen because these environments are often early indicators of ecosystem change because they are very sensitive to variations in MSL and the disturbances this can cause in their biogeochemical and hydrodynamic processes, as they represent biodiversity hotspots, supporting the presence of multiple habitat niches and, therefore, species of major environmental concern [71].

Therefore, wetland coastal urban (WCU) was included as a subsection of the CZM. Of the total number of articles analyzed in this study, 67 wetland-related articles are shown in Figure 11.

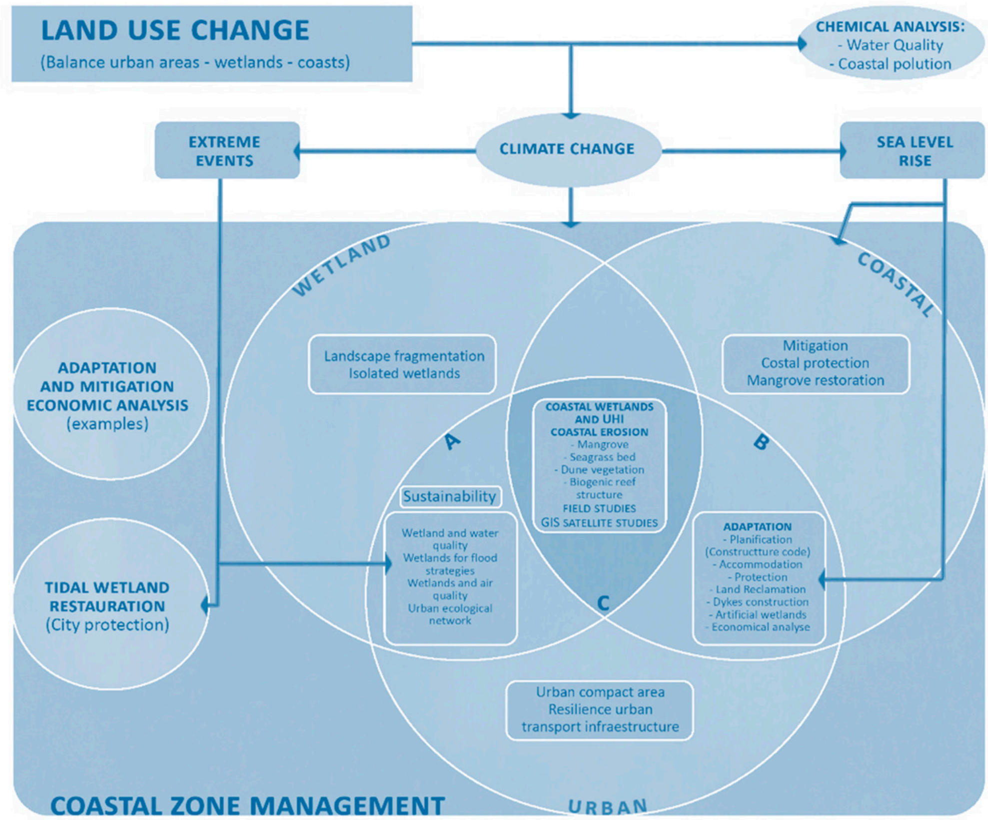

Figure 11. Summary of research trends in the entire time series of work on land use and management in coastal cities, focusing on wetland areas. A: Wetland–Urban Interaction; B: Urban–Coastal Interaction and C: Wetland–Coastal–Urban Interaction.

Figure 11 shows the connection between land use, urban wetland development, and their relationship with the riparian zone, all within the CZM. The figure shows how the works focused their analysis mainly on climate change and the various temporal dimensions of its effects and its impact on the riparian zone. On the one hand are extreme events (increasingly prevalent on the planet), namely the sustained mean sea-level rise, implications and problems for CZM, the first of which requires increased urban protection and economic problems generated by inadequate preparation for extreme events [53] and sustainability impacts (urban–wetland), in aspects such as water and air quality [72,73]. On the other hand, the rise in MSL, being a systematic condition of the planet, causes the need for adaptation in coastal cities and their housing infrastructure (urban-coastal), such as changes in building codes and regulations, creation of protection zones, artificial wetlands and amphibious housing [36,57,74,75].

