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# A TOPSIS-Based Multicriteria Approach for Reservoir Assessment

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**Abstract**

Abstract Water management in the Brazilian semi-arid region has been, for decades, a challenge for institutions and decision-makers due to its intrinsic characteristics. The density of human occupation makes the region very vulnerable to drought events and problems related to the quality and need for water use are central issues. For this reason, this study presents an approach to assess the situation of water reservoirs in the semiarid based on the Water Quality Index (WQI) and Multi-Criteria Decision Making (MCDM). The WQI was used to calculate water quality and later applied as a criterion for the MCDM model proposed. The model also considers the need and availability criteria to assess the reservoirs of the two largest drainage basins in Rio Grande do Norte state, Brazil. The MCDM method used was R-TOPSIS since it is more flexible and robust for future analyses in other situations. The results showed the condition of the reservoirs, in order to support decision-makers in the operation of these facilities and enable multiple use of the waters. The combined approach proposed may provide important contributions in the analysis of water reservoirs in order to supply the semiarid region, where water issue is critical.



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## INTRODUCTION

Water is a precious natural resource, given its importance in sustaining life, but its scarcity is one of the most serious problems in the world today (Banihabib; Shabestari, 2017). According to Al-Abadi (2017), the water demand has increased so rapidly in recent years that many parts of the world are facing shortages. The World Economic Forum's Global Risk Report of 2018 cites the water crisis as a global risk, that is, an event or uncertain condition that should it occur, could have a significant negative impact on several countries or sectors in the next 10 years (WEF, 2018).

In arid or semiarid regions, the situation is even more alarming, since water resources are not readily accessible and highly vulnerable (Saadatpour, 2020). With the constant growth in urban areas, the cities in these regions are increasingly faced with water management related problems (Haak; Pagilla, 2020).

In Brazil, the water supply in semiarid regions depends in large part on surface water accumulated in reservoirs, which are artificial ecosystems essential for the social and economic development of the region (Azevêdo *et al*., 2018). Reservoirs, one of the main mechanisms to deal with the variable water supply and demand (Deng *et al*., 2020), are considered a major priority of the global political agenda (Saadatpour, 2020).

However, according to a study coordinated by Agência Nacional de Águas (ANA - Federal agency responsible for the implementation of Brazilian water resources management) on the situation of 204 reservoirs in the Brazilian semiarid, only 85 were able to meet the new demands, while 119 were at the limit of their storage capacities (ANA, 2017). According to the same study, water management in the semiarid over the decades has been a challenge to institutions and decision-makers due to the intrinsic climatic conditions and increasing human occupation density, which has made the region vulnerable to drought.

In addition to the lack of available water in the region, there is also a problem with its quality. The rural communities that live near these reservoirs generally use the water directly without any filtering before consumption (Azevêdo *et al*., 2018). However, in any part of the world, it is essential to take into account the acceptable water quality to ensure healthy and diverse aquatic ecosystems (Singh *et al*., 2015), especially since only about 1% of the world's freshwater is accessible for direct human use (Yan *et al*., 2017).

Thus, knowing that water quality plays a vital role in all aspects of human and ecosystem survival, assessing its quality parameters is indispensable for planning and developing better water resource management (Walker *et al*., 2015; Roy *et al*., 2017). In this respect, although a few studies showed that the main indicators used by communities to assess water quality are color and odor (West *et al*., 2016), a concise, convenient, and easy to understand way is to use the Water Quality Index (WQI) (Sutadian *et al*., 2017; Mladenović-Ranisavljević *et al*. 2018).

Roy *et al*. (2017) explain that in practice, compound indicators involving different measuring methods, such as the WQI, are often used because a single measure likely will not provide a true representation of the state of the resource. The authors concluded that it became quite popular due to its ease of calculation and interpretation.

Although this process has been widely applied in the last four decades, there have been uncertainties that are not considered in the traditional assessment of water quality (Singh *et al*., 2015), since these methods often produce inaccurate information (Abbasi; Abbasi, 2012).

In order to eliminate these uncertainties, several authors started using Multi-Criteria Decision-Making (MCDM) methods such as Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), a more reliable approach in this process (Banihabib; Shabestari, 2017).

Li *et al*. (2012), for example, applied a model in conjunction with the TOPSIS method to assess groundwater quality in a semiarid area of China. Bozdağ (2015) combined AHP with GIS to evaluate irrigation water quality in a district of Central Anatolia, Turkey. Singh *et al*. (2015) used Fuzzy-AHP to assess the water quality of the Yamuna River in India. Finally, Yan *et al*. (2017) proposed a model based on AHP, KLDR and CWI to evaluate the quality of drinking water in Shanghai.

Additionally, some authors combined MCDM with the WQI. Some examples include Walker *et al*. (2015) and Mladenović-Ranisavljević *et al*. (2018), who analyzed the water quality of the Danube River in Serbia, Sutadian *et al*. (2017), who analyzed rivers in West Java, Indonesia, and Roy *et al*. (2017), who analyzed the waters of Tripura, India.

