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Spatial multicriteria approach to water scarcity vulnerability and analysis of criteria weighting techniques: a case study in São Francisco River, Brazil

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Abstract The water availability deficit is a governance crisis and an environmental, social, and economic risk. This study presents a spatial multicriteria approach for mapping Water Scarcity Vulnerability (WSV) and a comparative analysis of criteria weighting techniques to support the management of water resources in semiarid regions. Initially, nine vulnerability indicators were identified from a literature review and spatialized through a Geographic Information System (GIS) for a water donor region and another recipient from the São Francisco River, in the semiarid region of Brazil. Subsequently, one subjective and two objectives weighting techniques were implemented and compared to measure the weights of the indicators. Finally, the Viekriterijumsko Kompromisno Rangiranje (VIKOR) method was combined with GIS to construct WSV maps. The results indicate the conditions of WSV in the transposition water donor region can be more critical than the region receiver, and the choice of the weighting method influences the results of the multicriteria-GIS approaches. The WSV mapping approach can be helpful for water management decision-making to identify priority areas and spatial inequalities. The comparative analysis in this study can provide a valuable reference for choosing weighting methods in spatial multicriteria applications.

Keywords Vulnerability to water scarcity · Criteria weighting · VIKOR · Geographic information system · São Francisco River Basin

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Introduction

Vulnerability to water scarcity in watersheds can affect a series of vital elements related to the life of populations. The water availability deficit is an environmental, social, and economic risk and is primarily a crisis of governance of natural resource sustainability (Brito et al., 2021). Communities living in arid and semi-arid watersheds and regions are even more subject to risks related to water scarcity, so achieving a state of water security is the goal for efficient governance (Alves et al., 2021).

Living with the risk of water availability deficit is historical in Brazil, especially in the Northeast region, so the water supply in small towns in semi-arid regions can occur only once a week or even

once a month (Cordão et al., 2020). The São Francisco River Basin (SFRB), present in the Northeast and Southeast of Brazil, provides the São Francisco River Integration Project (PISF), the largest water infrastructure project in Brazil, which aims to ensure water security for 12 million people distributed in 390 municipalities, from the transposition of the waters of its main river to the watersheds of the Northern Northeast of Brazil (ANA, 2019).

Despite being a water donor, some studies (for example, Bezerra et al., 2019; Maneta et al., 2009; Sun et al., 2016) indicate strong and detrimental water-consuming activity in the SFRB and regions with characteristics of temporal and spatial irregularity of precipitation. The SFRB has the largest portion of the population (~62.5%) in the semiarid region, has about 21% of the population considered poor by Brazilian standards, and presents the growth of intense economic activities, noting an increasing pressure on its natural and water resources (Empinotti et al., 2018).

According to Rogers et al. (2020), integrating the management of water transposition projects from a donor basin with water planning in the receiving basins, such as the PISF in Brazil, is of great importance for efficient, rational and sustainable management of water use. In this case, the Paraíba River Basin (PRB) in the state of Paraíba, a receiving basin integrated with the SFRB, stands out because of its importance in water management, geomorphology, and socioeconomics in Northeast Brazil (Medeiros et al., 2019). The PRB suffers from recurrent meteorological and hydrological problems, droughts, low rainfall, and limited water availability, and stands out among other arid and semiarid regions of the world by having a dense population with approximately 30 million inhabitants in 2010 (IBGE, 2018).

In this context, Araujo et al. (2019) refer that analyzing complex water systems, such as for case studies of water regions with transboundary waters of the SFRB, requires the development of approaches to understanding the political, institutional, social, environmental, economic, and not only water context for water planning and management. In the literature, there are several studies focused on identifying optimal conditions for natural resource management, such as Othman et al. (2020), Chamanehpour (2017), and Jozaghi et al. (2018), and vulnerability to adverse

events from a spatial approach, as in the studies by Al-juaidi et al. (2018), Mosavi et al. (2020) and Morea and Samanta (2020). Since the use of Geographic Information Systems (GIS) has been a global trend in geoenvironmental spatial research, it can contribute to a complex of functions with advanced features that provide storage, retrieval, manipulation, and presentation of geographically located data operators (Nowak et al., 2020).

The different GIS works are generally presented in methodologies that vary between isolated use and hybrid approaches developed from combined methods or systems (Chen et al., 2018). According to Kabak et al. (2018), among the hybrid approaches, the use of GIS associated with multicriteria analysis methods to enhance geospatial studies stands out. In addition to manipulating and processing georeferenced data, multicriteria-GIS approaches can deal with the importance of complex decision problem elements, simplifying them in a classification structure (Souissi et al., 2020).

The Viekriterijumsko Kompromisno Rangiranje (VIKOR) method is one of the methods been used associated with GIS. Its principle is based on a proximity aggregation function with the ideal solution. The method was developed from the metric used in the multicriteria analysis study by Yu (1973), based on commitment scheduling. The VIKOR algorithm, based on a set of contradictory criteria present and their respective weights, classifies the alternatives in a performance index.

For years, procedures for determining criteria weights (essential for multicriteria models) have been a matter of research and scientific debate, and several approaches have been developed and discussed. The criteria weights of GIS-based multicriteria approaches have been accessed from subjective definition methods, such as the AHP method, in the applications of Solangi et al. (2019) and Kumar et al. (2020), and objective definition methods, as in the studies by Yang et al. (2018), Rani et al. (2019), Yacin and Unlu (2018), and Sharma and Gupta (2020), with the Shannon and CRITIC Entropy methods being the most common. Table 1 shows some studies focusing on water resource vulnerability analysis. As shown, it can be seen that a combination of GIS-Multicriteria methods (based on a weighting criteria method) was widely used in early studies.

Table 1 Recent studies on water support resource vulnerability analysis

Reference	Aim and scope	Method used
Chowdary et al. (2013)	Location of critical areas for prioritization of watersheds	AHP and GIS
Chung et al. (2014)	Water resource vulnerability by district's population size	Entropy, Delphi and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and GIS
Chung et al. (2016)	Watershed vulnerability based on the Intergovernmental Panel on Climate Changein	Entropy, Delphi and TOPSIS and GIS
Chitsaz, and Azarnivand (2017)	Water scarcity in arid regions with agricultural practices	Best Worst Method and AHP and GIS
Razavi et al. (2017)	Prioritizing and evaluating watersheds by governance criteria	Fuzzy DEMATEL, fuzzy ANP and fuzzy VIKOR and GIS
Brito et al. (2018)	Comparative of AHP and AHP in a Participatory flood vulnerability assessment approach	AHP, ANP and GIS
Spiliotis et al. (2019)	Estimation of drought vulnerability in selected Mediterranean countries	Meta-attribute approach
Balasubramani et al. (2019)	Characterization and prioritization of micro-watersheds	AHP and GIS
Dilling et al. (2019)	Perceptions of drought response by institutional actors across a variety of climate regimes	Multiple criteria and semi-structured interviews
Cordão et al. (2020)	Water shortage risk mapping for urban water supply systems	AHP and GIS
Meshram et al. (2020)	Prioritization of sensitive area at risk of water erosion	Compound Factor, VIKOR and Élimination et Choix Traduisant la Realité (ELECTREE) and GIS
Tsegaye et al. (2020)	A clustering methodology for better clustering of urban water systems into small and adaptable units	GIS
Alves et al. (2021)	Supporting water resources management by assessing the suitability of agricultural land	AHP and GIS
Mokarram et al. (2021)	Determining and forecasting drought susceptibility by environmental parameters	Fuzzy-AHP, cellular automata (CA)-Markov model and GIS
Current study	Mapping vulnerability to water scarcity in regions and river basins	Simplified AHP, Entropy, CRITIC, VIKOR and GIS

From the literature review of studies focusing on the water resource vulnerability analysis, the applicability of GIS-Multicriteria approaches is largely verified. The applications generally focus on drought event relations and structural supply at medium and large municipal scales. It is noted that studies generally approach the vulnerability problem from a climatic point of view and that users may experience the effects of water scarcity in different ways depending on their socioeconomic status, which suggests that the scarcity of the resource is also linked to spatial injustice generated by inequalities (Cordão et al., 2020). Similarly, there are limitations in studies analyzing the influence of the choice of weighting method on the results of GIS-MCDA approaches

from the perspective of water management since the results are obtained from a single weighting method.

