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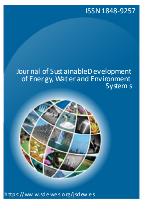

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Original Research Article

An Integrated and High-resolution Assessment of Territorial Water Vulnerability: The Case of the Gran Valparaiso Conurbation, Central Chile

***N. Alamos**[*1,2,3], **I. Lefort**[1,2,4], **A. Allendes**[2], **M. Billi**[1,2,5], **T. Monsalve**[2], **A. Urquiza**[1,2,6]*

[1]Center for Climate and Resilience Research, Santiago, Chile
[2] Systemic Transdisciplinary Research HUB (NEST.R3)
[3]Austral Patagonia Program, Universidad Austral de Chile, Valdivia, Chile
[4]Faculty of Engineering, Department of Hydraulic and Environmental Engineering, Pontificia Universidad Católica de Chile, Santiago, Chile
[5]Department of Rural Management and Innovation, University of Chile, Santiago, Chile
[6]Social Sciences Faculty, University of Chile, Ñuñoa, Chile
e-mail: nalamos@fen.uchile.cl

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ABSTRACT

Water security is a key objective for advancing sustainable development and is becoming increasingly difficult to achieve under the pressures of climate change. Ensuring water security requires equitable access to water services of adequate quantity and quality to meet diverse needs while guaranteeing these services' sustainability in the face of natural and anthropogenic threats. The concept of territorial water vulnerability is introduced as the propensity of a given territory to fail in adequately meeting water needs due to its structural susceptibility to socio-environmental stressors. The Territorial Water Vulnerability framework is applied to assess water security risks related to urban drinking water services in the Gran Valparaíso conurbation in Chile, a territory affected by a decade-long drought, pronounced social inequalities, and fragmented water governance. Using a fuzzy logic approach, an integrative index is developed that combines territorial indicators of sensitivity and response capacity, considering both technical and sociocultural factors driving household vulnerability to water scarcity at a fine spatial resolution. Through cluster analysis, neighbourhood profiles with common characteristics accounting for elevated vulnerability levels are identified. The results show that 4,841 out of 10,042 census blocks exceed a vulnerability threshold of 0.5, primarily due to sensitivity factors such as water supply constraints, coverage of informal settlements, and frequency of unscheduled annual outages, compounded by a consistently low response capacity (median 0.08 on a scale from 0 to 1). This research provides: (1) an analytical framework to assess urban water security from a household-level perspective that incorporates social dimensions; (2) a methodological approach for high-resolution vulnerability analysis that integrates technical and sociocultural systems; and (3) empirical evidence to inform public policy in a region where water security has been underexplored.

KEYWORDS

Water risk, Climate risk, Climate change, Territorial vulnerability, Risk assessment, Chile, Valparaiso

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[*] Corresponding author

INTRODUCTION

Water security is essential for achieving sustainable development. According to UN-Water [1], ensuring water security is fundamental for fostering economic growth, environmental sustainability, and social well-being. Furthermore, it is indispensable for human health [2] and poverty reduction [3].

While multiple definitions of water security exist depending on the type and scale of the system being analyzed [4], it is broadly understood as "the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability" [1].

Urquiza & Billi [5] argue that achieving water security requires ensuring equitable access to water services of sufficient quantity and quality to meet multiple needs and uses, while also guaranteeing the sustainability and resilience of these services in the face of natural and anthropogenic threats. The latter is becoming an increasingly hard challenge in the context of climate change [6] and increasing urbanization [7].

Mekonnen and Hoekstra [8] estimate that four billion people already face water security issues, considering seasonal and inter-annual climate variations in water availability, affecting adequate access to drinking water and, consequently, water security. Unfortunately, water security challenges are expected to intensify, as the IPCC [9] projects a reduction in renewable surface and groundwater resources, along with increased frequency and intensity of droughts and a deterioration in water quality, due both to higher concentrations of contaminants and more frequent heavy precipitation events. Thus, climate change must be assessed as a major threat to reach and sustain water security.

Climate change does not affect all territories equally; its impacts vary depending on multiple social, economic, and environmental factors [10] . Therefore, evaluating and addressing the water risk due to climate change requires integrated frameworks that capture the determinants and spatial distribution of water insecurity, which must be sensitive to each territorial context's ecological, technical and socio-cultural conditions [11]. Currently, most studies focus either on large scales (such as cities or watersheds) or very small scales (such as households). Mid-scale approaches for analyzing water security risks are lacking between these two levels.

To address this challenge, this paper adapts the Territorial Water Vulnerability (TWV) framework, previously proposed by the authors [12], as an integrated approach that combines ecological, technical, and socio-cultural factors to assess water security risks at a fine spatial resolution. The TWV framework links sensitivity factors (e.g., socioeconomic conditions, water infrastructure, demographic characteristics) and response capacity indicators (e.g., system flexibility, redundancy, and governance conditions) across different dimensions, including socioeconomic, technical and environmental, to develop a composite vulnerability index. This integration is operationalized through a fuzzy logic approach, which enables a nuanced aggregation of multiple variables while preserving the complexity of their interactions. The fine-grained resolution and use of integrative indexes enable unprecedented detail in understanding vulnerability patterns, making it a valuable tool for academic study and practical decision-making in water security governance.

This empirical approach is applied to the Gran Valparaíso conurbation in Chile, a territory facing significant water security risks in a highly vulnerable country to climate change. Central Chile has experienced a prolonged and intense hydrological drought, making it an important reference for understanding future water security challenges expected in other urban areas worldwide. Gran Valparaíso presents a combination of severe water scarcity, governance fragmentation, and socio-spatial inequalities, common in many rapidly urbanizing regions of Latin America and beyond. Studying this case provides insights into how urban water systems may respond to increasing climatic pressures and institutional challenges. While the analysis specifically focuses on drinking water risks, the TWV framework has broader applicability in evaluating various impacts of climate change on different water uses and processes.

The paper is structured as follows: Section 2 presents a literature review on water security. Section 3 outlines the conceptual framework. Section 4 introduces the study area, data, and methodology used to construct the TWV index. Section 5 presents the main results, identifying the most vulnerable areas and analyzing vulnerability drivers at both the commune and census block scales through cluster analysis. Section 6 discusses the key findings and the conceptual and methodological contributions of the study. Finally, Section 7 summarizes the main conclusions.

LITERATURE REVIEW

Two main broad methodological frameworks exist to quantify urban water security or at least some aspects. The first group of studies measures water security across only one dimension, as is the case with the hydric stress [13] or water poverty index [14] that provides relevant information on an aspect of water security. This approach can be applicable in territories with different geographic scales and characteristics (i.e., urban or rural), allowing a faster, simpler, more cost-efficient, and comparable way of measuring proxy water security. Nevertheless, these indexes fail to characterize urban water security dynamics properly [15] because they necessarily generalize and homogenize territorial diversity in their analysis [16]. These studies usually overemphasize the importance of focusing excessively on grey infrastructure, which may hide other important aspects affecting water security [17].

A second approach in the literature is measuring water-related issues using composite indexes [18] built from various indicators that attempt to consider the different and complex relationships in an urban territory [19]. These indices are developed for specific cities or regions, considering the available information and recognizing the multiple drivers influencing water security, as the integrated urban water security index proposed by Aboelnga et al. (2020) [13] and the Urban water security indicators proposed in Jensen & Wu (2018) [3]. These drivers include, for instance: technical conditions, such as the quantity, quality [20], affordability, accessibility [3], infrastructure, consumption [21], efficiency and alternatives sources used in water provision and wastewater treatment systems [22] socio-economic conditions, such as social capital, population, economic factors [23], legal and institutional and governance frameworks [24]; and environmental conditions such as pollution, green infrastructure, the propensity of hydro-climatic hazards and others natural risk [25] (A synthesis of indicators identified in the literature is available in Tables S1-S3, supporting information).

Notably, when including socio-economic variables, water security literature mostly relies on variables that describe the quantity and distribution of the population to quantify the number of people exposed to water security-related problems. For instance, Chang et al. (2015) [24] used the GDP as a proxy of socioeconomic status and applied it to a whole city in a homogeneous approach. Less attention has been given to variables aiming to characterize the differences in socio-economic vulnerability of the inhabitants of a city.

The geographic scale on which information is expressed is another relevant aspect to consider when constructing these indexes. Most studies are defined at the basin, city, or national level [26], often treating these as homogeneous territories [27]. However, the literature recognizes the need for new analytical frameworks and indexes to evaluate water security at a more detailed geographic scale, aiming to account for the specific characteristics of smaller territorial units [28]. Many drivers of water security, including infrastructural, sociodemographic, and cultural variables, vary significantly on smaller scales.

Actions aimed at fostering water security are most effective when performed at the local level, with a nuanced understanding of how different sources of risk interact with the specific conditions of particular areas and populations within human settlements. Therefore, a more detailed resolution in evaluating water security risks is required, allowing for the consideration of the characteristics of smaller territories [29]. Notable progress has been made in this direction by studies attempting to describe or assess household water insecurity (e.g., [21], [22]). However, a focus on households can often limit these studies' ability to encompass broader territorial dynamics that may condition risks affecting households. This highlights the strong need for a mid-range approach that explores water security risks at a scale between the household and the city or basin level, which remains underexplored in the current literature.

Latin America lacks robust empirical studies on water security risks [30], especially studies taking a territorial approach to this assessment. The concept of water security has only started to be used in recent years. Among studies that explicitly tackle this, there are investigations about specific social conflicts, like conflicts with mining projects [31] and urban or rural contexts [32]. Other studies evaluate water security by combining quantitative and qualitative variables in the cities of Río de Janeiro [33], Fortaleza [34] and La Paz [35]. In the latter, water security is evaluated exclusively considering the availability of raw water. Regarding documents from international organizations, [36] defines water security and offers a diagnosis of the water resources in the region and a perspective of the challenges and priorities for water. Recently, some advancements have been made in this direction by international organizations such as the Economic Commission for Latin America and the Caribbean (UN-ECLAC) and the Inter-American Development Bank (IADB). UN-ECLAC offers a conceptual definition and a diagnosis of water security in Latin America and identifies strategies and instruments for water security [5]. The IADB elaborates on a diagnosis of water security and a perspective of IDB for innovation and strategies for the future of water in Latin America [37].