However, the approaches proposed until then used the MCDM methods to help obtain the weights of water quality parameters or as a way of ranking/visualizing the results of analyses obtained with water quality indices, such as the WQI.

The present study aimed to expand previous investigations, proposing a multicriteria analysis model of the situation of reservoirs that considers not only water quality, using the WQI, but also the need and availability criteria, important aspects for the semiarid. A case study of 13 reservoirs in the two largest drainage basins of Rio Grande do Norte state, Brazil was used to validate the model.

Moreover, the proposed model is based on the MCDM R-TOPSIS method (Aires; Ferreira, 2019), an extension of TOPSIS (Hwang; Yoon, 1981), which is immune to rank reversal, a phenomenon that affects the MCDM techniques (see Aires and Ferreira (2018)). This method produces robust results, can be replicated and has the dynamicity required for the context analyzed, where new reservoirs can be subsequently included in the analysis.

## METHOD

### *WQI Method*

Numerous water quality indices have been formulated worldwide, but most were based on the WQI developed by the National Sanitation Foundation (NSF). This index was developed in 1970 by Brown *et al.* (1970) in order to produce a standardized method to compare the water quality of various sources based on nine parameters (Şener *et al.*, 2017). Temperature, pH, dissolved oxygen, turbidity, fecal coliform, biochemical oxygen demand, total phosphates, nitrates and total solids are analyzed (Şener *et al.*, 2017; Yaseen *et al.*, 2018; Bansal; Ganesan, 2019), resulting in values between 0 and 100 (Wills; Irvine, 1996). The calculation is made according to Equation 1.

$$WQI = \sum_{i=1}^{9} q_i \; x \; W_i \qquad (1)$$

in which, WQI is the water quality index, represented by a number on a continuous scale of 0 to 100; qi individual quality (sub-index of quality) of the nth parameter, between 0 and 100; and Wi the unit weight of the nth parameter.

The weights of parameters are in line with the values presented in Table 1 (Brown *et al.*, 1970). Based on the calculation, the range of values is presented in Table 2, the higher the WQI, the better the water quality.

**Table 1** - NSF WQI Analytes and Weights

| Analyte | WQI Weight |
|---|---|
| Dissolved Oxigen (% saturation) | 0.17 |
| Fecal Coliform Density (MLN/100mL) | 0.15 |
| pH | 0.12 |
| BOD5 (mg/L) | 0.10 |
| Nitrates (mg/L) | 0.10 |
| Total Phosphates (mg/L) | 0.10 |
| $\Delta t$ °C from Equilibrium | 0.10 |
| Turbidity (Tu) | 0.08 |
| Total Solids (mg/L) | 0.08 |

Source: Brown *et al.* (1970).

**Table 2** - Descriptor words and WQI value ranges

| Descriptor Word | Numerical Range |
|---|---|
| Very Bad | 0-25 |
| Bad | 26-50 |
| Medium | 51-70 |
| Good | 71-90 |
| Excellent | 91-100 |

Source: Brown *et al.* (1970).

The WQI can easily communicate technical information to the public, in addition to being used to identify waters that require priority actions, for example.

## *R-TOPSIS Method*

The TOPSIS method is characterized by its easy use and robust results, which led to its widespread application, as reported by Behzadian *et al.* (2012). Nevertheless, TOPSIS has been criticized due to the problem of rank reversal. Rank reversal refers to the change in the rank ordering of some alternatives after an alternative has been added or excluded from this previously ranked group (Aires; Ferreira, 2018). This phenomenon has been debated for over 30 years and for different MCDM methods.

In order to resolve this problem for TOPSIS, Aires and Ferreira (2019) proposed the R-TOPSIS. As their primary premise, the authors considered that changes in the original method should be minimal to make the new method easier for users of the TOPSIS method and maintain compatibility and rationality between them. Thus, the authors proposed two changes to the original TOPSIS method, as follows:

- The use of an additional input parameter called domain, i.e., a numerical value (integer or real) that represents the range of possible values that each criterion could take;
- A change in the normalization procedure. R-TOPSIS uses Max-Min normalization or Max normalization to fix the ideal solutions and ensure there is no change in the values of the normalized and weighted decision matrices after modifications are introduced to the initial decision problem.

Based on the changes proposed, the method proved to be robust and immune to the different RR cases presented in the literature when submitted to numerous simulated decision problems and a real student selection case - see Aires *et al.* (2018). Other applications can also be found in the studies by Aires and Ferreira (2022) and Aires and Salgado (2022). The different steps of the R-TOPSIS method are presented below.