In this sense, the present study aims to develop a spatial multicriteria approach for mapping WSV in regions of the integrated basin transposed from the São Francisco River and compare the influence of weighting methods choice on spatial analysis results. Unlike previous studies, which only consider structural and climatic aspects of water supply, this proposed GIS-MCDA approach considers a holistic perspective to analyse WSV as a tool to improve decision-making in arid and semiarid regions. Thus, this study raises the hypothesis that the proposed approach can be used to map areas with different levels of vulnerability to water scarcity due to institutional, political, economic

and social factors and can be a reference for weighting methods choice in GIS-MCDA approaches.

Materials and methods

The study focuses on proposing a spatial multicriteria approach for mapping WSV in regions of the integrated São Francisco River Basin and evaluating criteria weighting techniques applied to GIS-MCDA models. In order to describe the proposed methodology (Fig. 1), a four-step procedure is considered: in step 1, based on a review of studies, the water regions under study are defined and characterized by municipal boundaries. In step 2, we proceed to the definition, standardization and spatialization of the criteria that influence WSV. In the third step, the relative importance of the criteria (subjective and objective weights that determine the subsequent

contribution of each criterion related to water scarcity) and the combined GIS-VIKOR approach are conducted to generate the WSV maps. Finally, in step four, the results were compared through sensitivity analysis in the fourth step to analyze the impact of uncertainty related to the criteria. Details of the materials and methods are presented below.

Study area

To apply this approach, the first step is to define the hydrographic region as a study area so that this approach can be replicated for any water region with municipal boundaries. The present study applied the hybrid approach in the integrated hydrographic basin of the São Francisco River Basin (SFRB), with specificity for the Physiographic Region of the Middle São Francisco (MSF), and in the hydrographic Paraíba River Basin (PRB)–receiving basin integrated with

Fig. 1 Schematic representation for the proposed Water Scarcity Vulnerability analysis
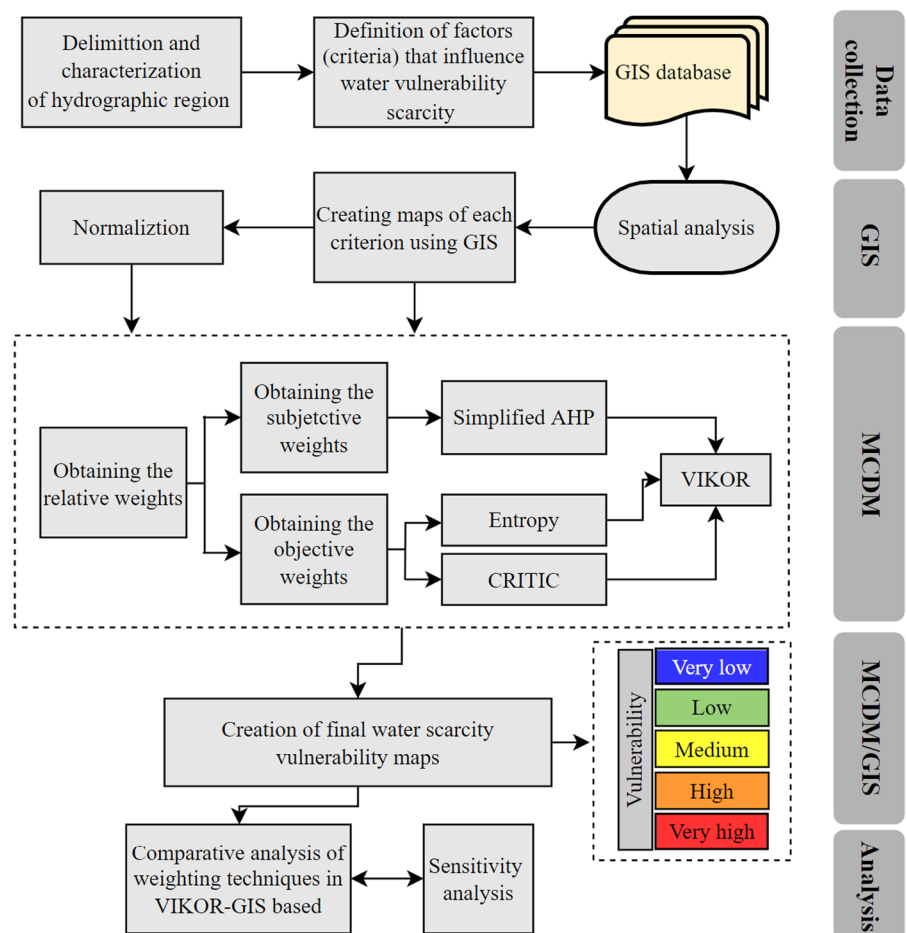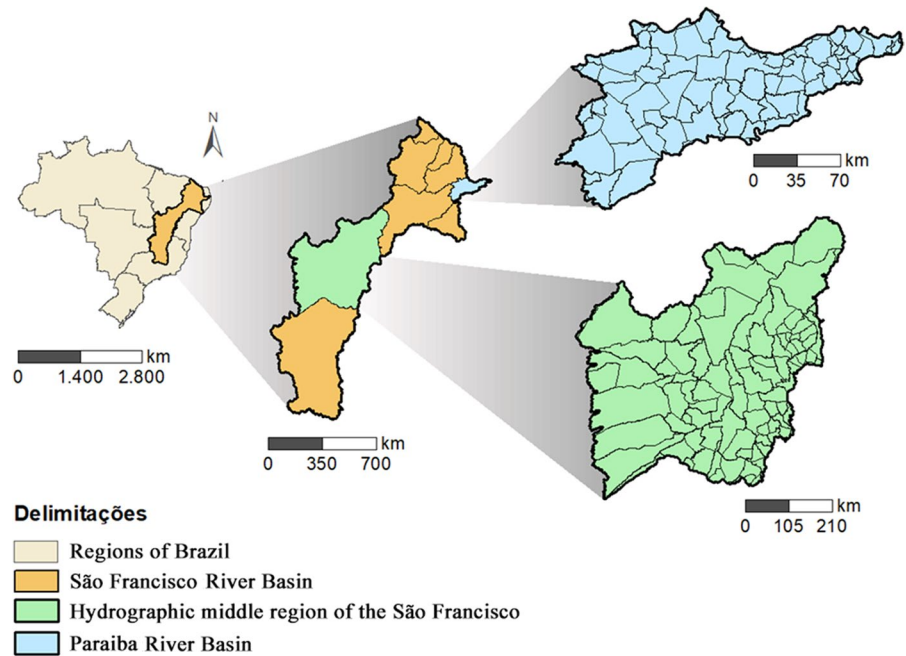
Fig. 2 Geographic limits are addressed throughout the study: the São Francisco River Basin–Brazil, The Middle São Francisco Region and the Paraíba River Basin (integrated watershed). *Source*: Elaborated from ANA (2019a, 2019b) and IBGE (2019)

the SFRB, with interest in investigating the vulnerability conditions of a donor and a recipient water region. Figure 2 shows the delimitation of the SFRB, the MSF Physiographic Region—onor of transposition waters, and the PRB delimitation.

SFRB, a water donor, afford the São Francisco River Integration Project, which aims to ensure water security for 12 million people in 390 municipalities in Brazil in the states of Ceará, Rio Grande do Norte, Paraíba, and Pernambuco, from the transposition of the waters of its main river to the hydrographic basins of the North-Northeast (ANA, 2017). The project is the most considerable hydraulic work in Brazil carried out under the Brazilian Water Resources Policy, with the transposition of water taking place through two axes, the North Axis and the East Axis, built by artificial channels that capture water in sub-basins located in Pernambuco (BRASIL, 2021).

The MSF was selected as an analysis cut-out, as it covers 39% of the SFRB (second largest region, second only to the upper region, which occupies 40%). Almost 60% of the MSF land use is occupied by agricultural establishments (principal activity), and the region has 76% of the underground water availability of the SFRB, in addition to having multiple uses of water resources aimed at industrial activity, irrigation, energy generation, mining, human supply,

among others. The MSF covers 98 municipalities distributed in 6 hydrographic sub-basins, which are: Alto Grande, Current, Medium/Low Grande, Verde/Jacaré, Sobradinho, and Paramirim/Santo Onofre/Carnaíba de Dentro, all located in the territory of Bahia state (CSFRB, 2016).

