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Research Paper

Development and assessment of a vulnerability index for access to rural drinking water and sanitation services in the semi-arid region of north–central Chile

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ABSTRACT

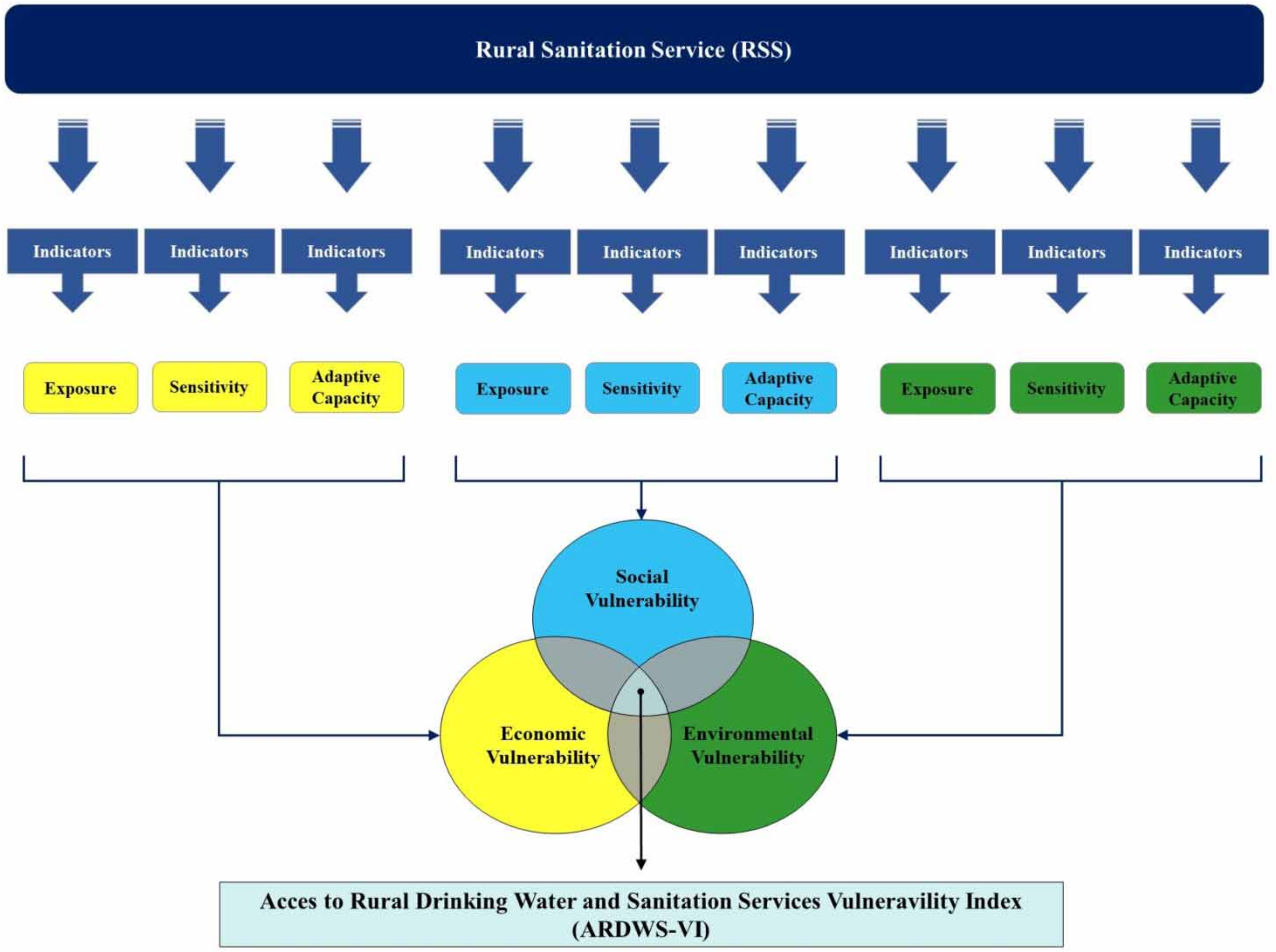
The present study aimed to develop and assess a vulnerability index for access to rural drinking water and sanitation services, which was applied to 42 Rural Sanitation Services in the Coquimbo Region, Chile. For the development and assessment of the vulnerability index, the construction of composite indicator methodology was employed. An underlying model based on 65 indicators, linked to nine sub-pillars and three pillars, was established. In addition, the COINTool software was used for the development and analysis of the composite indicator results. The vulnerability index results showed medium vulnerability at regional and provincial levels, with a greater degree of vulnerability at a commune level. At a Rural Sanitation Services level, 2.4% of the evaluated services presented high vulnerability, 73.8% presented medium vulnerability, and 23.8% presented low vulnerability. The vulnerability index values obtained for the Rural Sanitation Services fluctuated from a minimum value of 32.3% to a maximum value of 64.1%. The significance of the vulnerability indicator developed and assessed lies in its high potential as a tool and/or methodology to monitoring, from a multidimensional perspective, the effectiveness of policies, strategies, and/or actions implemented at the level of Rural Sanitation Services, contributing to strengthened decision-making in vulnerability reduction.

Key words: composite index, drinking water, rural areas, sanitation, semi-arid regions, vulnerability

HIGHLIGHTS

- Vulnerability associated with Rural Sanitation Services was investigated.
- A composite index of vulnerability was developed and assessed.
- The results show different degrees of vulnerability.
- The results allow four key questions to be answered about vulnerability.

GRAPHICAL ABSTRACT



INTRODUCTION

Vulnerability implies fragility, a threatening situation, or the possibility of suffering damage (Feito 2007) in a geographical space in a defined time and subsequently having difficulties to recover from the damage (Soares *et al.* 2014). This propensity to damage can be applied to any area or dimension (Wilches-Chaux 1989). Similarly, vulnerability must be understood as a changing dynamic condition, as well as a cumulative process of fragilities, deficiencies, or limitations that remain over time (Cardona 2001). It is worth mentioning that vulnerability is largely based on the condition and dynamics of the coupled human–environmental system exposed to threats; therefore, vulnerability analysis should encompass and address not only the system in question but also its multiple and varied links (Turner *et al.* 2003). Through a vulnerability approach, it is possible to obtain a picture that incorporates the main variables affecting a system and the causal networks that shape it (Abrams *et al.* 2021).

Determining the degree of vulnerability of a rural water and sanitation system should also be considered a standard practice, as it would make it possible to determine in advance the social, economic, and environmental consequences of a given event (Mejía *et al.* 2016).

Rural drinking water and sanitation services have different names around the world; in Latin America and the Caribbean (LAC), they are generally known as Water and Sanitation Service Community Organizations (OCSAS, for the Spanish acronym); in Chile, OCSAS are called Rural Sanitation Services (RSSs) (Vivanco *et al.* 2022). In LAC, there are more than 180,000 OCSAS that provide access to rural drinking water and sanitation services. However, the rural drinking water and sanitation sector, in global terms, presents a greater predisposition to developing high vulnerability, considering that eight out of 10 people lack basic drinking water services in rural areas and seven out of 10 people lack sanitation services in rural areas (UNICEF & WHO 2019). Furthermore, climate change projections indicate that rural sectors will be the most affected by extreme climate phenomena because they are in a more fragile environment with greater associated vulnerability (Mejía *et al.* 2016). In addition, the impacts in rural areas will occur in a much smaller time frame and will be linked mainly to the availability and supply of water and sanitation.

Although there are multiple evaluation studies focused on rural drinking water supply and/or sanitation systems, most of these assessments are aimed at measuring the degree of sustainability (Valcourt *et al.* 2020), water security (Penn *et al.* 2017), quality of service (Molinos-Senante *et al.* 2019), and/or service levels (Dang & Defo 2021). Many of these assessments elect to make visible only certain phenomena according to the logic of each one (Dang *et al.* 2021).