**Step 1**: Define a set of alternatives ($A = [a_i]_m$);

**Step 2**: Define a set of criteria ($C = [c_j]_n$), as well as a subdomain of real numbers $D = [d_j]_{2\,x\,n}$, where $d_j \in \mathbb{R}$, to evaluate the rating of the alternatives, where $d_{1j}$ is the minimum value $D_j$ and $d_{2j}$ the maximum value of $D_j$;

**Step 3**: Estimate the performance rating of the alternatives as $X = [x_{ij}]_{m\,x\,n}$;

**Step 4**: Elicit the criteria weights as $W = [w_j]_n$, where $w_j > 0$ and $\sum_{j=1}^{n} w_j = 1$;

**Step 5**: Calculate the normalized decision matrix $(n_{ij})$using *Max* or *Max-Min* as:

**Step 5.1**: *Max*

$$n_{ij} = \frac{x_{ij}}{d_{2j}}, i = 1,2 \ldots m; j = 1,2, \ldots, n. \quad (2)$$

**Step 5.2**: *Max-Min*

$$n_{ij} = \frac{x_{ij}-d_{1j}}{d_{2j}-d_{1j}}, i = 1,2 \ldots m; j = 1,2, \ldots, n. \quad (3)$$

**Step 6**: Calculate the weighted normalized decision matrix ($r\_ij$) as:

$$r_{ij} = w_j n_{ij}, i = 1,2, \ldots, m; j = 1,2, \ldots, n. \quad (4)$$

**Step 7**: Set the negative (*NIS*) and positive (*PIS*) ideal solutions as:

$$NIS = [r_1^-, \ldots, r_n^-], where\ r_j^- = \frac{d_{1j}}{d_{2j}} w_j\ if\ j \in B\ and\ r_1^- = w_j\ if\ j \in C \quad (5)$$

$$PIS = [r_1^+, \ldots, r_n^+], where\ r_j^+ = w_j\ if\ j \in B\ and\ r_j^+ = \frac{d_{1j}}{d_{2j}} w_j\ if\ j \in C \quad (6)$$

**Step 8**: Calculate the distances of each alternative $i$ in relation to the ideal solutions as:

$$S_i^+ = \sqrt{\sum_{j=1}^{n} \left(r_{ij} - r_j^+\right)^2}, i = 1,2, \ldots, m. \quad (7)$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(r_{ij} - r_j^-\right)^2}, i = 1,2, \ldots, m. \quad (8)$$

**Step 9**: Calculate the closeness coefficient of the alternatives ($CC_i$) as:

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (9)$$

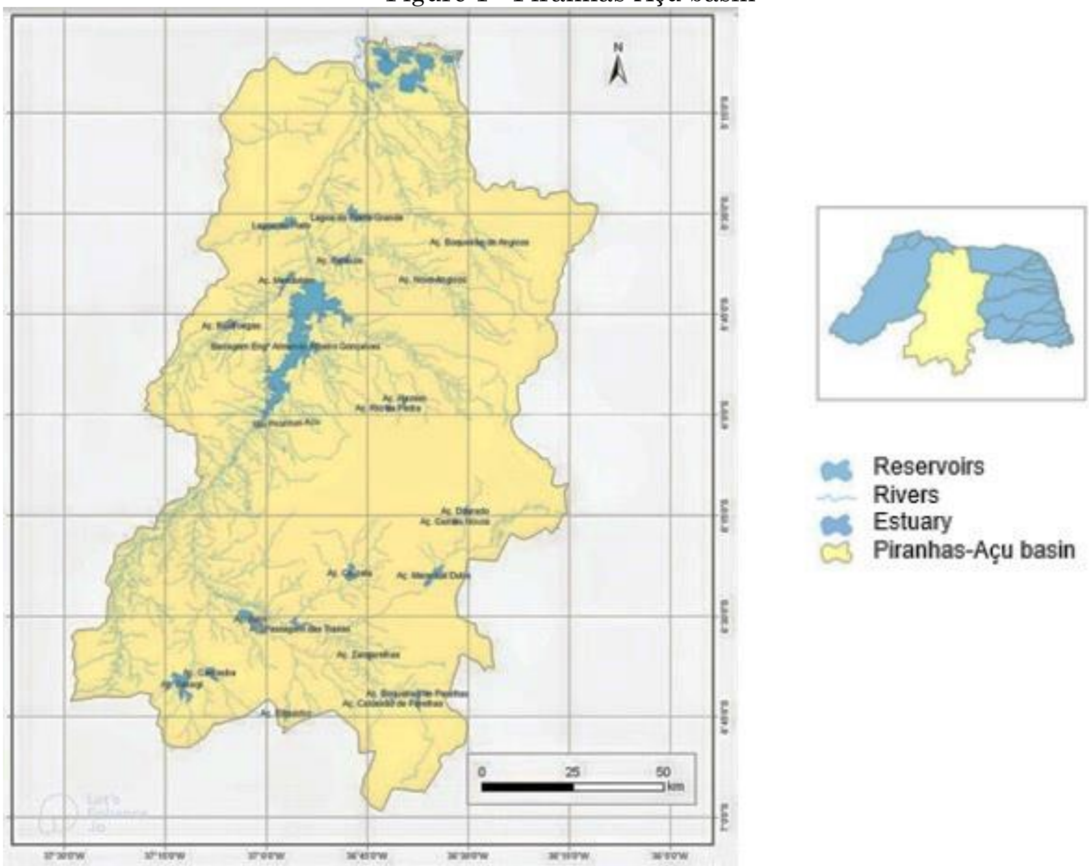
**Step 10**: Arrange the alternatives in descending order. The highest ($CC_i$) value indicates the best performance in relation to the evaluation criteria.