The Paraíba River Hydrographic Basin (PRB), as a case study for transposition water receiving basin, makes up the integrated basin of the São Francisco River through an area of 20,071.83 km^2 which places it as the second largest in the Paraíba state in terms of territorial extension. Two reservoirs stand out in PRB's water supply: the Epitácio Pessoa reservoir, better known as Boqueirão, located in the municipality of the same name, and has a storage capacity of 466.52 hm^3; and the Argemiro de Figueiredo dam, known as Acauã, which has a total volume of 253 hm^3 (AESA, 2021; IBGE, 2018).

Definition of WSV influencing factors

The second step in applying this approach is the determination of indicators (criteria) that influence WSV in the chosen hydrographic region. According to Brito et al. (2021), several aspects influence an analysis of WSV. The choice of indicators must consider the impulse of water scarcity risk

commonly generated by environmental, social, economic, cultural, and physical impacts associated with governance.

In this approach, national and local indicators were chosen and analysed to diagnose conditions of vulnerability to water scarcity in the specificities of the Brazilian semiarid region. Also aiming to follow a choice approach related to the fulfilment of the Sustainable Development Goals (SDGs) present in the Indicators Guide for Public Management in Brazil, the selection was based on six fundamentals based on the indicator choice methodology proposed by Almeida (2019): (1) Easy application; (2) Ease of calculation; (3) Relevance to the local level; (4) Existence of available data; (5) Contribution to the achievement of the goals of the SDGs; and (6) Data contemporaneity.

The criteria analyzed present a time frame that extends between 2012 and 2019. This time frame was selected because it corresponds to a period in which the Northeast region of Brazil was experiencing a multi-annual drought that lasted from 2012 to 2019 (Brito et al., 2021; Dantas et al., 2020). Table 2 shows the criteria, whether the standard is beneficial or not (z), the year of reference for the data, the description, and the respective source of realization. The types of data collected, preparation and purpose are handled below.

Data for all criteria (C1 to C9) is of vector type. C1—Water Security was prepared with each municipality comprising different territorial units of analysis; therefore, to standardize a single degree of water security for the municipality, the most recurrent degree in the territory was considered. The purpose was to indicate whether the municipality has a minimum, low, medium, high, or maximum degree of water security. The C2 – ES and SPC were prepared with data obtained through a spreadsheet that indicates all the annual decrees of the municipalities, and it was added up when the government recognized the decrees of each municipality. The purpose was to indicate how many decrees of Emergency Situation and State of Public Calamity the municipalities decreed for the multi-year drought in analysis.

The C3—Supply by cistern was prepared with data obtained through a spreadsheet that indicates the percentage of agricultural establishments in each municipality that have a cistern in relation to the total number of establishments in the municipality. The purpose was to indicate the municipality's capacity

in its rural establishments to store water in situations of droughts. The C4 – FMDI was prepared with data obtained through a spreadsheet that indicates each municipality's degree of socioeconomic development. The purpose is to indicate whether the municipality has a high, moderate, regular or low socioeconomic development, from the point of view of employment/income, education and health, which can make it more or less able to live with the effects of drought.

C5—Family Scholarship Program was prepared with the data obtained through a spreadsheet that indicates the number of families that receive financial aid from the federal government called "Bolsa Família" in Portuguese. The percentage was calculated in relation to the total number of existing families in each municipality, and therefore, the final value represents the % of families in poverty or extreme poverty. The purpose was to indicate how many families in each municipality under study live in poverty and extreme poverty since the benefit is only given to families with income per person of up to R$ 89.00 per month; and families with income per person between R$ 89.01 and R$ 178.00 per month, provided they have children or adolescents aged 0 to 17 years. This criterion makes it possible to verify the % of economically vulnerable families in each municipality that has great difficulties in dealing with the impacts of water scarcity.

The C6—Agricultural technical assistance was prepared with data obtained through a spreadsheet indicating the percentage of agricultural establishments with a technical assistance declaration related to the total number of agricultural establishments in the municipality. The data did not undergo any preparation. The purpose was to indicate the percentage of farming establishments that have technical assistance to deal with water scarcity in their farming activities in relation to the municipality's total number of farming establishments. The criterion, thus, makes it possible to identify whether a large or a small part of the rural producers have technical assistance capable of indicating what should be done in a situation of water scarcity.

For C7—Years of heard losses, with the value of losses calculated annually, it is verified if there were losses, gains, or if the value of production remained the same. When losses are verified, a value of 1 is assigned; for production maintained or gains, a value of 0 is assigned. In other words, the value 1 indicates

Table 2 Selected criteria related to vulnerability to water scarcity

Criteria		z	Reference year	Description	Source
C1	Water Security	+	2015	Water security considers four dimensions of the water security concept (human, economic, ecosystem and resilience) based on Brazilian Water Safety Index	ANA (2020)
C2	Emergency Situation (ES) and State of Public Calamity (SPC)	−	2015	Recognitions of ES and SPC carried out between 01/01/2013 and 12/31/2019	S2iD (2020)
C3	Supply by cistern (%)	+	2017	Percentage of agricultural establishments with cisterns, in relation to the total number of establishments in the municipality	Censo Agropecuário—IBGE (2021)
C4	FIRJAN Municipal Development Index (IFDM)	+	2016	Annually monitors the economic development of Brazilian municipalities, considering aspects of employment and income, health and education	Firjan (2020)
C5	Family Scholarchip Program (%)	+	set/17	Number of beneficiary families of the Family Scholarchip Program (FCP) in relation to the total number of inhabitants	Ministério da Cidadania (2020)
C6	Agricultural technical assistance	+	2017	Percentage of agricultural establishments with declaration of technical assistance in relation to the total number of agricultural establishments in the municipality	Censo Agropecuário—IBGE (2021)
C7	Years of heard losses	−	2016 a 2019	Sum of the number of years that there was a reduction in the municipal cattle herd compared to the previous year	Pesquisa da Pecuária Municipal (IBGE, 2019)
C8	Years of losses in Gross Domestic Product (GDP) services	−	2017	Variation in gross value added at current prices for services, excluding public administration, defence, education and health and social security (Thousand Reais) between 2017—2012	IBGE (2019)
C9	Irrigated agriculture (%)	−	2017	Percentage of agricultural establishments with a declaration of use of irrigation in relation to the total number of agricultural establishments in the municipality	Censo Agropecuário—IBGE (2021)

The sign (+/−) indicates that the value of the major/minor criterion is beneficial or non-beneficial for water management

that the harvested area (in hectares) is smaller than the planted area (registered losses) or that the cattle herd decreases between the previous year and the following year, with losses of 5% or more. The purpose was to indicate how many years of drought the municipalities had head losses in their cattle herds

and thus describe how vulnerable the municipalities are in dealing with the effects of drought on their livestock production. The C8—Years of losses in GDP services had data obtained through a spreadsheet indicating the variation in gross value added at current services prices, excluding public administration,

defence, education, health, and social security (thousand reais) between 2017 and 2012. The data did not go through any preparation. The purpose was to indicate whether the Gross Domestic Product of the municipalities, referring to the services sector, experienced an increase or a decrease between the initial year of drought (2012) and the year of more intense drought (2017). Thus, this criterion can demonstrate whether, with the advent of drought, the service sector is vulnerable or not to the effects of water shortage since trade is an activity of great contribution to the GDP of the municipalities under analysis.

Finally, for C9—Irrigated agriculture, the data was obtained through a spreadsheet that indicates the percentage of agricultural establishments with declared use of irrigation in relation to the total number of agricultural establishments in the municipality. The data did not undergo any kind of preparation. The purpose was to indicate the percentage of agricultural establishments with an irrigation system to deal with the effects of water scarcity in their agricultural activities in relation to the total number of establishments in the municipality. The criterion thus makes it possible to identify whether a large or small part of the rural producers has an irrigation system that can be used to provide water in a situation of water scarcity.

GIS based VIKOR approach

Based on the defined criteria (indicators), the third step is mapping vulnerability to water scarcity using the GIS-based VIKOR approach. This approach considers a holistic perspective to analyze vulnerability to water scarcity as a tool to improve decision-making in arid and semiarid. The multicriteria method VIKOR was chosen for this study for its popularity in providing nearly accurate results and the simplicity of the algorithms (Chatterjee & Chakraborty, 2016). The VIKOR has large usability in evaluating and supporting analyses with conflicting and non-commensurable (different units) criteria (Lee & Chang, 2018). The GIS-based multicriteria approach begins with defining the weights of pre-defined indicators and concludes with classifying municipalities in a performance index spatialized to the region under study.