In this context, applying a fine-grained analysis in an urban context is especially urgent, considering that the trend towards greater population concentration in urban areas is expected to continue, exacerbating water scarcity [8] and exposure to water-related risks.

CONCEPTUAL FRAMEWORK, METHODS AND DATA

In this paper, the conceptual and methodological framework developed by the authors in [12] for the Territorial Water Vulnerability (TWV) concept is utilized to assess the characteristics of the Gran Valparaíso territory that may hinder or limit the achievement of water security.

The concept of vulnerability is closely connected to risk, as defined by the Intergovernmental Panel on Climate Change (IPCC) in its fifth assessment report [10]. Risk is the probability that something valuable to society would be in danger with an uncertain outcome due to the interaction of three components: hazard, exposure, and system vulnerability. The TWV framework is explicitly designed as an integrated model, capturing the interdependencies between ecological, technical, and socio-cultural dimensions that contribute to water security challenges. Rather than analyzing these aspects in isolation, the TWV approach evaluates how they interact within the same territorial unit. In addition, the TWV will display a significant correlation with pre-existing water service access inequalities, influencing the water security actual state of the territory even without hazards (**Figure 1**).

Vulnerability can be decomposed into sensitivity and response capacity [10]. Sensitivity refers to the systemic characteristics that increase the probability of the exposed components suffering negative impacts. It is influenced by environmental, sociodemographic, infrastructure and technology conditions, economic and cultural resources, and knowledge of the territory regarding different components of the water system [38].

On the other hand, response capacity is a "reactive" mechanism that responds to disturbances encountered by the systemic capacity to face adverse conditions presented by hazards, exposure, and sensitivity. It relates to the flexibility of the system to adjust in the face of potential impacts, which is influenced by the diversity, connectivity, and redundancy of the components and structures involved in the provision of water services [11].

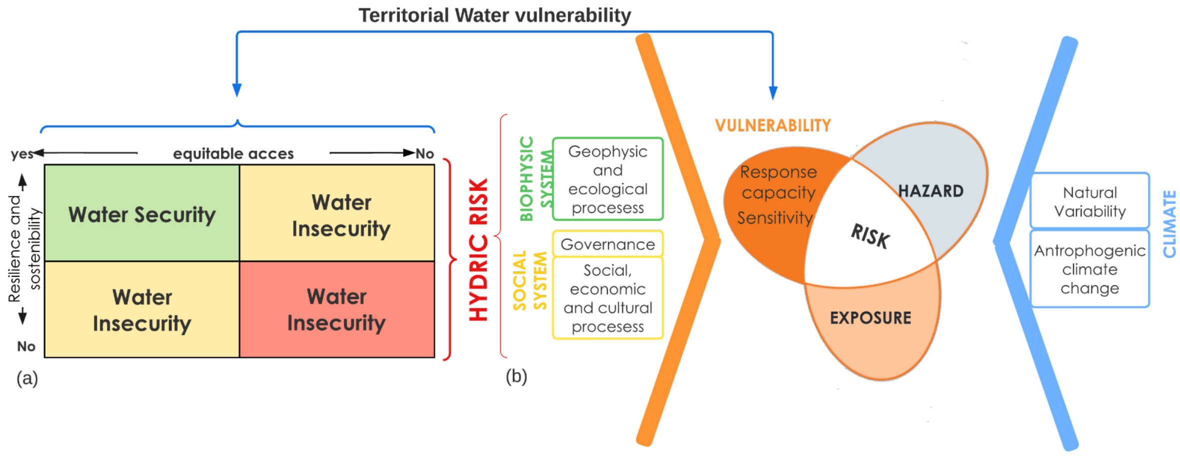

Figure 1. On (a) Conceptual relationships between water security, insecurity, equitable access, sostenibility and resilience (adapted from [5]) The sostenibility and response capacity (axis y) of the water services are determined by the hydric risk that the territory faces on (b) a conceptual framework of climate risk is presented. Territorial water vulnerability, as the territory's propensity to have water insecurity conditions, captures the vulnerability component of the hydric risk and the existing water access conditions of the territory.

In this article, the TWV framework was employed to address the vulnerability of the urban drinking water service of Gran Valparaíso through a five-step methodology. The steps are numbered from 0, intending that steps 1-4 coincide with those developed in sections 3.1 - 3.4.

0. **Define and conceptualize the observed water services:** Climate change may affect water security in several ways, depending on which kind of climate drivers and water services (and users) one considers and the scale of analysis [5]. Thus, the first step of the analysis implies defining which specific hazards and services are considered. This article focuses on the territorial water vulnerability of urban households' drinking water provision. In the Gran Valparaíso conurbation, this service is mainly provided by the ESVAL water utility company.

1. **Characterization of the system and its components and interrelationships:** After defining the service, the analysis should identify and characterize the key elements and processes that interact in the technical, socio-cultural and ecological water systems that sustain the observed service (in this case, household-level water provision). A territorial characterization should then be performed, considering the ecological, technical and socio-cultural elements implied in the service provision. This step is addressed in subsection 3.1.

2. **Characterization of the risk components faced by the system:** Once the system is defined, an analysis is conducted to assess how climate change may impact the system. To achieve this, the analytical framework of risk assessment from [39] is adapted, building an impact chain that represents the interaction between the components and variables influencing the risk faced by water services.
   Constructing the impact chain involves two potentially iterative steps: designing a theoretical impact chain (which summarizes all the relevant variables and interactions identified by existing literature and experts) and operationalizing that chain into concrete, measurable, and existing indicators.
   The first step is to identify the key climatic hazards that may impact the services, and the components of the system exposed to those hazards. This allows for distinguishing the direct and intermediate impacts of the selected hazards on the system and the service it provides. Next, the main factors explaining the system's sensitivity and its components are

characterized, particularly identifying the technical and sociocultural conditions affecting the drinking water service and the response capacity regarding the system's flexibility. This step is addressed in the impact chain subsection (3.2).

3. **Description of the Territorial Water Vulnerability and Risk:** As a result of the integration of sensitivity and response capacity indicators, the hydric vulnerability of the observed territory can be estimated. This vulnerability should be complemented with hazard and exposure analyses for risk assessment. In this study, only TWV and exposure are described due to the difficulty of differentiating the hazards at the analysis resolution, which considers units of the same hydrographic basin with drinkable water from the same technical system. Subsection 3.3 addresses the integration of the sensitivity and response capacity indicators on a single TWV index.

4. **Interpretation of the results:** Considering the scale of the information used in the previous stage, different multiscale relationships of the TWV indicators that define the water risk can be established, allowing the development of specific and efficient strategies for addressing the TWV. In subsection 3.4, a cluster analysis approach is described. The results presented correspond to a relative ordering between the census blocks in the study area, as the methodology does not try to 'quantify' the risk but rather to discriminate higher/lower risk areas and potential profiles of high-risk areas.

Study Area

This study focused on the case of the Gran Valparaíso conurbation in Central Chile. Climate change has severely impacted this region, with a drying trend leading to the so-called megadrought, affecting the country since 2010, with annual precipitation deficits ranging between 25% and 70% [40]. The megadrought has led to extreme water scarcity on the contributing catchment for urban drinking water services of the Gran Valparaiso conurbation, one of the most important urban settlements in the country.

Gran Valparaíso (33°03′S 71°37′W) is a metropolitan area located in the Valparaíso Region, Chile. It is the main urban settlement in the region and integrates the communes of Quilpué, Villa Alemana, Valparaíso, Viña del Mar and Concón (The commune is the smallest administrative and territorial unit in Chile and is equivalent to what is known in other countries as a municipality). According to the National Institute of Statistics, it has 951,150 inhabitants distributed over 402 km2, representing 6% of the country's total population. The drinking water production and distribution, as well as the wastewater treatment, are managed by the private water utility company ESVAL S.A. in its "Gran Valparaíso" system that integrates eight locations: Valparaíso, Placilla de Peñuelas, Curauma, Viña del Mar, Reñaca, Concón, Quilpué and Villa Alemana (**Figure 2**).

The water supply system is integrated by 42 raw water collection points (5 surface water sources, which represent 59% of total production and 37 underground water sources), four production facilities and 151 distribution reservoirs present in the eight localities, which supply 376,010 clients (at 2019), distributed in 2,655 barracks (the smallest territorial unit of the water utility company and corresponds to the sector of the distribution network in which the supply of Potable Water can be temporarily suspended, without affecting the general supply). Despite the many collection points, 76% of the water supply comes from 4 sources on the Aconcagua River (**Figure 2**). Thus, the river's water availability is essential to maintaining an effective drinking water supply in the Gran Valparaíso system.