This method is especially relevant for the analysis of the problem discussed in this paper, since it can be characterized as a decision-making problem in a dynamic context (Campanella; Ribeiro, 2011), where new reservoirs can change the assessment. In this context, RR problems are extremely undesirable.

## RESULTS AND DISCUSSION

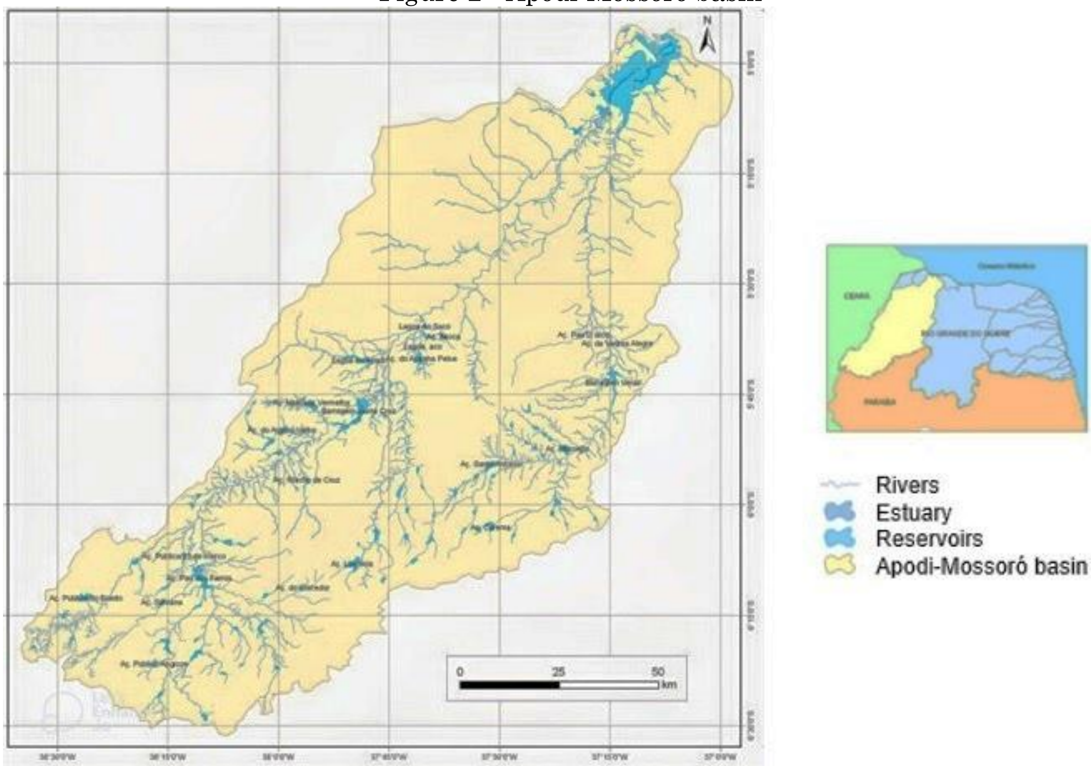
The present study investigated reservoirs from the two largest drainage basins in Rio Grande do Norte (RN) state, Brazil. These included nine reservoirs from the "Piranhas-Açu" basin (Figure 1), which covers about 32.8% of RN and is located in the middle of the state, and four reservoirs from the "Apodi-Mossoró" basin (Figure 2), which occupies around 26.8% of RN and is situated in the western part of the state. The water in the reservoirs analyzed is generally used to supply rural, urban and industry areas as well as for irrigation and livestock watering.

Figure 1 - Piranhas-Açu basin




Source: IGARN (2023).

Figure 2 - Apodi-Mossoró basin




Source: IGARN (2023).

The following Piranhas-Açu basin reservoirs were analyzed: Rio da Pedra, located in the municipality of Santana dos Matos; Caldeirão de Parelhas, in Parelhas; Mendubim, in Açu; Beldroega, in Paraú; Pataxós, in Ipanguaçu; Itans, in Caicó; Boqueirão de Parelhas, in Parelhas; Passagem das Traíras, in São José do Seridó; and Boqueirão de Angicos, in Afonso Bezerra.

The following Apodi-Mossoró basin reservoirs were analyzed: Bonito II, in the municipality of São Miguel; Riacho da Cruz II, in Riacho da Cruz; Barragem de Umari, in Upanema; and Rodeador, in Umarizal. For the purposes of this study, the data were collected from ANA (2017; 2018) and PAA (2017). It is important to underscore that the nine water quality parameters used in the WQI were observed in September and October 2016 (Table 3).