Among the different procedures to determine the weights of the criteria, the most common are the subjective and objective methods (Şahin, 2021).

Subjective methods use only the subjective evaluations of decision-makers to obtain the indicator weights. Furthermore, objectives use mathematical models and data without considering decision-makers preferences. Scholten et al. (2015) posited that uncertainty in attribute weights could result from inaccurate quantitative evaluations, then the weighting methods have been discussed for years (Sahin, 2021; Odu, 2019; Vujicik et al., 2017). Thus, potential uncertainties can be minimized by considering different weighting methods.

To this spatial multicriteria approach, we evaluate three weighting techniques justified and chosen in their applicability and ease of operation: the subjective simplified AHP weighting method proposed by Dortaj et al. (2020) and two objective methods, the Shannon Entropy (Shannon, 1951) and the CRITIC method (Diakoulac et al., 1995). The objective is to reveal the differences between subjective and objective methods and their influences on spatial multicriteria analysis in general.

Simplified AHP

In the simplified AHP method proposed by Dortaj et al. (2020), after defining multiple criteria, ten experts are invited to give their opinion on the weight of each criterion through a questionnaire based on the Saaty scale (1 to 9) (Saaty, 1982). In this method, the number 1 is assigned to the least essential criterion and 9 to the most crucial criterion.

Different relative weight calculation methods such as least squares, logarithmic least squares, eigenvector, and approximation methods can be implemented. So, in this work, the approximation method that applies the geometric mean was used to define the weight ratio. The geometric mean of each row of importance, related to experts, is used as the final weight of the criteria, and the pairwise comparison matrix is constructed.

Shannon entropy

Shannon entropy, derived from information theory, is a mathematical method for defining uncertainties in numerical data ta king into account all types

of information and thus quantifying the information flowing in the data (Shannon, 1951).

Similar to the applications of multicriteria analysis based on objective weighting methods of the criteria by Kun et al. (2018) and Dhanaraj and Angadi (2020), the present study uses Shannon's entropy as an objective approach to determining the criteria weights.

The calculation of Shannon entropy weights, according to Lotfi and Fallahnejad (2010), is presented below:

From a multicriteria approach, assuming municipalities as alternatives $m(A_1, A_2, \ldots, A_m)$ and n as WSV criteria $(C_1, C_2, \ldots, C_m)$, the initial matrix is;

$$\begin{bmatrix} a_{11} & a_{12} & \ldots & a_{1n} \\ a_{21} & a_{22} & \ldots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \ldots & a_{mn} \end{bmatrix} = [a_{ij}]_{mxn}$$

where your components a_{ij} denote i th city of the j th criterion.

Stage 1: Normalize the decision matrix

$$r_{ij} = \frac{a_{ij}}{\sum_{i=1}^{m} a_{ij}}, i = 1, 2, \ldots, m \tag{1}$$

Stage 2: Calculate entropy

$$e_j = -K \sum_{i=1}^{m} r_{ij} \ln r_{ij}, j = 1, 2, \ldots, n \tag{2}$$

where: $K = 1/\ln m$

Stage 3: Calculate the weights of each criterion

$$w_{ij} = \frac{1 - e_j}{\sum_{i=1}^{n} (1 - e_j)}, j = 1, 2, \ldots, n. \tag{3}$$

CRITIC

The CRITIC method, developed by Diakoulaki et al. (1995), belongs to the class of correlation methods applicable to multicriteria models. The method is based on test analysis of the decision matrix and aims to determine the information contained in the criteria by which the variants are evaluated. For each criterion xij, the membership function rij, which translates all values of the criteria fj in the interval [0, 1], is defined.

$$r_{ij} = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}} \tag{4}$$

The transformation is based on the concept of an ideal point. In this way, the initial matrix is converted into a matrix with generic elements *rij*.

Each vector has a standard deviation, which represents the degree to which the varying values for a given criterion deviate from a mean value. The amount of the information *Cj* contained in criterion *j* is determined as follows:

$$Cj = \sigma_j \sum_{i=1}^{m} (1 - r_{ij}) \tag{5}$$

The objective weights of the criteria are obtained by normalizing the *Cj* values:

$$w_{ij} = \frac{Cj}{\sum_{i=1}^{m} Ci} \tag{6}$$

VIKOR-GIS approach

Based on the criteria weights, the VIKOR multicriteria method is used to develop a ranking index combined with a GIS for mapping vulnerability to water scarcity. The VIKOR model is based on an aggregation function of proximity to the ideal, and its principle comes from the commitment programming method (Opricovic & Tzeng, 2007). The method represents the distance from the ideal solution, considering the relative importance of all criteria and a balance between total and individual satisfaction.

Based on a set of contradictory criteria present, the use of the VIKOR algorithm aims to classify the vulnerability of municipalities, as an output result, through four steps:

Step 1: Determine the largest f_i^* and smallest's f_i^- of the entire function, $i = 1, 2, \ldots, n$.

$$f_i^* = max_j f_{ij} \tag{7}$$

$$f_i^- = min_j f_{ij} \tag{8}$$

where: f_i^*: maximum value presented by indicator i by the set of municipalities; f_i^- : minimum value presented by indicator i r by the set of municipalities; and f_{ij}: the value of indicator i attributed to municipality j.

Step 2: Calculate the values S_j (is the maximum utility group) and R_j (is the minimum individual weight), $j = 1, 2, \ldots, n.$, in the relations, where w_i are the weights of the criteria obtained by the method of Shannon's entropy.

$$S_J = \frac{\sum_{i=1}^{n} w_i \left(f_i^* - f_{ij} \right)}{\left(f_i^* - f_i^- \right)} \qquad (9)$$

$$R_j = max_j \left[\frac{w_i \left(f_i^* - f_{ij} \right)}{\left(f_i^* - f_i^- \right)} \right] \qquad (10)$$

where: w_i: strategic weight (usually v = 0.5); f_i^*: maximum value presented by indicator i attributed by the set of municipalities; s f_{ij}: the value of indicator i assigned to municipality j; f_i^- : minimum value presented by indicator i by the set of municipalities.

Step 3: Calculate the values, Q_j $j = 1, 2, \ldots, j$, by the ratio, where $S^* = min_j S_j$, is entered $S^- = max_j S_j$ and $R^* = min_j R_j$, $R^- = max_j R_j$, the value of v is regularly conceived as $v = 0,5$.

$$Q_J = \frac{v \left(S_j - S^* \right)}{\left(S^- - S^* \right)} + \frac{(1 - v) \left(R_j - R^* \right)}{\left(R^- - R^* \right)} \qquad (11)$$

where: v: 0,5; Q_J: final score for municipality j; S^* : minimum group of maximum utility of the set of municipalities; S^- : maximum group of maximum utility of the set of municipalities; R_J : minimum individual weight; R^* : lowest minimum individual weight; R^-: and greater minimum individual weight.

Step 4: In the final step, the VIKOR method is combined with a GIS to specialize the Q_J values obtained for the municipalities in the study area. For that, we used ArcGIS Desktop, version 10.5.

Sensitivity analysis

As the fourth step of this vulnerability mapping approach, following Tscheikner-Gratl et al., (2017), it is suggested to carry out a sensitivity analysis as crucial to analyse the impact of criteria weights on the classifications of the multicriteria model. The results of MCDM classifications depend on the criteria nature used and especially on the distribution of weights among the criteria. It should also be taken into account that the criteria weights are usually established based on professional perception, which may be subjective in some cases and may vary according to each expert. Therefore, the effect of a possible deviation from the weight value should be evaluated. So, as in the applications by Shirvan et al. (2017), Lee and Chang (2018), Kaya et al. (2020), the sensitivity analysis was performed based on the gradual change in the percentages of the indicators in order to analyse the robustness of the model's results.

Results

The results are presented in four sections: (i) Mapping of factors that influence vulnerability to water scarcity; (ii) Determination and comparison of weights; (iii) Mapping and comparing WSV; (iv) Sensitivity analysis of classification results.