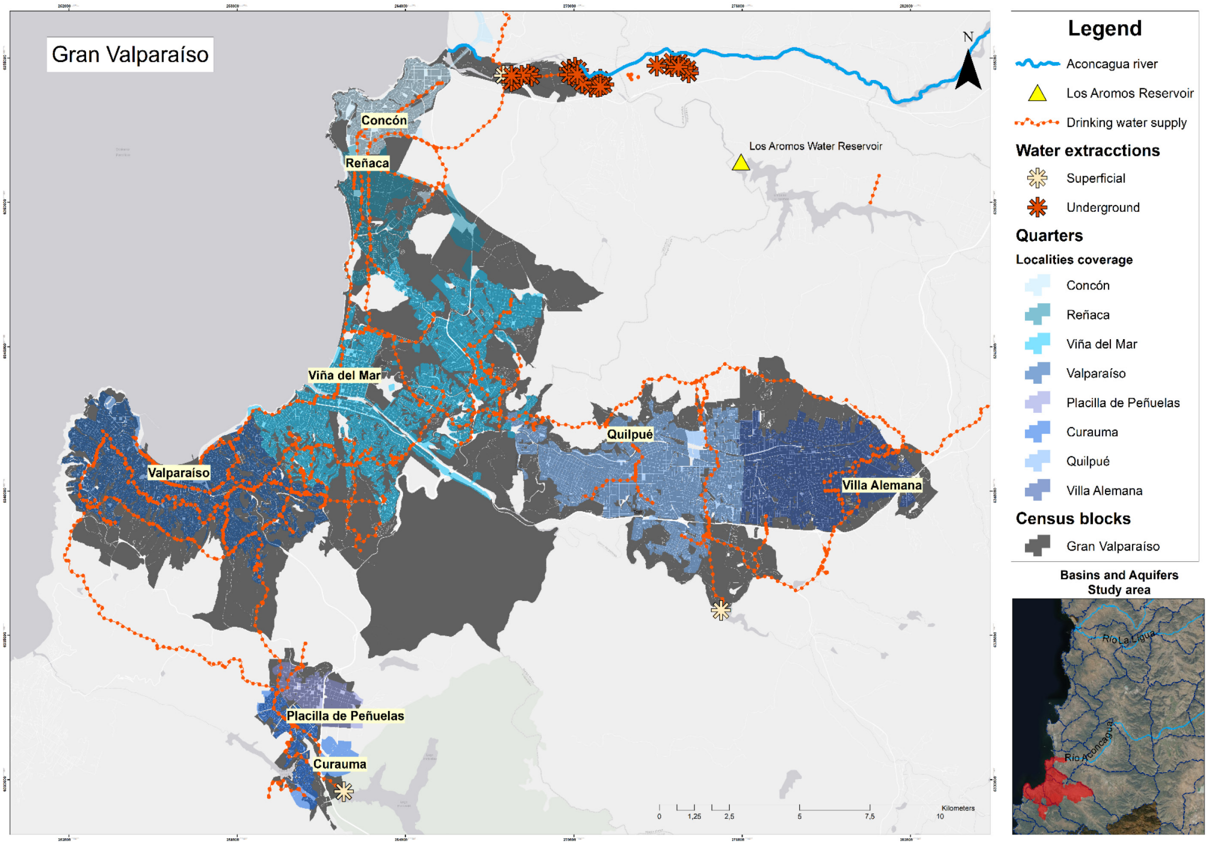

Figure 2. Gran Valparaíso Area, Aconcagua River, Los Aromos Reservoir, Surface and Underground Collections, Coverage of water utility Barracks and Census Blocks of Gran Valparaíso. Source: own elaboration.

The Aconcagua River has a snow-rain-fed fluvial regime, with an annual mean flow of 33 m3/s and 14.5 m3/s standard deviations [41] characterized by considerable flow fluctuations during the year, with maximum flows in the warm season due mainly to snow feeding. However, in the last decade, the river has presented an alarming decrease, registering a minimum flow of 2.7 m^3/s at the Romeral gauge station in 2019 [42]. At least two reasons explain this situation. The first one is associated with the drying trend observed in meteorological variables (precipitation and temperature) that has led to severe drought conditions affecting central Chile since 2010 [43]. This so-called 'mega-drought' has induced average streamflow deficits of 70% in the rivers located in the Valparaiso region and has affected the water regime by increasing the participation of glacier runoff contributions to the basin.

The second reason refers to the water overexploitation in the Aconcagua basin throughout its entire course, given the high water demand from productive mining activities in the upper part of the basin and agricultural activities in the middle and lower parts [42]. The lower river flows have led ESVAL to increase groundwater collection, promoting the creation of 45 new wells between 2011 and 2019 and purchasing raw water from third parties.

The spatial analysis of TWV is conducted at the finest resolution with relevant information available, which is at the census block scale, the smallest territorial unit with census information. The census block comprises a group of adjoining or separate dwellings, buildings, establishments, or properties delimited by geographical, cultural and natural features. In Gran Valparaíso, there are 10,042 census blocks with available information on which the TWV analysis is carried out.

Impact chain

As explained above, an indicator-based methodological structure is followed, inspired by the work of the IPCC Assessment Report 5 [44] and the GIZ climate change impact evaluation methodological guidelines [39], [45]. To describe the territory's sensitivity and response capacity in the face of hazards to urban water security, a set of indicators was estimated based on the vulnerability conditions identified in the literature and the information available for the study case (see Table 1).

Table 1. Indicators used for the sensitivity index.

Subdimension	Indicator	Description	Spatial resolution	Data Source	Year
Socioeconomic	Education level	Proportion of households with a low educational level (<8 years) of the household head	Census zone	Censo 2017	2017
	Income Poverty	Proportion of households under the Chilean poverty line.	Census zone	(Muñoz et al., 2019)	2018
Demographic	Territorial segregation index	Spatial Segregation Indicator, generated by the aggregation of 26 sub-indicators	Census zone	(Muñoz et al., 2019)	2017
	Ethnic population	Proportion of ethnic population	Census Block	Censo 2017	2017
	Child population	Proportion of population under <5 years old.	Census Block	Censo 2017	2017
	Elderly population	Proportion of population aged>65 years or older.	Census Block	Censo 2017	2017
	Migrant population	Proportion of migrant population	Census Block	Censo 2017	2017
	Overcrowded households	proportion of households with more than 2.5 people per bedroom	Census zone	Censo 2017	2017
	Women-led household	The proportion of women-led households with persons>65 or <5 years old.	Census zone	Censo 2017	2017
Water accessibility	Informal human settlements	Proportion of the census block surface covered by informal settlements	Census Block	(Ministerio de Vivienda y Urbanismo, 2019)	2019
	Well water supply	The proportion of dwellings whose water supply is from a well	Census Block	Censo 2017	2019
	Supply by cistern truck	The proportion of dwellings whose water supply is through cistern trucks	Census Block	Censo 2017	2017
	River water supply	Proportion of dwellings with river water supply	Census Block	Censo 2017	2017
Water consumes	Monthly average consumption	Monthly average consumption in m3	Barrack	Information provided by ESVAL	2018-2019
	Summer monthly average consumption	Monthly average consumption of m3 during summer months (December, January and February)	Barrack	Information provided by ESVAL	2018-2019
Other service conditions	Number of unscheduled outages	Annual average of the number of unscheduled outages	Barrack	Information provided by ESVAL	2014-2020
	Time of unscheduled outages	The annual average of the time that all the unscheduled outages lasted	Barrack	Information provided by ESVAL	2014-2020
	Number of critical infrastructure customers	The number of hospitals, shelters, care centers, courts, and municipalities, among other critical infrastructures, identified	Barrack	Information provided by ESVAL	2021
	Surface sources	Proportion of production provided by surface sources	Locality	Information provided by ESVAL	2021

The exposure is defined by the population and measured by considering the number of inhabitants (Inhab) and the population density per hectare (Inhab/Ha). In this way, the potential effect of the TWV on a greater number of individuals or some high population density areas is considered. Sensitivity depends on several factors related to the population's demographic and socio-economic conditions and water utility services' characteristics.

Regarding the demographic characteristics, according to the literature, the presence of elderly (above 65 years) [46] and childhood (under six years) [47] populations should be considered because they are more prone to diseases caused by a lack of water. Moreover, in a water scarcity context, women-led households tend to be unable to carry out domestic and care tasks related to water use and usually have higher poverty levels [48]. Also, minority groups such as ethnic minorities and migrants [49] are especially affected by social and economic inequality, increasing the risk of facing living conditions without access to drinking water and health and hygiene services, among others [50]. Similar is the case for overcrowded housing [51]. The economic poverty of the population is an important factor that limits access to improvements in drinking water infrastructure and devices [52]. This can exacerbate the population's sensitivity to water quality issues and may result in adopting alternative mechanisms, such as bottled water. The financial burden of buying bottled water can further exacerbate the economic challenges faced by low-income households, making it more difficult to meet their basic needs.

Concerning the coverage and access to drinking water, a series of indicators are used as a proxy for lack of water access: (1) urban households that are outside the water utility coverage area, depending on water supply provided by the river, wells or cistern trucks [53], (2) homes provided with cistern trucks, affected by the intermittency of said supply and the potential transmission of diseases that can put people's lives at risk [54], (3) the presence and area of informal human settlements [55], whose lack of legal protection further limits access to water supply sources [56].

Regarding the quality and continuity of the water supply service, indicators associated with the average water consumed in different periods of the year, the seasonality of consumption, and unexpected service interruptions were considered. Substantial variations in demand, especially in summer, require a greater adaptation capacity of the system and additional water sources to cover this seasonal demand, which exposes the system to losses in service continuity or low pressure [8].

Additionally, the presence of critical infrastructure, such as public services essential for the well-being and health of the population, such as hospitals, shelters, assistance centers, courts and municipalities, may see their functionality diminished in the event of a supply cut, increases the vulnerability of the area circumscribed to said service [57]. Finally, territories that depend on surface water production are more sensitive since meteorological drought affects them more quickly than groundwater sources [58].

The response capacity analysis is mainly associated with the system's flexibility, understood as the ability to adapt to the lack of water and could be characterized by the diversity of sources, planning for droughts and climate change and hours of distribution system's autonomy, among others [59] (see **Table 2**).

Table 2. Indicators used for the response capacity index

Dimension	Indicator	Description	Spatial resolution	Data Source	Year
Short-term response	Number and volume of alternative supply sources	This indicator measures the number and volume of storage in M3 of alternative supply sources	Barrack	Information provided by ESVAL	2021
	Distribution system autonomy	The amount of time for which the sanitary service can supply the average consumption of the population with the distribution system	Locality	Information provided by ESVAL	2020
Long-term response	Diversity of sources	The proportion of water produced at points other than the main source	Locality	Information provided by ESVAL	2021
	system water loss	The gap between the amount produced and actual consumption	Locality	Information provided by ESVAL	2015

The number and capacity of alternative supply sources, as well as the autonomy of the distribution system [3], are indicators of the system's short-term flexibility to respond to shocks that abruptly interrupt the service. On the other hand, the diversity of catchment sources [3] and water loss in the system are indicators used to evaluate the system's medium- and long-term flexibility. The increases in population and the effects of climate change will impact the effectiveness of the water supply system in providing the service that the population requires.