**Table 3** - Values of the water quality parameters of reservoirs

| | Parameters | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Alternatives | Dissolved Oxigen (% saturation) | Fecal Coliform Density (MLN/100 mL) | pH | BOD5 (mg/L) | Nitrates (mg/L) | Total Phosphates (mg/L) | Δ*t* °C from Equilibrium | Turbidity (Tu) | Total Solids (mg/L) | WQI |
| Bonito II | 6.4 | 7 | 7.8 | 9.0 | 19.37 | 2.233 | 27.3 | 11.3 | 1058.0 | 58 |
| Riachão da Cruz | 3.1 | <1 | 8.3 | 6.1 | 22.17 | 0.825 | 28.2 | 58.9 | 1126.0 | 51 |
| Umari | 9.9 | 7 | 8.0 | 10.8 | 7.22 | 0.366 | 28.0 | 4.1 | 322.0 | 70 |
| Rodeador | 12.4 | <1 | 9.0 | 14.7 | 13.9 | 4.018 | 31.7 | 103.3 | 714.0 | 37 |
| Boqueirão de Angicos | 7.3 | 3 | 8.3 | 10.4 | 7.1 | 0.490 | 24.6 | 38.9 | 3,980.8 | 64 |
| Beldroega | 5.3 | <1 | 8.4 | 1.1 | 3.3 | 0.226 | 26.7 | 119.4 | 1,240.4 | 61 |
| Mendubim | 9.2 | 2 | 8.5 | 10.7 | 2.0 | 0.640 | 27.9 | 25.2 | 388.8 | 69 |
| Pataxós | 7.9 | <1 | 8.4 | 9.5 | 1.6 | 0.800 | 27.5 | 7.4 | 294.4 | 75 |
| Rio da Pedra | 10.3 | <1 | 8.2 | 18.6 | 5.4 | 0.930 | 27.8 | 25.7 | 1,789.2 | 59 |
| Boqueirão de Parelhas | 9.4 | <1 | 8.7 | 12.5 | 2.2 | 0.530 | 29.0 | 22.2 | 938.4 | 66 |
| Caldeirão de Parelhas | 7.9 | 2 | 8.8 | 10.7 | 4.8 | 0.440 | 28.0 | 34.6 | 358.6 | 67 |
| Itans | 6.1 | 23 | 8.7 | 9.4 | 2.0 | 0.810 | 28.0 | 45.4 | 662.4 | 59 |
| Passagem de Traíras | 11.0 | 8 | 9.1 | 11.9 | 1.0 | 0.730 | 31.0 | 23.0 | 733.2 | 53 |

Source: The authors (2019).

As mentioned previously, the NSF WQI was used, classifying water quality as excellent (100-91), good (90-71), medium (70-51), bad (50-26) and very bad (25-0).

The WQI results show that the Pataxós dam has the best water quality (75 points), while the Rodeador dam has the worst (37 points). The quality of Piranhas-Açu basin reservoirs varied between 53 and 75 points, corresponding to medium water quality, and those from the Apodi-Mossoró basin ranged between 37 and 70 points, that is, bad and medium quality.

The WQI results were used to conduct a holistic analysis by applying the MCDM R-TOPSIS method, in which the WQI was only one of the 11 analysis criteria of the situation of the reservoirs. The other 10 criteria are presented in Table 4.

**Table 4** - Criteria used

| Category | Criterion | Description | Unit of measurement/Scale | Objective |
|---|---|---|---|---|
| Necessity | Urban supply (C1) | Consumptive demand for urban supply | Liters/second (l/s) | Minimization |
| | Rural supply (C2) | Consumptive demand for rural supply | Liters/second (l/s) | Minimization |
| | Livestock watering (C3) | Consumptive demand for livestock watering | Liters/second (l/s) | Minimization |
| | Irrigation (C4) | Consumptive demand for irrigation | Liters/second (l/s) | Minimization |
| | Industry (C5) | Consumptive demand for industry | Liters/second (l/s) | Minimization |
| Availability | Evaporation vector (C6) | Represents the amount of water lost annually through evaporation | Millimeters (mm) | Minimization |
| | Rainfall vector (C7) | Represents the amount of water added annually by rainfall | Millimeters (mm) | Maximization |
| | Total affluent volume (C8) | Represents the total annual volume that flows to the reservoir | Cubic hectometer ($hm^3$) | Maximization |
| | Volume (C9) | Measured useful volume | Cubic hectometer ($hm^3$) | Maximization |
| | Volume ratio (C10) | Represents the ratio between volume and capacity | Percentage (%) | Maximization |
| Quality | Water quality index – WQI (C11) | Assesses water quality for human consumption, varying from 0 to 100, whereby the higher the value the better the water quality | - | Maximization |

Source: The authors (2019).

The swing weight procedure was used to establish the relative importance of each criterion (Edwards; Barron, 1994). In order to more realistically model the decision-making problems, elicitations are based on changing attributes or direct attribution of weight intervals (Danielson; Ekenberg, 2019). This is because decision-makers can easily attribute weights.

Three specialists from the area were interviewed, two PhDs in natural resources and one researcher in soil and water management. In this procedure, first, a hypothetical situation is defined as the worst possible hypothesis for all the criteria (Mustajoki *et al*., 2005; Mustajoki *et al*., 2006). Thus, a value of 0 was established for all the cases.

The specialists were then consulted about which of the criteria was the most important, given the performance of the reservoir. The best assessed received a score of 100 and the others were defined proportionally according to their opinions. The final weight of each criterion is calculated based on the final weight of each criterion, calculated by dividing its score by the sum of the scores of all the criteria. Each decision-maker makes an assessment and the final weights are an average of the individual evaluations. The final result is presented in Table 5.

