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Papers

The Contribution of the FPEIR/TOPSIS Model in The Environmental Diagnosis of Water Security in Areas Affected by the B1 Dam, Brumadinho, MG

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Abstract

The Paraopeba River Basin, located in the state of Minas Gerais, Brazil, has been severely impacted by extreme climatic events and the 2019 Vale S.A. dam failures in Brumadinho. This study underscores the importance of integrating multi-criteria decision analysis with a conceptual model to diagnose water security in the region based on socio-environmental indicators. Employing the DPSIR methodology, socio-environmental indicators are proposed and analyzed to assess water security and to support the planning and management of water resources in the Paraopeba River Basin (BHRP). The approach combines the TOPSIS multi-criteria analysis model with the entropy weight method to rank municipalities according to their levels of water security. The analysis identified critical challenges, including population growth, industrialization, and agricultural expansion, which exacerbate water contamination. Brumadinho and Betim emerged as the most vulnerable municipalities, exhibiting high rates of waterborne diseases and inadequate wastewater treatment infrastructure. Intense industrial and agricultural activities have further heightened environmental risks, as exemplified by the dam failures. The study underscores socio-environmental pressures and highlights the importance of integrated approaches. The findings emphasize the need for robust public policies, sustainable agricultural practices, participatory management, infrastructure improvements, and climate change adaptation to ensure water security and improve quality of life.

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INTRODUCTION

The Paraopeba River Basin (BHRP) has suffered extreme climate-related events, including prolonged periods of drought and intense rainfall, in addition to being severely impacted by the 2019 rupture of the B-I tailings dam, part of the Córrego do Feijão mining complex, which belonged to the company Vale S.A. This was immediately followed by the collapse of the B-IV and B-IV-A dams which then reached the Ferro-Carvão Feijão stream and its flow into the Paraopeba River, in the municipality of Brumadinho. This has been extensively documented by several authors, such as Nero *et al.* (2024) and Lima *et al.* (2021). Furthermore, the region remains at risk of additional dam failures, thereby threatening the population's water supply and productive activities with the potential for serious water shortages (ARMBH, 2021). Within this scenario, integrated water resources management (IWRM) emerges as a viable approach to water planning and management. Addressing these risks requires collaborative efforts among government authorities, local institutions and the community, to facilitate the planning of conflict management and for the protection of water resources.

Advances in understanding the organization and functioning of environmental systems have driven research projects that assess the water security of river basins through environmental, economic and social indicators. For example, a study by Alves *et al.* (2024) analyzed the relationship between the water security index (WSI) and socioeconomic indicators in water and sewage microregions in the Brazilian Northeastern state of Paraíba. Their study employed the statistical method of principal component analysis (PCA) and demonstrated a positive correlation between the scores of the Human Development Index (HDI) and the Sustainable Cities Development Index (SCDI) with the WSI. Despite favorable conditions in terms of supply network coverage, the municipalities exhibited low to medium WSI rates in both microregions. Conversely, the resilience, ecosystem and economic dimensions, including investments and the Gross Domestic Product (GDP), demonstrated a negative correlation with the WSI, indicating that these variables rendered a negative influence on the WSI.

Zlat *et al.* (2024) quantified the impact of water security on economic and social development using a new structural equation model to identify changes in the latent variable WSI during the period 2000–2022 for the 27 Member States of the European Union. The methodology combined structural equation systems with the Kruskal-Wallis independent samples test to assess the influence of water security measures on economic and social indicators along with the regional disparities in the development of environmental policies in relation to economic and social development. The results revealed a significant correlation between population density, pollution levels and the costs associated with maintaining water quality. They ultimately concluded that the findings provide valuable insights for economic, environmental and social policy makers to optimize sustainable development strategies across Europe.

Building on this premise, the analysis of indicators enables the monitoring and assessment of the performance of river basins over time, identifies areas requiring improvement, and the implementation of appropriate actions to ensure water security in a balanced manner.

The present study aimed to analyze a set of socio-environmental indicators for diagnosing water security in municipalities in the Paraopeba River basin (BHRP), in Minas Gerais, and is based on a synthesis of the research developed by Honorato (2024). Thus, indicators were selected using the Driving Force-Pressure-State-Impact-Response (DPSIR) conceptual framework, (and were classified according to their potential to affect the state of water resources in terms of quantity and quality. In addition, the classification of municipal water availability, undertaken using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method, as applied by Aires and Salgado (2024), made it possible to identify the municipalities with the best performances in water security.