To ensure consistency across variables, all data with a spatial resolution different from the census block were calculated for the census block using a weighted average. Additionally, annual means were computed for indicators from the ESVAL data source, which spanned multiple years. These operations create a cross-sectional database with a singular value for each indicator in every census block.

Aggregation of indicators on a single territorial water vulnerability index

To assess territorial water vulnerability in Gran Valparaíso, the indicators from ecological, technical, and socio-cultural dimensions discussed earlier were first grouped into two sub-indexes: Sensitivity and Response Capacity. These sub-indexes were then aggregated into a single composite Vulnerability Index, allowing for a comprehensive evaluation of water insecurity risks at the census block level.

This aggregation was performed using a fuzzy logic approach [60], [61]. which enables the integration of diverse indicators with different measurement scales without assigning arbitrary weights. Instead of using a rigid numerical weighting system, fuzzy logic dynamically adjusts the contribution of each indicator based on its empirical distribution and predefined logical rules (see Supporting Information, Section 2, for details).

Raw data were processed to obtain indicators for each census block, which were then standardized using fuzzy membership functions. This transformation generated fuzzy set values for each variable, ranging from 0 to 1, representing the degree of membership of the census block to a "high" or "low" condition of the variable.

Depending on the variable's distribution, linear or S-type membership functions were applied, with the upper thresholds calibrated empirically using values between the 95th and 99th percentiles to avoid biases caused by potential outliers. This process was refined iteratively to identify the parameters that yielded the most consistent results. (See **Table S4** to see the parameters of the membership functions of each variable).

In the case of sensitivity, the indicators were first grouped into sub-dimensions and subsequently combined into a sensitivity index. The form of aggregation depended on the indicator's substitutability in reflecting the sub-dimension's presence. A boolean OR operator was used for highly substitutable indicators, where any indicator's presence activated the sub-dimension's relevance in the index. For complementary indicators, where two or more indicators were necessary to establish the significance of the sub-dimension in the index, the indicators were added using Boolean AND operators. (see Table S5 in the supporting information).

Then, the fuzzified indicators were combined using causal logic rules based on multiple conditions defined in the literature. If a set of conditions was met, the case was assigned a certain level (high, medium, or low) of the index analyzed (see Tables S6-S8 in the supporting information for sensitivity, response capacity and vulnerability indexes, respectively).

Finally, the centroid method was applied to the membership distributions of the resulting indexes to obtain a punctual index value in each census block in a 0-1.

Cluster analysis

The vulnerability is analyzed at the commune and census block levels according to the spatial scale of the different information sources. Cluster analysis is conducted to identify various profiles of census blocks at the extremes of the vulnerability index distribution. The study focuses on blocks in the first and last deciles of vulnerability. Different sample sizes of groups were tested to characterize the blocks with high and low TWV. In the first and last deciles, groups with significant differences in the indicators integrated into the vulnerability index appear, allowing the identification of markedly different census block profiles with extreme values of TWV.

To analyze all the indicators associated with the smaller units corresponding to census block or barrack (see Tables 1 and 2), a hierarchical cluster analysis was performed using Ward's method and Euclidean affinity as a similarity measure [62]. On the other hand, all the variables associated with a spatial unit greater than the census block (census zone, locality, commune) are not considered in the cluster analysis and are only analyzed at the commune level.

The inertia curve and dendrogram of each decile of data were considered to choose the optimal number of clusters, considering the minimum Euclidean affinity between the elements of each group and the maximum distance between the different groups. According to the results of both methods (see Figure S1, supporting information), three clusters were made for the observations of the high-vulnerability group and three for the low-vulnerability group. At this number of groups, the inertia curve presents an inflection point in the inertia gain of having one more group and the Euclidean distance in the dendrogram is maximized.

RESULTS

As highlighted in the methods, the results presented correspond to a relative ordering between the census blocks in the study area. Figure 3 displays the distribution of four indices: sensitivity, response capacity, vulnerability, and exposure.

The histograms reveal a right-skewed distribution for sensitivity and exposure, with most census blocks clustered below the threshold value of 0.5. The sensitivity index's mean is 0.32, with 85% of the blocks below the threshold. However, a notable concentration of 523 blocks exhibits high sensitivity values exceeding 0.9. The Response Capacity Index, in contrast, is highly skewed to the right, with a median of just 0.08, highlighting the generally low response capacity across the region. Interestingly, around 2,500 blocks fall within a range of 0.35–0.4, but only 74 blocks (less than 1%) have response capacity values exceeding 0.9, emphasizing the scarcity of high-capacity blocks.

The Vulnerability Index shows a more balanced distribution, with approximately half of the census blocks (4,841 out of 10,042) surpassing the 0.5 threshold. This reflects the interplay between low response capacity and heightened sensitivity, which drives significant vulnerability across large portions of the study area.

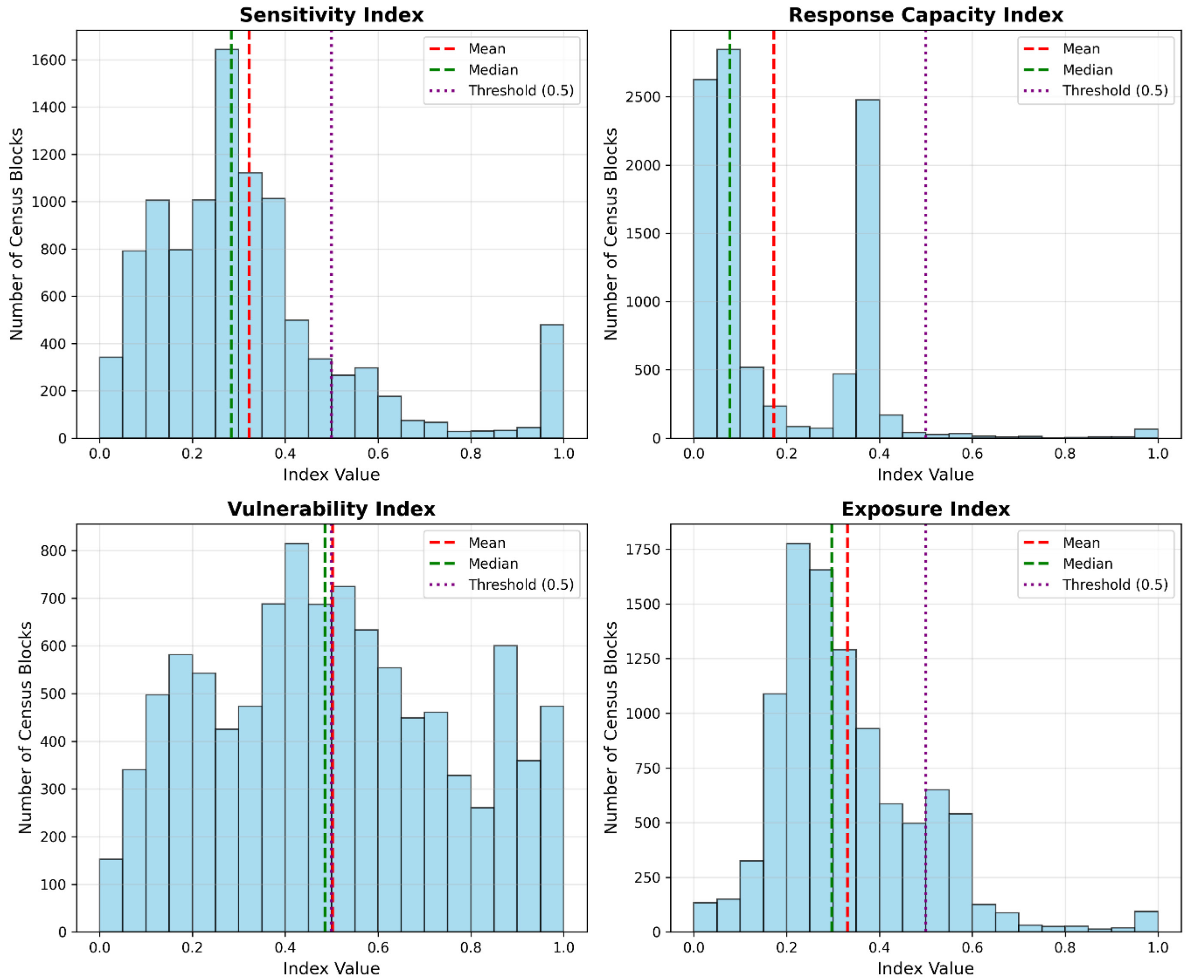

Figure 3: Distribution of Sensitivity, Response Capacity, Vulnerability, and Exposure indices across census blocks in the study area. Each histogram illustrates the frequency of index values, with dashed lines marking the mean (red), median (green), and a reference threshold of 0.5 (purple). Source: own elaboration.

Maps of exposure, sensitivity, response capacity and vulnerability indexes are shown in Figure 4. The spatial distribution of the exposure index in terms of quantity and density of the population is shown in Figure 4a, showing a heterogeneous distribution of the exposure, driven by higher density on the smaller central census blocks and by higher population levels on the bigger census blocks on the outskirts of each locality. The sensitivity map (Figure 4b) reveals the census blocks with a greater susceptibility to being impacted by water stress. The most sensitive census blocks are located on the outskirts of each locality, with a particular concentration in areas with a strong presence of informal settlements, homes without drinking water utility service and precarious socioeconomic conditions. No substantial difference exists between communes in the sensitivity index (Table 3).

The results of the response capacity index (Figure 4c) show the capacity of a given territory to respond in the face of a supply shortage. In this way, the communities of Concón and Valparaíso present better response levels due to the greater number of autonomy hours of their distribution systems, two or three times greater than the other localities (Table 3). On the other hand, higher capacities of alternative supply are found in some census blocks of the localities of Valparaíso, Reñaca, Viña del Mar and Quilpué, raising their response capacity. The Diversity of sources and System Water Losses has a lower influence on determining the response capacity due to the small variability of the distribution of these variables (Table 3) between the evaluated localities.

