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

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

[1] Center for Climate and Resilience Research, Santiago, Chile, [2] Systemic Transdisciplinary Research HUB (NEST.R3), [3] Department of Rural Management and Innovation, University of Chile, [4]Social Sciences Faculty, University of Chile, Ñuñoa, Chile

Corresponding author: Nicolás Álamos (nalamos@fen.uchile.cl)

Key Points:

- A flexible analytical and methodological framework based on the concept of water security risk is proposed
- Fuzzy logic and cluster analysis were used to develop and analyze a Territorial Water Vulnerability Index
- Sensitivity and response conditions of the technical and sociocultural study area systems related to drinking water services were evaluated
-

Abstract

Water security is a key goal to advance towards sustainable development and an increasingly hard challenge in a climate change context. Achieving water security requires advancing towards equitable access to water services in sufficient quantity and quality to satisfy multiple needs and uses and to ensure the sustainability of such services to various natural and anthropogenic threats. We introduce the notion of 'territorial water vulnerability' (TWV) as a measure of the propensity of a particular territory to be or become unable to satisfy relevant water needs and uses adequately as a result of its structural condition to be negatively affected by socio-natural threats and stressors. On this basis, we develop a set of territorial indicators of sensitivity and response capacity for drinking urban water services and apply them to the Gran Valparaiso conurbation on the central coast of Chile. A particularly relevant territory considering the extreme water scarcity of the contributing catchment. A fuzzy logic approach was used to develop a single TWV index at the census block level; through cluster analysis, census blocks profiles are identified whose common characteristics explain their high vulnerability levels. This paper provides at least three relevant contributions to fill gaps identified in the existing literature): (1) an analytical framework to assess urban water security observed from households, considering social dimensions, (2) a methodological approach to carry out high-resolution analysis that considers the ecological, technical and social systems and (3) evidence to guide public policies in the scarcely studied Chilean Case.

Plain Language Summary

This paper offers an analytical framework and methodology to evaluate and describe the characteristics that influence the capacity of a territory to ensure the water security of its population. Formally, we called this "territorial water vulnerability (TWV)". This framework was applied to evaluate the TWV associated with the provision of drinking water services for urban domestic use, in the Gran Valparaíso conurbation of central Chile. A fine-grained analysis was made considering the sensitivity and response conditions of the technical and sociocultural systems of the study area. This high-resolution analysis favors the design and implementation of adaptation measures taking into account the most significant vulnerability variables in spatial units within the cities, reducing water insecurity in an efficient and place-specific way, focusing on water security at a household level, instead of considering the city as a relatively homogeneous unit. Finally, according to our results and considering the most vulnerable census block profiles from the analysis, some relevant policies and actions to reduce TWV for the urban drinking water system of Gran Valparaíso are recommended.

Keywords: Water Security, Climate Change, Territorial Vulnerability, Risk assessment, Chile

Key Index: 4330 Vulnerability; 4333 Disaster risk analysis and assessment; 1817 Extreme events (4313); 1807 Climate impacts (4321), 1894 Instruments and techniques: modeling

1 Introduction

Water security is a key condition to achieving sustainable development (UN-Water, 2013) and necessary for human health and well-being (Adams et al., 2020; Jensen & Wu, 2018; Wood et al., 2019). While multiple definitions of water security exist, depending on the type of system analyzed and its scale (Hoekstra, 2018), in broad terms, it can be 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" ((UN-Water, 2013, p1)

Accordingly, achieving water security requires at once to advance toward equitable access to water services in sufficient quantity and quality to satisfy multiple needs and uses and to ensure the sustainability and resilience of said services to various natural and anthropogenic threats (Urquiza & Billi, 2020). The latter, in particular, is becoming an increasingly hard challenge in the context of climate change (Farinosi et al., 2018; Kristvik et al., 2019) and increasing urbanization (Srinivasan et al., 2013)

Mekonnen & Hoekstra (2016) estimate that four billion people already face water scarcity considering seasonal and inter-annual climate variations in water availability. Unfortunately, water security issues are expected to increase, as IPCC (2021) projects a reduction in renewable superficial and underground water resources, as well as an increase in frequency and intensity of droughts and a deterioration of water quality, the latter due to both higher concentration of contaminants and a higher frequency of heavy precipitation events. Thus, climate change must be assessed as a major threat to reach and sustain water security.

Climate change does not impact all the territories homogenously but yields differential impacts depending on multiple social, economic and environmental parameters (IPCC, 2022) Therefore, evaluating the water risk due to climate change requires developing integrated frameworks able to capture the determinants and spatial distribution of water insecurity, which must be sensitive to the particular ecological, technical and socio-cultural conditions of each territorial context.

Usually, water security analyses are performed at a basin or city level (Karimi Alavijeh et al., 2021) but many of the drivers of water security, including infrastructural, sociodemographic, and cultural variables, vary at smaller scales. Also, actions aimed at fostering water security are most effective when performed at the local level, with a keener understanding of how different sources of risk interact with the specific conditions of particular areas and populations within human settlements. We then need a more detailed resolution in the evaluation of water security risks allowing to consider the characteristics of smaller territorial(Assefa et al., 2018; Bartel, 2015; Datu, 2020; Shrestha et al., 2018; Victor et al., 2022).

In Latin America, there is a lack of robust empirical studies on water security risks. Recently, international organisms such as the Economic Commission for Latin America and the Caribbean (UN-ECLAC) and the Inter-American Development Bank (IADB) have published documents that advance a conceptual framework for water security and water vulnerability. Some studies from a Latino-American perspective, (Bretas et al., 2020; Peña, 2016; Urquiza & Billi, 2020) are considered on the paper.

Considering this advancements, this paper introduces the concept of territorial water vulnerability (TWV) as a proxy for the territorial conditionings of water insecurity risk. Providing an empirical analysis for the Gran Valparaíso conurbation (central coast of Chile), offering a high-resolution assessment spanning ecological, technical and sociocultural conditions driving the vulnerability of households to water scarcity risks. A fuzzy logic approach was used to develop a single TWV index from the population, water services and infrastructure information at the census block level, a resolution unprecedented in the country and of great interest both for the academic understanding of patterns of vulnerability and decision makers responsible for water security.

Noticeably, this particular application of the index is specifically tailored to urban contexts. Cities are significantly exposed to water stress, as the trend towards greater population concentration in urban areas is expected to continue. 66% of the world population is expected to be living in cities by 2050, likely leading to an exacerbation of water scarcity (Mekonnen & Hoekstra, 2016), as well as exposure to water-related disasters. In this sense, the application of a fine-grained TWV analysis in an urban context is especially interesting. Moreover, in the specific case of Chile is necessary to differentiate water scarcity analyses in urban and rural contexts because they depend on very different provision systems, with cities having received less attention so far. Nevertheless, our general framework can be adapted to any kind of territory, urban or rural.

The paper is structured as follows: Section 2 presents a literature review on water security. Section 3 develops the conceptual framework. Section 4 introduces the study case, the data and methodology used to estimate and analyze a TWV index. Section 5 illustrates the main results, identifying the most vulnerable territories of the study case and analyzing the vulnerability drivers at the commune scale and the census block scale through cluster analysis. Section 6 discusses the main results and the conceptual and methodological contributions developed in the paper. Finally, Section 7 summarizes the main conclusions of this work.

2 Literature Review

In general, two broad types of methodological frameworks exist to quantify urban water security. The first group of studies measures water security across only one dimension, as is the case with the hydric stress or water poverty index (Aboelnga et al., 2020; Jensen & Wu, 2018). 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 water security. Nevertheless, these indexes fail to properly characterize urban water security dynamics (Gassert et al., 2014; Komnenic et al., 2009) because they necessarily generalize and homogenize territorial diversity in their analysis (Karimi Alavijeh et al., 2021)These studies usually overemphasize the importance of focusing excessively on gray infrastructure, which may hide other important aspects affecting water security (Danielaini et al., 2019)

A second approach existing in the literature is measuring water security using composite indexes (Damkjaer & Taylor, 2017), built from various indicators that attempt to consider the different and complex relationships in an urban territory (Howlett & Cuenca, 2017). These indices are developed for specific cities or regions, considering the available information and recognizing the multiple drivers influencing water security (Aboelnga et al., 2020; Jensen & Wu, 2018).

These drivers include, for instance: technical conditions, such as the quantity, quality, affordability, accessibility, infrastructure, consumption, efficiency and alternatives sources used in water provision and wastewater treatment systems (Aboelnga et al., 2020; Assefa et al., 2018; Chang et al., 2015; Huang et al., 2015; Jensen & Wu, 2018; Shrestha et al., 2018; van Ginkel et al., 2018); socio-economic conditions, such as social capital, population, economic factors, legal and institutional and governance frameworks (Aboelnga et al., 2020; Chang et al., 2015; Jensen & Wu, 2018; van Ginkel et al., 2018); and environmental conditions such as pollution, green infrastructure, the propensity of hydro-climatic hazards and others natural risk (Aboelnga et al., 2020; Chang et al., 2015; Jensen & Wu, 2018; van Ginkel et al., 2018; Yin et al., 2017) (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, van Ginkel et al. (2018) and Chang et al. (2015) used the GDP as a proxy of socio-economic status, applied 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 in which the information is expressed is another relevant aspect to consider in constructing these indexes. Most studies are defined at a city level, i.e., considering the city as a homogeneous territory and sometimes including relationships with the contributing basins (Medina, 2021; Tellman et al., 2018; van Ginkel et al., 2018). Finer-grained studies are rare. Nevertheless, the literature recognizes the need for new analytical frameworks and indexes to evaluate water security at a more detailed geographic scale, intending to take into account the specific characteristics of small territorial units (Assefa et al., 2018; Bartel, 2015; Datu, 2020; Shrestha et al., 2018).