Given that the study of vulnerability makes it possible to identify the most vulnerable dimensions and the factors that trigger this phenomenon, this study proposes to develop the first research that develops and evaluates multidimensional vulnerability in a key sector for the fulfillment of human rights to access to drinking water and sanitation services, with a special focus on the rural sector of an arid and semi-arid zone of Chile.

MATERIALS AND METHODS

This investigation addresses vulnerability according to the definition presented in the Fourth Assessment Report of the United Nations Intergovernmental Panel on Climate Change – IPCC (2007) – where vulnerability is the result of exposure, sensitivity, and adaptive capacity. In addition, the investigation used a multidimensional approach to vulnerability by incorporating its social, economic, and environmental dimensions.

However, the article follows the proposal of Martínez & Aguilar (2018) on emphasizing the perspective of the entity providing the service, drinking water and sanitation services in this case. Furthermore, the vulnerability approach poses a few key questions to be addressed: Who is most vulnerable? Why is one vulnerable? How is vulnerability differentiated? What is the extent of the vulnerability? (Hoddinott & Quisumbing 2003; Kohlitz *et al.* 2020). To answer these questions, the composite indicator creation methodology was used to quantify vulnerability as a study phenomenon (Nardo *et al.* 2005), based on an underlying model (Dunn 2020), that considers different elements such as variables, individual indicators, dimensions, and target (Camacho & Horta 2020).

The methodology was based on both the work of Ortega-Gaucin *et al.* (2016) and the recommendations in the Handbook on Constructing Composite Indicators (Dunn 2020). The conceptual model adopted to develop and assess the Access to Rural Drinking Water and Sanitation Services Vulnerability Index, which hereafter will be abbreviated as 'ARDWS-VI,' is presented in Figure 1.

For a better comprehension of the conceptual model presented in the Figure 1, the detail of the procedure in every step is described below.

Development of conceptual framework

To build the ARDWS-VI, a structure of relationships among the variables, base indicators, sub-pillars, and pillars of the ARDWS-VI was proposed to establish the underlying model.

Selection of rural drinking water and sanitation services

The study was conducted in the Coquimbo Region (Chile), located between 29° S and 32° S latitude. The Coquimbo Region has an area of 40,579 km^2 (5.4% of Chile's total area). According to Sanitation Services Superintendence, as of December 2019, the Coquimbo Region had a total of 193 RSSs, which accounted for 50,581 household water connections, benefitting 69,487 people (Figure 2). Of the 193 RSSs in the Coquimbo Region, 42 participated voluntarily, accounting for 21.8% of the total. Thus, the selection represented a 95% confidence level and a 13.4% margin of error. However, these 42 RSSs together account for a total of 11,629 household water connections out of a regional total of 50,581, representing 23% of the regional total with a 95% confidence level and a margin of error of 0.8%. Similarly, these 42 RSSs together add up to a total of 39,891 beneficiaries of a regional total of 69,487, representing 57.4% of the regional total of people beneficiaries with a 95% confidence level and a margin of error of 0.32%.

Selection of indicators

The following criteria were established for the indicator selection:

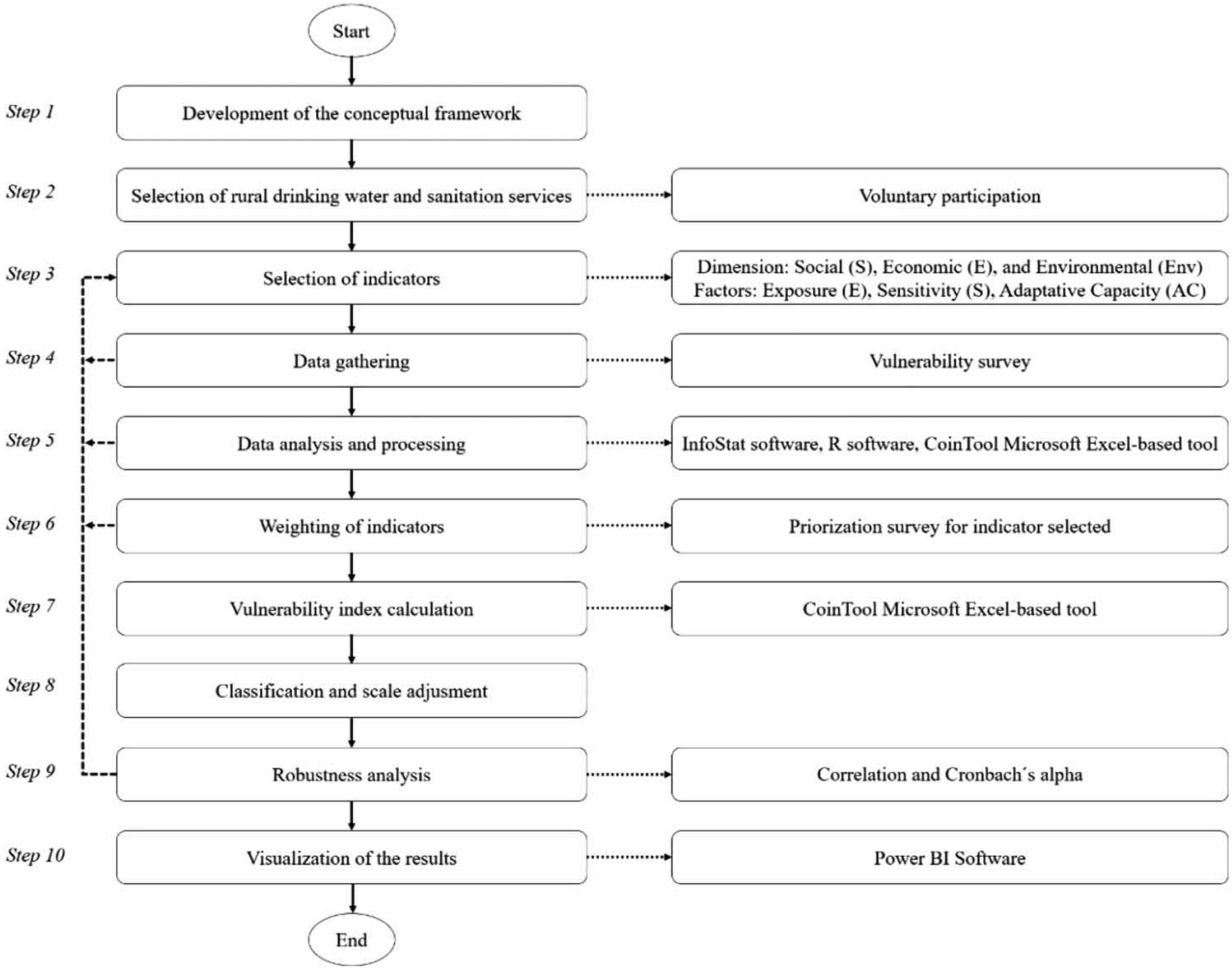


Figure 1 | Conceptual model used to obtain the ARDWS-VI. *Source:* Adapted from Ortega-Gaucin *et al.* (2016).

a. Be related to at least one of the dimensions (social, economic, environmental), to represent multidimensionality.
b. Be related to at least one of the vulnerability factors (exposure, sensitivity, lack of adaptive capacity).
c. Be based on variables constructed from reliable, quality, representative information with an adequate temporal resolution.
d. Present a minimum of three base indicators for each dimension, with five and seven base indicators recommended.

Data gathering

Official sources with data available were mainly used to construct the indicators. This was complemented with the design of a vulnerability survey, which was validated by nine national experts and tested on one RSS prior to its application to the rest of the RSSs. The national experts were selected considering the interdisciplinarity and expertise in issues related to vulnerability and RSSs to validate that the survey would consider a multidimensional perspective. The national experts were selected from a list provided by the Water Center for Arid and Semi-Arid Zones of Latin America and the Caribbean (CAZALAC) linked to the topic. From this list, the convenience sampling methodology was used, making use of the snowball technique. All the selected experts were contacted and agreed to participate in the development and validation of the vulnerability survey.