Theoretical Foundation

The use of conceptual models and multi-criteria analyzes is essential for addressing the complexity of environmental and social systems, especially in regions facing water security challenges (Salamé *et al.*, 2020; Araújo *et al.*, 2019). Conceptual models, such as the DPSIR, enable the structuring of problems based on causal relationships and socio-environmental dynamics, thereby facilitating the identification of pressures, impacts and responses (Liu *et al.*, 2018). Multi-criteria analyses, such as TOPSIS, offer robust methods for classifying and prioritizing alternatives, incorporating multiple indicators and criteria (Zhang *et al.*, 2023).

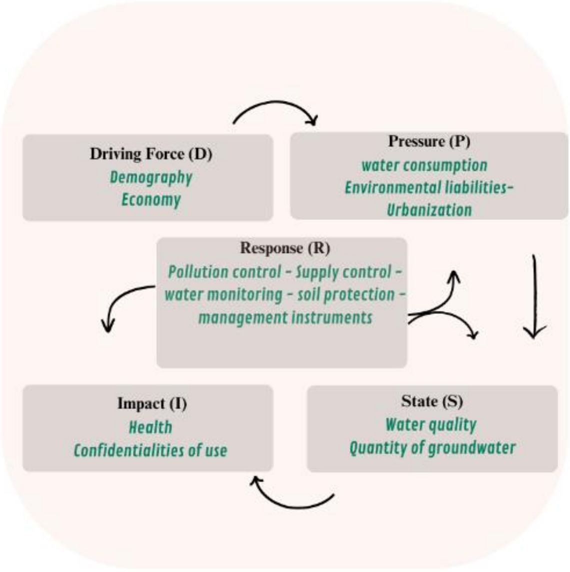
The Driving Forces – Pressure – State - Impact – Response (DPSIR) Framework

The Driving Force-Pressure-State-Impact-Response (DPSIR) was proposed by Rapport and Friend (1979).

This framework offers a structure for identifying environmental problems in a given location, including their causes, impacts and possible solutions through indicators. For example, Shi *et al.* (2021) successfully applied the model to assess water security in river basins in the Jiangxi province, China. Similarly, a study by Acostupa *et al.* (2018) employed the model in the environmental diagnosis of the Lucre-Huacarpay Pantanal.

The circular structure of the DPSIR model captures the continuous cycle of influences (Figure 1), emphasizing the interconnectedness of driving forces, pressures, state changes, impacts and responses. This interrelationship ultimately guides decision-making for sustainable development and for the allocation of resources in water systems (Pirrone *et al.*, 2005).

Figure 1 – Example of the conceptual scheme of DPSIR indicators



Source: The authors (2024).

Water security, as defined by the United Nations (UN, 2013), refers to the ability of a population to ensure sustainable access to adequate quantities of water of an acceptable quality, in order to sustain health, human well-being, socioeconomic development and the preservation of ecosystems. In order to carry out the water security analysis in the middle course of the BHRP, 30 indicators were selected (Table 1), including seven driving forces (D), five pressure indicators (P), four status indicators (S), two impact indicators (I) and twelve responses (R). The selection of indicators was based on an assessment of the state of water resources and their relationships with the Driving Force, Pressure, Impact and Response indicators.

Table 1 – Water Security Indicators

Name	Magnitude	Unit	Name	Magnitude	Unit
D.01	Geometric Annual Growth Rate	% p.a.	**S.04**	Exploitable water depth	mm/year
D.02	Inhabitants per km^2	hab./km^2	**I.01**	Waterborne diseases	nº
D.03	Agricultural establishments	nº	**I.02**	Conflict of use	nº
D.04	Cultivated Area	%	**R.01**	Households connected to the sewage network	%
D.05	Industrial establishments	nº	**R.02**	Sewage treatment	%
D.06	Mineral exploration	nº	**R.03**	Selective collection	yes/no
D.07	Urbanized area	%	**R.04**	Landfill	yes/no
P.01	Total water consumed per year	m^3/year	**R.05**	Inspections	nº
P.02	Total water treated	m^3/year	**R.06**	Households connected to the supply network	%
P.03	Environmental accidents	nº	**R.07**	Percentage of water losses	%
P.04	Tailings dams	nº	**R.08**	Monitoring Stations	nº
P.05	municipal human development index	-	**R.09**	Fluviometers	nº
S.01	average water quality index	-	**R.10**	Native vegetation cover	%
S.02	Parameters changed as per DN 08/22	nº	**R.11**	Protected area	%
S.03	Minimum flow rates ($Q_{7\ 10}$)	nº	**R.12**	Management instruments	nº

Source: The authors (2024).

To diagnose the water security of municipalities, the approach assessed 30 indicators segmented by the DPSIR model. Qualitative indicators were coded as binary variables, with "YES" assigned to 1 and "NO" to 0. The application of TOPSIS and the calculation of weights were modeled using Excel® and Python language, with the pandas, numpy and matplotlib libraries.