In the particular case of Latin America, the scientific literature related to water security is still incipient. This does not mean that there is no water-related issues literature in the region, but rather that the concept of water security has only started to be used in recent years. Among the studies that use the water security concept, there are investigations about specific social conflicts, like conflicts with mining projects (Lutz Ley, 2020) in urban or rural contexts(Serrano et al., 2019). Other studies evaluate water security by combining quantitative and qualitative variables in the cities of Río de Janeiro (Formiga-Johnsson & Britto, 2020; B. B. M. Santos, 2016), Fortaleza (Silva et al., 2019) and La Paz (Medina, 2021) . In the latter, water security is evaluated exclusively considering the availability of raw water. In documents from international organizations, some relevant publications are from Peña (2016) defining water security, and offering a diagnosis of the water resources in the region and a perspective of the challenges and priorities for water, Urquiza and Billi (2020), by UN-ECLAC, offer a conceptual definition and a diagnosis of waster security in Latin America and identifies strategies and instruments for water security. Finally, Bretas et al. (2020) for IADB (Interamerican Development Bank), elaborates a diagnosis of water security and a perspective of IDB for innovation and strategies for the future of water in Latin America.

In Chile, (Donoso et al., 2012) carried out a comprehensive statistical data collection to describe the use of water in the country, while (Fuster et al., 2017) focused on reaching consensus on the water security definition among various national stakeholders and defining critical variables for water security in a climate change context. In public policy topics, the "Informe Final de la Mesa Nacional del Agua" (Ministerio de Obras Públicas, 2022) places water security as a priority element for water resources management and the national Climate Risk Atlas performed an assessment of water security risk both in urban and rural domains, providing risk indexes for each of the country's municipalities. (Ministry of environment, 2020)

3 Conceptual framework

To fill the gaps identified above, in this paper, we aim to elaborate and exemplify a methodology to assess the characteristics of a territory that can hamper or limit the achievement of water security. Here, we define water security as a territory's ability to provide equitable access—in quantity and quality—to resilient and sustainable hydric services, that allow human and ecological development. Conversely, we denominate 'territorial water vulnerability' (TWV) as the assessment of the factors which may hamper its ability to reach and maintain a water security condition over time.

According to Urquiza & Billi (2020), the assessment of water security should involve two complementary types of analyses: a) understanding the existing degree of equality in the access to water services across different individuals and groups at a given time, and the territorial dynamics that favor or hamper this access; b) understanding the probability that the availability or access to these services can be affected due to possible future socio-natural hazards. TWV focuses particularly on the latter dimension, analyzing how the current state of the characteristics of a territory conditions its propensity to see its water security affected by hazards to which the territory is exposed, with particular focus on hydro climatic hazards (figure 1). Although, often, TWV will display a significant correlation with pre-existing access inequalities, and in turn, greater vulnerability means a higher risk of impact, which in turn can contribute to reproducing said inequalities

Here, the concept of 'territory' points to a spatially delimited unit of analysis, constituted by the dynamic coupling between processes and systems of different nature: ecological (natural resources, regulating ecosystem services), technical (extraction, transformation, distribution and use of water, between others) and socio-cultural (habits, preferences, social norms, organizational structures, governance). Therefore, analyzing TWV requires analyzing the specific characteristics of each one of these systems.

The concept of vulnerability is closely connected to the idea of risk (see figure 1a). Following the conceptualization of the Intergovernmental Panel on Climate Change (IPCC) in its fifth assessment report, the risk is understood as the probability that something valuable to society would be in danger with an uncertain outcome as a result of the interaction between three components: hazard, exposure, and vulnerability of the system (Centro de Ciencia del Clima y la Resiliencia, 2018; IPCC, 2022). Under this approach, territorial water risk, i.e., the probability that water services are exposed to a particular threat, depends as much on the expected probability and intensity of that threat, on the presence of services that can be affected by that threat, and on the propensity of the territory to see these services affected: the last is, TWV. Usually, a territory offers multiple water services and is affected by multiple hazards. TWV provides a transversal outlook as a proxy of the risk that the territory's different water services may face due to multiple possible threats.

Likewise, Vulnerability can be decomposed into two dimensions: sensitivity and response capacity (GIZ, 2017; IPCC, 2022). Sensitivity is understood as the systemic characteristics that increase the probability of the exposed components suffering negative impacts and it is a function of the environmental, sociodemographic, infrastructure and technology conditions, economic and cultural resources, and knowledge of the territory concerning the different components of the water system (Calvo et al., 2021)

Meanwhile, response capacity is essentially a "reactive" mechanism responding to disturbances aboard the systemic capacity of facing adverse conditions presented by hazards, exposure and sensitivity (Biggs et al., 2015; Binder et al., 2017; Calvo et al., 2021; Urquiza et al., 2021). The response capacity relates to the flexibility of the system to adjust in the face of an eventual impact, which in turn is driven by the diversity, connectivity, and redundancy of the components and structures involved in the water services provision (Calvo et al., 2021).

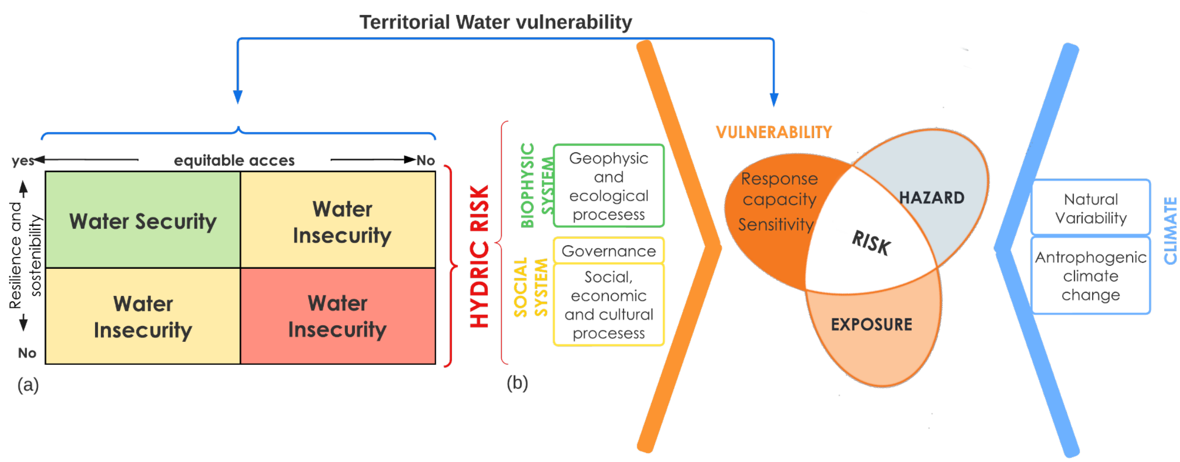


Figure 1: on (a) Conceptual relationships between water security, insecurity, equitable access, sostenibility and resilience (adapted from Urquiza & Billi, 2020). The sostenibility and response capacity (axis y) of the water services are determined by the hydric risk that the territory faces (b) on (b) conceptual framework of climate risk (adapted from CR2, 2018). Territorial water vulnerability as the territory's propensity to have water insecurity conditions captures the vulnerability component of the hydric risk and the water access conditions of the territory.

Evaluating water vulnerability means assessing the elements and indicators that compose the sensitivity and response capacity dimensions, which requires a multidimensional and multiscale high complexity analysis. To achieve this, we have adapted the (GIZ, 2017) analytical framework of risk assessment, building an impact chain that represents the interaction between the components and variables which influence the risk faced by water services. It is important to be aware that the impact chains can consider different risks at the same time, explicitly including the possibility that impacts over particular systems or processes (for example, over ecological services) turn into a source of hazards for other systems or processes (over economic activities, human health and welfare, etc.). These are known as "nested" or "cascade" impacts (see figure 2). Under the impact chain method, territorial water vulnerability will embrace all those dimensions and indicators of sensitivity and resilience of ecological, technical and sociocultural systems identified as relevant in the impact chains.

The process of impact chain construction includes two potentially iterative moments: the design of a theoretical impact chain (which summarizes all the relevant variables and interactions observed by existing literature and experts) and the operationalization of that chain into concrete, measurable and existing indicators. Moreover, summary indexes and indicators can be created to integrate the different variables of the impact chain into a unique value for each analytical category, enabling decision-makers or other actors to evaluate and compare, in a simplified way, the present risk and vulnerability in the territories of interest.