Data analysis and processing

Once the vulnerability survey was applied, the data collected for each of the variables were digitized, building a database in Microsoft Excel. Subsequently, an exploratory data analysis was carried out for each of the variables using InfoStat software

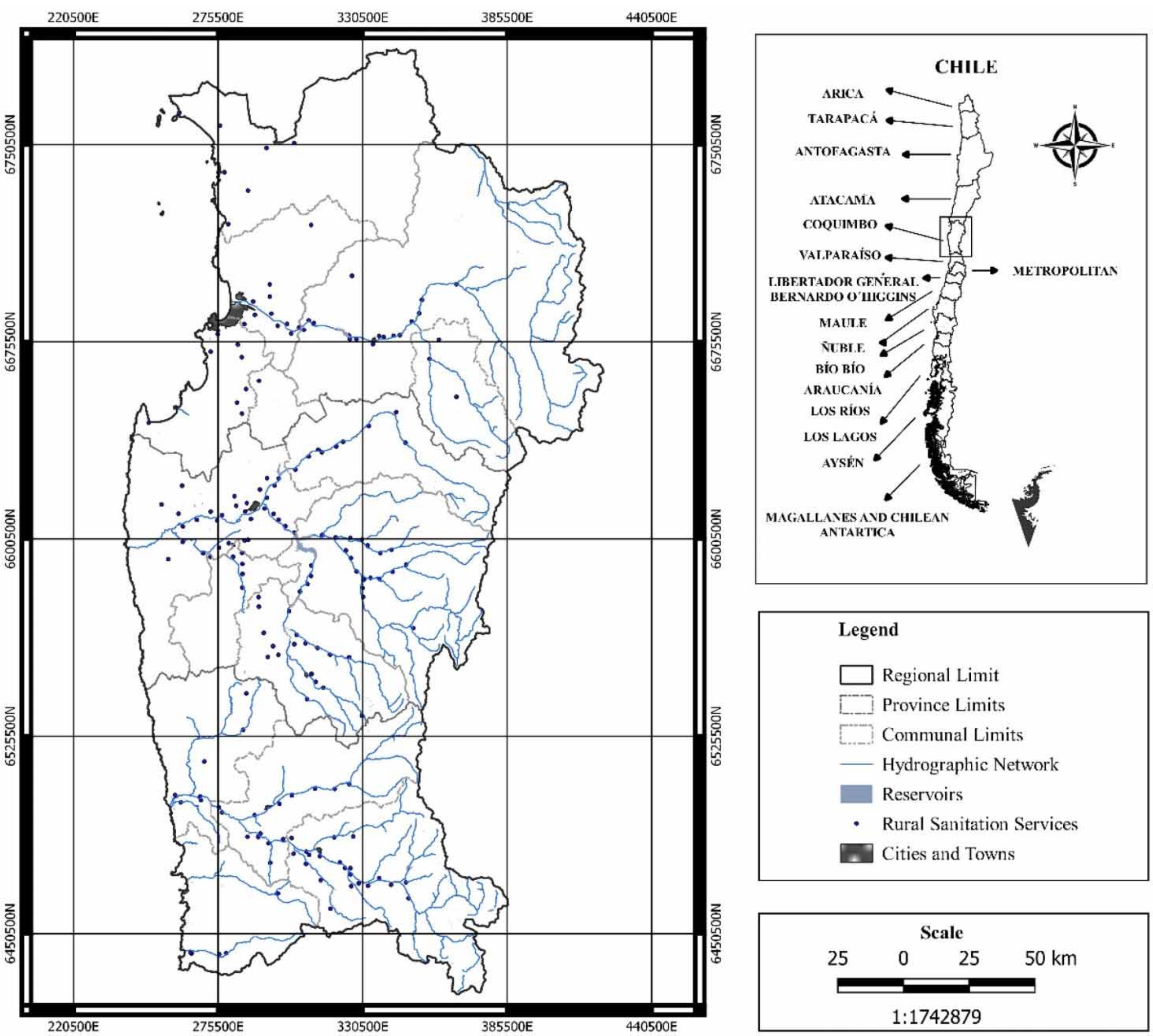


Figure 2 | Locations of RSSs in the Coquimbo Region, Chile.

(Di Rienzo *et al.* 2012) and a statistical programming environment and language R (R Core Team 2020). To build the ARDWS-VI, COINTool software was used, which has been applied widely (Becker *et al.* 2019).

Weighting of indicators

To obtain the weights of each indicator, sub-pillar, and pillar of the ARDWS-VI, an indicator prioritization survey was designed and conducted to incorporate expert opinion. The original list of experts for the prioritization of indicators was composed of 25 professionals specialized in water resources, all belonging to the Master's Program in Water Resources Management in Arid and Semi-Arid Zones of the University of La Serena (Promotion 2020). Of these 25 professionals, 23 collaborated with the prioritization activity. The 23 professionals were from public institutions (43.5%), private institutions (26.1%), academia (26.1%), and NGOs (4.3%). All professionals were related to water resources, drinking water, sanitation, and the rural sector. In addition, all 23 professionals were from the Coquimbo Region. The survey was answered using the Crowdsignal online application (https://crowdsignal.com/). The prioritization survey was developed based on the rating scale and ranking classification questions, in addition to open-ended questions to increasing feedback.

Vulnerability index calculation

Based on the construction of the indicators (I) and their weighting (w_i), exposure (Ex), sensitivity (Se), and lack of adaptive capacity (Ac), which are the sub-pillars of the underlying model, were calculated (Equations (1)–(3)):

$$\mathrm{Ex} = \sum_{i=1}^{n} I = I_{1(w_{i1})} + I_{2(w_{i2})} + I_{n(w_{in})}, \tag{1}$$

$$\mathrm{Se} = \sum_{i=1}^{n} I = I_{1(w_{i1})} + I_{2(w_{i2})} + I_{n(w_{in})}, \tag{2}$$

$$\mathrm{Ac} = \sum_{i=1}^{n} I = I_{1(w_{i1})} + I_{2(w_{i2})} + I_{n(w_{in})}. \tag{3}$$

Once the values of the sub-pillars (Ex, Se, Ac) are obtained and the weightings (w_i) were established, the pillars were calculated, which account for the social (So), economic (Ec), and environmental dimensions (En) (see Equation (4)):

$$\mathrm{So},\ \mathrm{Ec},\ \mathrm{En} = \sum_{i=1}^{n} (\mathrm{Ex}\, w_i + \mathrm{Se}\, w_i + \mathrm{Ac}\, w_i) \tag{4}$$

Finally, with the results of each pillar (So, Ec, En) and their respective weighting (w_i), ARDWS-VI was calculated (see Equation (5)):

$$\mathrm{ARDWS} - \mathrm{VI} = [\mathrm{So} \times w_i] + [\mathrm{Ec} \times w_i] + [\mathrm{En} \times w_i]. \tag{5}$$

Classification and scale adjustment

The ARDWS-VI results were adjusted according to the following categories (Table 1).

Robustness analysis

Two robustness analyses were carried out, one evaluating the differences between the chosen normalization methods and the other using Cronbach's alpha indicator.

Visualization of the results

The results of the ARDWS-VI calculation were represented visually using PowerBI software, maintaining consistency between the categorization (Table 1) and the size and color of the visual figure that represents it.

RESULTS AND DISCUSSION

Construction of the underlying model

The underlying model adopted a six-level hierarchical structure for the construction of the composite indicator considering access to drinking water and sanitation services as a goal (Figure 3); that is, less access to drinking water and sanitation services implies an increase in vulnerability. Thus, the construction of the underlying model both contributes to generate a solid

Table 1 | Categorization of vulnerability based on the obtained ARDWS-VI values

Category	Value (percentile)
Very high vulnerability	$80 < \text{ARDWS-VI} \leq 100$
High vulnerability	$60 < \text{ARDWS-VI} \leq 80$
Medium vulnerability	$40 < \text{ARDWS-VI} \leq 60$
Low vulnerability	$20 < \text{ARDWS-VI} \leq 40$
Very low vulnerability	$0 < \text{ARDWS-VI} \leq 20$

Note: Created by authors based on the study by Ortega-Gaucin *et al.* (2016).