Mapping WSV influencing criteria

The influence criteria were spatialized in a GIS environment to map the WSV in the study areas. The classification method to delimit the legend is based on equal intervals, and the indicators were arranged in flags according to the colour scales presented. Classifying in equal intervals is due to the advantage of being a method of easy applicability, having a simple calculation methodology and being easily understandable, as pointed out by Slocum et al. (2014). Maps have negative limits on red flags and positive limits on blue flags. Figures 2 and 3 are the nine criteria for the MSF—transposition water donor region and the PRB—water receiving part.

The Water security (C1) spatialization showed high and maximum values (green and blue flags) for the municipalities in the east of the MSF and low performance (orange flag) for the municipalities in the west of the same region. PRB presented predominantly orange flag water security values for all municipalities. So, even though the MSF is a transposition water donor region, more than 30% of the municipalities have low water security, just like the municipalities in the receiving basin (Fig. 4).

The spatialized performance for C2, which represents the recognition of ES and SCP by drought in the analysis period, represents the historical recurrence of drought events in both regions. In the MSF, more
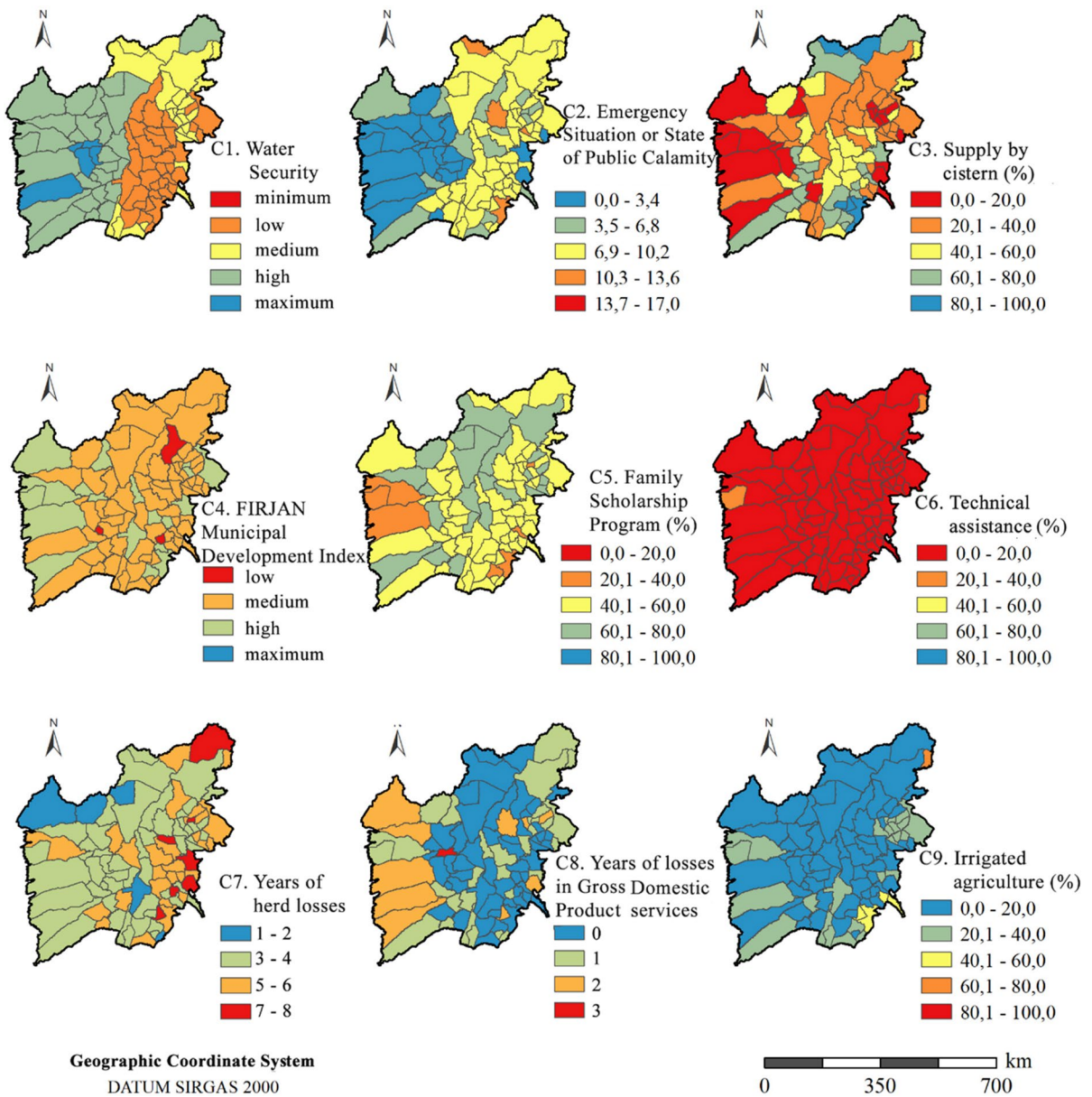
Fig. 3 Indicators/Criteria of vulnerability to water scarcity for the Middle-São Francisco region. *Source*: Elaborated from ANA (2019a, 2109b) e IBGE (2019)

than 50% of the municipalities presented the yellow flag with recognition of SE and ECP from 6.9 to 10.2 times in the period. In the PRB, more than 70% of the municipalities took the orange flag, with the declaration in 10.3 to 13.6 times. As a case of extreme recurrence at PRB, the municipality of Queimadas-PB presented a red flag with 17 SE and ECP advertisements due to drought and drought.

The percentage of establishments with cisterns (C3) indicates lower values for the MSF and higher for the PRB, representing a greater adaptive capacity to water scarcity for the region receiving transposition waters. The IFDM (C4) was not high for any of the municipalities representing a low performance in employment, income, health, and education, which
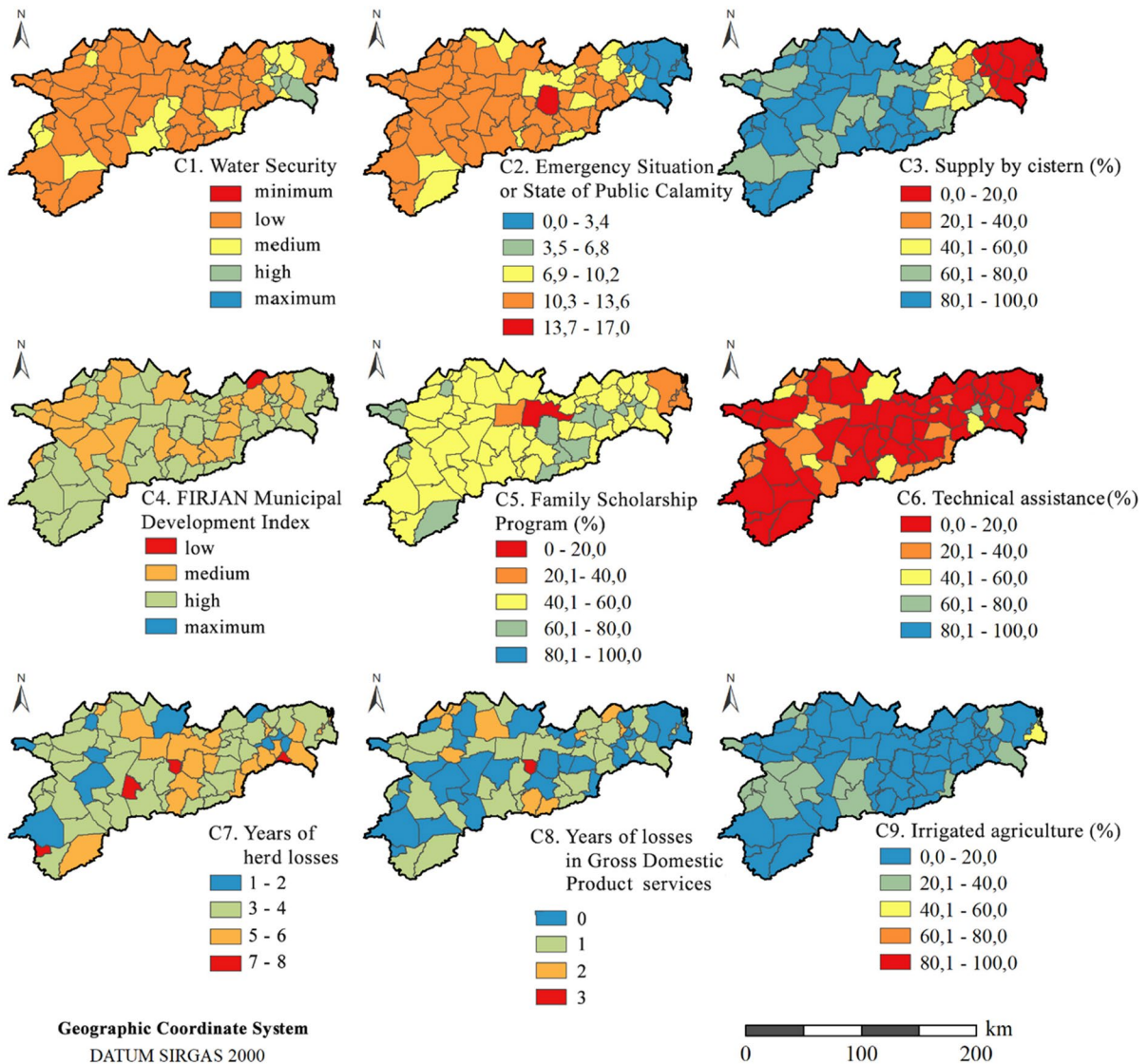
Fig. 4 Indicators/Criteria of vulnerability to water scarcity for the Paraíba River Basin. *Source*: Elaborated from ANA (2020, 2019a, 2019b), S2iD (2020), IBGE (2019, 2021), Firjan (2020)