Analyzing the problem of finding a balance between these three aspects, studies over all time periods showed a steady loss of wetland areas because of urban development. As early as the 1980s, it was shown that human settlement in the South Florida wetlands altered CH_4 sources, resulting in an area loss of about 33.6% between 1900 and 1973 [76]. Alternatively, using GIS methodology to estimate urban areas in Mazatlán, Mexico [49], an increase in urban areas between 1973 and 1997 (25.1 km^2 to 54.5 km^2 + 117.3%) and a decrease in mangroves (9.11 km^2 to 7.71 km^2 − 15.5%) was found. These were not the only works that showed this trend; other works, such as [71,77–80], highlight this problem worldwide. On the other hand, wetlands with coastal influence add to the anthropogenic threats of surface loss, the effect of climate change responsible for SLR. Early work in this area warned that a sea-level rise could reduce 2800 km^2 of wetlands, requiring a protection cost of USD 43.6 billion (1990) [53]. Therefore, recent decades have seen work showing numerous alternatives for protecting wetlands and coastal infrastructure [26,57,64,74,81], as shown in Figure 12.

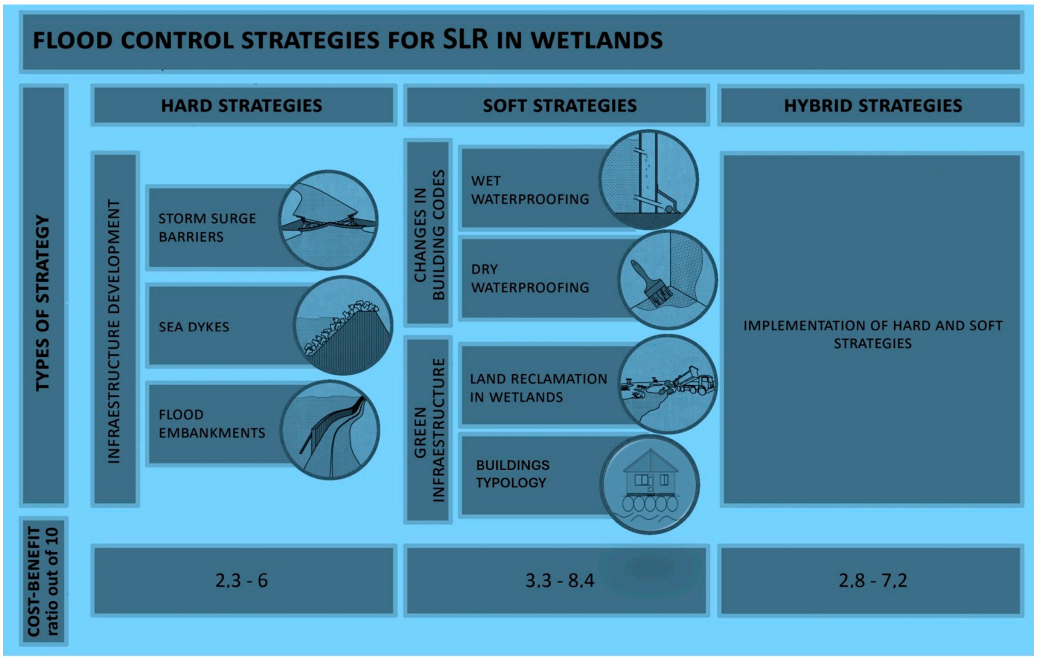

Figure 12. Flood control strategies for SLR in wetlands and its cost/benefit ratio of 10 according to [57].

All of these flood control strategies described above were subjected to a cost–benefit analysis to assess the economic feasibility of their implementation [82]. In the case of the cost–benefit scale in Figure 12, it is the element of economic evaluation proposed by Aerts et al., 2014 [83], that estimates both the initial investment and the cost of maintaining each solution in Figure 12. Benefits are expressed as a reduction in the expected annual damage of the evaluated site; if the cost/benefit ratio > 1, then the NPV (net present value) > 0, and the strategy is economically attractive [57]. In all strategies shown in Figure 12., the cumulative benefits can recover the total costs (i.e., initial investment and maintenance costs).

As for hard strategies, they mainly correspond to storm surge barriers, sea dikes and floodwalls. The main purpose of these elements is to prevent the area in question from flooding during a storm or high tide. In the case of a storm surge barrier, it is usually a mobile structure that usually closes before a storm and then opens again to facilitate the transport of goods and boats, while seawalls and flood control walls are rigid structures that are used to protect coastal communities, tidal inlets, rivers and estuaries from extreme weather events [84]. These solutions were used in projects such as the Venice Lagoon, the Port of Rotterdam, Shanghai and New York City [64,84–86].

On the other hand, soft strategies are related to indirect flood risk protection planning, such as the improvement of building codes, including, for example, wet flood protection materials, dry flood protection or the provision of flotation and/or rising of dwellings [16,82,83,87].