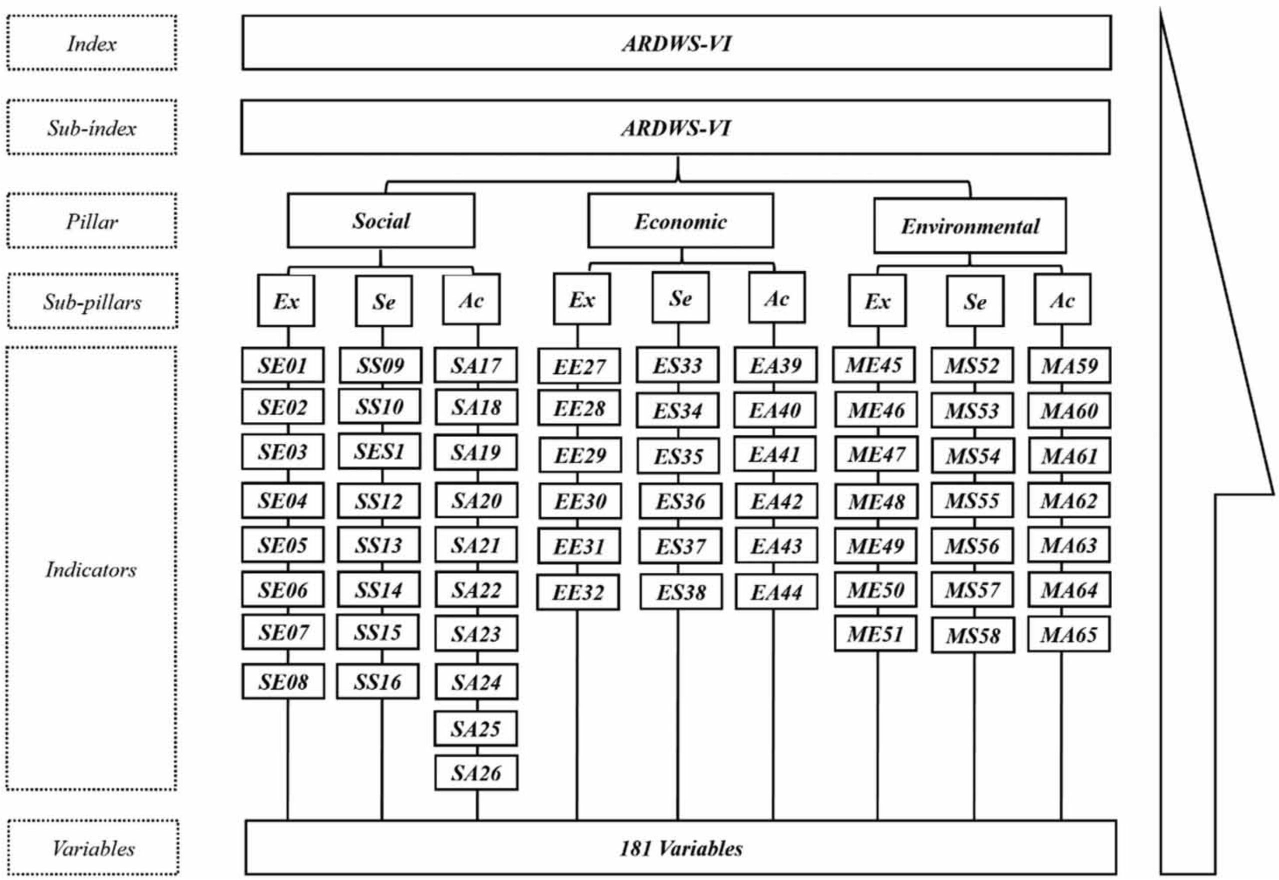


Figure 3 | Underlying model used to calculate the ARDWS-VI.

conceptual framework (Moret 2014) and to statistical support through which the vulnerability of rural sanitary services can be explained as a study phenomenon.

Indicator selection

A total of 65 indicators were used to account for vulnerability in access to drinking water and sanitation services. Of these indicators, 56 were of quantitative type (86.2%), while nine were of qualitative type (13.8%). At least six indicators per vulnerability dimension/factor were considered, thereby complying with the recommendations of the Handbook on Constructing Composite Indicators (Dunn 2020). All the indicators considered were built with a positive polarity (P); that is, as the value of the indicator increases, the degree of vulnerability also increases (Table 2).

Calculation of ARDWS-VI

Who is most vulnerable?

To ascertain which RSSs of the evaluated sample are most vulnerable, 10 RSSs that presented the highest ARDWS-VI values were ranked. The ranking includes the RSSs of La Higuera, El Sauce, Quelén Bajo, San Agustín, El Queñe, Los Morales, Arboleda Grande, Quilimarí, Cuncumén, La Colorada, and Tambo Centro (Table 3).

Who is least vulnerable?

Similarly, special attention is paid to the 10 RSSs that presented the lowest ARDWS-VI values: Las Tapias, La Silleta, El Molle, Puerto Aldea, Las Cardas, Las Rojas, La Unión Yaconi, El Guindo, Los Trigales de Guanaqueros, and Gabriela Mistral (Table 3).

Table 2 | Indicators selected to construct the ARDWS-VI

	Vulnerability factors								
	Exposure			Sensitivity			Adaptive capacity		
Dimension	No.	Indicator name	P	No.	Indicator name	P	No.	Indicator name	P
Social	1	Drinking water coverage gap	+	9	50% subsidies	+	17	Legal formation	+
	2	Sanitation coverage gap	+	10	100% subsidies	+	18	Board meeting deficit	+
	3	Consumption gap	+	11	Claims and fees	+	19	Assembly session deficit	+
	4	Maximum consumption coefficient	+	12	Child morbidity	+	20	Incorporation of water and sanitation technologies	+
	5	Physicochemical quality	+	13	Supply discontinuity	+	21	Educational level	+
	6	Bacteriological quality	+	14	Service interruption	+	22	Gender equity gap	+
	7	Growth rate	+	15	Rurality index by commune	+	23	Unlinked social organizations	+
	8	Potential unincorporated population	+	16	Inactive human capital	+	24	Personnel age range	+
							25	Regulatory framework	+
							26	Non-participation of users	+
Economic	27	Fixed drinking water fee	+	33	Communal unemployment	+	39	Lack of public sector investment in the RSS	+
	28	Fixed sanitation fee	+	34	RSS years of operation	+	40	Lack of RSS's own investment	+
	29	Base drinking water consumption value	+	35	Water bill delinquency	+	41	Economically active youth population	+
	30	Base wastewater treatment value	+	36	Non-revenue water valuation	+	42	Knowledge gap regarding funding sources	+
	31	Base energy consumption value	+	37	Provision for fee changes	+	43	Tanker truck supply	+
	32	Energy variation	+	38	Multidimensional poverty	+	44	Development of economic activities (sector)	+
Environmental	45	Total cumulative precipitation deficit	+	52	Legal availability per meter	+	59	Water storage capacity	+
	46	Maximum temperature	+	53	Aridity index	+	60	Unconsidered energy alternatives	+
	47	Maximum water source variation	+	54	Basin with depletion decree	+	61	Environmental protection actions	+
	48	Quantity of water produced (extracted)	+	55	Hydrogeological restriction area	+	62	Culture of natural resource protection	+
	49	Infrastructure in flood zones	+	56	Wastewater treatment status	+	63	Environmental awareness actions	+
	50	Artificial storage gap	+	57	Water scarcity declarations	+	64	Lack of adaptation to climate change	+
	51	Accumulation by dispossession	+	58	Climate migrants	+	65	Returned non-revenue water volume	+

Note: No., indicator number; P, polarity with respect to vulnerability; +, positive polarity (as the indicator value increases, vulnerability increases).