The vulnerability map (**Figure 4d**) shows a combination of patterns observed for the previously discussed sub-indexes. The situation of Curauma, Placilla de Peñuelas and in part of the census blocks of Villa Alemana and Quilpué (see location in **Figure 4**) stands out in that, despite not having an elevated sensitivity, these areas are highly vulnerable because of their low response capacity. Finally, a high vulnerability persists in most of the territories, displaying a high sensitivity, indicating that, in general, there are low levels of response capacity.

Special attention should be given to census blocks with high TWV and exposure index values, as their combination implies heightened water insecurity risk. Although the correlation between the two indices is weak and negative (r = -0.09), reflecting lower population densities in more vulnerable peripheral blocks, a significant overlap exists. Of the 4,648 blocks with TWV values above 0.5, 719 also have exposure index values exceeding 0.5, underscoring their increased water risk.

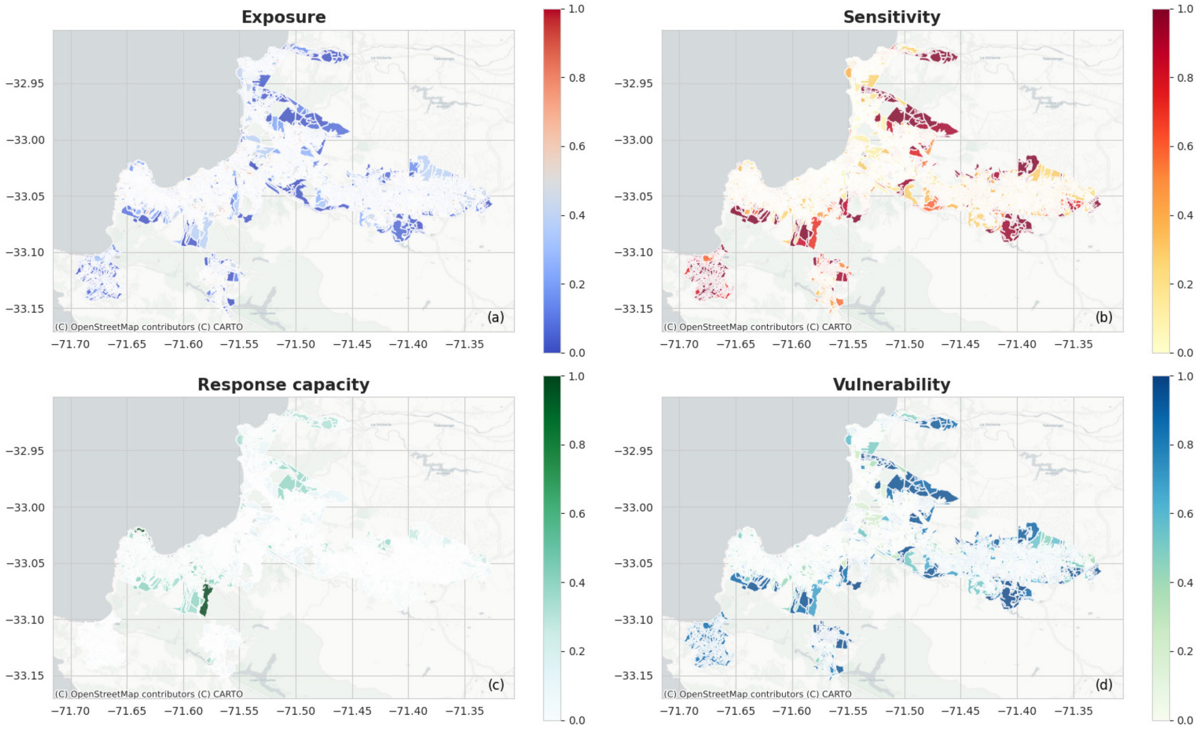

Figure 4. Exposure, sensitivity, response, and vulnerability index spatialized by census block on the study area are represented on maps a), b), c), and d), respectively. Source: own elaboration.

Table 3. Average values for sensitivity and response capacity indicators at the communal level.

Dimension	**Commune**	**Valparaíso**	**Concón**	**Viña del Mar**	**Quilpué**	**Villa Alemana**	**Mean**
Sensitivity	Education level*	10.2%	6.9%	9.1%	8.3%	7.8%	9.0%
	Income Poverty*	19.4%	21.5%	29.0%	26.0%	28.0%	25.1%
	Territorial segregation index*	14.1%	22.8%	20.0%	16.6%	20.4%	17.8%
	Ethnic population	5.32%	3.91%	4.83%	5.06%	4.57%	4.95%
	Child population	4.1%	4.3%	3.6%	3.8%	4.3%	3.9%
	Elderly population	12.1%	9.5%	12.9%	13.2%	12.6%	12.5%
	Migrant population	1.0%	2.5%	1.4%	0.6%	0.6%	1.1%
	Overcrowded households*	6.7%	3.9%	5.1%	4.2%	4.2%	5.3%
	Women-led household*	23.9%	21.0%	22.9%	23.8%	23.9%	23.4%
	Informal humman settlements	1.8%	0.2%	6.8%	0.7%	1.1%	3.2%
	Non potable water acces	2.0%	0.5%	2.1%	1.7%	3.3%	2.1%

	Monthly average consumption (m3)	13.36	19.74	14.67	15.23	13.93	14.50
	Summer monthly average consumption (m3)	13.58	22.61	15.91	14.88	14.52	15.17
	Number of unscheduled outages	1.22	2.65	1.90	1.41	1.08	1.53
	Time of unscheduled outages (min)	609.41	841.44	673.31	457.02	319.53	578.32
	Number of critical infrastructure customers	0.15	0.07	0.15	0.07	0.07	0.12
	Surface sources (percentage)*	67.27%	73.40%	70.43%	65.10%	63.90%	67.83%
	Sensitivity Index	0.349	0.206	0,272	0.385	0.355	0.322
Response capacity	The volume of alternative supply sources (mean m3)	8.20	7.47	8.85	7.78	7.62	8.25
	Distribution system autonomy (Days) *	0.90	1.61	1.08	0.59	0.51	0.51
	Diversity of sources *	0.68	0.67	0.73	0.70	0.65	0.64
	System water loss *	42.94%	44.10%	41.61%	42.10%	43.30%	42.40%
	Response Capacity Index	0.462	0.341	0.099	0.039	0.042	0.173
	Vulnerability Index	0.488	0.322	0.41	0.674	0.617	0.502

Note: Indicators with * are associated with a territorial unit bigger than the census block. Census zone, locality, or commune.

Profiles in high and low territorial water vulnerability at the census block level

Based on the hierarchical cluster grouping, the profiles of the households that fell into the most and least vulnerable deciles of the population were studied (**Figure 5**).

In general, the most vulnerable census blocks are located on the outskirts of the cities in the study area. Cluster 1H (**Figure 5a** in red) groups 121 census blocks distributed throughout the territory, with an elevated quantity of unscheduled shortcuts, an annual mean of 2373 minutes without water services and households with high consumption (about 16 cubic meters monthly). Moreover, this cluster shares with Cluster 3H the presence of critical infrastructure.

Cluster number 2H (**Figure 5a** in blue) contains 75 census blocks with a high frequency and time of unscheduled shortcuts. On average, 30% of the area of the census block of this cluster is covered with informal settlements; meanwhile, in clusters 1H and 2H, the coverage with this kind of settlement is about 12% of the surface, and in the whole study area, it is 3%. The water consumption of this census block (cluster 2H) is only ten cubic meters per month and has lower levels of alternative supply to face the great levels of average shortcuts time (7,072 minutes).

Cluster 3H (**Figure 5a** in green) is composed of the largest number of census blocks (708) and highlights having the worst accessibility to drinking water, with 8.8% of the households without access to the public drinking water network, in comparison to the 4.4% and 3.6% of the group's 1 and 3 respectively, the average is 2% in the whole study area. On the other hand, the problems associated with the supply shortcuts are quite small compared to those of different groups, which have 1.4 shortcuts for the year.

Regarding the sociodemographic characteristics of these groups, the variables migrant population, elderly population and Child population are close to the average for all the census blocks in the study area (10.8%, 12.5%, and 3.91%, respectively). Meanwhile, the ethnic origin population is nearly 7% in every group, significantly higher than the average in the study area of 4.95%.