**Table 5** - Criteria weight

| Criterion | Final Weight |
|---|---|
| C1 | 0.1833 |
| C2 | 0.0500 |
| C3 | 0.0433 |
| C4 | 0.1100 |
| C5 | 0.0633 |
| C6 | 0.2000 |
| C7 | 0.0933 |
| C8 | 0.0267 |
| C9 | 0.0500 |
| C10 | 0.0767 |
| C11 | 0.1033 |

Source: The authors (2019).

To facilitate the result presentation, the 13 reservoirs were assigned a code, as shown in Table 6.

Finally, the input data analyzed for each of the 13 criteria that make up the decision matrix is presented in Table 7.

**Table 6** - Analyzed Reservoirs

| Drainage basin | Reservoir |
|---|---|
| Apodi-Mossoró | Bonito II (A1)<br>Riacho da Cruz II (A2)<br>Umari (A3)<br>Rodeador (A4) |
| Piranhas-Açu | Boqueirão de Angicos (A5)<br>Beldroega (A6)<br>Mendubim (A7)<br>Pataxós (A8)<br>Rio da Pedra (A9)<br>Boqueirão de Parelhas (A10)<br>Caldeirão de Parelhas (A11)<br>Itans (A12)<br>Passagem de Traíras (A13) |

Source: The authors (2019).

**Table 7** - Decision matrix

| Alternatives | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C6 | C10 | C11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | 53 | 41 | 22 | 6 | 0 | 2376 | 901 | 13.3 | 9.64 | 1.29 | 58 |
| A2 | 24 | 5 | 6 | 4 | 0 | 2452 | 744 | 17.1 | 8.97 | 75 | 51 |
| A3 | 385 | 27 | 39 | 123 | 0.95 | 2432 | 662 | 148.34 | 279.26 | 36.52 | 70 |
| A4 | 47 | 6 | 18 | 3 | 0 | 2481 | 838 | 35.69 | 20.18 | 81.82 | 37 |
| A5 | 6 | 36 | 36 | 0 | 0 | 2434 | 515 | 6.64 | 15.05 | 7.49 | 64 |
| A6 | 0 | 0 | 0 | 6 | 0 | 2507 | 606 | 34.54 | 7.4 | 51.74 | 61 |
| A7 | 0 | 2 | 2 | 4 | 0 | 2530 | 554 | 55.91 | 72.01 | 67.37 | 69 |
| A8 | 0 | 8 | 4 | 4 | 0 | 2563 | 554 | 31.72 | 14.25 | 57.66 | 75 |
| A9 | 13 | 17 | 19 | 0 | 0 | 2617 | 724 | 8.9 | 10.94 | 19.23 | 59 |
| A10 | 50 | 12 | 9 | 0 | 1.9 | 2727 | 533 | 23.04 | 83.91 | 30.03 | 66 |
| A11 | 6 | 3 | 8 | 1 | 0 | 2773 | 533 | 6.52 | 8.69 | 75 | 67 |
| A12 | 90 | 5 | 82 | 82 | 0 | 2833 | 695 | 38.97 | 76.95 | 1.09 | 59 |
| A13 | 12 | 3 | 14 | 49 | 0 | 2874 | 695 | 150.93 | 48.78 | 1.33 | 53 |

Source: The authors (2019).

Based on Table 7, the R-TOPSIS was applied. After the decision matrix (step 1) was defined, the domains of all the criteria (step 2) were established, based on the extreme values for all the reservoirs of the semiarid of Rio Grande do Norte state, including reservoirs not considered in this analysis (ANA, 2017; 2018). The domains used are presented in Table 8.

**Table 8** - Domains

| Domain | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C6 | C10 | C11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Maximum | 867 | 41 | 60 | 3123 | 573 | 2886 | 901 | 2307.78 | 583.84 | 81.82 | 100 |
| Minimum | 0 | 0 | 0 | 0 | 0 | 2356 | 428 | 3.38 | 4.16 | 1.09 | 0 |

Source: The authors (2019).

The decision matrix and domains were used to apply R-TOPSIS and normalized using Max. The result is presented in Table 9 in terms of the distances of each alternative from the positive (PIS) and negative ideal situation (NIS), closeness coefficient (CC) and ranking position.

**Table 9** - Results

| Alternatives | DPIS | DNIS | Closeness Coefficient | Position |
|---|---|---|---|---|
| A7 | 0.0880 | 0.2476 | 0.7378 | 1 |
| A8 | 0.0937 | 0.2466 | 0.7247 | 2 |
| A6 | 0.0971 | 0.2450 | 0.7162 | 3 |
| A2 | 0.0968 | 0.2410 | 0.7135 | 4 |
| A11 | 0.0996 | 0.2446 | 0.7105 | 5 |
| A10 | 0.0986 | 0.2321 | 0.7018 | 6 |
| A4 | 0.1041 | 0.2353 | 0.6932 | 7 |
| A9 | 0.1045 | 0.2358 | 0.6930 | 8 |
| A13 | 0.1105 | 0.3178 | 0.6807 | 9 |
| A1 | 0.1165 | 0.2317 | 0.6654 | 10 |
| A5 | 0.1182 | 0.2346 | 0.6650 | 11 |
| A12 | 0.1217 | 0.2219 | 0.6458 | 12 |
| A3 | 0.1145 | 0.2355 | 0.6191 | 13 |

Source: The authors (2019).