The TOPSIS Method

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method is a widely used resource in multi-criteria decision analysis, also known as the method for determining the shortest distance to the ideal solution.

It is a decision-making technique that assesses alternatives based on a set of criteria and is widely applied in areas such as environmental management, engineering, economics and other disciplines that require complex decision-making involving multiple factors. Initially proposed by Hwang and Yoon (1981), TOPSIS has been extensively adopted in various studies. For example, Aires and Salgado (2024) used a multi-criteria approach based on R-TOPSIS to assess water reservoirs in semi-arid Brazil. Another relevant study by Zhang *et al.* (2023) applied TOPSIS to analyze the performance of agricultural ecological governance in Henan Province, China. Elshoubaky *et al.* (2023) applied the method to select sustainable construction materials, considering life cycle assessment. Furthermore, the adaptation of TOPSIS to a diffuse environment, as described by Carnero (2020), enables the assessment of the environmental responsibility of healthcare organizations, contributing to the promotion of public health through improved environmental sustainability practices. The application of the method follows the outlined steps below:

Step 1 – Calculate the weights (w) (Equation 1): First, the entropy for each indicator is calculated using the entropy weight method, initially proposed by Shannon and Wiener in 1949. This method has found widespread application across several fields, as in Yang *et al.* (2022), who used it in engineering decision-making, while Luo *et al.* (2022) applied it to assess the risks associated with zoonotic visceral leishmaniasis.

$$w = \frac{1-E_j}{\sum_{j=1}^{m}(1-E_j)} \tag{1}$$

Entropy (E) is a measure of diversity or uncertainty in data, used to determine the relative importance of each indicator in decision-making. Indicators with a higher entropy reflect greater variability in the data and are therefore assigned lower weights, while criteria with lower entropy receive higher weights (Table 2).

Step 2 - Construct the normalized decision matrix (Equation 2): A normalized decision matrix is created, where each line represents a municipality, and each column represents an indicator. This matrix is essential for calculating the distances between alternatives and ideal values.

Step 3 - Multiply the weights (Equation 3): The weights (w, Equation 1) are then multiplied by the normalized decision matrix.

$$V = v_{ij\ (mxn)} = r_{ij}\ x\ w_{ij} \tag{2}$$

Step 4 – Determine the ideal values (Equations 4 and 5): Two types of ideal solutions are calculated: the best and the worst.

$$A = (v_{ij})_{nxm=} \begin{pmatrix} \mathrm{v}_{11} & \cdots & \mathrm{v}_{1m} \\ \vdots & \ddots & \vdots \\ \mathrm{v}_{n1} & \cdots & \mathrm{v}_{nm} \end{pmatrix} \tag{3}$$

Positive Ideal Solution A+: Contains the best values for each indicator

$$\mathrm{SIP} = v^{+} = \left(max_i, v_{ij} \mid j \in j_b\right), \left(min_i v_{ij} \mid j \in j_{nb}\right) \mid \in [1 \ldots m] \tag{4}$$

Negative Ideal Solution A−: Contains the worst values for each indicator

$$\mathrm{SIN} = v^{-} = \left(min_i, v_{ij} \mid j \in j_b\right), \left(max_i v_{ij} \mid j \in j_{nb}\right) \mid \in [1 \ldots m] \tag{5}$$

Step 5 – Calculate the distances: Calculate the Euclidean distance between each alternative and the ideal solutions (positive and negative) (Equations 6 and 7). These distances are used to determine how close each alternative is to the ideal solutions.

$$SIP = D_i^{+} = \left\lfloor \sum_{j=1}^{m}(V_i - V_j^{+})^2 \right\rfloor^{0,5} \tag{6}$$

$$SIN = D_i^{-} = \left\lfloor \sum_{j=1}^{m}(V_i - V_j^{-})^2 \right\rfloor^{0,5} \tag{7}$$

Step 6 - Determine the relative proximity (Equation 8): Based on the calculated distances, the relative proximity of each alternative to the ideal solutions is determined. The closer to a positive ideal solution and further from the negative ideal solution, the better the alternative.