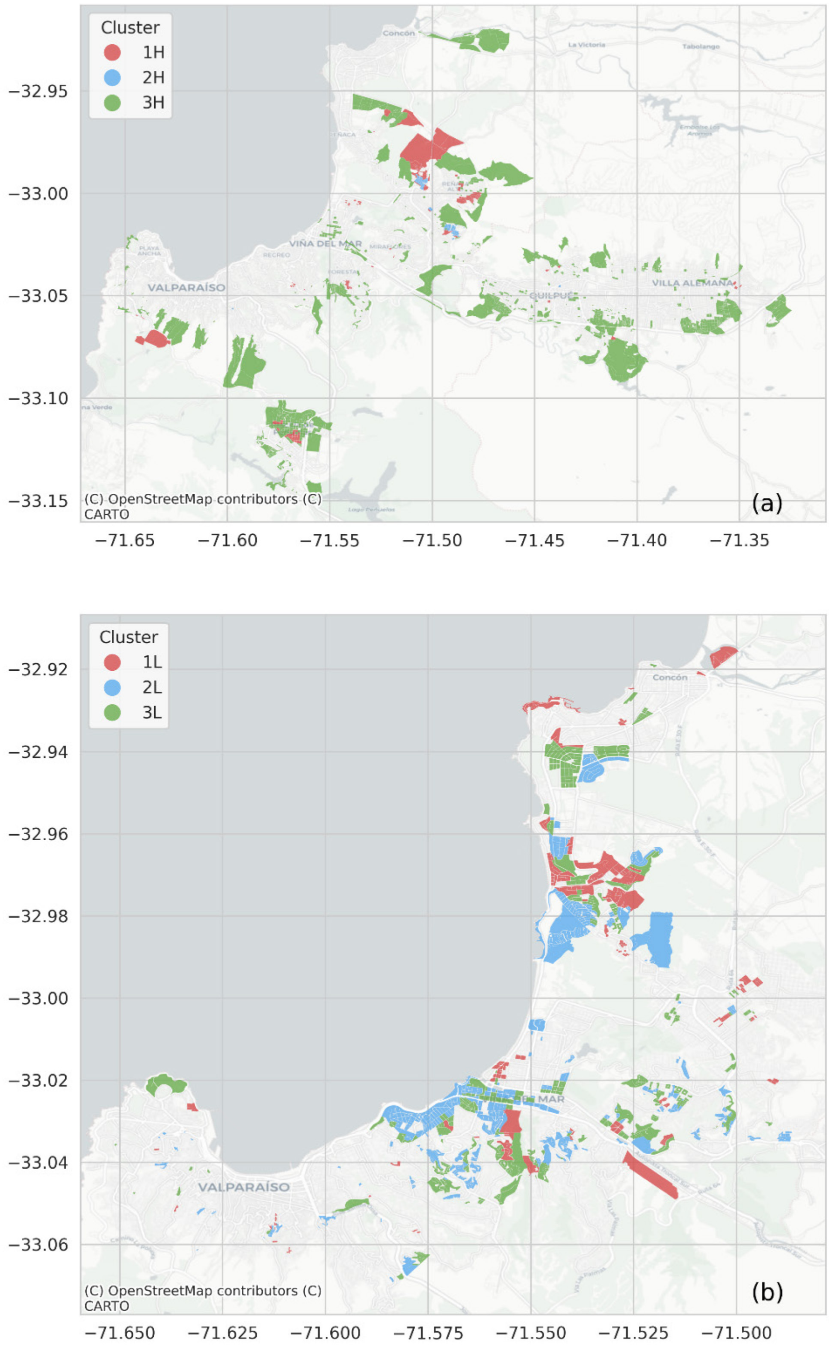

Figure 5. Spatialized clusters for the highest (a) and lowest (b) decile of the vulnerability index. Source: own elaboration.

Conversely, the 10% least vulnerable census blocks are found in the central zones in the localities of Concón, Valparaíso and Viña del Mar. There is no census block from Quilpué and Villa Alemana due to their reduced response capacity, driven by the low autonomy of the distribution system (See **Table 4**).

The census block belonging to the 3 clusters associated with the less vulnerable decile shares common characteristics (See **Table 4**): a low presence of households without drinking water access and a very low area of informal settlements. An elevated water consumption (above 17 m^3 compared to the 14.5 m^3 of the study area) and alternative supply sources volume above average. The socio-demographic characteristics are also similar, with ethnic and child populations below the study area's average. Meanwhile, the elderly and migrant populations are above the average in the studied territory. Although these variables should boost the vulnerability, this is probably attenuated because they belong to households with medium or high-income rates.

Table 4. Average values for vulnerability indicators for each of the three clusters of the lowest and the highest decile of the vulnerability Index

	Low Vulnerability			High Vulnerability		
cluster	**1L**	**2L**	**3L**	**1H**	**2H**	**3H**
No potable water Supply	0.10%	0.10%	0.00%	4.40%	3.60%	8.80%
Ethnic population	1.70%	2.50%	2.00%	6.40%	7.80%	7.00%
Elderly population	12.7%	13.9%	15.1%	10.90%	7.40%	8.90%
Migrant population	2.00%	2.20%	1.70%	1.20%	0.30%	1.20%
Child population	3.20%	2.90%	3.10%	4.10%	4.00%	5.40%
Number of unscheduled outages	1.677	0.918	0.253	6.331	15.079	1.438
Time of unscheduled outages (minutes)	674.4	269.84	65.921	2373.119	7072.465	460.672
Number of critical infrastructure customers	0.012	0.011	0.007	0.216	0	0.205
surface with Informal human settlements	0.30%	0.00%	0.10%	12.30%	32.40%	12.90%
Monthly average consumption (m^3)	17.431	18.656	19.047	16.555	10.550	14.713
Summer monthly average consumption (m^3)	19.459	21.058	21.327	18.805	11.563	14.807
Number of alternative supply sources	0.007	0.006	0.007	0.007	0.002	0.004
Alternative supply sources volume (m^3)	13.251	11.126	13.454	13.468	4.395	7.624
Vulnerability Index	0.313	0.306	0.303	0.694	0.702	0.692
Total Census Block	70	406	415	121	75	708

Note: Only indicators associated with a spatial resolution of census block and barracks are included

The main difference between the three clusters is the number and time of unscheduled shortcuts, with 674, 269, and 65 minutes of average shortcuts for the census blocks of clusters 1L, 2L, and 3L, respectively.

While interpreting each cluster's results, it must be remembered that these clusters only consider the variables at a census block scale. Furthermore, census blocks in the same cluster but in different localities may have substantial and relevant differences, like the autonomy level of the distribution system, which affects the TWV index.

DISCUSSIONS

This paper makes at least three relevant contributions to fill gaps identified in the existing literature (see also section 2): (1) an analytical framework to assess water security observed in households, considering its social dimensions; (2) prove a methodological approach to conduct high-resolution analyzes that take into account the ecological, technical, and social systems of a territory; and (3) specific evidence to guide public policies in the study case, which, until now, have been scarcely studied. The discussion is organized into three parts: first, the contribution of the proposed TWV framework to broader literature; second, actionable policy recommendations derived from the results; and third, methodological limitations and directions for future research.

Contribution to the literature of the Territorial Water Vulnerability framework

The analytical and methodological framework of the TWV enables the assessment of water security by identifying vulnerability drivers and interdependence across the systems present in a territory, including households, the health sector, governance actors, and ecological dynamics. By addressing the heterogeneity of urban areas, the framework supports high-resolution and integrated analyses, providing critical information to design risk-informed adaptation strategies at sub-city scales.

This approach moves beyond traditional diagnoses where water security is studied from a sectoral perspective and at the city or basin level, often assuming spatial homogeneity [16], [22]. By contrast, the TWV framework captures intra-urban disparities and recognizes the interdependence of ecological, technical, and socio-demographic dimensions. That is central to understanding water insecurity in highly unequal urban environments.

While urban water vulnerability has received increasing attention globally, very few studies in Latin America quantitatively address intra-urban dynamics. Prior work in cities such as Rio de Janeiro [33], Fortaleza [63] and La Paz [35] often lacks granular spatial resolution and does not incorporate systemic risk quantitatively. Furthermore, recent Latin American literature [5], [36] has contributed conceptually without translating these frameworks into operational tools. With the TWV analytical and methodological framework, this gap is addressed.

In addition, the **flexibility of the index structure** allows it to be adapted to different territorial realities and levels of data availability. This is reinforced by using a **fuzzy logic-based aggregation method**, which enables the inclusion of heterogeneous indicators without relying on arbitrary weighting and preserves the complexity of their relationships. This makes it particularly suitable for use in other cities. By doing so, the TWV framework contributes to academic knowledge and practical tools for territorial planning and water governance.

Public policy recommendations

The application of the TWV framework to the Gran Valparaíso conurbation offers key inputs for public policy. There is an urgent need to design effective water security strategies in Chile, especially given that in 2022, 47.5% of the population lived in communes under official water scarcity decrees. The findings reveal critical policy gaps and help prioritize interventions based on localized vulnerability patterns.

Based on the census block profiles identified through cluster analysis, several adaptation measures emerge for Gran Valparaíso: increasing the autonomy and efficiency of the drinking water network, improving distribution infrastructure to reduce unscheduled outages, regularizing water access in areas currently served by cistern trucks, promoting educational programs on water efficiency, and expanding the use of alternative water sources. These actions should be tailored to each commune or neighbourhood's specific vulnerability profiles and local conditions. Their implementation requires strong coordination between municipal governments, the water utility company, and civil society.

High-resolution data and analysis at the sub-city scale allow a deeper streamlining of adaptation within city and land use planning, a key condition to foster a more integrated and robust governance at the city level. This is particularly important in the Chilean context, where water governance has historically been fragmented across multiple public and private actors. Recent policy advances toward greater coordination and risk-sensitive infrastructure planning for water security [64] and water governance [65] can benefit from the study's findings and methodological approach.

While rooted in a specific territorial context, the results of this study offer lessons applicable to broader settings. Many urban areas in Chile and globally face similar challenges, including prolonged droughts, unequal access to water, and fragmented governance. The Gran Valparaíso case illustrates how structural factors, such as dependence on surface water, the prevalence of informal settlements, and low system redundancy, exacerbate vulnerability to climate-driven water stress. In this sense, the adaptation measures recommended here, particularly those aimed at strengthening response capacity (e.g., increasing system autonomy, diversifying supply sources, and enhancing inter-institutional coordination), can inform policy in other territories confronting similar socio-hydrological risks. In addition, urban territories facing water stress could benefit from applying the Territorial Water Vulnerability Index from an integrated socio-ecohydrological approach. The index structure's flexibility should allow the methodology's adaptation by incorporating local data and participatory processes, making it a valuable tool for territorial planning and integrated watershed management.

Methodological limitations and future improvements

The analysis presented in the article relies on a significant amount of spatially disaggregated information, which is not always readily available. This data gap, coupled with the challenges in accessing relevant data, hinders the widespread application of this methodology. While the TWV framework proved effective in the Gran Valparaíso conurbation, its dependence on high-resolution data poses challenges for scaling up to larger or less data-rich regions. Broader applications require integrating diverse data sources, such as regional and national datasets, often lacking the granularity to capture localized vulnerabilities. Careful calibration would be necessary to maintain the framework's methodological robustness in larger-scale contexts.

In the Chilean context, the institutional fragmentation of water management poses a further obstacle to accessing and utilizing high-quality information for the sector. Information sources include the superintendence of water utility services, the Ministry of Public Works water department, the regional government, and household surveys. Notably, the self-reporting processes conducted by water utility companies to the superintendence lack transparency, sufficient accessibility for users, and optimal quality control of the reported data. Addressing these issues is crucial, and there is an urgent need to develop indicators estimated by robust methods that support evidence-based decision-making in water resources management. These methods must adhere to standards of credibility, legitimacy, and relevance **[66]**.