These measures are aimed at protecting individual property, while artificial wetlands, which correspond to land reclaimed from the sea (through sand reclamation) [81], and the different types of flood resilient housing, which, according to the U.S. Federal Emergency Management Agency and the Canadian Building Design Council, for a home to be less vulnerable to coastal flooding, it must have certain characteristics [37,38], like height; the dwelling should be built to an adequate height to prevent floodwater from entering the house.

The flood risk can be greatly reduced by hard protection strategies (e.g., storm surge barriers). In comparison, soft strategies (e.g., wetlands) have a higher cost/benefit ratio but result in higher residual risk. A hybrid strategy that combines the elements of hard and soft strategies is superior to both single-strategy approaches in terms of reduced future risk and a higher cost/benefit ratio [57]. As shown in Figure 12, it can be seen that the greatest cost–benefit can be obtained from soft solutions that originate from both material solutions and housing construction strategies [57]. Measures related to the reclamation of land redirected to anthropogenic construction sites led to a significant reduction in natural habitat. This, combined with economic activities associated with massive construction, can lead to contamination of the entire coastal ecosystem [74]; therefore, these types of soft solutions are not recommended for use by themselves, and solutions with different housing typologies are recommended.

This can start with houseboats, which range from simple structures to luxury homes with modern conveniences. Some houseboats are small and compact, whereas others are large and spacious [88]. Houseboats can also be permanent or mobile, meaning that they can move from one location to another. Houseboats are typically built on a floating platform made of timber, metal or fiberglass. Houseboats can also be connected to an electrical and water grid, or they can be self-sufficient with solar panels and rainwater-harvesting systems [75].

3.3. Analysis of Building Typologies

Four housing typologies were previously identified in the bibliometric analysis summarized in Figure 12: housing with an open first floor, floating housing, amphibious housing, and housing on stilts.

For open first-floor dwellings, physical vulnerability was observed, implying possible damage to the buildings. The intrinsic characteristics of the building design are relevant, such as the quality and quantity of the openings, as well as the orientation of the walls with respect to water flow [89]. In addition, their main structural construction material is reinforced concrete and ventilated roofs are made of aluminum or PVC plus glass, whose carbon footprint is very high [90]. Another aspect that affects the selection of this type of housing for the study area is the seismic component, which affects the perimeter protection of this type of housing, which is not necessarily flooded. Floating homes are typically built on floating platforms made of timber, metal or fiberglass [75]. The problem with this type of housing is that in Chile, there are no regulations that regulate it, in addition to being at the mercy of the effects of tsunamis that typically hit the heights of this country [91].

According to the aforementioned, the implementation of amphibious and resilient pile housing was selected for a deeper analysis. A cost–benefit analysis was performed to evaluate the economic feasibility of its application [82], and one of the amphibious types and the other built on piles were analyzed. Their construction is considered in Chile, and both share the same architecture and precepts of the Ministry of Housing and Urbanism. The area of application will be the city of Valdivia, as it is one of the main cities in the country and a center of tourism and economic development in the Los Ríos Region [92]. In addition, its geomorphological conditions, being immersed in a wetland area and having one of the rivers with the highest rainfall discharge during the year [93], as well as suffering from the effects of the earthquake and subsequent tsunami of 1960 [91], make it a promising study area for applying resilient construction solutions.

3.3.1. Structural Weights and Materials for Typical Housing

Table 2 shows the calculation results of the structural weight of each of the elements described in Section Proposed Resilient Building Solutions in Chile for the selected SERVIU house, as well as its overloading according to Chilean standard NCh1537 [94], establishes the requirements for the design and construction of earthquake-resistant buildings in Chile. It defines parameters to evaluate the strength and stability of structures, considering the seismic activity of the country. In addition, it addresses aspects such as soil classification, seismic loads and requirements for safe construction in seismic events.

Table 2. Weights of superstructure and secondary elements for studied house.