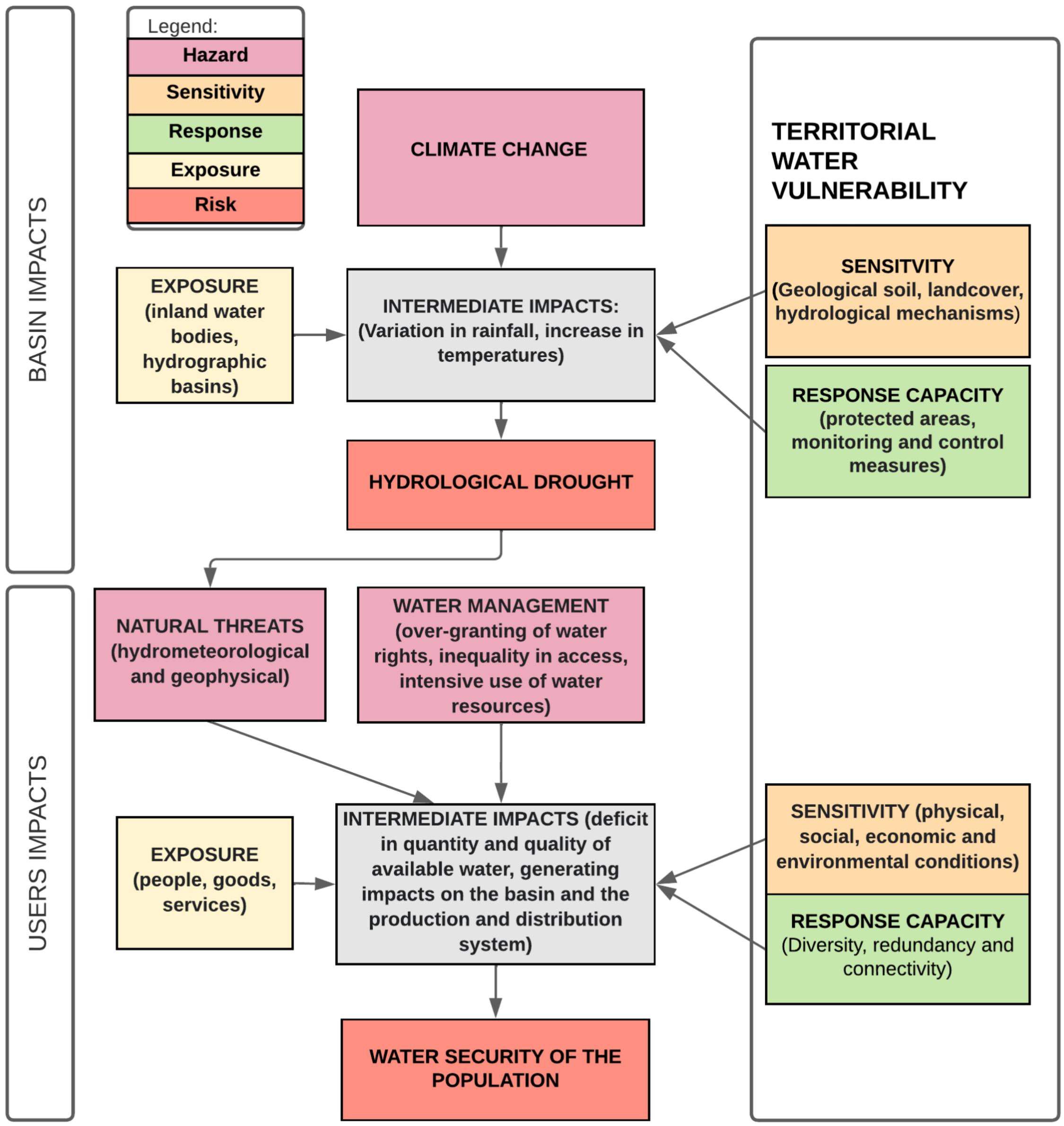


Figure 2. Example of a nested Chain of Impacts that describes the components affecting the population's drinkable water security risk.

4 Methods and Data

This paper employs a five-step methodology to evaluate the territorial hydric vulnerability, in accordance with the conceptual framework described in the previous section. The steps are numbered from 0 with the intention that steps 1-4 coincide with what is developed in sections 4.1 - 4.4.

0. Define and conceptualize the observed water services: Climate change may affect water security in several possible ways, depending on which kind of climate drivers and water services (and users) one considers and the scale of analysis (Urquiza & Billi, 2020). 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 components and processes that interact in the technical, sociocultural 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 4.1.

2. Characterization of the risk components faced by the system: Once the system has been defined, we build an impact chain illustrating how climate change may be impacting the system. First, we identify the key climatic hazards which may have an impact on the service and the components of the system which may be exposed to those hazards. This allows us to distinguish the direct and intermediate impacts of the selected hazards, on the system and the service it provides. Then, we characterize the main factors explaining the system's sensitivity and its components: particularly, we identify the technical and sociocultural conditions that affect the drinkable water service and those of response capacity in terms of the system's flexibility. This step is addressed in the impact chain subsection (4.2).

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. To get a risk assessment, this vulnerability should be complemented with hazard and exposure analyses. In this study, only TWV and exposure is described due to the difficulty of differentiating the hazards at the analysis resolution, which considers units of the same hydrographic basin provided with drinkable water from the same technical system. In subsection 4.3, the integration of the sensitivity and response capacity indicators on a single TWV index is addressed.

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 aboard the TWV. In section 4.4, a cluster analysis approach is described.

4.1 Study Area

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, is managed by the private water utility company ESVAL S.A in his "Gran Valparaíso" System that integrates eight locations: Valparaíso, Placilla de Peñuelas, Curauma, Viña del Mar, Reñaca, Concón, Quilpué and Villa Alemana (figure 3).

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 3). Thus the river's water availability is essential to maintaining an effective drinking water supply in the Gran Valparaíso system.

The Aconcagua river has a snow-rain-fed fluvial regime, with an annual mean flow of 33 m^3/S and 14.5 m^3/s standard deviations (CR2, Climate Explorer) 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 M3/s at the Romeral Station in 2019 (Carvallo & González, 2020). 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 (Garreaud et al., 2017). 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 along its entire course, given the high water demand by productive mining activities in the upper part of the basin and agricultural activities in the middle and lower parts (Carvallo & González, 2020).

The low 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 consists of 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.

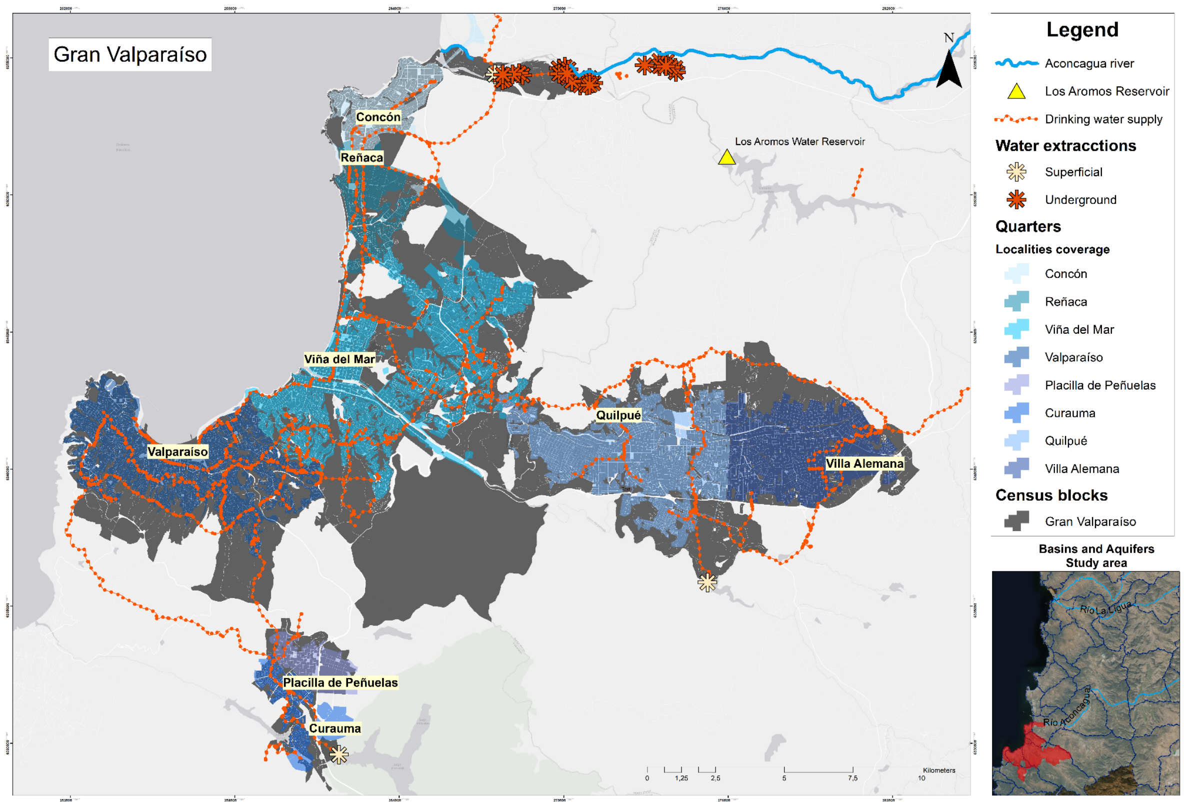


Figure 3. Gran Valparaíso Area, Aconcagua River, Los Aromos Reservoir, Surface and Underground Collections, Coverage of water utility Barracks and Census Blocks of Gran Valparaíso.

4.2 Impact chain

As explained above, we follow an indicator-based methodological structure inspired by the work of IPCC Assessment Report 5 and GIZ climate change impact evaluation methodological guidelines (GIZ, 2017; GIZ & EURAC, 2017; IPCC, 2012). To describe the territory's sensitivity and response capacity facing hazards to urban water security, we estimated a set of indicators according to the vulnerability conditions identified in the literature and the information available for the study case (see table 1).

The exposure is defined considering the population, measured considering the number of inhabitants (Inhab) and the population density per hectare (Inhab/Ha) present in the territorial unit. In this way, the potential effect of the TWV on a greater number of individuals or some high population density areas is take into account.

Sensitivity depends on several factors related to socio-demographic and socio-economic conditions of the population and characteristics associated with the provision of water utility services conditions, among others.