Why is one vulnerable?

The RSS evaluation results show, as a general average, an ARDWS-VI value of 46.2%, evidencing medium vulnerability for the RSS set. Likewise, the dimensions associated with the ARDWS-VI presented average values of 42.4% for the social dimension, 47.5% for the economic dimension, and 52.6% for the environmental dimension. While all the dimensions present medium vulnerability, the environmental dimension evidences the greatest vulnerability, consistent with the findings of Garreaud *et al.* (2015) and Abrams *et al.* (2021), who state that climate change and the megadrought have caused changes in hydrological regimes, which can worsen access in already vulnerable regions. In this regard, the ARDWS-VI includes 22 indicators that account for the environmental aspect, with essential climate variables such as the following represented: precipitation, temperature, groundwater level, and flood zone, among others (Table 3).

Regarding the vulnerability factors, it was found that the greatest contribution to vulnerability is associated with adaptive capacity (54.4%), followed by sensitivity (45.5%), and, finally, exposure (44.8%). These results differ from what was stated by

Table 3 | ARDWS-VI results, ranking, and heat map of indicator, pillars, and sub-pillars

Ranking	RSS name	I	p1	p2	p3	sp1	sp2	sp3	sp4	sp5	sp6	sp7	sp8	sp9
		ARDWS-VI	So	Ec	En	SoE	SoS	SoAc	EcE	EcS	EcAC	EnE	EnS	EnAc
1	La Higuera	64.1	66.1	75.6	48.5	48.1	90.9	34.6	47.9	80.3	88.9	25.4	53.5	66.7
2	El Sauce	55.7	59.0	48.5	56.5	48.7	69.3	48.7	34.6	51.7	52.9	64.3	47.1	58.0
3	Quelén Bajo	54.8	51.9	51.0	64.3	46.4	52.7	55.9	32.5	44.2	89.8	63.5	65.3	64.2
4	San Agustín	54.7	42.1	63.0	71.5	40.2	37.2	53.7	40.3	63.0	85.6	76.3	78.8	59.5
5	El Queñe	54.3	49.7	54.3	63.4	64.0	47.8	39.1	42.7	46.4	89.8	60.5	51.4	78.3
6	Los Morales	54.0	47.4	53.6	67.5	46.8	45.2	52.5	34.0	50.3	83.2	68.9	68.1	65.6
7	Arboleda Grande	54.0	49.9	55.1	61.0	27.3	63.1	46.2	45.7	63.3	39.8	60.1	57.2	65.8
8	Quilimarí	53.8	42.5	70.7	59.6	26.4	52.9	37.8	33.3	83.0	71.4	59.5	73.6	45.6
9	Cuncumén	51.6	41.7	50.5	72.7	35.4	43.0	45.3	16.6	61.2	52.3	84.3	61.7	72.1
10	La Colorada	51.3	50.1	46.6	58.3	53.9	49.0	48.5	52.2	37.1	69.5	63.8	77.2	33.8
11	Tambo Centro	50.8	49.8	49.6	54.1	39.0	47.1	66.0	35.3	49.3	64.8	74.8	35.1	52.3
12	Llimpo	49.9	39.2	53.1	68.3	41.3	32.0	51.4	42.3	48.6	77.3	59.1	78.7	67.1
13	Limahuida	49.6	41.3	57.4	58.5	40.1	40.2	44.5	35.0	54.3	88.9	79.2	25.1	71.3
14	Coirón	49.1	46.1	48.8	55.5	35.0	45.8	57.7	19.5	49.1	77.3	71.3	48.9	46.3
15	Colliguay	48.9	44.7	51.9	54.3	44.9	38.4	57.1	37.8	43.9	89.8	61.4	60.9	40.6
16	San Marcos	48.6	48.2	53.7	44.2	52.4	45.4	49.7	36.7	70.7	19.5	57.0	45.5	30.2
17	Vado Hondo	48.5	43.5	61.3	45.7	64.6	32.4	44.6	58.9	52.1	91.5	60.5	38.3	38.3
18	El Maitén	48.5	46.5	42.4	58.5	40.3	50.8	43.9	36.0	32.7	77.8	49.7	62.4	63.5
19	Panguesillo	48.1	42.7	46.1	60.9	37.5	42.8	47.7	22.5	44.9	73.1	81.1	62.0	39.6
20	Batuco	47.7	47.3	45.7	50.3	53.2	43.2	49.8	19.6	43.8	77.3	77.0	57.2	16.7
21	Carachilla	47.3	46.9	55.6	39.6	34.7	48.6	55.9	33.9	59.1	66.7	18.4	61.5	38.8
22	Plan de hornos	47.0	48.5	43.0	47.9	54.1	44.5	50.7	23.9	38.7	75.0	53.9	36.5	53.4
23	Tambo Oriente	46.9	39.1	53.1	56.3	40.6	37.0	41.8	40.7	56.0	56.4	58.0	56.7	54.2
24	El Manzano	46.9	52.9	38.2	43.6	51.9	52.3	54.9	43.2	43.8	16.7	45.4	39.9	45.5
25	El Tome Alto	46.5	37.1	52.2	59.7	34.9	30.5	52.5	25.6	56.2	66.5	63.9	57.1	58.0
26	Punta Azul	46.1	51.7	35.6	45.4	54.7	54.3	43.5	22.9	25.1	79.5	54.5	26.7	55.1
27	Huintil Norte	45.4	38.7	44.5	59.9	54.2	25.9	48.7	39.8	38.7	66.7	46.8	57.5	75.4
28	Sol del Pacifico	45.3	41.7	46.1	51.9	64.1	25.1	52.5	53.2	33.2	77.8	11.7	75.8	68.2
29	Tambillos	44.3	37.6	52.2	49.8	43.6	32.1	42.5	65.8	46.6	55.6	38.4	57.2	53.7
30	Coyuntagua Norte	43.1	37.8	47.6	49.0	68.2	25.5	32.2	18.2	52.9	61.1	60.9	61.2	24.9
31	Mincha norte	41.0	41.1	39.2	42.7	28.9	43.0	49.6	33.2	24.6	88.9	42.5	47.3	38.4
32	Serón	40.6	30.7	49.7	51.4	29.7	18.4	56.2	27.1	44.2	88.9	56.0	46.6	51.5
33	Los Tapias	39.8	25.7	43.3	64.6	45.1	9.9	37.7	9.2	46.9	66.5	55.3	72.4	66.3
34	La Silleta	39.5	40.8	32.7	43.6	65.9	20.0	57.3	46.6	14.9	72.2	14.9	44.5	71.4
35	El Molle	38.2	37.6	35.0	42.6	28.9	35.8	49.8	38.9	30.0	46.1	63.9	31.0	32.9
36	Puerto Aldea	37.1	39.3	24.3	45.3	73.8	21.6	40.2	5.8	34.8	11.1	53.0	33.8	49.1
37	Las Cardas	36.5	29.9	38.8	47.2	41.7	11.4	55.2	88.2	22.4	38.9	44.9	42.5	54.4
38	Las Rojas	36.2	30.2	48.1	36.4	40.9	12.2	55.5	34.2	65.1	11.1	39.6	39.8	29.8
39	La Unión Yaconi	34.8	32.8	31.8	41.8	43.5	16.7	54.3	39.0	27.0	38.9	19.9	51.6	54.0
40	El Guindo	33.9	31.7	39.3	33.0	40.2	15.9	54.6	24.2	53.7	11.1	30.6	39.1	29.3
41	Trigales de Guanaqueros	33.4	26.4	40.0	40.6	38.9	13.4	39.7	54.4	35.6	38.9	22.5	30.2	69.3
42	Gabriela Mistral	32.3	31.1	24.8	42.2	21.9	31.0	40.6	43.7	19.3	22.2	28.8	44.0	53.8

Note: i, index; si, sub-index; p, pillar; sp, sub-pillar; SoE, social – exposure; SoS, social – sensitivity; SoAc, social – adaptive capacity; EcE, economic – exposure; EcS, economic – sensitivity; EcAc, economic – adaptive capacity; EnE, environmental – exposure; EnS, environmental – sensitivity; EnAc, environmental – adaptive capacity.