Wall			
Component	Area (m^2)	Unit weight (kg/m^2)	Total weight (kg)
Groove Pine Plywood	120.72	9.8	1183.1
Non-ventilated air chamber	120.72	0	0
Expanded polystyrene	120.72	0.7	84.504
Pine wood plank	120.72	10.26	1238.5872
		Total:	2506.19
Roof			
Component	Area (m^2)	Unit weight (kg/m^2)	Total weight (kg)
Asphalt shingles	27.36	7	191.52
OSB	27.36	7.65	209.304
Moisture barrier	27.36	0	0
EPS	27.36	3	82.08
Vapor Barrier	27.36	0	0
Cardboard plaster RH	27.36	35	957.6
Pine 3/4 × 4″ × 4″ tongue-and-groove joint	294.12	0.94	276.47
Pine 2 × 6	47.88	2.76	132.15
		Total:	1849.1256
Ceiling			
Component	Area (m^2)	Unit weight (kg/m^2)	Total weight (kg)
Waterproofing	49.6	0.005	0.248
Concrete overlay	49.6	48	2380.8
Structural paving	49.6	7.74	383.904
EPS	49.6	2	99.2
Cardboard plaster St	39.5	11.8	466.1
Cardboard plaster Rh	10.1	35	353.5
		Total:	4014.95
Floor			
Component	Area (m^2)	Unit weight (kg/m^2)	Total weight (kg)
Moisture barrier	-	-	-
Truss 2 × 3	160	1.21	193.6
Polystyrene	-	-	-
Pine main beam 2″ × 6″	48	2.76	132.48
Mortar	49.6	48	2380.8
Structural plywood	49.6	7.74	383.904
Perforated fiber cement board	49.6	3	148.8
Ceramic	49.6	1.11	55.056
		Total:	3294.64
		Total weight	11,664.91

An additional weight should be considered due to the overload of use (NCh 1537, 2009), which is 200 kg/m^2. This value refers to the weight of people and all objects in a dwelling. For this 50 m^2 house, the total live load weight would be 10,000 kg. Therefore, the total weight is, with the wall, 21,664.91 kg.

3.3.2. Design Amphibious House

The house is mounted on four stainless steel guide posts that allow the house to be raised and lowered with water. Residents can enter through the front steps, and a stop is placed on the guide rod at the height of the maximum flood level. The waterline is the point where a building begins to float due to Archimedes' principle of buoyancy (Equation (1)) [16].

$$U = \frac{G}{(A * P)} \tag{1}$$

where U is the vertical drop below the waterline in m, G is the dead load of a built structure in KN, A is the area of the floating body in m^2 and P is the density of water in kN/m^3. If the weight of the vane is less than the thrust force it experiences, it will float. For this purpose, it is necessary to implement buoyancy systems, which are described below.

With the background of the weight of the structure, we proceed to determine the elements for buoyancy using the method developed by [16]. A total of 11 fiberglass tubes 8.2 m long and 0.6 m in diameter are recommended, as they can displace an amount of water equivalent to 24,860 m^3. The weight of the displaced water is 24,860 kg, which is greater than the total weight of the structure, including the floating base, which is 21,330 kg. The difference between the two most unfavorable weights is 3530 kg in favor of buoyancy. The arrangement of the piping system can be seen in Figure 13.

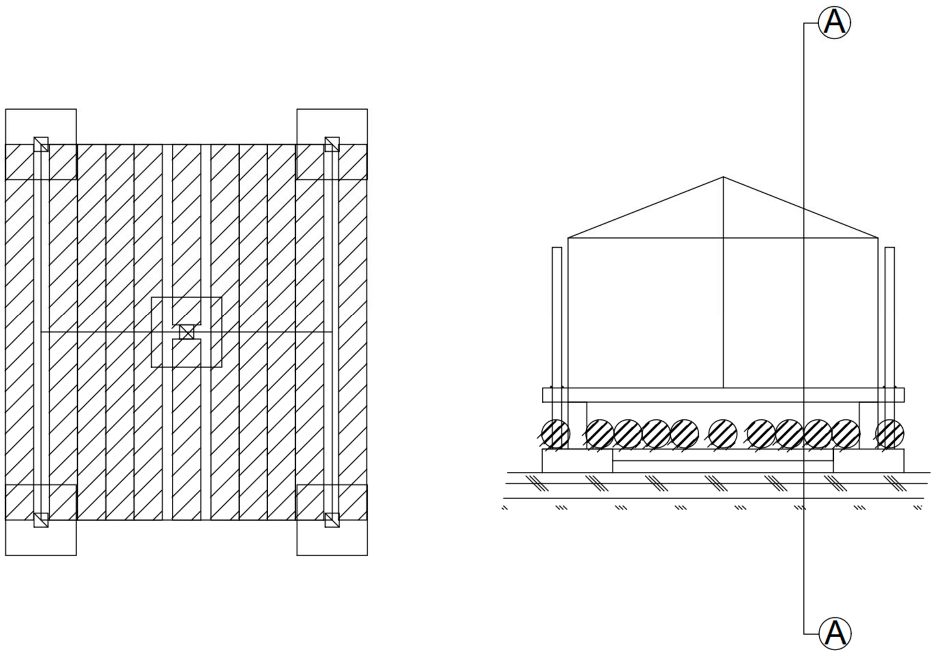

Figure 13. Arrangement of the fiberglass tubes, both in plan and in elevation view.