Regarding the socio-demographic characteristics, according to the literature, the presence of elderly (above 65 years) and childhood (under six years) populations should be considered because they are more prone to diseases caused by lack of water (Kinay et al., 2019; Laborde et al., 2015; Mertens et al., 2019). 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 levels of poverty (Huynh & Resurreccion, 2014; Hyland & Russ, 2019). Minority groups such as ethnic minorities and migrants are especially affected by social and economic inequality, increasing the risk of facing living conditions without access to drinking water, health and hygiene services, among others (Ge et al., 2019; Rahaman et al., 2018). Similar is the case for overcrowded housing (Rahman et al., 2019; Scovronick et al., 2015).

The economic poverty of the population is relevant in that it reduces the possibility of opting for improvements in drinking water access (in terms of infrastructure or devices) (Adams et al., 2020) or choosing alternative mechanisms such as the purchase of bottled water, exacerbating their sensitivity.

Concerning the coverage and access to drinking water, we use a series of indicators as a proxy for lack of water access: 1) urban households that are outside the ESVAL coverage area (Ahmed et al., 2016), (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 (Mohan Kumar et al., 2013; Yenneti & Day, 2016), (3) the presence and area of informal human settlements, whose lack of legal protection further limits access to water supply sources (S. Dos Santos et al., 2017).

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 (Mekonnen & Hoekstra, 2016).

Additionally, the presence of public services essential for the wellbeing and health of the population, such as hospitals, shelters, assistance centers, courts and municipalities, among others, which may see their functionality diminished in the event of a supply cut, increases the vulnerability of the area circumscribed to said service (D'Ercole & Metzger, 2009). Finally, territories that depend mainly on surface water production are more sensitive since meteorological drought affects them more quickly than groundwater sources (Gampe et al., 2016; Rekha et al., 2011)

The response capacity analysis is mainly associated to 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 (Jensen & Wu, 2018; Rogers et al., 2020)(see table 2).

The number and capacity of alternative supply sources, as well as the autonomy of the distribution system (Jensen & Wu, 2018), are considered 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 (Jensen & Wu; 2018) and water loss in the system indicators are used to evaluate the system's flexibility in the medium and long term. 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.

Table 1: Indicators used for the sensitivity index

Subdimension	Indicator	Description
Socioeconomic	Education level	Proportion of households with a low
	Income Poverty	Proportion of households under the
Demographic	Territorial segregation index	Spatial Segregation Indicator, genera
	Ethnic population	Proportion of ethnic population
	Child population	Proportion of population with <5 ye
	Elderly population	Proportion of population with >65
	Migrant population	Proportion of migrant population
	Overcrowded households	proportion of households with more
	Women-led household	Proportion of women-led households
Water accessibility	Informal human settlements	Proportion of the census block surfa
	Well water supply	Proportion of dwellings whose water
	Supply by cistern truck	Proportion of dwellings whose water
	River water supply	Proportion of dwellings with river wa
Water consume	Monthly average consumption	Monthly average consumption on m3
	Summer monthly average consumption	Monthly average consumption on m3
Other service conditions	Number of unscheduled outages	Annual average of the number of uns
	Time of unscheduled outages	Annual average of the time that all
	Number of critical infrastructure customers	Number of hospitals, shelters, care c
	Surface sources	Proportion of production provided b

Table 2: Indicators used for the response capacity index

Dimension	Indicator	Description
Short-term response	Number and volume of alternative supply sources	This indicator measures the numb
	Distribution system autonomy	Amount of time in which the sanit
Long-term response	Diversity of sources	The proportion of water produced
	system water loss	The gap between the amount prod

4.3 Aggregation of indicators on a single TWV index

The different indicators discussed above were aggregated into indexes of the population's sensitivity and response capacity, thus allowing an aggregated assessment of the water security in Gran Valparaíso. Then, a vulnerability index was built by aggregating the sensitivity and response capacity sub-indexes. In the case of sensitivity, the indicators were first aggregated into subdimensions (see table S4, supporting information) and then these sub-dimensions were aggregated into a sensitivity index.

For this aggregation, we used a fuzzy logic method (Zadeh, 1965; 1988). First, the raw data was processed to have indicators for each census block. These indicators were then standardized based on fuzzy membership functions, transforming each variable into a fuzzy set value ranging between 0 and 1, representing the census block membership degree to a "high" or "low" condition of the variable.

Either linear or S-type membership functions were used, depending on the nature of the distribution of the variable. In both cases, we took the lowest point as 0, and set as 1 an empirical value of the variable between the 90th and 99th percentiles as appropriate, to avoid biases due to possible outliers.

The fuzzified indicators were then combined using causal logic rules: multiple sets of conditions were defined based on the literature. If a set of conditions is met, the case will have a certain level (high, medium, or low) of the index analyzed (see tables S4-S6, supporting information).

The form of aggregation depends on the substitution capacity that the indicators present in reflecting the presence of the subdimension. When indicators have a high degree of substitutability, that is, the presence of any indicator activates the relevance of the subdimension in the index, a Boolean OR operator was used. In the case of complementary indicators, where the presence of 2 or more indicators is necessary to establish the relevance of the subdimension of the index, the indicators are added using boolean AND operators.

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

4.4 Cluster analysis

The vulnerability is analyzed at the commune and census block level, 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 analysis 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 first and last deciles, groups with significant differences in the indicators integrated into the vulnerability index appear, allowing the identification of markedly different block profiles with extreme values of TWV.

To analyze all the indicators associated with a spatial unit equal to or smaller than the census block (see tables 1 and 2), a hierarchical cluster analysis (HCA) was performed using Ward's method and Euclidean affinity as a similarity measure (Murtagh & Legendre, 2014). 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 solely analyzed at the commune level.

The inertia curve and dendrogram of each decile 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) we decided to make three clusters for the observations of the high vulnerability group and other 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.

5 Results

Maps of exposure, sensitivity, response capacity and vulnerability of water security associated with drinkable water for Gran Valparaíso 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 and 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 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 front of a supply shortcut. 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, being 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 have 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 two sub- indexes discussed before. The situation of Curauma, Placilla de Peñuelas and in part of the census blocks of Villa Alemana and Quilpué (see location in figure 3) 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 the majority of the territories displaying a high sensitivity, indicating that in general low levels of response capacity.

Special attention should be given to those blocks that have a high TWV and exposure index, given that the combination of both conditions implies a greater risk in the case of an event that affects the drinking water supply.

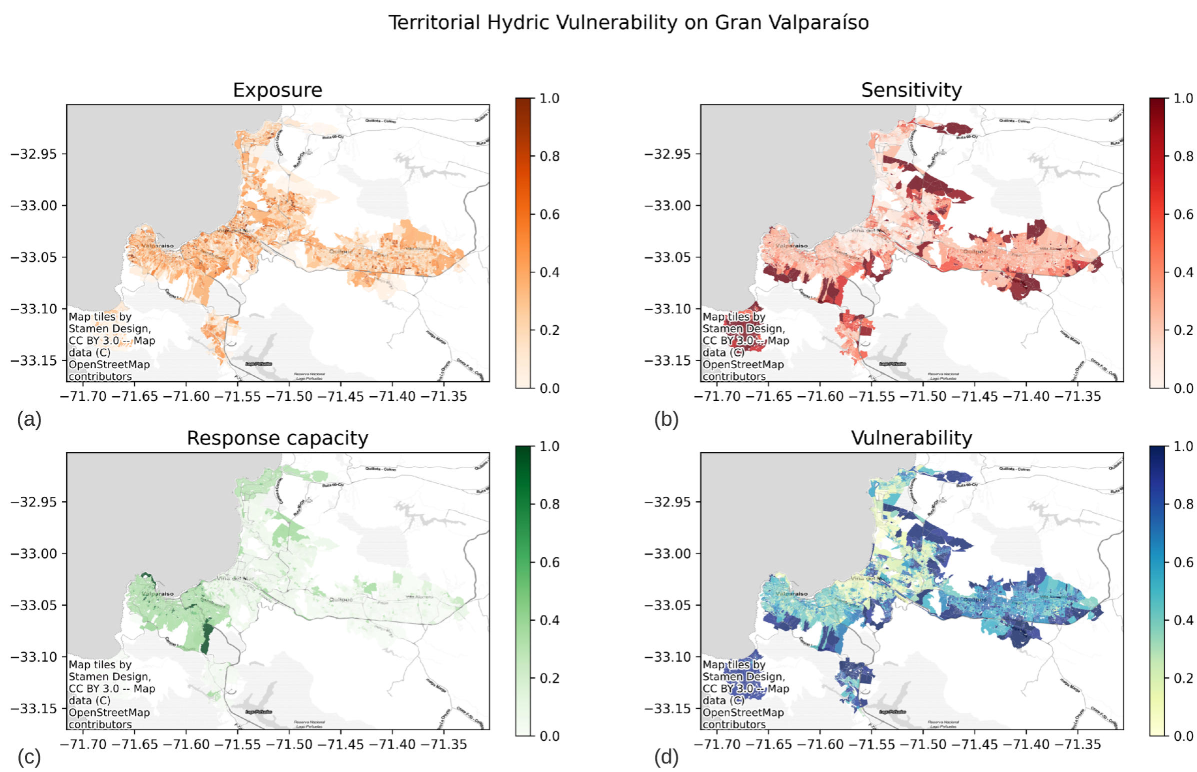


Figure 4: Exposure, sensitivity, response and vulnerability index spatialized by census block on the study area are represented on maps a), b), c) and d) respectively