In addition, the literature highlights the importance of characterizing two dimensions not addressed in the TWV analysis in this paper due to the lack of information: governance aspects that affect water management **[23]** and environmental degradation at the watershed level. Water governance was not explicitly considered due to the lack of systematized data in the Chilean context, while ecological degradation aspects affecting the whole basin fall outside the fine grid and territorial scope of the study.

Another dimension that should be characterized in a TWV analysis is the domestic dynamics of households regarding water (e.g., reuse, efficiency, special needs, and perceptual scarcity). This aspect was not addressed in the present study due to the absence of household surveys capturing such information. The only household survey with relevant data is the national census, which includes information on the origin of household water access (a variable incorporated in this study). However, this census is conducted only every ten years, complicating the monitoring and updating of water access information.

Further research should be addressed to cover these aspects and continue advancing in an integrated TWV analysis according to the analytical framework presented. First, it is necessary to evaluate the system's hazards and quantify the vulnerability of the ecological systems that sustain the water services of the study area. A nested vulnerability approach across territorial systems could also be considered, since evaluating the vulnerability of the ecological system would allow the modelling of the natural hazards impacting water services. This would enhance the current work by progressing from vulnerability quantification to risk assessment of water insecurity for exposed populations. However, this study excluded hazard assessments due to insufficient data resolution for intra-city analyses.

Expanding the TWV framework should also include evaluating additional water services such as productive, cultural, recreational, and ecosystem uses and their interrelationships. In the Chilean context, distinguishing water risk analyses for urban and rural areas is particularly important, as these rely on fundamentally different provision systems. To date, urban areas have received less attention in this regard. Nonetheless, the TWV framework is adaptable to both urban and rural territories.

To deepen the understanding of water (in)security, it is essential to complement the longitudinal assessment of risks with a cross-sectional evaluation of insecurity (see Figure 1). This approach requires analyzing equitable access to water services within the territory, considering quality and quantity dimensions, and identifying specific gaps in the present **[5]**.

Finally, future work should include a more formal and systematic sensitivity analysis. As discussed in Section 3, the current methodology incorporates a limited sensitivity analysis through an iterative calibration process. This process involved testing different combinations of membership functions and aggregation rules to evaluate their performance regarding discrimination power, theoretical robustness, and coherence. However, future research should extend the sensitivity analysis to other parameters, including selecting variables used in the fuzzy model. Such advancements would further refine the methodology and enhance its capacity to capture the complex dynamics of water insecurity.

CONCLUSIONS

This work develops an analytical, methodological and applied proposal to address and evaluate territorial water vulnerability related to urban water insecurity. Therefore, a broad and flexible analytical framework based on the concept of water security and risk is used, capable of being applied to different systems (ecological, technical and sociocultural) and scales (basins, administrative units, among others), considering the complexity and variety of dimensions of water security. Then, the framework was applied to evaluate the TWV associated with providing drinking water for urban domestic use in the Gran Valparaíso conurbation of central Chile.

Sensitivity and response capacity indicators related to urban drinking water systems are evaluated across more than 10,000 census blocks using a fuzzy logic-based index. The results reveal that 4,841 out of 10,042 census blocks exceed the vulnerability threshold of 0.5, driven primarily by the interplay between low response capacity and heightened sensitivity, which drives significant vulnerability across large portions of the study area. Also, 719 have exposure index values exceeding 0.5, implying an increased water risk.

The cluster analysis identified distinct vulnerability profiles, revealing common territorial patterns that can support more efficient and equitable decision-making. Problems with water supply access, informal settlement coverage, and long unscheduled annual cuts appear as the main drivers of a high TWV index in the clusters. Recognizing these shared characteristics allows for the design of adaptation measures that respond to the specific needs of different areas, moving beyond generic, one-size-fits-all interventions.

The TWV framework not only advances academic understanding of water insecurity in complex urban settings but also provides concrete tools for policy design. Addressing the challenges identified, particularly those requiring coordination between public institutions, water utilities, and civil society, will be key to improving urban resilience to socio-hydrological risks in Chile and beyond.

ACKNOWLEDGMENT

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SUPPORTING INFORMATION

The database containing all the indicators used and the code developed for the fuzzy logic process to generate the vulnerability index and the associated tables, figures, and analyses is available in the Open Science Framework repository. (OSF | Dataset for "An Integrated and High-resolution Assessment of Territorial Water Vulnerability: The Case of the Gran Valparaiso Conurbation, Central Chile") (Alamos, N. 2022).

Indicators used for measuring drinking water security in literature.

Table S1. The literature review Identified indicators for measuring the drinking water utility dimension of water security.

Subdimension	Indicators
Quantity	Total water resources/Total population (Aboelnga et al., 2020)
	Water resources per capita (Huang et al., 2015)
	Total water supply (Chang et al., 2015)
	Supply continuity of reservoirs and lakes
	Dependency on overexploited aquifers (van Ginkel et al., 2018)
Quality	The proportion of drinking water samples meeting WHO and local standards (Aboelnga et al., 2020)
	Number of potable water contamination incidents (Aboelnga et al., 2020)
	Percent of samples of tap water free from bacterial contamination (Khan et al., 2020)

Affordability	Total monthly expenditure (Shrestha et al., 2018) Water tariff m3 (Assefa et al., 2018) Gasto en agua en proporción al ingreso del hogar (Aboelnga et al., 2020)
Accessibility	Financial water, sanitation and hygiene (WASH) expenditure as a percentage of household income (Assefa et al., 2018) Percentage of households with access to tap water supply (Jensen & Wu, 2018b) Duration of piped water supply (hours/week) (Aboelnga et al., 2020; Khan et al., 2020; Shrestha et al., 2018)
Infrastructure	Coverage of water supply system (van Ginkel et al., 2018) Continuity of water supply (van Ginkel et al., 2018)
Consumption	Per capita water consumption per day in liters (Shrestha et al., 2018) Total water demand (Assefa et al., 2018; Chang et al., 2015) Water resources utilization rate (Huang et al., 2015) Domestic water use (van Ginkel et al., 2018)
Efficiency	Water loss (NRW) in the network (Assefa et al., 2018)
Alternatives sources	Ground water use (Shrestha et al., 2018) Rainwater (Shrestha et al., 2018) Tanker water use (Jensen & Wu, 2018b; Shrestha et al., 2018) Jar water use (Shrestha et al., 2018) Rate of rejuvenated water use (%) (Huang et al., 2015) Desalinated water m^3 (Jensen & Wu, 2018) Percentage of the contribution of alternative sources (Aboelnga et al., 2020; Huang et al., 2015; Jensen & Wu, 2018b)

Table S2. Identified indicators used for measuring socioeconomic dimensions of water security in the literature review.

Subdimension	**Indicators**
Social Capital	Associated with a community group (Shrestha et al., 2018) Consumer awareness and interest (Khan et al., 2020) Conflicts over water supply (van Ginkel et al., 2018)
Population	Population growth (van Ginkel et al., 2018) Total population (Chang et al., 2015) Urban population (Chang et al., 2015) Rural population (Chang et al., 2015) Urbanization rate (Chang et al., 2015)
Economic	GDP (Chang et al., 2015; van Ginkel et al., 2018) Water-intensive industries (van Ginkel et al., 2018)
Legal	Numbers of illegal uses, Numbers of total complaints (Aboelnga et al., 2020)
	Corruption (van Ginkel et al., 2018)

Institutional framework	Accountability (van Ginkel et al., 2018) Vertical coordination (van Ginkel et al., 2018)
Governance	Strategic planning (Jensen & Wu, 2018b; van Ginkel et al., 2018) Access to data and information (van Ginkel et al., 2018) Degree of public participation (van Ginkel et al., 2018) Financial resources (van Ginkel et al., 2018) Comprehensive and transparent regulation of water utilities (Jensen & Wu, 2018b)

Table S3. The literature review used Identified indicators to measure environmental dimensions of water security.

Subdimension	Indicators
Pollution	Percentage of safely treated wastewater flows (Aboelnga et al., 2020) The total volume of wastewater discharged (Yin et al., 2017) Water pollution accidents (Yin et al., 2017) Rate of industrial sewage discharge (Yin et al., 2017)
Green surfaces (drainage)	Rate green land areas (Aboelnga et al., 2020; Chang et al., 2015) Rate of forest covered (Aboelnga et al., 2020)
Hazards	Numbers of floods over three years (Aboelnga et al., 2020; Jensen & Wu, 2018b) (Jensen & Wu, 2018) Flood frequency (Yin et al., 2017) Numbers of droughts (Aboelnga et al., 2020; van Ginkel et al., 2018) The surface area of the flood-prone area regarding total surface area (Aboelnga et al., 2020) Average annual precipitation (Aboelnga et al., 2020; van Ginkel et al., 2018; Yin et al., 2017) Average annual temperature (Aboelnga et al., 2020) Flood protection infrastructure (van Ginkel et al., 2018) Fatalities due to floods per year (Jensen & Wu, 2018a)

Fuzzy logic process

This annex details the parameters and processes used in each step of the fuzzy logic methodology to enhance transparency and replicability. Table S4 details the membership function parameters used for each indicator, Table S5 shows the Aggregation rules for sensitivity subdimension indexes, while Tables S6, S7 and S8 present the rules used to aggregate the indicators and subindexes of sensitivity, response capacity and vulnerability indexes, respectively.