Step 7 – Rank the alternatives (Table 2): Finally, the alternatives are classified according to their relative proximity to the ideal solutions, with those closest to the positive ideal solution being considered the best options.

$$CC_i = \frac{D_i^{-}}{D_i^{+} + D_i^{-}} \tag{8}$$

Table 2 – Weights of the indicators according to the entropy method

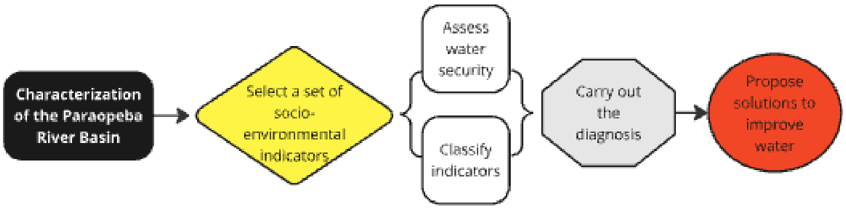
Indicator	Weight (w)	Indicator	Weight (w)
D.01	0.0198	**S.04**	0.0879
D.02	0.0216	**I.01**	0.0690
D.03	0.0234	**I.02**	0.0311
D.04	0.0149	**R.01**	0.0183
D.05	0.0219	**R.02**	0.0303
D.06	0.0418	**R.03**	0.0122
D.07	0.0144	**R.04**	0.0122
P.01	0.0507	**R.05**	0.0463
P.02	0.0469	**R.06**	0.0156
P.03	0.0242	**R.07**	0.0215
P.04	0.0530	**R.08**	0.0709
P.05	0.0246	**R.09**	0.0387
S.01	0.0287	**R.10**	0.0293
S.02	0.0531	**R.11**	0.0267
S.03	0.0207	**R.12**	0.0303

Source: The authors (2024).

MATERIAL AND METHODS

The methodology (Figure 2) of this study is based on two main pillars: the technical report from the Institute for Technological Research (IPT, 2008) and the study by Yin and Yuan (2022).

Figure 2 - Methodological pathway of the research.



Source: The authors (2024).

The IPT report diagnosed the state of water resources in the Rio Grande Basin (SP/MG) using the DPSIR model. The study by Yin and Yuan assessed the green development of the Beijing-Tianjin-Hebei region by combining the DPSIR -TOPSIS frameworks with the entropy weights method. Together, these elements provide a robust approach to understanding and managing water resources sustainably, contributing to sustainable management strategies and water security policies in the Paraopeba River basin.

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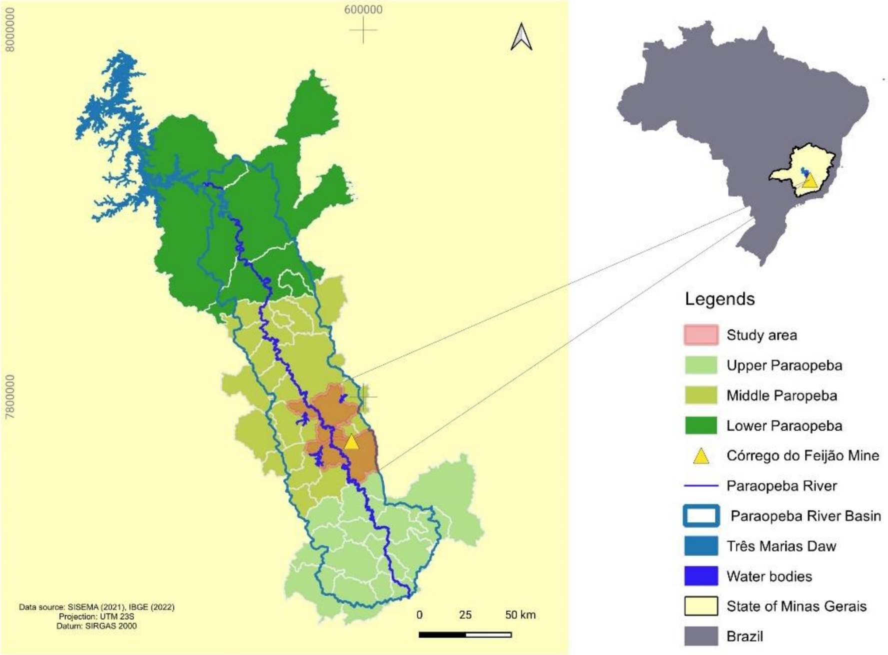
The steps involved in the classification of indicators were modeled using spreadsheets and Python language with the pandas, numpy and matplotlib libraries.

Characterization of the study area

The Paraopeba River Basin (BHRP) (Figure 3), located in the central region of the state of Minas Gerais, spans approximately 13,640 km^2 and forms part of the Alto São Francisco region. It is strategically significant for water supply, mining and industrial activities.