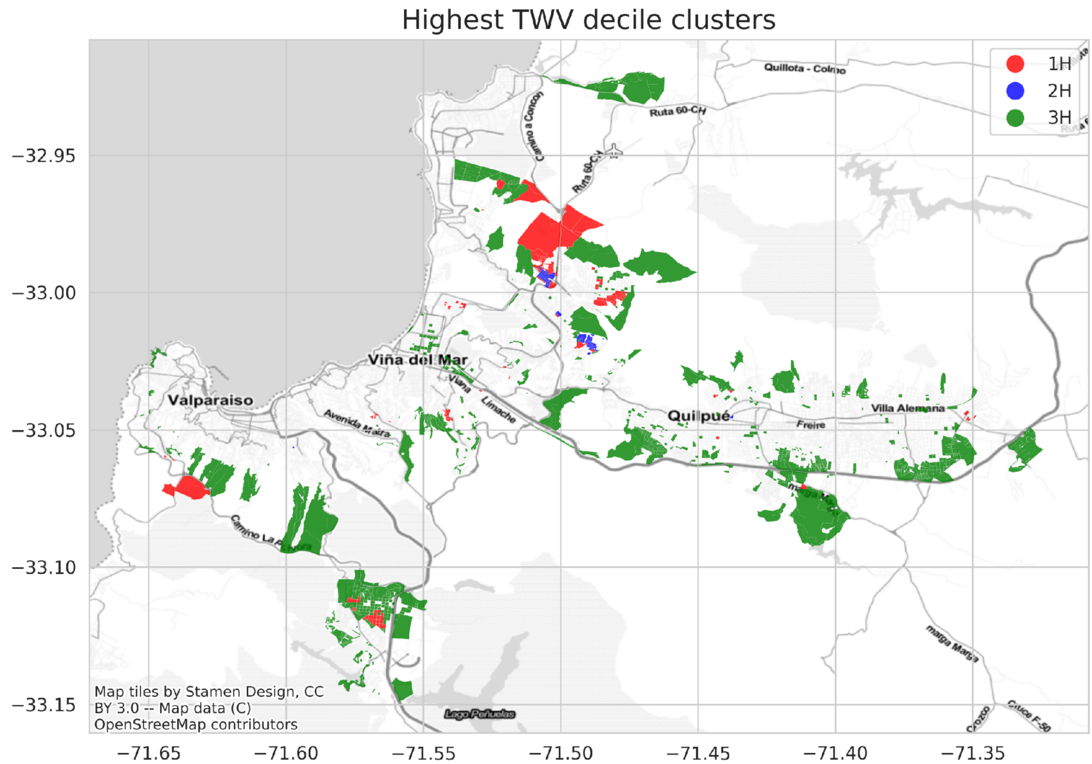
Table 3: Average values for sensitivity and response capacity indicators at communal level.

	Commune	Valparaíso	Concón	Viña del Mar	Quilpué
Sensitivity	Women-led household	23.9%	21.0%	22.9%	23.8%
	Education level	10.2%	6.9%	9.1%	8.3%
	Overcrowded households	6.7%	3.9%	5.1%	4.2%
	Income Poverty	19.4%	21.5%	29.0%	26.0%
	Territorial segregation index	60.8%	56.0%	56.1%	61.0%
	Surface sources	0.141	0.228	0.200	0.166
	Sensitivity Index	0.433	0.366	0.397	0.449
Response capacity	Distribution system autonomy (Days)	1.613	1.080	0.587	0.506
	Diversity of sources	0.673	0.734	0.704	0.651
	System water loss (percentage)	44.1%	41.6%	42.1%	43.3%
	Response Capacity Index	0.498	0.487	0.360	0.329
	Vulnerability Index	0.487	0.411	0.451	0.571

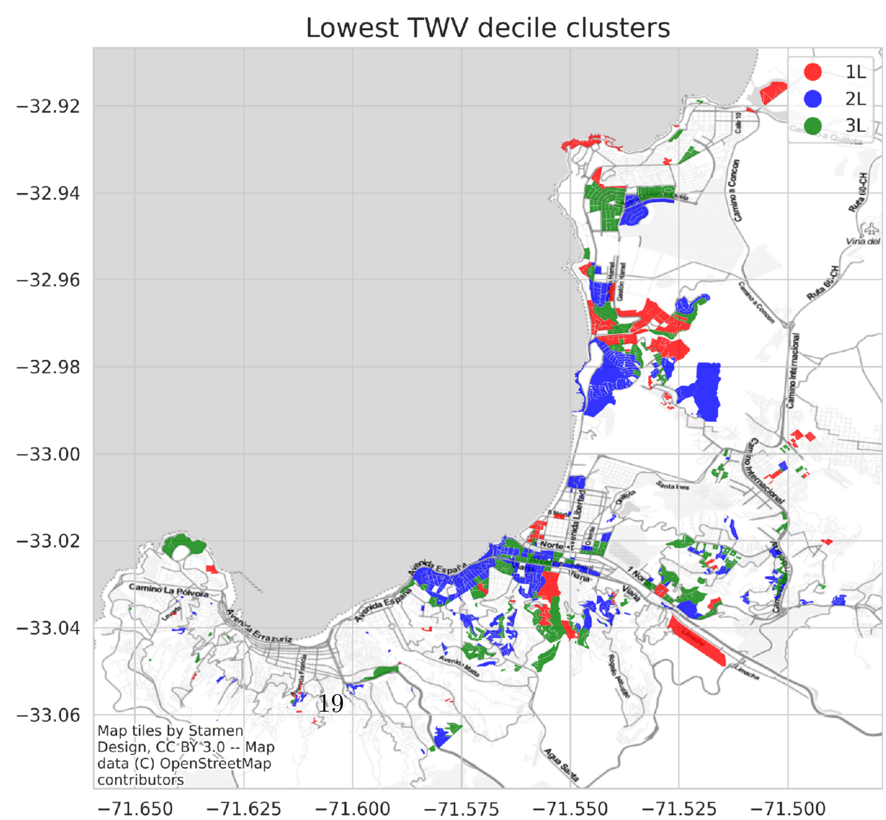
Note: Only indicators associated with a territorial unit bigger than the census block are included.

5.1 Profiles in high and low territorial water vulnerability at census Block level

Based on the hierarchical cluster grouping of all the variables with a spatial resolution, equal to or smaller than a census block (according to their spatial resolution in table 1), we studied the profiles of the households which fell into the most and least vulnerable deciles of the population (Figure 5).


Highest TWV decile clusters
1H
2H
3H
−32.95
−33.00
−33.05
−33.10
−33.15
−71.65
−71.60
−71.55
−71.50
−71.45
−71.40
−71.35
Viña del Mar
Valparaiso
Quilpué
Villa Alemana
Map tiles by Stamen Design, CC BY 3.0 -- Map data (C) OpenStreetMap contributors

(a)


Lowest TWV decile clusters
1L
2L
3L
−32.92
−32.94
−32.96
−32.98
−33.00
−33.02
−33.04
−33.06
−71.650
−71.625
−71.600
−71.575
−71.550
−71.525
−71.500
Map tiles by Stamen Design, CC BY 3.0 -- Map data (C) OpenStreetMap contributors

(b)

Figure 5: spatialized clusters for the highest (a) and lowest (b) decile of the vulnerability index.

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 settlements is about 12% of the surface and in the whole study area, it's the 3%. The water consumption of this census blocks (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 groups 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 less than other groups having 1.4 shortcuts to 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 it is near 7% in every group, significantly higher than the study area average of 4.95%.

Conversely, the 10% least vulnerable census blocks are found in the central zones in the localities of Concón and Viña del Mar. And, there is not any census block from Quilpué and Villa Alemana, which have higher TWV according to its reduced response capacity, driven by the low distribution system autonomy (See table 3).

The census block belonging to the 3 clusters associated with the less vulnerable decile share common characteristics (See table 4): a low presence of households without drinking water access associated with a very low area of informal settlements. An elevated water consumption (above 17m^3 in comparison 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 average. Meanwhile, elderly and migrant populations are above the average in the studied territory. Although these variables should boost the vulnerability, this is attenuated probably because they belong to households with medium or high-income rates.

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.

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**
No potable water Supply	0.10%	0.10%	0.00%	4.40%
Ethnic population	1.70%	2.50%	2.00%	6.40%
Elderly population	12.7%	13.9%	15.1%	10.90%
Migrant population	2.00%	2.20%	1.70%	1.20%
Child population	3.20%	2.90%	3.10%	4.10%
Number of unscheduled outages	1.677	0.918	0.253	6.331
Time of unscheduled outages (minutes)	674.4	269.84	65.921	2373.119
Number of critical infrastructure customers	0.012	0.011	0.007	0.216
Informal human settlements	0.30%	0.00%	0.10%	12.30%
Monthly average consumption (m^3)	17.431	18.656	19.047	16.555
Summer monthly average consumption (m^3)	19.459	21.058	21.327	18.805
Number of alternative supply sources	0.007	0.006	0.007	0.007
Alternative supply sources volume (M^3)	13.251	11.126	13.454	13.468
Vulnerability Index	0.313	0.306	0.303	0.694
Total Census Block	70	406	415	121

Note: Only indicators associated with a territorial unit equal or smaller than the census block is included.

6 Discussion

This paper provides 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 from households considering its social dimensions, (2) a methodological approach to carry out high-resolution analysis that considers the ecological, technical and social systems of a territory; and (3) specific evidence to guide public policies in the Chilean case, which have up to the moment been currently scarcely studied.