The results of Table 9 demonstrated that the Mendubim and Umari dams exhibit the best and worst situations, respectively. Obtaining acceptable values in relation to all the criteria was the main reason the Mendubim dam was classified as the best, while displaying the worst values for three of the criteria analyzed (urban supply, irrigation, and evaporation vector) contributed to the Umari dam's ranking last.

Analysis of the reservoirs in the drainage basins shows that the top three rankings belong to the Piranhas-Açu basin, while two of the last four positions are from the Apodi-Mossoró basin. This aspect is critical in that only four reservoirs from the latter basin were analyzed here.

These classification results show several differences from those obtained in analysis that considered only the WQI, reinforcing the relevance of having considered more analysis criteria. Table 3 demonstrates that the Pataxós dam has the best water quality, but in the model that included more criteria, it ranked second. Likewise, the Rodeador dam exhibited the poorest water quality, but ranked seventh in the holistic model.

### *Sensitivity analysis*

Sensitivity analysis was carried out to assess the impact caused by a 10% variation (plus or minus) in the weights of the criteria on the stability of the final classification. As any of the weights were increased or decreased, the difference was equally distributed among the rest of the criteria. Tables 10 and 11 present the positive and negative variations, respectively, in the weights and percentage change in the ranking.

**Table 10** - Sensitivity Analysis (+10%)

| Criterion | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 | C11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| C1 | 0.2017 | 0.1828 | 0.1829 | 0.1822 | 0.1827 | 0.1813 | 0.1824 | 0.1831 | 0.1826 | 0.1828 | 0.1823 |
| C2 | 0.0482 | 0.0550 | 0.0496 | 0.0489 | 0.0494 | 0.0480 | 0.0491 | 0.0497 | 0.0492 | 0.0495 | 0.0490 |
| C3 | 0.0415 | 0.0428 | 0.0477 | 0.0422 | 0.0427 | 0.0413 | 0.0424 | 0.0431 | 0.0426 | 0.0428 | 0.0423 |
| C4 | 0.1082 | 0.1095 | 0.1096 | 0.1210 | 0.1094 | 0.1080 | 0.1091 | 0.1097 | 0.1092 | 0.1095 | 0.1090 |
| C5 | 0.0615 | 0.0628 | 0.0629 | 0.0622 | 0.0697 | 0.0613 | 0.0624 | 0.0631 | 0.0626 | 0.0628 | 0.0623 |
| C6 | 0.1982 | 0.1995 | 0.1996 | 0.1989 | 0.1994 | 0.2200 | 0.1991 | 0.1997 | 0.1992 | 0.1995 | 0.1990 |
| C7 | 0.0915 | 0.0928 | 0.0929 | 0.0922 | 0.0927 | 0.0913 | 0.1027 | 0.0931 | 0.0926 | 0.0928 | 0.0923 |
| C8 | 0.0248 | 0.0262 | 0.0262 | 0.0256 | 0.0260 | 0.0247 | 0.0257 | 0.0293 | 0.0259 | 0.0262 | 0.0256 |
| C9 | 0.0748 | 0.0762 | 0.0762 | 0.0756 | 0.0760 | 0.0747 | 0.0757 | 0.0764 | 0.0843 | 0.0762 | 0.0756 |
| C10 | 0.0482 | 0.0495 | 0.0496 | 0.0489 | 0.0494 | 0.0480 | 0.0491 | 0.0497 | 0.0492 | 0.0550 | 0.0490 |
| C11 | 0.1015 | 0.1028 | 0.1029 | 0.1022 | 0.1027 | 0.1013 | 0.1024 | 0.1031 | 0.1026 | 0.1028 | 0.1137 |
| % | 69.23 | 84.62 | 100.00 | 84.62 | 84.62 | 84.62 | 100.00 | 100.00 | 84.62 | 84.62 | 53.85 |

Source: The authors (2019).