For the Archimedes equation for vertical drop (Equation (1)), the vertical drop below the waterline, U in meters, is equal to the dead load of the constructed structure, G in KN, divided by the area of the floating body, A in m^2, times the density of the water, P in kN/m^3. For this structure, G = 216.66 kN, A = 50 m^2 and P = 10 kN/m^3, so U = 216.66/(50 $\times$ 10) = 0.43 m.

According to Archimedes' principle, the upward force exerted by a fluid that opposes the weight of an object immersed in it is equal to the weight of the fluid that is displaced by the object. The depth of a building's foundation is calculated by considering the weight of the building and the weight of any object that will be placed in it.

Therefore, it is advisable to adopt a minimum drop of 1 m below ground level. It is not necessary to check the stability of the proposed house because it is attached to vertical guide posts.

Footings were used to calculate the foundations, as shown in Figure 14a. These footings had a dimension of 1.0 m by 1.0 m and a thickness of 0.5 m and were checked for shear and overturning. The footings were placed outside the floating structure, as shown in Figure 14b.

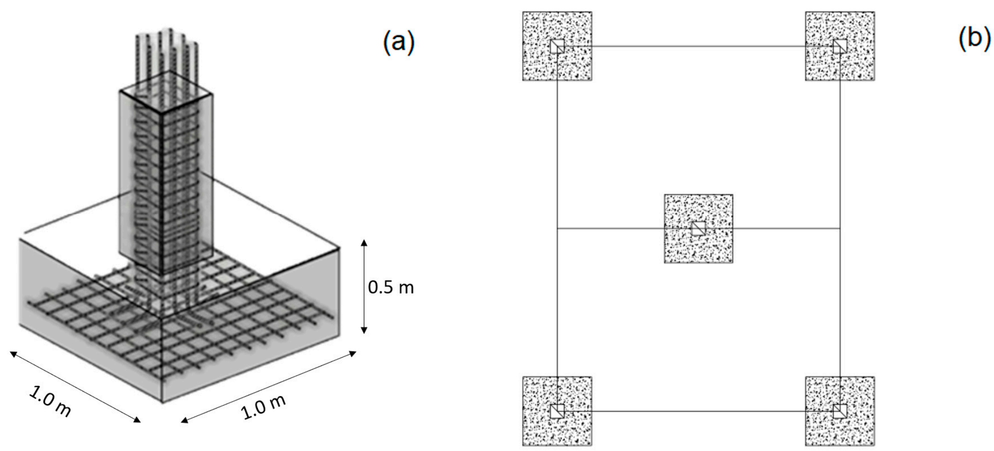

Figure 14. (**a**) Diagram of the type of isolated footing and its proposed dimensions. (**b**) Distribution of isolated footings under the surface of the amphibious house.

For the guide posts, there will be four stainless steel posts of section 20 × 20 cm, which will be interconnected to the floating structure of the house. The vertical mooring system will be anchored to the platform by means of the fender rollers [95]. Figure 15 illustrates this system, which shows how the pile rollers transmit the horizontal loads to the lateral system. These allow the house to move up and down through permanent connections to the water level. Residents can access the house via steps leading to the porch and front door. In addition, a stop is placed on the guide post at the height of the maximum flood level from the top of the platform [96]. The maintenance actions of the amphibious house elements were exposed to a humid–salty environment. For the fiberglass tubes, it is necessary to use epoxy resin paint, as it provides a coating and resistance to water and reagents such as chlorine, salt and PH variations. For the metal structure, an anticorrosive paint is applied, which forms a protective layer on the surface of the metal that prevents contact with oxygen and water, and finally, spray lubrication for the fender rollers [16].