may imply difficulties related to rational, modern and sustainable water use.

The performance related to the percentage of families that receive from the PBF social program (C5) indicates that the MSF donor region has a more significant fraction of municipalities under the green flag than the PRB. This condition favours the performance of low-income families during drought events. The municipality of Campina Grande, in the PRB, presented a red flag, which may represent a

delay in meeting the program and a risk to the adaptive capacity of lower-income families.

The C6, corresponding to the percentage of agricultural establishments with a declaration of technical assistance, demonstrates a critical situation for the two regions under study. It is noted that, for the MSF, practically all municipalities have less than 20% of agricultural establishments with technical support that allows them to adapt, among other issues, to the recurrent droughts in the region.

The years of heard losses (C7) reflect the occurrence of droughts that historically decimated populations and cattle herds in the Brazilian semiarid region. The west axis of the MSF municipalities concentrates the municipalities with the highest occurrence of losses. There were 7 to 8 years of herd losses in 7 municipalities, while in PRB, there was the same period of casualties in 4 municipalities.

As for the annual losses related to the GDP of Services (C8), representing the number of years in which there was a reduction in GDP compared to the previous year, the eastern region of the PRB stood out as a region with a possible decline in the source of income production coming from the trades, which can also be a risk factor for adaptive capacity to events of water scarcity.

The last indicator (C9), representing agricultural establishments that use irrigation, presented extreme minimum values for both study areas. The results show that the municipalities of MSF and PRB have less than 40% of agricultural establishments with irrigable crops, except for the capital of the State of Paraíba, João Pessoa, and other five municipalities in the east of the MSF.

Determination and comparison of weights

The most crucial step in multicriteria analysis is the weighting of criteria, as it is possible to aggregate the criteria into a single performance value from the weights. In this study, the simplified AHP, Shannon entropy, and CRITIC methods were used and compared to weight the attributes of the multicriteria analysis of WSV.

To apply the simplified AHP, a questionnaire survey was distributed to ten experts, as in Dortaj et al. (2020). In this case, PhD professors with experience in SFRB water management and planning were invited to give their opinions about the weight of each criterion through a Saaty scale (1 to 9) questionnaire. The experts signed number 1 to indicate minimal importance to criterion, and 9 for maximum importance, with the other proportional values. As shown in Table 3, the geometric mean method is used to calculate (aggregation) the score of different expert opinions and provide a single value for each criterion. Based on the experts' assessment, it is possible to calculate the weights of the factors in this subjective analysis.

The mathematical procedures (Eq. (1) to Eq. (6)) were applied for the Shannon and CRITIC objective entropy weighting methods. Overall weights can

Table 3 Suggested weights for the different criteria of vulnerability to water scarcity obtained by 10 experts and geometric mean

Criteria		Weights suggested by 10 experts										Goemetric mean
		Nº1	Nº2	Nº3	Nº4	Nº5	Nº6	Nº7	Nº8	Nº9	Nº10	
C1	Water Security	9	9	9	9	7	9	6	9	7	8	8,122
C2	ES or SPC	5	8	7	9	7	6	7	9	6	8	7088
C3	Supply by cistern (%)	7	8	6	8	4	8	9	8	6	7	6943
C4	IFDM	9	7	8	5	5	7	7	5	5	5	6148
C5	PBF (%)	5	5	2	5	4	9	5	5	3	6	4579
C6	Technical assistance (%)	9	7	5	4	7	7	7	6	5	8	6333
C7	Years of heard losses	7	5	3	6	3	7	7	3	4	7	4888
C8	Losses in GDP services	7	6	1	6	6	7	5	7	4	6	4953
C9	Irrigated agriculture (%)	7	9	4	8	4	7	9	7	4	8	6392

Table 4 Weights of simplified AHP, Shannon entropy and CRITIC methods

Method	C1	C2	C3	C4	C5	C6	C7	C8	C9
Simplified AHP	0,1465	0,1278	0,1252	0,1109	0,0826	0,1142	0,0882	0,0893	0,1153
Entropy	0,1211	0,1161	0,1158	0,1223	0,1217	0,1058	0,0916	0,1209	0,0847
CRITIC	0,1143	0,1301	0,1700	0,0828	0,0919	0,0967	0,1356	0,0967	0,0820

Table 5 Spearman correlation coefficients for weighting methods

	Simplified AHP	Shannon entropy	CRITIC
Simplified AHP	1,000	−0,1417	0,2917
Shannon entropy		1,000	−0,1333
CRITIC			1,000

establish a basis for establishing a suitable model for mapping indicators related to water scarcity. The criteria weights provided by the three methods are shown in Table 4, and Spearman's correlation coefficients in Table 5.

As seen in Table 4, the results of the three methods differ, even though the Entropy and CRITIC methods are based on the same principle of calculation objectivity. The Simplified AHP results indicate that the most crucial criterion is Water security, followed by ES and SPC recognition for drought and Supply by cisterns. According to the entropy results, the IFDM is the most significant criterion, followed by the number of PBF beneficiary families and Years with herd losses. Furthermore, for the CRITIC method, the most crucial attribute is the Supply by cisterns, followed by Years of herd losses and SE and ECP Recognitions for Drought and Drought. The Spearman correlation results presented in Table 5 indicate that the correlations between the weighting methods are weak.

Mapping Water Scarcity Vulnerability

Based on the GIS-based multicriteria approaches presented by Roodposhti et al. (2016), Ding et al. (2018) and Vanolya and Niaraki (2021), the WSV maps are presented in Fig. 5. Using the weights for the indicators (Table 4), the vulnerability values were aggregated into a performance index by VIKOR, which can range from 0 to 1. The highest vulnerability values refer to the greater probability of occurrence of water scarcity in the counties. The classification is according to five classes, according to the natural breakdown method (Jenks): very low, low, medium, high, and very high vulnerability.

Analysing the mapping WSV in Fig. 5, it is noted that there is no uniformity of vulnerability to water scarcity related to the geographic location in both

regions. The results indicate that the conditions of the vulnerability of the municipalities of the MSF—donor region of transposition waters are as critical (or worse) than the conditions of the PRB–recipient municipalities.

From the multicriteria spatial approach applied to the case study, it is possible to guarantee that the classification results provided by the VIKOR method in a GIS environment vary according to the choice of the weighting method. This divergence is due to the weighting methods processing the calculations in different ways, and the VIKOR algorithm procedures try to scale the objectives that affect the weights already chosen (Zanakis et al., 1998; Pehlivan et al., 2018).

In the Simplified AHP-VIKOR (Fig. 5a) and Entropy-VIKOR (Fig. 5b) methods, municipalities with moderate and high vulnerability are predominately in the eastern part of the MSF. In contrast, high vulnerability occurs in the north of the PRB. The Simplified AHP-VIKOR showed two municipalities with very high vulnerability to water scarcity: Sobradinho and São Domingos do Cariri, while the Entropy-VIKOR represented the municipalities of Itaguaçu da Bahia and, similarly, São Domingos do Cariri.