The analytical and methodological framework of the TWV allows addressing water security based on a deep understanding of the vulnerability drivers associated to different systems presents in a territory (households, health system, decision-makers, ecological system). This allows considering the heterogeneity of urban areas, making it possible to carry out high-resolution analyses. These, in turn offer fundamental information to assess water security from a risk-informed approach, favoring the design and implementation of adaptation measures taking into account the most significant variables for TWV and spatial units within the cities, and thus contributing to reduce water insecurity in an efficient and place specific way. Our methodology allows to extend the analysis to the level of households grouped in small territorial units (census blocks), which is a relevant contribution to the literature as very few studies carry out robust evaluations of water security at a fine-grained scale, instead opting for focusing at the city level, understood as a relatively homogeneous unit (Karimi Alavijeh et al., 2021; Shrestha et al., 2018).

In addition, this article uses robust methodological tools for operationalizing the conceptual framework proposed. For the study, indicators that describe the territorial water vulnerability focusing on the characteristics of the urban drinking water service were developed. According to our results, variables such as informal settlement coverage, socioeconomic and demographic population conditions and water utility direct services to households should be considered in water security and TWV studies.

This type of evaluation is not very common for urban territories in the Latin American contexts. Studies in the region address notions of water security that do not integrate risk as an important element, and the few urban studies in Rio de Janeiro (Formiga-Johnsson & Britto, 2020; B. B. M. Santos, 2016), Fortaleza (Silva et al., 2019) and La Paz (Medina, 2021) do not analyze the intra-urban differences and the domestic dimensions of water security quantitatively. On the other hand, recent Latin American literature (Peña, 2016; Urquiza & Billi, 2020) has advanced in the conceptual discussion without proposing a methodological approach. With the TWV analytical and methodological framework, this gap is addressed.

The TWV framework application on the Gran Valparaiso conurbation offers relevant inputs to guide and evaluate public policies in this matter. In particular, in the Chilean case, it is urgent to promote the design of public policies to achieve water security, which is at severe risk, considering that 47.5% of the population in 188 of the 346 communes in the country are under scenarios of water scarcity (DGA, 2022)

According to our results and considering the more vulnerable census block profiles from the cluster analysis, some relevant measures that should be addressed for the urban drinking water system of Gran Valparaíso are: increasing the autonomy and efficiency of the drinking water network, strengthening the distribution system to reduce the frequency and duration of unscheduled outages, the regularization of continuous access to drinking water in places supplied by cistern trucks, the development of education programs on water efficiency criteria and the use of alternative sources for the different needs of the system, among others. The design of these adaptation actions should consider the cluster profile of the census block, as well as the characteristics at the commune and locality levels where it's located. These indicators could not be included in the cluster analysis because of lack of data at the census block level, but could reveal key information, such as the different levels of autonomy in the distribution system. In addition, it should be considered that measures aimed at the provision of water services must be addressed in conjunction with the water utility company and the households affected, implying a coordination challenge between local decision-makers, private companies and civil society.

The analysis presented in the article requires a large amount of spatially disaggregated information, which is not always easily available. The gap in the available data (and the difficulty in its access) restrict the application of this methodology. In the Chilean case, the fragmentation of the institutionality linked to water management and in charge of raising relevant information for the sector is an obstacle to using and accessing quality information. Some information sources come from the superintendence of water utility services, The Ministry of Public Works water department, the regional government, and household surveys, among others. Specifically, we observe that the self-reporting processes carried out by the water utility companies to the superintendence lack a transparency system, adequate accessibility for users, and optimal quality control of what is reported. In this sense, it is urgent to develop methods of indicators, which serve as support for evidence-based decision-making in water resources management, and meet the standards of credibility, legitimacy and relevance for it (Jensen & Wu, 2018; Lehtonen, 2015; Norman et al., 2013).

In addition, the literature highlights the importance of characterizing two dimensions that are not addressed in the TWV analysis in this paper because of the lack of information: governance aspects that affect water management (Jensen & Wu, 2018; van Ginkel et al., 2018) and environmental degradation at the watershed level. For the latter, it is especially important to characterize the ecosystems and basins that support the provision of water (Castellar et al., 2021; Orimoloye et al., 2021) and the risks of natural disasters to which they are exposed (Aboelnga et al., 2020; van Ginkel et al., 2018) which were not included in the applied methodological framework, because they were outside the territorial extension of the study. Likewise, we did not explicitly consider water governance in this because of the lack of systematized data in the Chilean case. Another dimension that should be characterized in a TWV analysis is the domestic dynamics of households around water (reuse, efficiency, special needs and perceptual scarcity, among others). This was not addressed in the present study due to the lack of household surveys that capture this information. The only household survey with information on household water dynamics is the national census asking about the origin of access to water (variable included in this study), carried out every ten years, making water access monitoring and updating difficult.

Further research should be addressed to cover these aspects and continue advancing in an integrated TWV analysis according to the analytical framework presented. In the first place, as anticipated, it is necessary to evaluate and quantify the vulnerability of the ecological systems that sustain the water services of the study area.

It should also be noted that a nested vulnerability approach between the different systems in the territory could be considered. Evaluating the vulnerability of the ecological system would allow modeling the natural threats that affect water services and expand the present work, from the quantification of vulnerability to the risk of water insecurity faced by the population exposed (Giupponi et al., 2015; Scott et al., 2021).

On the other hand, to advance in territorial analyzes that evaluate the different edges of the TWV, the evaluation of other water services must be considered, such as productive, public interest, cultural, recreational and ecosystem uses, as well as their interrelationships.

Finally, to strengthen the understanding of water (in)security, it is necessary to complement the longitudinal perspective (risks) with the cross-sectional observation of insecurity (see figure 1). This requires evaluating the equitable access to water services in the territory in terms of quality and quantity, showing specific gaps in the present (Urquiza & Billi, 2020).

7 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 the provision of drinking water service for urban domestic use in the Gran Valparaíso conurbation of central Chile.

In the study area, the sensitivity and response conditions of the technical and sociocultural systems related to the provision and consumption of drinking water services were evaluated. To develop a single TWV index for each census block, a fuzzy logic method was used to aggregate the indicators considered.

Through cluster analysis, different profiles of census blocks are identified whose common characteristics explain their high vulnerability levels. Problems with water supply access, informal settlement coverage, a long time of unscheduled annual cuts appear as the main drivers of a high TWV index in this cluster. Identifying these groups with common characteristics will make it easier for decision-makers to plan and implement public policies by designing packages of measures that respond to the conditions of the block as a whole.

From the TWV Analysis some relevant adaptation measures were recommended in the discussion. These actions must be addressed by policy makers in conjunction with the water utility company and the households affected, implying a coordination challenge between local decision-makers, private companies and civil society.

Acknowledgments

The authors would like to thank the Ministry of Science and Technology of Chile, Center for Climate and Resilience Research (FONDAP #1511009), for institutional support to this research.

Open Research

The data used in this study can be accessed at the Open Science Framework. DOI 10.17605/OSF.IO/Z273G

References

Aboelnga, H. T., El-Naser, H., Ribbe, L., & Frechen, F. B. (2020). Assessing water security in water-scarce cities: Applying the integrated urban water security index (IUWSI) in Madaba, Jordan. *Water (Switzerland)*, *12*(5). https://doi.org/10.3390/W12051299Adams, E. A., Stoler, J., & Adams, Y. (2020). Water insecurity and urban poverty in the Global South: Implications for health and human biology. *American Journal of Human Biology*, *32*(1), 1–12. https://doi.org/10.1002/ajhb.23368Ahmed, T., Scholz, M., Al-Faraj, F., & Niaz, W. (2016). Water-related impacts of climate change on agriculture and subsequently on public health: A review for generalists with particular reference to Pakistan. *International Journal of Environmental Research and Public Health*, *13*(11), 1–16. https://doi.org/10.3390/ijerph13111051Assefa, Y. T., Babel, M. S., Sušnik, J., & Shinde, V. R. (2018). Development of a generic domesticwater security index, and its application in Addis Ababa, Ethiopia. *Water (Switzerland)*, *11*(1). https://doi.org/10.3390/w11010037Bartel, R. (2015). Legal geography, geography, and the research-policy nexus. *Geographical Research*, *54*(3), 233–244. https://doi.org/10.1111/1745-5871.12159Biggs, R., Schluter, M., & Schoon, M. L. (2015). *Principles for Building Resilience Sustaining Ecosystem Services in Social Ecological Systems Natural resource management, agriculture, horticulture and forestry Cambridge University Press*. 290. http://www.cambridge.org/gb/academic/subjects/life-sciences/natural-resource-management-agriculture-horticulture-and/principles-building-resilience-sustaining-ecosystem-services-social-ecological-systemsBinder, C. R., Mühlemeier, S., & Wyss, R. (2017). An indicator-based approach for analyzing the resilience of transitions for energy regions. Part I: Theoretical and conceptual considerations. *Energies*, *10*(1). https://doi.org/10.3390/en10010036Bretas, F., Casanova, G., Crisman, T., Embid, A., Martin, L., Miralles, F., & Muñoz, R. (2020). Agua para el futuro: estrategia de seguridad hídrica para América Latina y el Caribe. In *IADB*.Calvo, R., Amigo, C., Billi, M., Fleischmann, M., Urquiza, A., Álamos, N., & Navea, J. (2021). Territorial Energy Vulnerability Assessment to Enhance Just Energy Transition of Cities. *Frontiers in Sustainable Cities*, *3*(July), 1–19. https://doi.org/10.3389/frsc.2021.635976Carvallo, C. R., & González, P. H. (2020). La gestión del agua en la región de valparaíso. *Universidad de Val-*