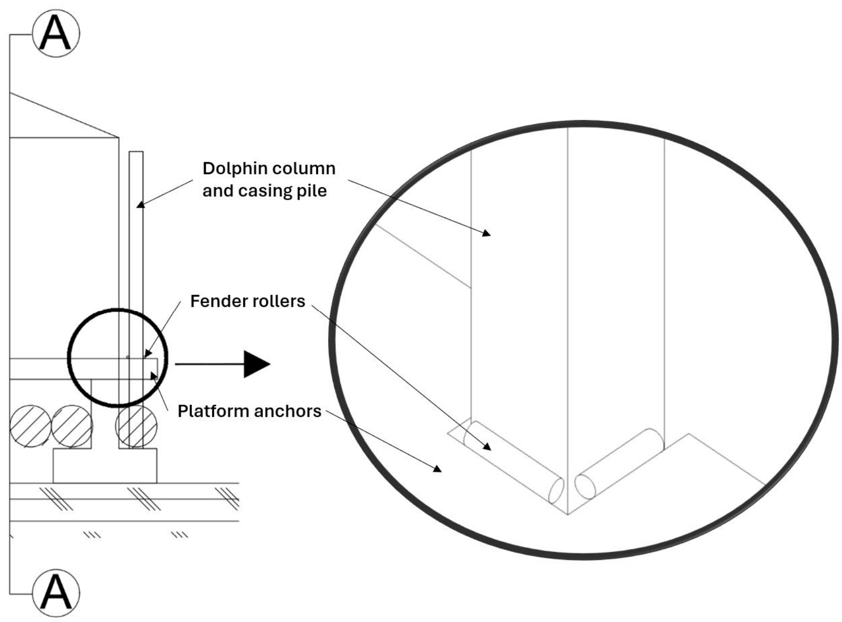

Figure 15. Example of anchoring and sliding guide posts to the floating house structure design house on stilts.

In Chile, construction on stilts is highly popular on the island of Chiloé, where they are called "palafitos", a series of houses built on timber pillars found on the coast. These houses originated in the 19th century when the fishermen of the area needed a place to store their tools and fishing nets. Over time, the "palafitos" became permanent homes for the fishermen and their families [87]. As indicated in the "palafitos" protection manual, the posts of the houses on piles must receive preservative paint that protects the supporting structure from the action of humidity and salinity of the environment. In this case, we selected the paint called carbolineum, also known as vegetable creosote, a liquid of natural origin that has antiseptic and preservative properties [97].

In the case of the design of the piles for this house, a distribution of elements will be followed, as shown in Figure 16. With a total of 13 piles, verification will be carried out for an unfavorable study area soil of the sandy silt type with σ_{adm} = 0.5 kg/cm^2.

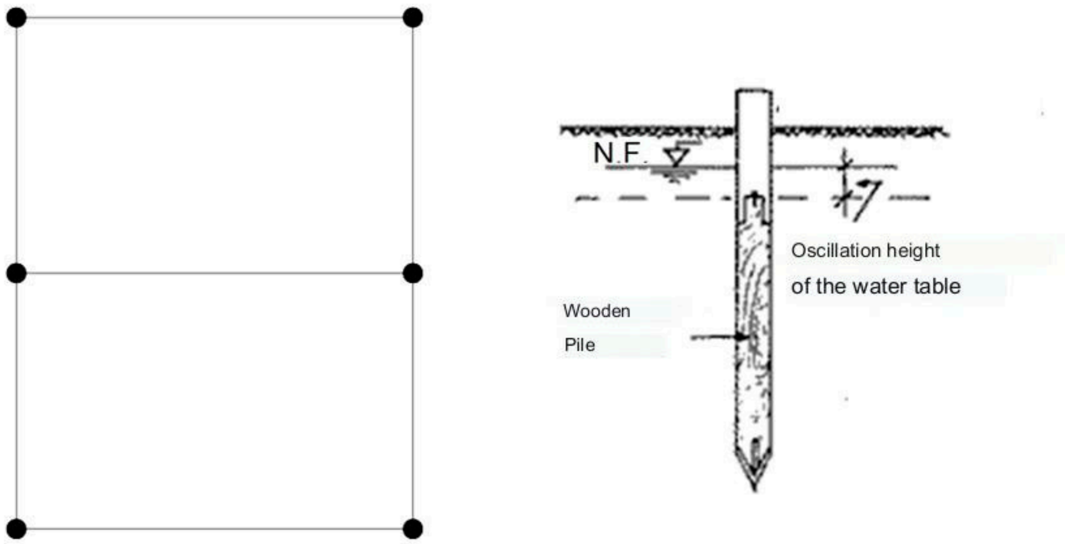

Figure 16. Pile layout and detail of timber pile to be installed.

The following values show that, initially, there is a permanent load and overload of use for small housing: $P_D = 113.76$ kN and $P_L = 98.1$ kN.

When opting for a solution consisting of timber piles, it should be taken into consideration that the maximum length of most timber piles is between 10 m and 20 m. The timber must be straight, strong, and free of defects. The American Society of Civil Engineers' "Manual of Practice", No. 17 (1959) stipulates that the type of function required would demand the use of Class B piles. Class B piles must have a minimum diameter of 305 to 330 mm and a service pressure of $P_{serv} = 34.81$ kN. This value should be less than the capacity of the pile tip.