Comparing the CRITIC-VIKOR (Fig. 5c) to the Entropy-VIKOR, 17 municipalities regressed from high to moderate vulnerability, and seven municipalities worsened from moderate to high classification. In its general aspect, the third combination presented an attenuation in the vulnerability classification of the municipalities. Spearman's correlation coefficients for the results of the three combinations were calculated and are shown in Table 6.

In summary, higher results for the correlation coefficient represent a stronger correlation between models. The correlation coefficients between the weights of the weighting methods showed a weak correlation (Table 5). However, the combinations of these and VIKOR (Table 6) performed better. The correlation between the combined Simplified AHP-VIKOR method and the Entropy-VIKOR showed the highest Spearman's coefficient, even though the comparison is subjective and objective weighting methods.

Fig. 5 Mapping of water scarcity in the Middle São Francisco Region—Donor Region and the Paraíba river Hydrographic Basin— receiving region, by the combination of methods: **a** Simplified AHP-VIKOR **b** Entropy-VIKOR; **c** CRITIC-VIKOR
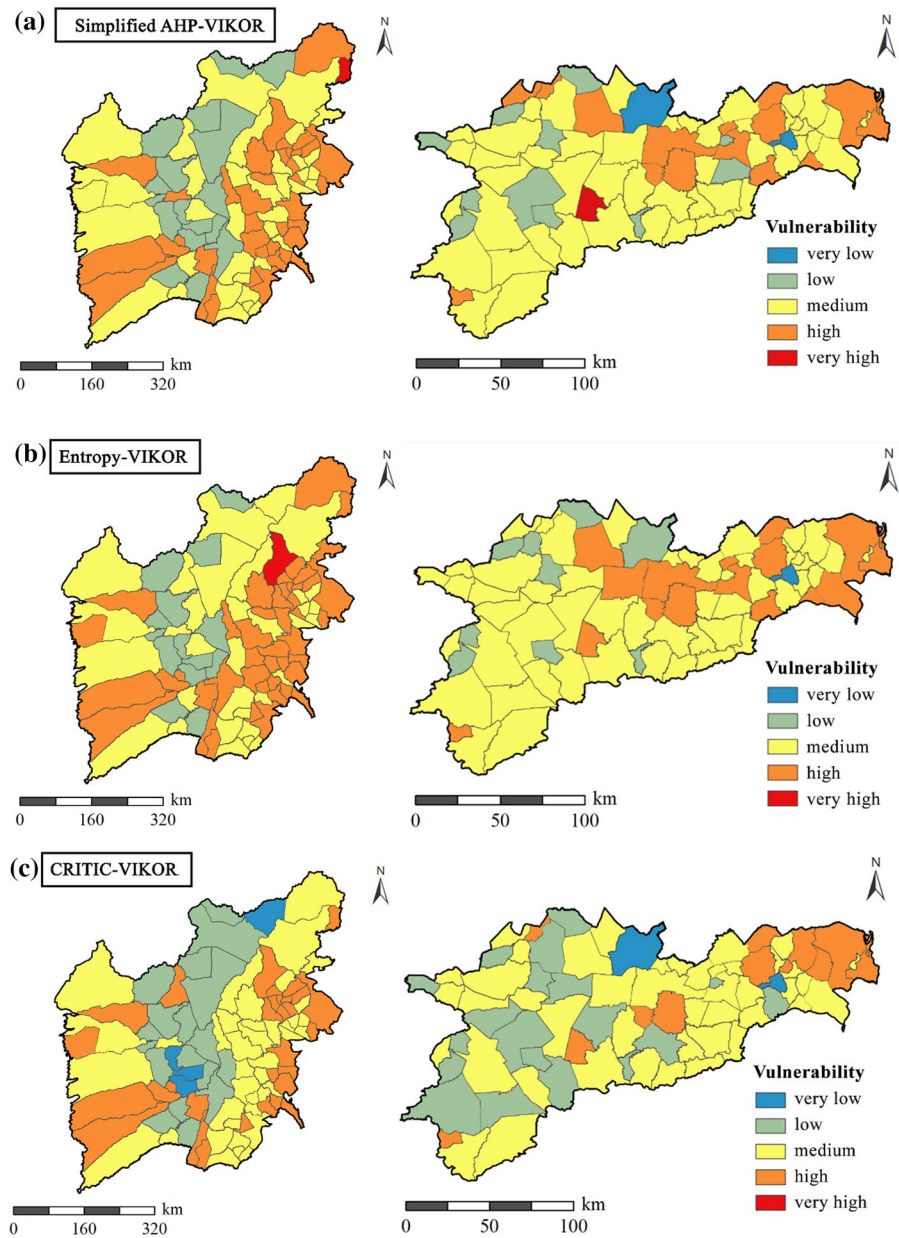

Table 6 Spearman correlation coefficients for the VIKOR classification under different weighting methods

Combine methods	Simplified AHP- VIKOR	Shannon Entropy-VIKOR	CRITIC-VIKOR
Simplified AHP-VIKOR	1,000	0,933*	0,822*
Shannon Entropy-VIKOR		1,000	0,825*
CRITIC-VIKOR			1,000

*The correlation is significant at the 0.05 level (two-tailed)

Table 7 Ranking changes in criteria adjustment

Methods combined	Changed classifications fraction											
	< 0,3	[0,3;0,7]	> 0,7	< 0,3	[0,3;0,7]	> 0,7	< 0,3	[0,3;0,7]	> 0,7	< 0,3	[0,3;0,7]	> 0,7
	Change in criterion weight											
	− 5%			5%			− 50%			50%		
	Number of criteria that changed classification											
Simplified AHP- VIKOR	9	0	0	9	0	0	5	4	0	4	4	0
Entropy-VIKOR	9	0	0	8	1	0	6	3	0	1	7	0
CRITIC-VIKOR	9	0	0	9	0	0	6	2	1	4	5	0

Sensitivity analysis

A sensitivity analysis was performed to quantify the level of crosstalk between criteria and classification, revealing how the results changes due to varying weights of the criteria. In this paper, two types of sensitivity analysis were conducted based on the sensitivity analysis methodology applied by Mulliner et al. (2016) and Lee and Chang (2018).

First, changes in classifications of municipalities were evaluated using a sensitivity coefficient. In this case, the coefficient represents the fraction of municipalities that changed the ranking by adjusting the criterion to increase or decrease by 5% or 50%. The criteria are evaluated individually, so when the weight of one criterion increases or decreases, the other criteria are adjusted accordingly. Table 7 presents the percentage range of changes in the classifications of the municipalities, the adjustment factor in each criteria weight, and the number of criteria that performed the changes in the classifications.
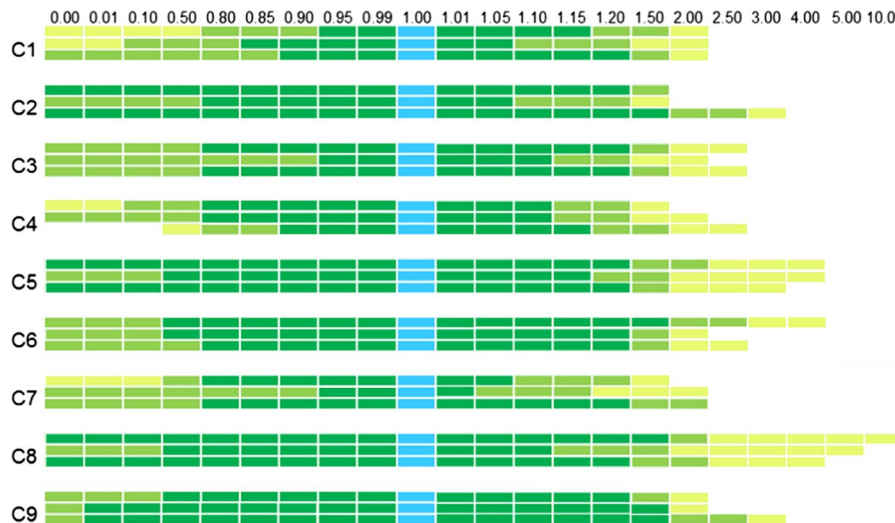

Fig. 6 Sensitivity of the VIKOR-weighting method combination. The graph represents the sensitivity analysis results, showing how changing the criterion weight affects the vulnerability ranking. Dark green rectangles indicate tolerable criterion weight change of up to 10% of municipalities, for which the alternative classification is not very sensitive. In comparison, light green rectangles represent the range contributing up to 30% of changes, and yellow ones for up to 70% of changes. In principle, the length of the horizontal bar indicates the sensitivity of the criteria to change, so the shorter the bar, the greater the sensitivity level. The results for three combinations in each criterion panel are displayed in the following order: Simplified AHP-VIKOR (top), Entropy-VIKOR, and CRITIC-VIKOR (bottom)

Subsequently, the analysis was performed for a gradual adjustment of the weights of the criteria, shown in Fig. 6. Each criterion was analysed using the combinations of simplified AHP-VIKOR, Entropy-VIKOR, and CRITIC-VIKOR.