**Table 11** - Sensitivity Analysis (-10%)

| Criterion | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 | C11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| C1 | 0.1650 | 0.1838 | 0.1838 | 0.1844 | 0.1840 | 0.1853 | 0.1843 | 0.1836 | 0.1841 | 0.1838 | 0.1844 |
| C2 | 0.0518 | 0.0450 | 0.0504 | 0.0511 | 0.0506 | 0.0520 | 0.0509 | 0.0503 | 0.0508 | 0.0505 | 0.0510 |
| C3 | 0.0452 | 0.0438 | 0.0390 | 0.0444 | 0.0440 | 0.0453 | 0.0443 | 0.0436 | 0.0441 | 0.0438 | 0.0444 |
| C4 | 0.1118 | 0.1105 | 0.1104 | 0.0990 | 0.1106 | 0.1120 | 0.1109 | 0.1103 | 0.1108 | 0.1105 | 0.1110 |
| C5 | 0.0652 | 0.0638 | 0.0638 | 0.0644 | 0.0570 | 0.0653 | 0.0643 | 0.0636 | 0.0641 | 0.0638 | 0.0644 |
| C6 | 0.2018 | 0.2005 | 0.2004 | 0.2011 | 0.2006 | 0.1800 | 0.2009 | 0.2003 | 0.2008 | 0.2005 | 0.2010 |
| C7 | 0.0952 | 0.0938 | 0.0938 | 0.0944 | 0.0940 | 0.0953 | 0.0840 | 0.0936 | 0.0941 | 0.0938 | 0.0944 |
| C8 | 0.0285 | 0.0272 | 0.0271 | 0.0278 | 0.0273 | 0.0287 | 0.0276 | 0.0240 | 0.0274 | 0.0272 | 0.0277 |
| C9 | 0.0785 | 0.0772 | 0.0771 | 0.0778 | 0.0773 | 0.0787 | 0.0776 | 0.0769 | 0.0690 | 0.0772 | 0.0777 |
| C10 | 0.0518 | 0.0505 | 0.0504 | 0.0511 | 0.0506 | 0.0520 | 0.0509 | 0.0503 | 0.0508 | 0.0450 | 0.0510 |
| C11 | 0.1052 | 0.1038 | 0.1038 | 0.1044 | 0.1040 | 0.1053 | 0.1043 | 0.1036 | 0.1041 | 0.1038 | 0.0930 |
| % | 100.00 | 84.62 | 84.62 | 100.00 | 100.00 | 100.00 | 53.85 | 100.00 | 100.00 | 84.62 | 100.00 |

Source: The authors (2019).

The last line of Tables 10 and 11 (denominated %) contains the percentages of cases in which the ranking of the alternatives was the same as the classification initially presented in Table 9. In general, the rankings obtained showed good stability in response to changes in criterion weights. When the weights increased and decreased, stability was on average 84.62 and 91.61%, respectively. The changes were greater when the weights of criteria C1 (urban supply) and C11 (water quality index) increased and that of criterion C7 (rainfall vector) decreased.

Only six alternatives changed ranking with an increase or decrease in weights, as follows:

- Alternatives A1 and A5 inverted their positions with a weight increase in criteria C1, C2, C9, C10 and C11 and a decrease in C3 and C7;
- Alternatives A9 and A4 inverted their positions with a weight increase in criteria C1, C4, C5, C6 and C11 and decrease in criteria C2, C7 and C10;
- Alternatives A2 and A11 inverted their positions with a weight increase in criterion C11 and decrease in criterion C7.

This can be explained by the fact that the alternatives exhibit closeness coefficients very near the original result and are therefore more sensitive to variations. The difference between alternatives A2 and A11 from the original result is only 0.003, while the difference between alternatives A9 and A4, and A1 and A5 is even smaller: 0.0002 and 0.0004, respectively.

Finally, it is important to underscore that the first three positions did not change in any of the scenarios analyzed, reinforcing the good stability of the model.

## FINAL CONSIDERATION

The reservoir situation in the two largest drainage basins of Rio Grande do Norte state was assessed using a multicriteria model that considered water quality-related aspects, applying the WQI, as well as those related to the need and availability of water. The proposal to include the WQI as a criterion in a holistic model that assesses reservoirs provides a more complete picture of the situation investigated. Furthermore, the combination proposed produced more information than traditional methods based only on indices such as the WQI.

The results presented also demonstrated that the use of the R-TOPSIS method is more appropriate for adding new reservoirs to the analysis with no risk of undesirable inversions, in addition to allowing possible replications.

As such, the approach is applicable to any reservoir assessment, and is important for decision-makers in terms of water management. It can simplify the selection of reservoirs with more critical supply situations, where appropriate measures must be taken to remedy these scenarios. In order to create better supply conditions, the present study highlights the importance of adequate reservoir management. In some of the reservoirs, such as Beldroega, there is a predominance of non-priority demands, which is especially important for a reservoir that, despite exhibiting only a small water balance deficit, has reached its limit in terms of annual recovery capacity.

In summary, the main findings of the study were (i) presenting an MCDM model that combines aspects of quality, using the WQI, and those related to need and availability in order to obtain a more complete analysis of reservoir situations, with a view to supporting decision-makers in the operation of these facilities and enable the multiple use of waters, and providing contributions for the analysis of reservoirs that are extremely important in supplying the semiarid region, where water is critical.

Finally, the findings of the present study may be useful to institutions and policy makers interested in the adequate water management of reservoirs in the semiarid of Rio Grande do Norte state, and the results of the approach applied may serve as the basis for future research on the situation of other reservoirs in this or other similar regions.

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## AUTHORS CONTRIBUTION

Renan Felinto de Farias Aires conceptualized the project, did the formal analysis, did the project administration, and carried out the funding acquisition. Renan Felinto de Farias Aires and Camila Cristina Rodrigues Salgado did the methodology and investigation. Both authors prepared the original draft, wrote the review, and edited the project. All authors have read and agreed to the published version of the manuscript.