Timber piles do not withstand high driving forces, so the capacity of the pile is limited to avoid crushing the fibers due to hammer blows, a phenomenon also known as splintering.

Assuming a low bearing capacity in the soil, for which it would be uneconomical to overextend the length of each pile until a more resistant bedrock or substrate is found, the design of each element can be considered for frictional resistance and lateral adhesion, in addition to the capacity at the tip, which is usually low in these cases.

Regarding the resistance or bearing capacity of a pile, considering Vesic's theory (Equation (2)) for cavity expansion, one would have (for a 12 m long timber pile):

$$Q_p = A_p \, \overline{\sigma}_0{}' N_\sigma^* \tag{2}$$

where Q_p is the pile tip capacity, A_p corresponds to pile tip area, $\overline{\sigma}_0{}'$ is the mean normal effective stress of the soil at the pile tip level. N_σ^*, corresponds to the carrying capacity factor. In the case of the study area

Loamy soil in Valdivia [98]: $\gamma \approx 8.04 \, \frac{\text{kN}}{\text{m}^3}$

Internal friction angle: $\phi \approx 27^{\circ}$
Cohesion: $c \approx 2.13$ kPa
Pile area: Ap = 0.07 m^2
Effective pressure (Equation (3)):

$$q' = \gamma \cdot h = 8.04 \, \frac{\text{kN}}{\text{m}^3} \cdot 12 \text{ m} = 96.48 \text{ kPa} \quad (3)$$

Normal effective stress, e.g., for sandy silt (Equation (4)):

$$K_0 = 1 - sin(27) = 0.5616 \quad (4)$$

$$\overline{\sigma}'_0 = \frac{1 + 2K_0}{3} q' == \frac{1 + 2 \cdot 0.5616}{3} \cdot 96.48 \text{ kPa} = 68.28 \text{ kPa}$$

According to Vesic's theory (Equation (5))

$$N^*_\sigma = f(I_{rr}) \quad (5)$$

where I_{rr} corresponds to the reduced stiffness index for the soil, which is obtained from Equation (5):

$$I_{rr} = \frac{I_r}{1 + I_r \Delta} \quad (6)$$

Δ corresponds to the average volumetric unit strain in the plastic zone below the pile tip. On the other hand, the intervals of Ir for a sandy silt soil are in the order of 70 [99]. With these data, it is possible to obtain Δ from Equation (6):

$$\Delta = 0.005(1 - \frac{\phi' - 25}{20}) \frac{q'}{p_a} \quad (7)$$

With p_a as atmospheric pressure (≈100 kPa)

With the above, we have a value of Δ = 0.0044 m, which makes it possible to calculate the value of I_{rr}, = 58.46. Now, from Table 11.7, the "Carrying capacity factor" of the *Fundamentals of Foundation Engineering* book [99] can be obtained N^*_σ with $\phi \approx 27^{\circ}$; this support factor will be 29.29.

Then, we replace, in Equation (2), to determine pile tip capacity, Q_p = 123.71 kN. Chilean regulations require a safety factor of 3 to 5 in these cases; we take 4.5 so that the Q_{adm} = Qp/(3.5) = 31.28 kN.

Finally, it is verified that $Q_{adm} > P_{serv}$; therefore, the section and length of the pile meet the load requirements.

3.4. Economic Analysis for Proposed Houses

The following is an analysis of construction prices of the supporting structures for the same type of 50 m^2 houses as described in the previous sections. As the geometry and materiality of the house are the same for both the pile structure and the amphibious support, this value will not be considered in the precise analysis. Tables 3 and 4 summarize the main construction elements of both options, compared to a traditional foundation structure, which considers a precast concrete support system, for a value of only USD 125, including installation.

When analyzing both budgets and their respective estimates, a lower construction complexity is observed in the case of houses on piles. This translates to a lower construction cost of more than 50%. This, together with the existence of construction regulations in Chile for this timber pile construction methodology, raises this alternative solution to flooding as feasible in this country.

Houses on stilts and amphibious dwellings were designed for use in flood-prone areas. It is worth mentioning that houses on stilts are usually more affordable and easier to build, while amphibious houses are usually more durable and able to withstand the forces of water and waves. A resumed comparison between the two construction solutions is shown in Table 5.

Table 3. Construction values of the supporting structure for an amphibious house.