The comparative analysis of the distribution of the sensitivity coefficients (Table 7) revealed that the simulated 5% change in criterion weight (increase and decrease) had no significant influence on the simplified AHP-VIKOR and the CRITIC-VIKOR. However, it did have a criterion with that order changes in Entropy-VIKOR. Ratings were also less affected based on the simulated 50% change in Simplified AHP-VIKOR and CRITIC-VIKOR.

Figure 6 shows that all criteria demonstrate sensitivity to variations in weights. That is, the percentage change in all of them can affect rankings. Criteria C2, C5, and C8 were the most robust for the three methods combined, with the smallest range of classifications. The results also reveal that C1, C3, C4, and C7 have the highest sensitivity. In this sense, possible changes in the weights of these criteria represent the most significant influence on classification changes.

Discussions

The analysis shows the importance of WSV mapping since the fragilities are not uniformly distributed, even if in the same administrative units (regions and watersheds). The results show that mapping WSV factors in river basin regions from a holistic perspective, not only hydroclimatic, in other words, with integrated social, economic and environmental aspects, can be important for decision-makers in the various spheres of society not only for agencies responsible for Water Management. The approach allowed for a deeper understanding of comparing conditions of municipalities in transposing water regions (donor and recipient) and the factors that drive most water scarcity management.

Vulnerability factors and WSV maps generated by municipal boundaries can be important for all spheres of planning in Brazil, especially for municipalities and government actions with more local applicability, particularizing the causes of conditions and underpinning implementations of measures by priority zones. Most studies were assessing vulnerabilities related to water scarcity focus on distribution systems within

the boundaries of a municipality (Chung et al., 2014; Cordão et al., 2020; Tsegaye et al., 2020) or on the basin approach in climate aspects (Chung et al., 2016; Spiliotis et al., 2019; Mokarram et al., 2021). Few works analyze vulnerability to scarcity concerning socioeconomic spatial aspects and its importance in water management and decision-making.

To compare the results of this study with the previous results, some studies are considered. The vulnerability scarcity classifications are consistent with the analysis by Marengo et al. (2020), Bezerra et al. (2019) and Silva et al (2021). They have identified that the last multi-year drought (2012–2018) affected the Northeast and the integrated São Francisco River basin regions (for example, the MSF and PRB) with significant impacts. The GIS-VIKOR classifications of vulnerability to water scarcity with "High" categorization, predominantly in the eastern municipalities of the MSF – donor region, and the PRB – recipient region, converge with the analyses of the cited authors and with Brito et al. (2021), that drought prevention actions in Brazil focus on the construction of large and expensive water infrastructure works, despite the adaptive capacity to drought coming from the socio-economic development of the population in the semi-arid region.

The methodology presented can subsidize the decision-making of public policies related to supporting the combat of inequalities in water supply in water regions and guide the management of the areas most susceptible to water scarcity. The vulnerability mapping methodology can be a dynamic tool, fed with data and complemented with operational data, to foster a framework plan for municipalities. Based on the argument of spatial inequality, the results of this study can help planners and decision-makers to develop activities and goals for planning, territorial development, and implementation of actions and measures aimed at mitigating the impacts of various types of water scarcity.

Unlike most studies that develop a spatial multicriteria approach by only a single weighting technique (Achu et al., 2020; Cordão et al., 2020; Ding et al., 2018; Hasan & Rai, 2020), the WSV rankings based on the three weighting methods showed differences between the final maps. The results of the weighting methods in the GIS-MCDA approach contribute to the literature by presenting a perspective that uses different methods added to the VIKOR multicriteria

model, including objective and subjective weighting. As stated by Chung et al. (2016), who obtained a rank correlation estimate of 0.80 between subjective and objective methods, and further that the present study showed a correlation of 0.93 between Shannon Entropy-VIKOR and Simplified AHP-VIKOR approach, considering different weighting methods is important for reliably assessing water resource vulnerability, and similarly for GIS-MCDA analyses in general.

Analyses with little or no information are a critical problem in studies with spatial data. The small number of criteria and the uncertainty surrounding subjective weightings can be considered limitations of this study. Other criteria, such as water quality and households supplied by Water Supply System, could be included and would improve the suitability of the assessment. A clear meeting with all related parties in a full discussion, from choosing criteria to weighting, could make the analysis more consistent and comprehensive. This study considers stakeholder opinions (subjective process) and data analysis (objective process) for robust decision-making processes. However, the proposed approach does not necessarily need the methods used to be implemented oppositionally, as described in this study. Instead, they can be combined to be part of the decision process.

Conclusions and recommendations

Water scarcity is a risk with environmental, social, and economic implications, and it is necessary to develop adequate approaches to assess the vulnerability of municipalities to drought events. To develop a reasonable model approach, this study considered a donor and recipient region of the integrated São Francisco River basin, in Brazil, as an example of application. The article proposed a GIS-based multicriteria VIKOR approach, proving to apply to the analysis of vulnerability to water scarcity and possible to group beneficial and non-beneficial assessment criteria based on the multiple aspects of the problem. However, it was emphasized that the variation in the choice of weighting method could produce different classification results; thus, we evaluated the changes in a spatialized study unprecedentedly.

In this sense, were evaluated the weighting methods—simplified AHP, Shannon Entropy, and

CRITIC—combined with the VIKOR GIS-based model in a comparative study. Nine influence factors were used based on ease of application and calculation, relevance to the local level, the existence of available data; contribution to the achievement of the SDG goals; and contemporaneity of the data. The criteria were first spatialized, then subjectively and objectively weighted, and finally aggregated to vulnerability maps to consider their applicability to aid in water resources management and identify differences and similarities in the mapping results.

In the spatial multicriteria approach presented, it was possible to assay the current conditions of WSV in the studied regions. The mapping of risk conditions in the MSF region, as a case study of a transposition water donor region, compared to PRB, a transposition water recipient, allows us to verify that the conditions of municipalities in donor regions can be as critical as those of municipalities recipients. In this sense, we suggest that management actions in Brazil should not be exclusively focused on the construction of large and expensive water infrastructure works as an example of transposition, but that better management should be done through a plan to cope with drought for solutions rational, modern and sustainable.

The comparative analysis of weighting methods revealed a low correlation between the criteria weights, but their applications in the VIKOR model represented more significant agreement. When choosing the weighting method, we suggest that, whenever possible, more than one method is used, making the assessment more complete. Furthermore, preferably the implementation of the simplified AHP is carried out, as it is simpler and accesses experts' opinions with less risk of misinterpretation by the decision-maker.

As a guideline for future research, the spatial multicriteria approach can be proposed as a framework plan (classification) of river basin districts and available in a web environment. In addition, future scenarios can be evaluated and made available to the general public based on projections of water demand growth and economic development. New studies can address water security by using modern, decentralized, and sustainable practices to supplement conventional water supply. In this way, rainwater harvesting, water reuse, and water-saving mechanisms can be evaluated as indicators

(influence factors). For future research on the evaluation of weighting methods in spatial multicriteria approaches, the traditional AHP method proposed by Saaty (1982), based on the set of paired comparison matrices, could be compared to the simplified AHP and other objective weighting methods (standard deviation, mean weight, among others), as well the influence of the variation of the multicriteria model used (VIKOR) on the WSV maps.

Declarations

Conflict of interest The corresponding author declares that he is responsible for providing all information on behalf of all authors.

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