Figure 3 - Location map of the Paraopeba River Basin



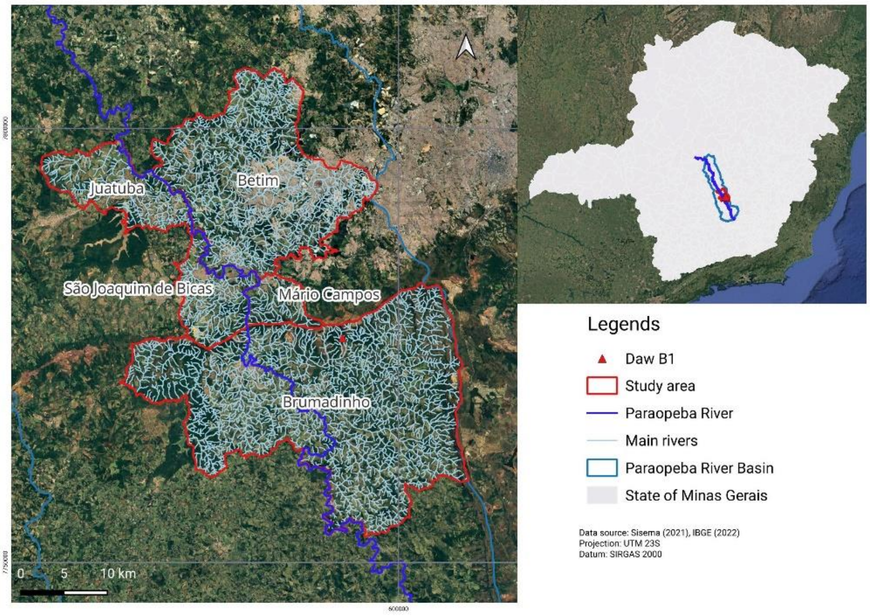
Source: The authors (2024).

The river drains into the reservoir of the Três Marias Hydroelectric Plant, which has a total power generation capacity of around 396 MW. It is crucial for water supply and ecological sustainability, since it provides 53% of the water for the state capital, Belo Horizonte. Its varied topography includes plateaus and depressions, while a diverse geology features rocks in the Crystalline Complex, iron formations in the Minas Group and sedimentary deposits, in addition to fault systems that influence underground hydrology (COBRAPE, 2020). The predominant climate is tropical high altitude (Cwb), with average temperatures between 18°C and 22°C and an annual rainfall of 1,000 to 1,400 mm, primarily concentrated in the summer, while winters are dry (COBRAPE, 2020). The soils in the region vary between Oxisols, Cambisols, Argisols and Fluvic Neossolos (COBRAPE, 2020). The original vegetation, composed of a transition between Cerrado and Atlantic Forest, including typical Cerrado, riparian forests, and semi-deciduous forests. However, much of this vegetation has been largely replaced by pastures, agriculture and mining, with only fragments remaining in protected areas (COBRAPE, 2020). Economically, the Paraopeba River Basin is highly diverse, with significant activities in mining, steel, petrochemicals and automobile industries, beverage production, services, hydroelectric power generation, livestock and agriculture. The region hosts a well-developed industrial sector, with metallic and non-metallic mineral extraction, metallurgy, steel production, and the manufacturing of food, textiles, clothing, and footwear. Key environmental impacts include mining – particularly dam failures - deforestation and urbanization, all of which affect water quality, soil health and biodiversity. These issues underscore the need for making robust environmental planning essential for the region.

The basin is hydrologically subdivided into three sectors: Upper, Middle and Lower Paraopeba. Each sector exhibits distinct characteristics in terms of geomorphology and land use. Mining activities, particularly the exploration of iron and manganese ores, are concentrated in the "iron quadrangle", in the middle Paraopeba region, significantly affecting the water quality and aquatic life.

The present study focuses on five municipalities located in the middle course of the Paraopeba River: Betim, Brumadinho, Mário Campos, Juatuba and São Joaquim de Bicas (Figure 4).

Figure 4 - Location of the study area.



Source: The authors (2024).

These municipalities were selected due to their direct or indirect exposure to the impacts of the B1 dam collapse on January 25, 2019, in the municipality of Brumadinho. This disaster underscored the basin's vulnerability in relation to industrial and mining activities, highlighting the urgent need for effective water resource management and conservation measures to prevent future environmental crises. By focusing on these municipalities, the study enables an in-depth analysis of the most affected and vulnerable areas, facilitating the development of targeted strategies to mitigate impacts and promote water sustainability across the region.