paraíso, *3*, 1–26.Castellar, J. A. C., Popartan, L. A., Pueyo-Ros, J., Atanasova, N., Langergraber, G., Säumel, I., Corominas, L., Comas, J., & Acuña, V. (2021). Nature-based solutions in the urban context: terminology, classification and scoring for urban challenges and ecosystem services. *Science of the Total Environment*, *779*, 146237. https://doi.org/10.1016/j.scitotenv.2021.146237Centro de Ciencia del Clima y la Resiliencia. (2018). Simulaciones climáticas regionales y marco de evaluación de la vulnerabilidad. In *mandatado por el Ministerio del Medio Ambiente* (Issue Fondap 1511009). http://www.cr2.cl/wp-content/uploads/2019/06/MARCO_VULNERABILIDAD_CR2_2018.pdfChang, Y. T., Liu, H. L., Bao, A. M., Chen, X., & Wang, L. (2015). Evaluation of urban water resource security under urban expansion using a system dynamics model. *Water Science and Technology: Water Supply*, *15*(6), 1259–1274. https://doi.org/10.2166/ws.2015.092CR2. (n.d.). *Climate explorer*. Retrieved September 5, 2022, from https://explorador.cr2.cl/D'Ercole, R., & Metzger, P. (2009). Las dimensiones espaciales del manejo de crisis. Interés de la investigación y aplicación en Quito. *Bulletin de l'Institut Français d'études Andines*, *38*, 893–915. https://doi.org/10.4000/bifea.2543Damkjaer, S., & Taylor, R. (2017). The measurement of water scarcity: Defining a meaningful indicator. *Ambio*, *46*(5), 513–531. https://doi.org/10.1007/s13280-017-0912-zDanielaini, T. T., Maheshwari, B., & Hagare, D. (2019). An assessment of household water insecurity in a rapidly developing coastal metropolitan region of Indonesia. *Sustainable Cities and Society*, *46*(June 2018), 101382. https://doi.org/10.1016/j.scs.2018.12.010Datu, K. (2020). Geographies of local government. *Geographical Research*, *58*(3), 304–309. https://doi.org/10.1111/1745-5871.12404Dos Santos, S., Adams, E. A., Neville, G., Wada, Y., de Sherbinin, A., Mullin Bernhardt, E., & Adamo, S. B. (2017). Urban growth and water access in sub-Saharan Africa: Progress, challenges, and emerging research directions. *Science of the Total Environment*, *607–608*, 497–508. https://doi.org/10.1016/j.scitotenv.2017.06.157Farinosi, F., Giupponi, C., Reynaud, A., Ceccherini, G., Carmona-Moreno, C., De Roo, A., Gonzalez-Sanchez, D., & Bidoglio, G. (2018). An innovative approach to the assessment of hydro-political risk: A spatially explicit, data driven indicator of hydro-political issues. *Global Environmental Change*, *52*, 286–313. https://doi.org/10.1016/j.gloenvcha.2018.07.001Formiga-Johnsson, R. M., & Britto, A. L. (2020). Water security, metropolitan supply and climate change: some considerations concerning the Rio de Janeiro case. *Ambiente e Sociedade*, *23*, 1–24. https://doi.org/10.1590/1809-4422ASOC20190207R1VU2020L6TDFuster, R., Escobar, C., Silva, K., & Aldunce, P. (2017). Estudio de Seguridad Hídrica en Chile en un contexto de. *Laboratorio de Análisis Territorial de La Universidad de Chile*, 129.Gampe, D., Nikulin, G., & Ludwig, R. (2016). Using an ensemble of regional climate models to assess climate change impacts on water scarcity in European river basins. *Science of the Total Environment*, *573*, 1503–1518. https://doi.org/10.1016/j.scitotenv.2016.08.053Garreaud, R. D., Alvarez-Garreton, C., Barichivich, J., Pablo Boisier, J., Christie, D., Galleguillos, M., LeQuesne, C., McPhee, J., & Zambrano-Bigiarini, M. (2017). The

2010-2015 megadrought in central Chile: Impacts on regional hydroclimate and vegetation. *Hydrology and Earth System Sciences*, *21*(12), 6307–6327. https://doi.org/10.5194/hess-21-6307-2017Gassert, F., Landis, M., Luck, M., Reig, P., & Shiao, T. (2014). Aqueduct Global Maps 2.1: Constructing decision-relevant global water risk indicators. *World Resources Institute*, *April*, 31.Ge, Y., Yang, G., Chen, Y., & Dou, W. (2019). Examining social vulnerability and inequality: A joint analysis through a connectivity lens in the urban agglomerations of China. *Sustainability (Switzerland)*, *11*(4), 1–19. https://doi.org/10.3390/su11041042Giupponi, C., Mojtahed, V., Gain, A. K., Biscaro, C., & Balbi, S. (2015). Integrated Risk Assessment of Water-Related Disasters. *Hydro-Meteorological Hazards, Risks, and Disasters*, 163–200. https://doi.org/10.1016/B978-0-12-394846-5.00006-0GIZ. (2017). *The Vulnerability Sourcebook Concept and guidelines for standardised vulnerability assessments*. https://www.adaptationcommunity.net/download/va/vulnerability-guides-manuals-reports/vuln_source_2017_EN.pdfGIZ, & EURAC. (2017). *Risk Supplement to the Vulnerability Sourcebook. Guidance on how to apply the Vulnerability Sourcebook's approach with the new IPCC AR5 concept of climate risk*. http://www.adaptationcommunity.net/wp-content/uploads/2017/10/GIZ-2017_Risk-Supplement-to-the-Vulnerability-Sourcebook.pdfGuillermo Donoso, Elisa Blanco, wiliam Foster, Gabriela Franco, J. L. (2012). *Seguridad Hídrica y Alimentaria en América Latina y España : El Caso de Chile*. *December*, 1–463.Howlett, M. P., & Cuenca, J. S. (2017). The use of indicators in environmental policy appraisal: lessons from the design and evolution of water security policy measures. *Journal of Environmental Policy and Planning*, *19*(2), 229–243. https://doi.org/10.1080/1523908X.2016.1207507Huang, Y., Xu, L., Yin, H., Cai, Y., & Yang, Z. (2015). Dual-level material and psychological assessment of urban water security in a water-stressed coastal city. *Sustainability (Switzerland)*, *7*(4), 3900–3918. https://doi.org/10.3390/su7043900Huynh, P. T. A., & Resurreccion, B. P. (2014). Women's differentiated vulnerability and adaptations to climate-related agricultural water scarcity in rural Central Vietnam. *Climate and Development*, *6*(3), 226–237. https://doi.org/10.1080/17565529.2014.886989Hyland, M., & Russ, J. (2019). Water as destiny – The long-term impacts of drought in sub-Saharan Africa. *World Development*, *115*, 30–45. https://doi.org/10.1016/j.worlddev.2018.11.002INE (Instituto Nacional de Estadísticas). (2017). *Censo 2017*. INE [Data Set]. http://www.censo2017.cl/microdatosIPCC. (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation: Special report of the intergovernmental panel on climate change*. Cambridge University Press.IPCC. (2021). *Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.IPCC. (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability:water Summary for Policymakers*.Jensen, O., & Wu, H. (2018). Urban water security indicators: Development and pilot. *Environmental Science and Policy*, *83*(September