Table S4: membership function parameters for the indicators considered

Dimension	Subdimension	Indicator	Lowest value	highest value
Sensitivity	Socioeconomic	Education level	0	percentile 99
		Income Poverty	0	percentile 98

	Demographic	Territorial segregation index	0	percentile 98
		Ethnic population	0	percentile 98
		Child population	0	percentile 98
		Elderly population	0	percentile 95
		Migrant population	0	percentile 98
		Overcrowded households	0	percentile 98
		Women-led household	percentile 1	percentile 99
	Water accessibility	Informal human settlements	0	percentile 98
		Well water supply	0	percentile 97
		Supply by cistern truck	0	percentile 97
		River water supply	0	percentile 97
	Water consumes	Monthly average consumption	percentile 1	percentile 99
		Summer monthly average consumption	percentile 1	percentile 99
	Other service conditions	Number of unscheduled outages	0	percentile 99
		Time of unscheduled outages	0	percentile 99
		Number of critical infrastructure customers	0	percentile 99
		Surface sources	percentile 1	percentile 100
Response Capacity	Short-term response	Number and volume of alternative supply sources	0	percentile 100
		Distribution system autonomy	0	percentile 100
	Long-term response	Diversity of sources	0	percentile 100
		system water loss	0	percentile 100

For the sensitivity, the indicators were first grouped into sub-dimensions and subsequently combined into a sensitivity index. The form of aggregation depended on the indicator's substitutability in reflecting the sub-dimension's presence. A boolean OR operator was used for highly substitutable indicators, where any indicator's presence activated the sub-dimension's relevance in the index. For complementary indicators, where two or more indicators were necessary to establish the significance of the sub-dimension in the index, the indicators were added using Boolean AND operators.

Table S5: Aggregation rules for sensitivity subdimension indexes

Subdimension value	Aggregation rules of indicators
Socioeconomic[low]	Income Poverty['low'] AND Education level['low']
Socioeconomic[high]	Income Poverty['high'] OR Education level['high']
Demographic[low]	(Child population['low'] AND Elderly population['low'] AND Women-led household['low'] AND Overcrowded households['low']) OR (Ethnic population['low'] AND Migrant population['low'] AND Territorial segregation index['low'])
Demographic[high]	(Child population['high'] OR Elderly population['high'] OR Women-led household['high'] OR Overcrowded households['high']) AND (Ethnic population['high'] OR Migrant population['high'] OR Territorial segregation index['high'])

Water accessibility[low]	alternative water supply['low'] AND Informal human settlements['low'])
Water accessibility[high]	alternative water supply['AND'] OR Informal human settlements['low'])
Water consumes[low]	Monthly average consumption['low'] AND Summer monthly average consumption['low']
Water consumes[high]	Monthly average consumption['high'] OR Summer monthly average consumption['high']
Other service conditions[low]	Number of unscheduled outages['low'] AND Time of unscheduled outages['low'] AND Number of critical infrastructure customers['low'] AND Surface sources['low'])
Other service conditions[high]	Number of unscheduled outages['high'] OR Time of unscheduled outages['high'] OR Number of critical infrastructure customers['high'] ORSurface sources['high'])

Aggregation rules used in the construction of fuzzy logic vulnerability indexes.

For the fuzzy aggregation of the indicators in the sensitivity, resilience and vulnerability dimensions, rules were built according to the categories established in **Table S6**, Table S7 7 and Table S8. The tables summarize the rules used, indicating the result of crossing the categories arranged on the X and Y axes in each box. For example, the first box in **Table S6** indicates that under conditions of high socioeconomic sensitivity, high demographic sensitivity, low water accessibility, high sensitivity conditions of other services (mainly unscheduled outages) and high consumption levels, a high sensitivity for the census block is considered.

Table S6. Rules of aggregation used in the fuzzy logic model for the sensitivity index construction.

Sensitivity levels			**High socioeconomic level**		**Low socioeconomic level**	
			High demographic condition	**Low demographic condition**	**High demographic condition**	**Low demographic condition**
Low Water accessibility	High other service conditions	High water consumption	High sensitivity	High sensitivity	High sensitivity	High sensitivity
		Low water consumption	High sensitivity	High sensitivity	High sensitivity	High sensitivity
	Low other service conditions	High water consumption	High sensitivity	High sensitivity	High sensitivity	High sensitivity
		Low water consumption	High sensitivity	High sensitivity	High sensitivity	High sensitivity
High Water accessibility	High other service conditions	High water consumption	High sensitivity	High sensitivity	High sensitivity	Medium sensitivity
		Low water consumption	High sensitivity	Medium sensitivity	Medium sensitivity	Low sensitivity
	Low other service conditions	High water consumption	High sensitivity	Medium sensitivity	Low sensitivity	Low sensitivity
		Low water consumption	Medium sensitivity	Low sensitivity	Low sensitivity	Low sensitivity

Table S7. Rules of aggregation used in the fuzzy logic model for the response capacity index construction.

Response capacity level		**High Distribution system autonomy**		**Low Distribution system autonomy**	
		High alternative supply sources	**Low alternative supply sources**	**High alternative supply sources**	**Low alternative supply sources**
High diversity of sources	Low system water loss	High response capacity	High response capacity	Medium response capacity	Medium response capacity
	High system water loss	High response capacity	Medium response capacity	Medium response capacity	Low response capacity
Low diversity of sources	Low system water loss	High response capacity	Medium response capacity	Medium response capacity	Low response capacity
	High system water loss	High response capacity	Medium response capacity	Low response capacity	Low response capacity

Table S8. Aggregation rules are used in the fuzzy logic model for the vulnerability index construction.

Vulnerability level	High sensitivity	Medium sensitivity	Low sensitivity
High response capacity	Medium vulnerability	Medium vulnerability	Low vulnerability
Medium response capacity	High vulnerability	Medium vulnerability	Low vulnerability
Low response capacity	High vulnerability	High vulnerability	Low vulnerability

Choice of the number of clusters used to analyze extreme deciles of vulnerability.

The inertial curve and dendrogram of the dataset are analyzed to choose the optimal number of clusters for each decile. The inertia value corresponds to the quadratic sum of the intra-cluster variance and indicates how coherent the different groups are. Lower inertia values indicate more similar units within the group. However, many groups will be less representative of many blocks, making it difficult to interpret the data. In the dendrogram, similar objects are represented by a link whose position is determined by the level of similarity between the objects or groups of objects. According to the results of both methods (**Figure S1**), three clusters for the high and low-vulnerability groups were decided to be made. At this number of groups, the inertia curve presents an inflection point in the inertia gain of having one more group, and the Euclidean distance in the dendrogram is maximized.

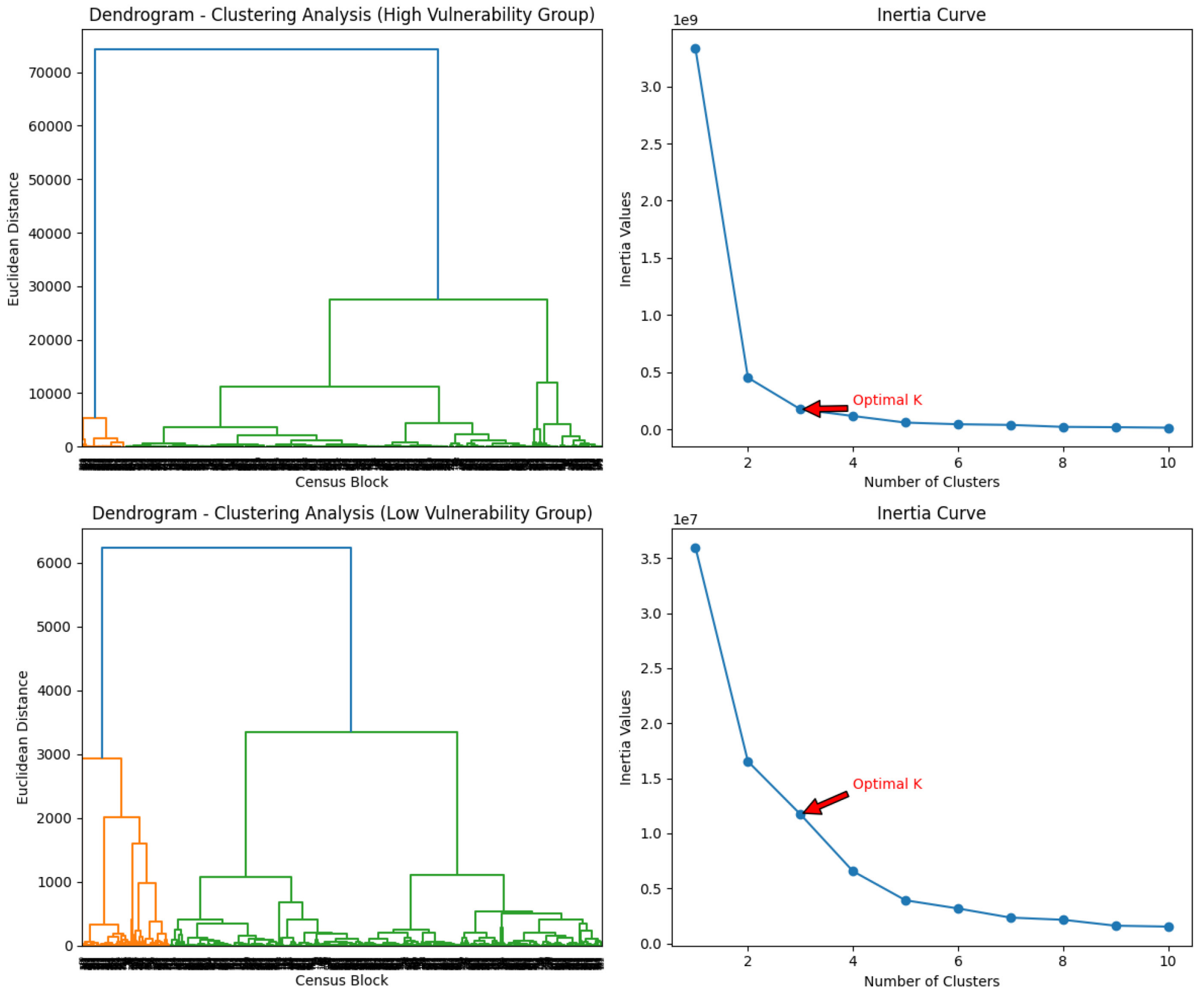

Figure S1. Analytical graphs choose the optimum number of clusters for each analysis. In a) and c), dendrograms for the high and low vulnerability groups are chosen respectively, while in b) and d), the results of the inertia curve for each group are shown.

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