RESULTS AND DISCUSSION

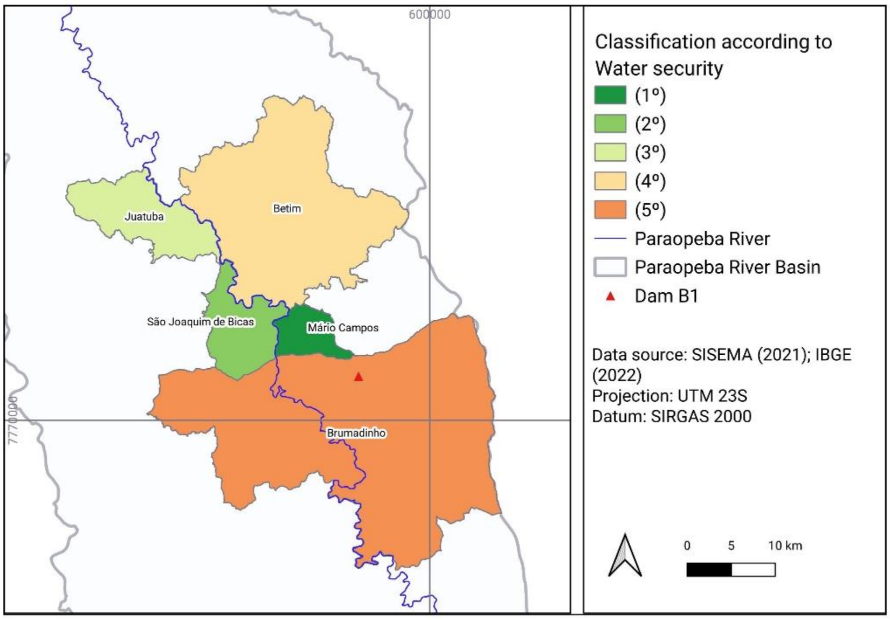
The analysis ranked the municipalities according to their levels of water insecurity, placing Brumadinho at the top, followed by Betim, São Joaquim de Bicas, Juatuba and Mário Campos (Table 3 and Figure 5).

Table 3 - Classification of municipalities according to the TOPSIS method

Municipality	Similarity Index
Brumadinho	0.5949
Betim	0.4873
Juatuba	0.2389
São Joaquim de Bicas	0.2364
Mário Campos	0.2317

Source: The authors (2024).

Figure 5 - Classification of municipalities in relation to water security



Source: The authors (2024).

Based on the relationship between the indicators presented in Table 4, a matrix was constructed to analyze the quality and quantity of surface and underground water supplies in the municipalities under analysis, aiming to understand how these indicators function in the middle portion of the Paraopeba River Basin (BHRP).

Municipalities classified at the highest level in the classification face greater water insecurity due to high rates of environmental accidents, water-borne diseases, water loss and low rates of sewage treatment. Municipalities in lower positions demonstrate better water security, with higher rates of sewage treatment, fewer environmental accidents and better native vegetation cover.

Brumadinho requires significant attention due to the high incidence of waterborne diseases (7,353), which reflects problems in the quality of sanitation and access to drinking water, negatively impacting public health and water security. The municipality presents a mixed performance in sewage collection (50.6%) and treatment (10.7%). Additionally, it leads in changed parameters according to the DN08 normative resolution of 2022, thereby further compromising water security.

Intense mineral exploration, with 306 active mining processes, places considerable pressure on water resources. The 24 tailings dams pose a significant risk, increasing the likelihood of environmental disasters. The collapse of the Córrego do Feijão dam is a clear example of the contamination risks that these structures can pose. Brumadinho also has the largest number of agricultural establishments (443) and the highest total water demand (643.36 million m^3/year), making it the largest water consumer in the region.

Table 4 - Indicators of the status of water quality and quantity

	Indicator	**Unit**	**Betim**	**Brumadinho**	**Juatuba**	**Mário Campos**	**São Joaquim de Bicas**
Driving force	**D.01**	% a.a.	0.69	1.14	2.75	1.57	2.5
	D.02	inhab/km²	1197.01	60.86	316.6	451.76	478.66
	D.03	nº	233	443	42	140	120
	D.04	%	47.64	43.54	52.76	53.02	49.82
	D.05	nº	48	20	27	13	52
	D.06	nº	123	306	32	35	66
	D.07	%	27.82	1.62	17.02	13.86	18.97
Pressure	**P.01**	m³/ year	87.03 million	643.36 million	1.90 million	98.69 million	2.58 million
	P.02	m³/ year	19.16 billion	2.56 billion	2.28 billion	882.13 million	2.76 billion
	P.03	nº	50	30	19	1	6
	P.04	nº	3	24	0	3	0
	P.05	-	0.735	0.712	0.705	0.678	0.674
State	**S.01**	-	61.3	65.3	48.1	47.4	53.3
	S.02	nº	2	4	sd	2	3
	S.03	nº	0.2085	0.4256	1.0486	1.6805	1.4739
	S.04	mm/ year	58.75	58.75	58.75	58.75	58.75
Impact	**I.01**	nº	125838	7353	6118	2946	2001
	I.02	nº	8	32	3	0	8
Response	**R.01**	%	76	50.6	32.39	13.8	36.5
	R.02	%	76.4	10.7	29.89	9.9	0
	R.03	%	1	1	1	1	0
	R.04	-	1	1	1	1	1
	R.05	nº	1721	833	226	169	192
	R.06	%	89.0	82.9	89.6	97.2	90.9

Source: The authors (2024).