2017), 33–45. https://doi.org/10.1016/j.envsci.2018.02.003Karimi Alavijeh, N., Falahi, M. A., Ahmadi Shadmehri, M. T., Salehnia, N., Larsen, M. A. D., & Drews, M. (2021). Perspectives of current and future urban water security in Iran. *Journal of Cleaner Production*, *321*(December 2020), 129004. https://doi.org/10.1016/j.jclepro.2021.129004Kinay, P., Morse, A. P., Villanueva, E. V., Morrissey, K., & Staddon, P. L. (2019). Direct and indirect health impacts of climate change on the vulnerable elderly population in East China. *Environmental Reviews*, *27*(3), 295–303. https://doi.org/10.1139/er-2017-0095Komnenic, V., Ahlers, R., & Zaag, P. van der. (2009). Assessing the usefulness of the water poverty index by applying it to a special case: Can one be water poor with high levels of access? *Physics and Chemistry of the Earth*, *34*(4–5), 219–224. https://doi.org/10.1016/j.pce.2008.03.005Kristvik, E., Muthanna, T. M., & Alfredsen, K. (2019). Assessment of future water availability under climate change, considering scenarios for population growth and ageing infrastructure. *Journal of Water and Climate Change*, *10*(1), 1–12. https://doi.org/10.2166/wcc.2018.096Laborde, A., Tomasina, F., Bianchi, F., Bruné, M., Buka, I., & Comba, P. (2015). *Review Children ' s Health in Latin America : The Influence of Environmental Exposures*. *123*(3), 201–210.Lehtonen, M. (2015). Indicators: Tools for informing, monitoring or controlling? *The Tools of Policy Formulation: Actors, Capacities, Venues and Effects*, *April*, 76–99. https://doi.org/10.4337/9781783477043.00015Lutz Ley, A. N. (2020). Minería y seguridad hídrica en el noroeste de México: un análisis de doble exposición. *Región Y Sociedad*, *32*, e1295. https://doi.org/10.22198/rys2020/32/1295Medina, C. (2021). Modelación Hidrológica Bajo Escenarios De Cambio Climático Para Un Embalse De Abastecimiento De Agua En La Paz, Bolivia. *Investigacion & Desarrollo*, *21*(1), 63–78. https://doi.org/10.23881/idupbo.021.1-5iMekonnen, M. M., & Hoekstra, A. Y. (2016). Sustainability: Four billion people facing severe water scarcity. *Science Advances*, *2*(2), 1–7. https://doi.org/10.1126/sciadv.1500323Mertens, A., Balakrishnan, K., Ramaswamy, P., Rajkumar, P., Ramaprabha, P., Durairaj, N., Hubbard, A. E., Khush, R., Colford, J. M., & Arnold, B. F. (2019). Associations between high temperature, heavy rainfall, and diarrhea among young children in rural Tamil Nadu, India: A prospective cohort study. *Environmental Health Perspectives*, *127*(4), 47004. https://doi.org/10.1289/EHP3711Ministerio de Obras Públicas. (2022). *Mesa Nacional del Agua*.Ministry of environment. (2020). Informe Proyecto ARCLIM: Asentamientos Humanos. In *Centro de Ciencia del Clima y la Resiliencia , Red de Pobreza Energética, Iniciativa ENEAS: Energía, Agua y Sustentabilidad y Núcleo de Estudios Sistémicos Transdisciplinarios*.Mohan Kumar, M., Manohar, U., Pallavi, M. R. M., & Rajakumar, A. (2013). Urban Water Supply and Management. *Journal of the Indian Institute of Science*, *93*, 295–318.Murtagh, F., & Legendre, P. (2014). Ward's Hierarchical Agglomerative Clustering Method: Which Algorithms Implement Ward's Criterion? *Journal of Classificatio*, *31*(1), 274–295. https://doi.org/10.1007/s00357-014-9161-zNorman, E. S., Dunn, G., Bakker, K., Allen, D. M., & de Albuquerque, R. C. (2013). Water Security Assessment: Integrating Governance and Freshwater Indicators. *Water Resources Management*, *27*(2), 535–551. https://doi.org/10.1007/s11269-012-0200-4Orimoloye, I. R., Zhou, L., & Kalumba, A. M. (2021). Drought disaster risk adaptation through ecosystem services-based solutions: Way forward for south africa. *Sustainability (Switzerland)*, *13*(8). https://doi.org/10.3390/su13084132Peña, H. (2016). Desafíos de la seguridad hídrica en América Latina y el Caribe. In *dwwq*. https://repositorio.cepal.org/bitstream/handle/11362/40074/S1600566_es.pdf?sequence=1&isAllowed=yRaha M. A., Rahman, M. M., Bahauddin, K. M., Khan, S., & Hassan, S. (2018). Health Disorder of Climate Migrants in Khulna City: An Urban Slum Perspective. *International Migration*, *56*(5), 42–55. https://doi.org/10.1111/imig.12460Rahman, M. M., Ahmad, S., Mahmud, A. S., Hassan-uz-Zaman, M., Nahian, M. A., Ahmed, A., Nahar, Q., & Streatfield, P. K. (2019). Health consequences of climate change in Bangladesh: An overview of the evidence, knowledge gaps and challenges. *Wiley Interdisciplinary Reviews: Climate Change*, *10*(5), 1–14. https://doi.org/10.1002/wcc.601Rekha, V. B., Thomas, A. P., Suma, M., & Vijith, H. (2011). An Integration of Spatial Information Technology for Groundwater Potential and Quality Investigations in Koduvan Ár Sub-Watershed of Meenachil River Basin, Kerala, India. *Journal of the Indian Society of Remote Sensing*, *39*(1), 63–71. https://doi.org/10.1007/s12524-010-0050-6Rogers, B. C., Dunn, G., Hammer, K., Novalia, W., de Haan, F. J., Brown, L., Brown, R. R., Lloyd, S., Urich, C., Wong, T. H. F., & Chesterfield, C. (2020). Water Sensitive Cities Index: A diagnostic tool to assess water sensitivity and guide management actions. *Water Research*, *186*, 116411. https://doi.org/10.1016/j.watres.2020.116411Santos, B. B. M. (2016). Water security in the metropolitan region of rio de janeiro: Contributions to the debate. *Ambiente e Sociedade*, *19*(1), 103–120. https://doi.org/10.1590/1809-4422ASOC150132R1V1912016Scott, C. A., Zilio, M. I., Harmon, T., Zuniga-Teran, A., Diaz-Caravantes, R., Hoyos, N., Perillo, G. M. E., Meza, F., Varady, R. G., Neto, A. R., Velez, M. I., Martin, F., Escobar, J., Piccolo, M. C., Mussetta, P., Montenegro, S., Rusak, J. A., & Pineda, N. (2021). Do ecosystem insecurity and social vulnerability lead to failure of water security? *ENVIRONMENTAL DEVELOPMENT*, *38*(SI). https://doi.org/10.1016/j.envdev.2020.100606Scovronick, N., Lloyd, S. J., & Kovats, R. S. (2015). Climate and health in informal urban settlements. *Environment and Urbanization*, *27*(2), 657–678. https://doi.org/10.1177/0956247815596502Serrano, A. S., Garro, Á. B., Sanabria, G. D., Conejo, J. R., Cantillano, D. R., & Watson, A. G. (2019). Seguridad hídrica: Gestión del agua en comunidades rurales del Pacífico Norte de Costa Rica. *Revista de Ciencias Ambientales*, *53*(2), 25–46. https://doi.org/10.15359/rca.53-2.2Shrestha, S., Aihara, Y., Bhattarai, A. P., Bista, N., Kondo, N., Futaba, K., Nishida, K., & Shindo, J. (2018). Development of an objective water security index and assessment of its association with quality of life in urban areas of developing countries. *SSM - Population Health*, *6*(July), 276–285. https://doi.org/10.1016/j.ssmph.2018.10.007Silva, S. M. O., Filho, F. de A. S., Cid, D. A. C., de Aquino, S. H. S., & Xavier, L. C. P. (2019). Proposal of integrated urban waters management as a strategy to promote water security: The fortaleza case. *Engenharia Sanitaria e Ambiental*, *24*(2), 239–250. https://doi.org/10.1590/s1413-41522019181776Srinivasan, V., Seto, K. C., Emerson, R., & Gorelick, S. M. (2013). The impact of urbanization on water vulnerability: A coupled human-environment system approach for Chennai, India. *Global Environmental Change*, *23*(1), 229–239. https://doi.org/10.1016/j.gloenvcha.2012.10.002Tellman, B., McDonald, R. I., Goldstein, J. H., Vogl, A. L., Flörke, M., Shemie, D., Dudley, R., Dryden, R., Petry, P., Karres, N., Vigerstol, K., Lehner, B., & Veiga, F. (2018). Opportunities for natural infrastructure to improve urban water security in Latin America. *PLoS ONE*, *13*(12), 1–28. https://doi.org/10.1371/journal.pone.0209470UN-Water. (2013). Water Security & the Global Water Agenda. In *United Nations University.*Urquiza, A., Amigo, C., Billi, M., Calvo, R., Gallardo, L., Neira, C. I., & Rojas, M. (2021). An Integrated Framework to Streamline Resilience in the Context of Urban Climate Risk Assessment. *Earth's Future*, *9*(9), 1–26. https://doi.org/10.1029/2020EF001508Urquiza, A., & Billi, M. (2020). Seguridad hídrica y energética en América Latina y el Caribe Definición y aproximación territorial para el análisis Gracias por su interés en esta publicación de la CEPAL. In *Documentos de Proyectos (LC/TS.2020/138), Santiago, Comisión Económica para América Latina y el Caribe (CEPAL).*van Ginkel, K. C. H., Hoekstra, A. Y., Buurman, J., & Hogeboom, R. J. (2018). Urban Water Security Dashboard: Systems Approach to Characterizing the Water Security of Cities. *Journal of Water Resources Planning and Management*, *144*(12), 04018075. https://doi.org/10.1061/(asce)wr.1943-5452.0000997Victor, C., Vega Ocasio, D., Cumbe, Z. A., Garn, J. V., Hubbard, S., Mangamela, M., McGunegill, S., Nalá, R., Snyder, J. S., Levy, K., & Freeman, M. C. (2022). Spatial heterogeneity of neighborhood-level water and sanitation access in informal urban settlements: A cross-sectional case study in Beira, Mozambique. *PLOS Water*, *1*(6), e0000022. https://doi.org/10.1371/journal.pwat.0000022Wood, E. A., Douglas, H., Fiore, A. J., Bernier, R., & Chapman, K. S. (2019). Perceptions of water insecurity from urban and peri-urban Haiti: A quantitative analysis. *PLoS ONE*, *14*(4), 1–12. https://doi.org/10.1371/journal.pone.0214789Yenneti, K., & Day, R. (2016). Distributional justice in solar energy implementation in India: The case of Charanka solar park. *Journal of Rural Studies*, *46*, 35–46. https://doi.org/10.1016/j.jrurstud.2016.05.009Yin, S., Dongjie, G., Weici, S., & Weijun, G. (2017). Integrated assessment and scenarios simulation of urban water security system in the southwest of China with system dynamics analysis. *Water Science and Technology*, *76*(9), 2255–2267. https://doi.org/10.2166/wst.2017.333Zadeh, L. A. (1965). Fuzzy sets. *Information and Control*, *8*(3), 338–353. https://doi.org/10.1016/S0019-9958(65)90241-XZadeh, L. A. (1988). Fuzzy Logic. *Computer*, *21*(4), 83–93. https://doi.org/10.1109/2.53