Zhou *et al.* (2023), who indicate that exposure is the key factor in the case of Guizhou Province (China); in the case of the Coquimbo Region (Chile), adaptive capacity is the most relevant key factor.

How is vulnerability differentiated?

None of the assessed RSSs present ARDWS-VI values that would put them in the very high or very low vulnerability categories. Meanwhile, 2.4% of the RSSs present high vulnerability, 73.8% of the RSSs present medium vulnerability, and 23.8% of the RSSs present low vulnerability. The ARDWS-VI values for the RSSs fluctuate from a minimum of 32.3% to a maximum of 64.1% (Table 3). These vulnerability results take on relevance considering that the Coquimbo Region is known for experiencing frequent water scarcity situations. Since 2008, the General Water Directorate (DGA) of the Ministry of Public Works (MOP) declared water scarcity in the Coquimbo Region on 32 occasions, which represents 13.8% of the total number of decrees issued nationwide.

The ARDWS-VI values by province were 49.4% for the Choapa Province; 45.1% for the Limarí Province, and 41.5% for the Elqui Province. In terms of social, economic, and environmental dimensions, the three provinces share the same situation, with the Choapa, Limarí, and Elqui provinces positioned from greatest to least vulnerable in each of the indicated dimensions, respectively. Thus, the Choapa Province would be the one with the greatest degree of vulnerability.

The ARDWS-VI values by commune, from greatest to least, were 64.1% for La Higuera, 53.8% for Los Vilos, 51.9% for Combarbalá, 50.9% for Salamanca, 47.2% for Monte Patria, 46.9% for Andacollo, 46.7% for Illapel, 42.1% for Vicuña, 41.0% for Canela, 40.6% for Río Hurtado, 40.2% for Ovalle, 37.8% for Coquimbo, and 34.3% for La Serena. Thus, La Higuera Commune is the only one that presented high vulnerability; Los Vilos, Combarbalá, Salamanca, Monte Patria, Andacollo, Illapel, Vicuña, Canela, Río Hurtado, and Ovalle communes presented medium vulnerability; and Coquimbo and La Serena communes presented low vulnerability. Paihuano and Punitaqui communes, which are also part of the Coquimbo Region, were not assessed because the RSSs of these communes did not participate in the study.

Taking into account the highest values obtained by the RSSs for each dimension in terms of exposure, sensitivity, and adaptive capacity (sub-pillars); the variability of the results; and that vulnerability values range from 0 to 100% (see Table 1), the following RSSs were identified as having with the highest vulnerability values:

- Social exposure (mean 44.9%; interquartile range (IQR) 16.4%): Puerto Aldea 73.8%.
- Social sensitivity (mean 38.0%; IQR 22.6%): La Higuera 90.9%.
- Social adaptive capacity (mean 48.6%; IQR 11.4%): Tambo Centro 66.0%.
- Economic exposure (mean 36.6%; IQR 18.1%): Las Cardas 88.2%.
- Economic sensitivity (mean 46.2%; IQR 19.3%): Quilimarí 83.0%.
- Economic adaptive capacity (mean 62.3%; IQR 35.9%): Vado Hondo 91.5%.
- Environmental exposure (mean 52.9%; IQR 22.1%): Cuncumén 84.3%.
- Environmental sensitivity (mean 52.4%; IQR 21.9%): Llimpo 78.7%.
- Environmental adaptive capacity (mean 52.5%; IQR 26.5%): El Queñe 78.3%.

Finally, it is important to highlight the dynamism of vulnerability over time. De Ruiter & Van Loon (2022) point out three key elements for this: the underlying dynamics of vulnerability, changes in vulnerability during long-lasting disasters, and changes in vulnerability during compounding disasters, to delve into the factors that can increase or reduce vulnerability. In this way, the present research will lay the foundations for further evaluation and study of the factors mentioned above. Moreover, studies on RSSs should consider the study of dimensional vulnerability to avoid a low interlinkage between risk and sustainability indicators, implying, for example, that there is no considerable improvement in risk reduction expected by improving water reuse sustainability, and vice versa.

As stated by Molinos-Senante *et al.* (2019), in rural settings, the presence of water supply infrastructure does not guarantee access to reliable and high-quality drinking water. From this study, we can add that only the presence of RSSs does not equally guarantee access to drinking water and RSSs without vulnerabilities due to the multidimensional problems they present.

Visualization of results

To answer the question '*What is the extent of the vulnerability?*' the results obtained from the ARDWS-VI were represented visually using PowerBI software, in which maps showing the ARDWS-VI results and results for each dimension were developed (Figures 4–7).

As can be seen in Figure 4, there is a tendency to find RSSs with higher vulnerability in the central and southern areas of the Coquimbo Region. However, the greatest vulnerability is seen in the extreme north, the area where the Atacama Desert begins. Thus, as RSSs are further away from the main urban sectors, vulnerability increases; on the contrary, vulnerability decreased in RSSs close to population centers such as La Serena, Coquimbo, Ovalle, and Los Vilos.

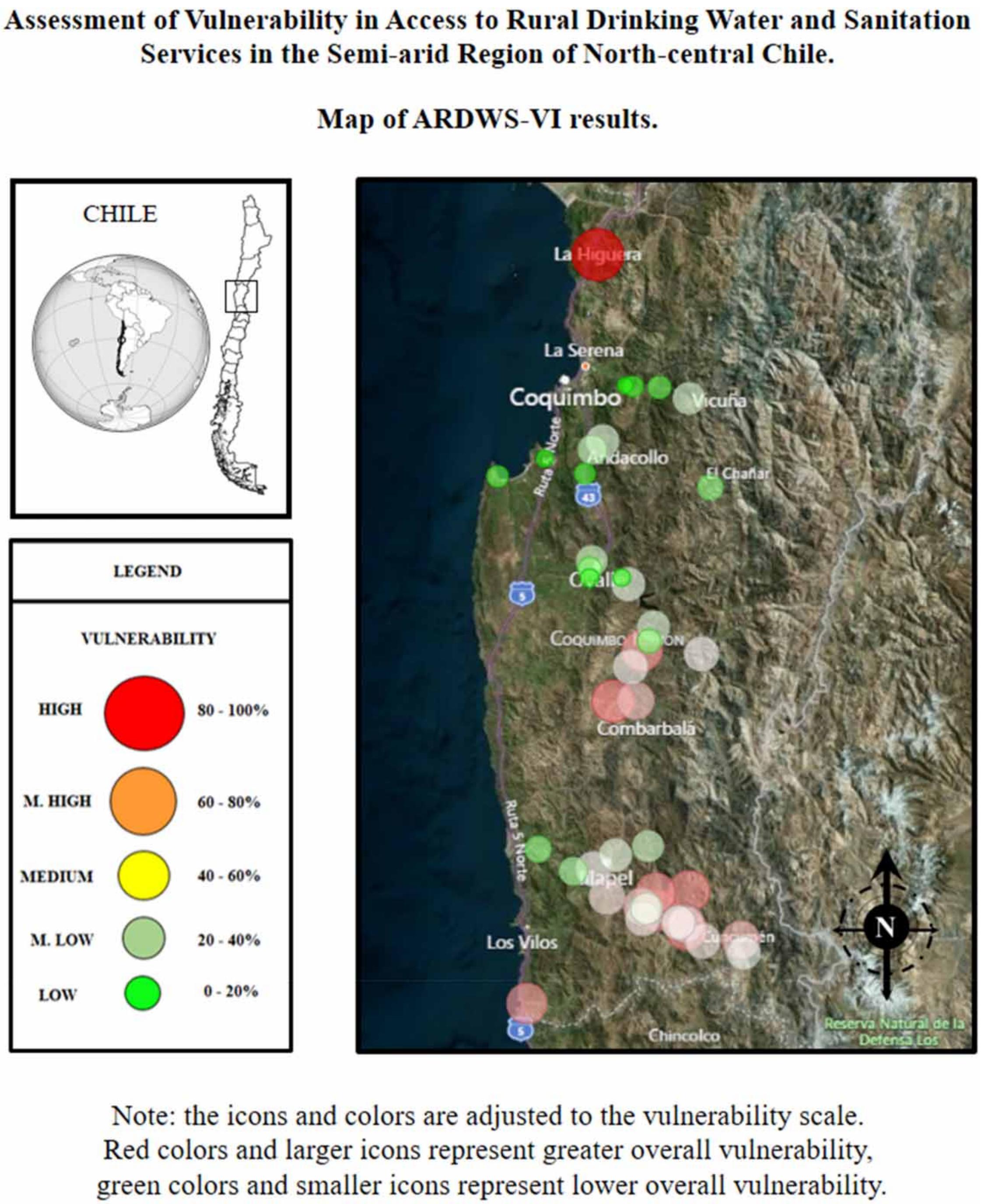


Figure 4 | Map of ARDWS-VI results.