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Despite exhibiting high efficiency in water supply (31.8, considered excellent), the high-water demand characterizes a potential water security problem in the context of climate change, which could lead to water shortages. The indicator S04, which is the exploitable water depth (mm/year), is high across all municipalities, signaling extensive groundwater exploitation, contributing to significant vulnerability.

The analysis consistently ranks Betim as the second municipality with the poorest water security performance. Betim faces high water insecurity due to several critical factors. During the 1990s, it experienced rapid population growth, driven by the influx of new industries, although by 2022, this rate had slowed down. However, despite this slowdown, Betim has remained the most densely populated municipality in the region, with 1,197.01 inhabitants per km^2. The combination of high population density with ongoing population growth indicates continued pressure on water resources, both in terms of demand and potential pollution from urban and industrial effluents (Honorato, P., 2024). With the high number of agricultural establishments (233) in Betim, plus the fact that 47.64% of the territory is dedicated to cultivated land, the municipality faces a significant strain on local water resources. Intensive agriculture and livestock farming require large volumes of water for irrigation and animal management, thereby heightening the risk of water security and pollution of water sources. This situation compromises water security, affecting both human water supply and the sustainability of the region's aquatic ecosystems. In addition to agricultural establishments, Betim has a considerable number of industrial establishments (48), and faces intense mineral exploration with 123 active mining processes, in addition to three dams. These activities place severe pressure on local water resources, increasing the water demand and the risk of contamination, thus compromising water security and the sustainability of aquatic ecosystems. The situation is further exacerbated by excessive water consumption (87.03 million m^3/year) and the treatment of large volumes of water (19.16 billion m^3/year).

Between 2014 and 2022, Betim recorded the highest number of environmental accidents (50), highlighting the need for more stringent supervision of potentially polluting activities to mitigate risks to water resources. Even with 1,721 inspections conducted from 2006 to 2023, it is clear that efforts need to be intensified to prevent accidents and safeguard water sources, which are crucial for both water supply and environmental sustainability.

Betim also presents the highest number of waterborne diseases (125,838), especially dengue (116,678), likely due to deficiencies in basic sanitation, inadequate solid waste management and insufficient urban drainage infrastructure. Although the indicators for sanitary effluent collection (76%), treatment (76.4%) and proper disposal of solid waste and selective collection have revealed positive results, the proliferation of disease-transmitting mosquitoes remains a significant challenge. There is a pressing need to intensify environmental education, and vector control efforts, and improve urban infrastructure to reduce these cases.

Betim has also presented poor efficiency in public water supply (50.90%), with significant water losses during the process. This is particularly concerning given the high demand for water in the municipality, emphasizing the urgent need for improvements in infrastructure and water resource management.

São Joaquim de Bicas faces significant challenges in water security, with a demographic density of 478.66 inhabitants/km^2 and a population growth of 2.5% p.a. The municipality treats 2.76 billion m^3 of water per year, but loses 57.7%, indicating inefficiency in the distribution system. The lack of sewage treatment (0%) and low regular collection rates (36.5%) negatively impact public health, as reflected in 2,001 cases of waterborne diseases. With 120 agricultural establishments and 49.82% of the territory under cultivation, the pressure on water resources is substantial. Improvements in infrastructure and water management are essential to ensure sustainability and to protect public health.

Juatuba, ranked fourth, faces moderate challenges in water security. With 19 environmental accidents and 6,118 cases of waterborne diseases, there is a clear need for improvements in environmental management and basic sanitation. The low sewage treatment rate (29.89%) affects public health, while the high rate of water loss (55.3%) during distribution reveals significant inefficiencies in the water infrastructure. The growing urbanization (17.02%) is a further strain on water resources, underscoring the need for sustainable urban planning. Juatuba treats 2.28 billion m^3 of water per year, with 89.6% of households connected to the supply network, reflecting good access to drinking water. However, improving infrastructure to reduce losses, making more efficient use of resources, and expanding sewage treatment are crucial to improve the efficiency of public healthcare and protect the environment.