Amphibious Housing Structure				
Description	**Unit**	**Amount**	**Unit Price**	**Total**
Excavations	m^3	2.5	USD 61	USD 153
Fiberglass Tubes 8.2 m (Diameter 0.6 m)	un	5	USD 320	USD 1600
Stainless steel guideposts	m	42	USD 70	USD 2940
Elevating roller systems	un	8	USD 280	USD 2240
Metal structure for pipes	kg	350	USD 5	USD 1750
Concrete foundations	m^3	2.5	USD 200	USD 500
Foundation armor	kg	200	USD 2	USD 400
Molded foundations	m^2	10	USD 15	USD 150
Manufacture and assembly of amphibious system	MHrs	1080	USD 8	USD 8640
Epoxy paint for fiberglass	gl	5	USD 30	USD 150
Anticorrosive paint	gl	2	USD 35	USD 70
			Total:	USD 18,593

Prices in USD.

Table 4. Construction values of the supporting structure for house on stilts.

House on Stilts Structure				
Description	**Unit.**	**Amount**	**Unit Price**	**Total**
Timber piles	m	54	USD 50	USD 2700
Pile-driving system	hr	32	USD 40	USD 1280
Support structure house	m^2	50	USD 85	USD 4250
Carbolineum timber preservative	gl	6	USD 25	USD 150
			Total:	USD 8380

Prices in USD.

Table 5. Comparative table between amphibious houses and houses on stilts.

	Stilt Houses	Amphibious
Desing	Pylon houses are usually built with lightweight materials, such as timber or bamboo, and are designed to rise above the ground to protect them from floods and other natural disasters.	Amphibious houses are usually built with more durable materials, such as steel or concrete, and are designed to withstand the force of water and waves.
Adventages	Stilt houses offer a number of advantages, such as protection against floods, pests and alluvium. They can also provide better ventilation and privacy than houses built on the ground.	Amphibious housing offers a number of advantages, such as the ability to move with the tides, the ability to withstand flooding and the possibility of being used for a variety of water activities.
Disadvantages	Houses on pillars can be more expensive to build and maintain than those built on the ground. They can also be more vulnerable to storms and other natural disasters.	Amphibious housing can be more expensive to build than houses on stilts. They can also be more difficult to access and maintain.

4. Conclusions

This study examined the evolution of knowledge related to LUM-CC, showing 3882 articles searched in the WoS platform from 1987 to 2022. The analysis of results identified the main subject areas, the most important authors and the countries in which most LUM-CC-related research was conducted. This led to the most significant findings of this article, which are presented below:

In general, the analysis of published LUM-CC papers shows that the risk of inundation due to sea level rise is a dominant theme across all time periods and coastline types.

This is reflected in the evolution of the predominant keywords in the scientific literature analyzed in five time periods, as it goes from "Land use" to "Floods", then the evolution from "Coastal cities" to "Risk factor" and ends in the last period with the concept of "Vulnerability". It is reflected in the early years of research, when it referred to the fight against climate change, then to the development of mitigation measures, and today to the creation of adaptability to new climate scenarios.

This will directly affect our way of conducting coastal urbanism because it highlights the need to explore proactive models of adaptation to this new climate reality that are more effective in reducing flooding in the long term, taking into account technical, administrative, economic and social factors. These adaptation plans must include the following: (1) protecting, (2) accommodating or (3) removing coastal infrastructure. Implementing intelligent management strategies to help solve the coastal erosion problem, considering a multi-criteria decision analysis to identify the most desirable management regimes. In addition to climate change, human action catalyzes the loss of these ecosystems, generating environmental, economic and social problems, which, coupled with local morphological conditions, makes the study of estuaries and wetlands an important area of research related to LUM-CC.

Flood risk reduction can be achieved through rigid protection measures such as storm surge barriers. On the other hand, soft strategies, such as wetlands, offer a higher cost/benefit ratio but carry a higher residual risk. A hybrid strategy that combines the elements of both strategies is superior to either an individual approach in terms of reduced future risk and a higher cost/benefit ratio. Amphibious houses are a promising solution to flooding because they are highly mobile, durable, energy-efficient, and can be manufactured from sustainable materials. The challenges associated with their construction are the cost of acquisition and maintenance and the availability of suitable sites. However, these challenges are likely to be overcome as the technology continues to develop. It should be noted that in the case of Chile and its high seismicity, as this house is not anchored to the ground but rather has an integrated structure, it has good seismic and flood-proof performance.

Houses on poles are more common in southern Chile, and it is important to consider several factors, such as the soil type, height of the water table, wind and seismic loads, and materials to be used. In Chile, a regulatory framework was established by NCh433.Of96, guaranteeing the safety and resistance of these structures during seismic events.

In addition to the design of houses, it is also important to have user protection strategies in the case of flooding. This includes having an immediate emergency response plan as well as providing temporary housing and other assistance to people displaced by floods.

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