Núñez *et al.* (2017) analyzed the water security vulnerability to drought in water use sectors in the Elqui River Basin, showing that the vulnerability studied increased downstream of the basin. In the case of vulnerability, access to drinking water and rural sanitation increases upstream.

Robustness analysis

The composite indicator results depend on the selection of variables, normalization, weighting, and aggregation technique, such that it is necessary to examine the robustness of the indicator against these elements. One of the most recommended

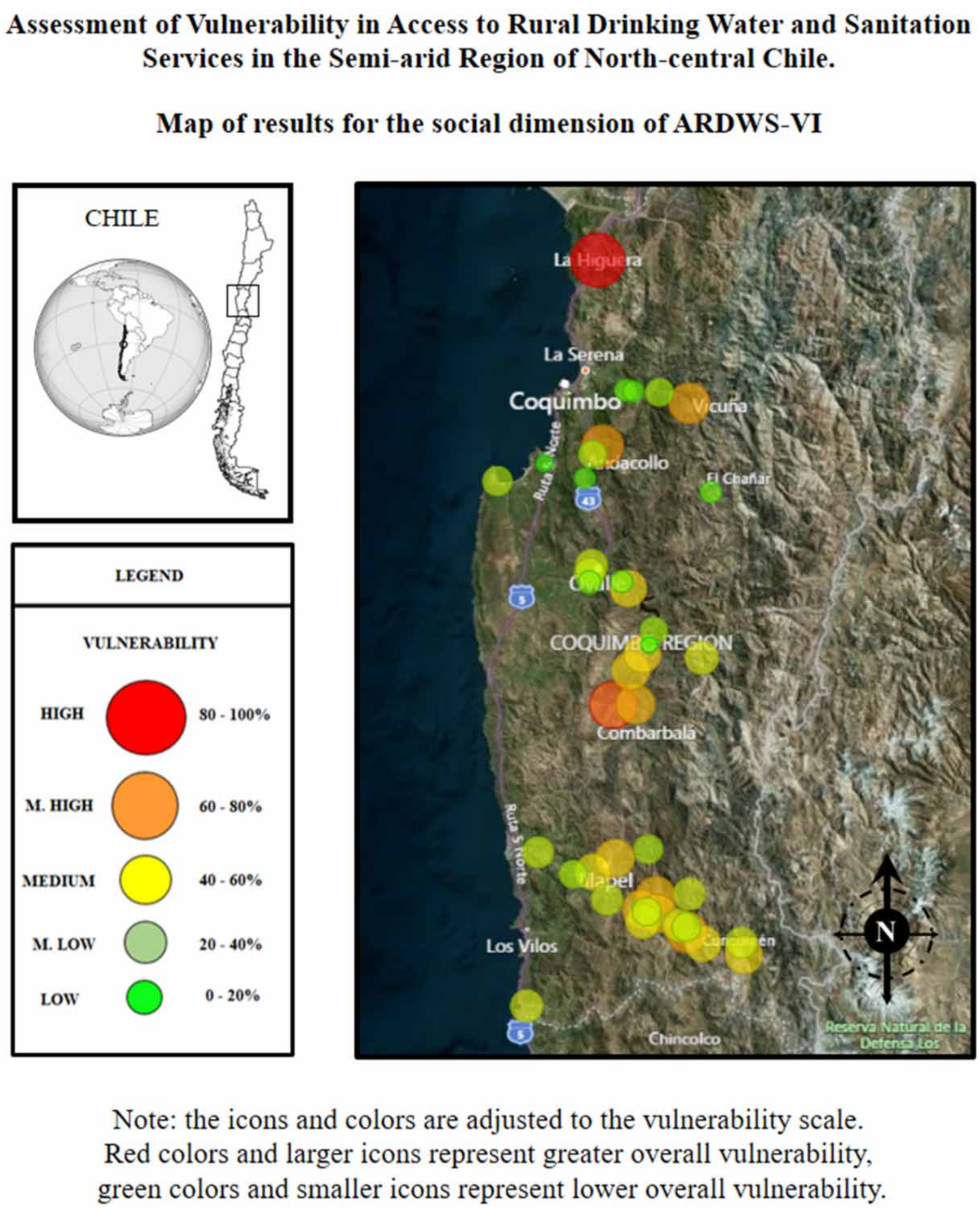


Figure 5 | Map of results for the social dimension of vulnerability.

techniques consists of measuring the correlation between the resulting compound indicator and its constituent items (Talukder *et al.* 2017).

The robustness analysis was carried out based on the normalization options available in COINTool. It was found the normalization method selected for the development and assessment of the ARDWS-VI, Min-Max, was the most suitable according to the results delivered by the robustness analysis.

Similarly, Cronbach's α was evaluated based on the correlation matrix for the following cases: (a) all the elements that compose the composite indicator, (b) those that include only sub-pillars, and (c) those that include only pillars. The results indicate that for case (a), $\alpha = 0.724$; for case (b), $\alpha = 0.943$; and for case (c), $\alpha = 0.973$. Thus, the results showed good to very high consistency or reliability of the instrument considered.