Mário Campos, ranked in fifth place, faces lesser challenges in water security, with 2,946 cases of waterborne diseases attributed to deficiencies in basic sanitation and a low rate of sewage treatment (9.9%). Water losses (34.7%) indicate inefficiencies in the distribution system, and the increase in urbanized areas (13.86%) intensifies the demand for water. However, the municipality benefits from a high level of native vegetation cover (47.41%) and a significant amount of treated water (882.13 million m³/year). Protected areas (33.12%) reflect a commitment to preservation, demonstrating investments in environmental conservation and in the efficient management of water resources.

Thus, the integrated management of water resources must be strengthened, through participatory planning and management, ensuring the involvement of all stakeholders, including local communities, industries and farmers. The use of scientific data and analysis to inform policy decisions ensures that the measures adopted are grounded in the best practices and available evidence. Similarly, sustainability policies and environmental education are fundamental. The continuous monitoring and assessment of water quality and quantity, supported by advanced systems and automation technologies, are crucial for effective management.

FINAL CONSIDERATIONS

Using an interdisciplinary methodology, we have aimed to understand the dynamics of pressure and response within a river basin, assessing how socioeconomic and environmental factors influence the management of water resources.

The study has demonstrated the applicability of the DPSIR model in complex contexts, such as that of the BHRP, providing a foundation for public policies and management strategies that offer a holistic view of the environment. The importance was reiterated of integrated approaches, such as the DPSIR model, alongside multi-criteria analysis methods, such as TOPSIS, for diagnosing and managing water security. Understanding the driving forces and pressures on the environment and water resources can guide more effective and sustainable responses, which are essential for protecting water resources that are vital for socioeconomic development and sound environmental management in the region.

The results have demonstrated that the DPSIR model is effective in mapping interactions between human activities and environmental health, identifying the driving forces and pressures that impact water security. The application of specific indicators facilitated the analysis of the current state of water resources, highlighting critical areas that require intervention to mitigate risks of contamination and scarcity. Interpretation of the data has confirmed that pressures, such as increased industrial and mining activities and intensive land use are degrading the water quality of the region. This suggests that current responses have been insufficient and require more robust public policies and effective community engagement.

The municipalities of Brumadinho, Betim, Juatuba, São Joaquim de Bicas and Mário Campos were assessed for water security using the TOPSIS method, considering critical indicators and the existence of management plans.

The management plans (Plano Municipal de Gestão Integrada de Resíduos Sólidos – PMGIRS - Municipal Integrated Solid Waste Management Plan; Plano Municipal de Saneamento Básico – PMSB - Municipal Basic Sanitation Plan; Plano de Segurança Hídrica da Região Metropolitana de Belo Horizonte - PSH-RMBH - Water Security Plan for the Metropolitan Region of Belo Horizonte; Plano Diretor- PD - Master Plan, Plano Nacional de Recursos Hídricos – PNRH - National Water Resources Plan and Plano Diretor de Desenvolvimento Municipal – PDDMA - Municipal Development Master Plan), reinforce the commitment of the municipalities to water security. These plans provide a structured framework to address critical issues related to water, sanitation and waste management, essential for long-term sustainability and for mitigating the problems faced by each municipality.

The study faced limitations related to the accessibility of long-term data and the lack of specific indicators on local dynamics, such as the supply of mineral water and tanker water by Vale S.A., following the dam collapse. By 2022, Vale S.A had supplied around 3.9 billion liters of water to the riverside population, with 100 tanker trucks making daily emergency water deliveries (Vale S.A. 2022). Although this practice is well-known in the affected territories, this data is unavailable per municipality. Another valuable indicator for the analysis would be the number of riverside dwellers and fishermen who had to abandon their activities due to the ban on the use of raw water from the Paraopeba River.

These gaps have hindered a more accurate assessment of some responses and management strategies adopted in the region. Future research could provide a more in-depth study into local dynamics and gather primary data on indicators that describe in more detail the context of water security for the populations affected in the municipalities of the Paraopeba River Basin. Furthermore, it would also be of great value to develop methodologies that more effectively integrate climate variability and long-term anthropogenic impacts.

To address the challenges identified in water security in the Paraopeba River basin, it is essential to implement robust, innovative response strategies. Primarily, it is crucial to improve water collection and treatment infrastructure. Adopting advanced treatment technologies and expanding treated water reuse systems for agricultural irrigation and industrial processes can help to alleviate the pressure on natural water resources.

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Priscila Aparecida da Rocha Honorato: conception, data collection, data analysis, preparation of the manuscript, writing, discussion of results.

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Marcelo Antonio Nero: writing, review

Plinio da Costa Temba: review

Helder Lages Jardim: review.

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A Contribuição do Modelo FPEIR/TOPSIS no Diagnóstico Ambiental da Segurança Hídrica de Áreas Atingidas pela Barragem B1, Brumadinho, MG

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