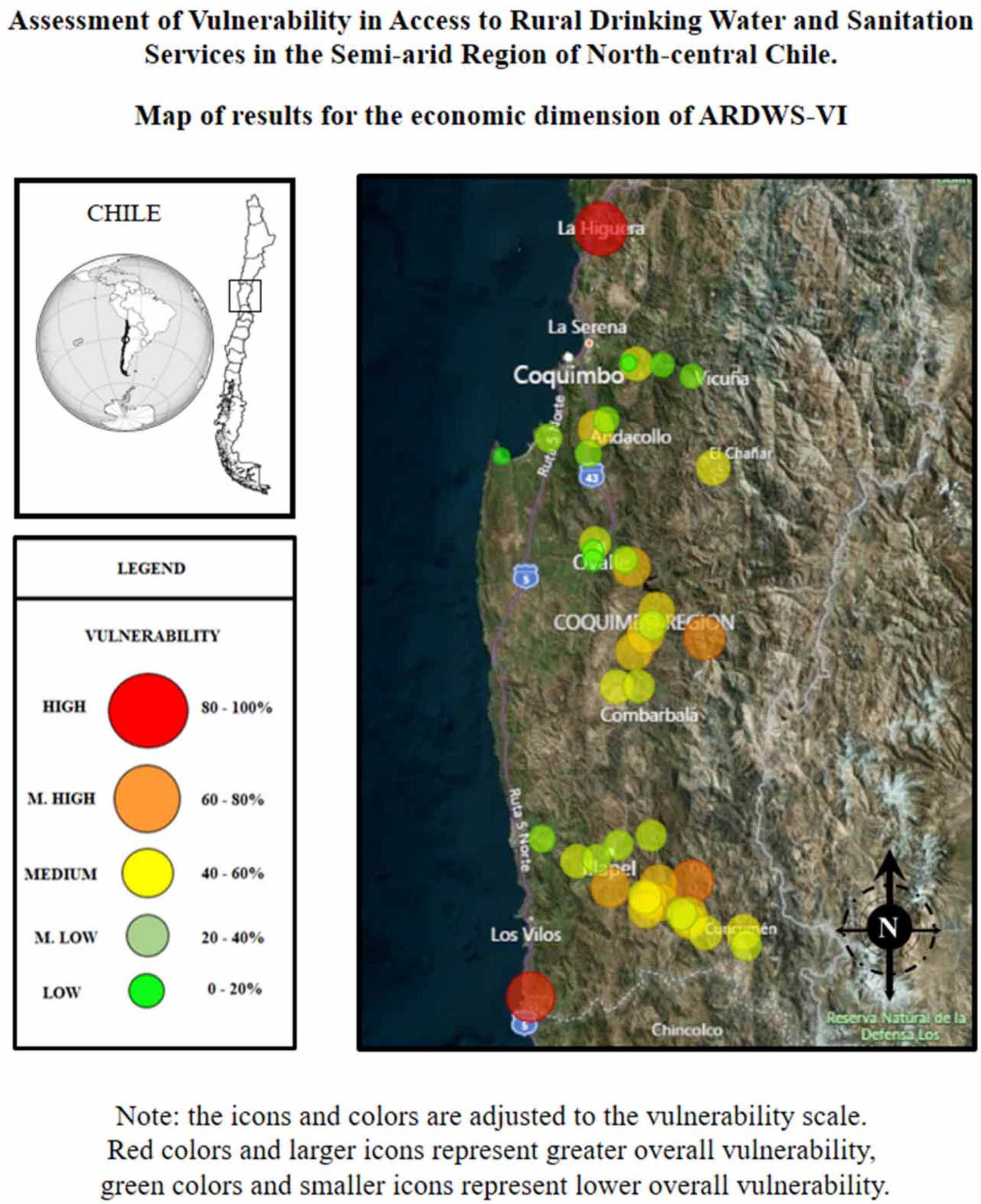


Figure 6 | Map of results for the economic dimension of vulnerability.

CONCLUSIONS

This research allowed the development and evaluation of an indicator of vulnerability (multidimensional) in access to drinking water and RSSs. This indicator made it possible to answer the basic vulnerability questions: Who is most vulnerable? Why is one vulnerable? How is vulnerability differentiated? What is the extent of the vulnerability? The answers to these questions represent an important contribution, for both public and private decision-makers related to the rural water and sanitation sector. Likewise, the answers to these questions have a significant relevance in terms of adaptation and mitigation actions at different scales, starting from the level of RSSs horizontally and vertically. Through

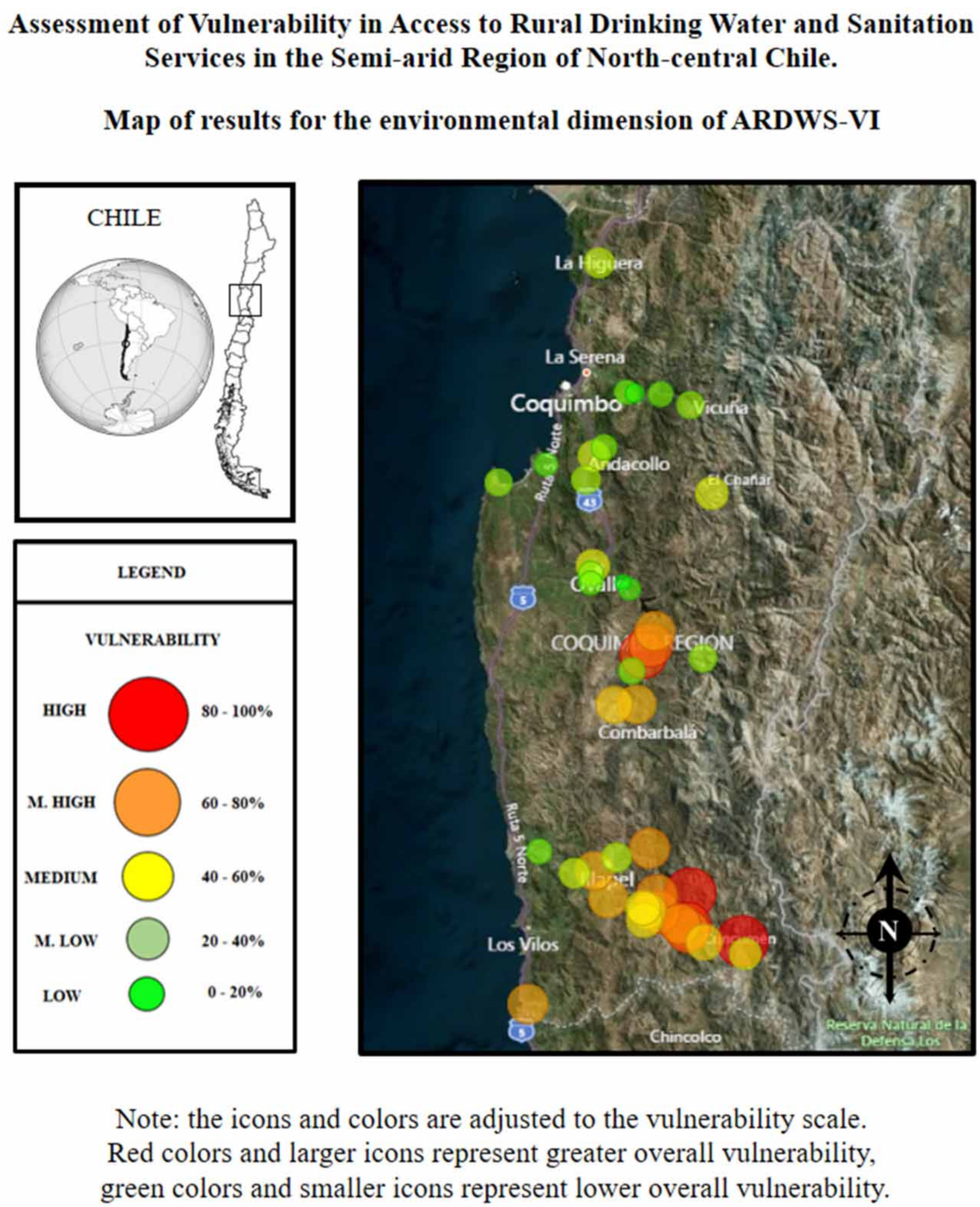


Figure 7 | Map of results for the environmental dimension of vulnerability.

the results of the vulnerability indicator, it is hoped to clarify the causes that trigger vulnerability and to orient possible future actions to those factors that show greater vulnerability or to develop actions focused on reducing vulnerability associated with the basic indicators. The implementation of this indicator could be associated with policies, plans, or programs centered on the reduction of risks related to water emergencies and/or the adaptation to the effects of climate change. It has the versatility to assess vulnerability from various perspectives (administrative divisions, at the watershed level, by dimension, or vulnerability factor). In this way, the authors hope to contribute with a vulnerability indicator that accounts for multidimensional vulnerability, includes multidisciplinary social input, synthesizes a large amount of information, monitors results over time, and evaluates the effectiveness of actions, strategies, or policies implemented to reduce the vulnerability of RSSs.

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AUTHOR CONTRIBUTIONS

CVC, principal investigator with experience in water resources management in arid and semi-arid zones, developed the research, carried out the analysis of results, and prepared the drafts and final document. JNC, with experience in drought and hydrology, oriented the methodological development of the research regarding vulnerability and water resources in arid and semi-arid zones and the use of software and reviewed the preliminary drafts and final document. GME, with experience in integrated water resources management, provided logistical support for the development of the research and contributed as a reviewer of the preliminary drafts and final document. SSB, with experience in social vulnerabilities, climate change, desertification, and water conservation in rural communities, contributed as a reviewer of the preliminary drafts and final document.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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