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ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.61, n.1, p. 69 – 91, 12/2024
http://dx.doi.org/10.5380/raega.v61i1.95473

A model for selection of decentralized sanitary sewer systems for small municipalities

Modelo de seleção de sistemas de tratamento de esgoto sanitário descentralizados para municípios de pequeno porte

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http://dx.doi.org/10.5380/raega.v61i1.95473

Abstract

The precariousness of sanitation services in small Brazilian municipalities is exacerbated by technical and financial limitations. In these places treatment technologies need to be simple, sustainable, economically viable, and socially accessible. This work aims to propose a selection model for decentralized sewage treatment technologies for small municipalities. The PROMETHEE II multi-criteria method was used to rank the technologies with aid decision-making agents to prioritize technical, environmental, economic, and social criteria based on the characteristics of the sewer basins. After validating the method in the sewage catchment areas of four municipalities in Paraíba, the results showed that the constructed wetlands technology occupied the best position in 88.9% of the sewer basins. This technology stands out for its high organic matter and suspended solids removal efficiency, in addition to not generating sludge and performing well in terms of social criteria (odor production and vectors). The septic tank and septic tank + anaerobic filter alternatives ranked lower in the basins studied. The robustness of the method and the assignment of preferences to criteria for sewer basins with different classifications indicate that the model is replicable for small municipalities. Thus, the study contributes to the optimization of decision-making for sewage treatment systems, allowing the better use of resources, the reduction of vulnerabilities, and promotion of municipal development.

Keywords:
Environmental sanitation, Multicriterial model, PROMETHEE II.

Resumo

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A precariedade dos serviços de esgotamento sanitário em municípios brasileiros de pequeno porte acentua-se pela limitação técnica e financeira, sendo fundamental que as tecnologias de tratamento sejam simples, sustentáveis, economicamente viáveis e socialmente acessíveis. Desse modo, este trabalho tem por objetivo propor um modelo de seleção de tecnologias de tratamento de esgoto sanitário descentralizado para municípios de pequeno porte. Utilizou-se o método multicritério PROMETHEE II para o ranqueamento das tecnologias e o auxílio de agentes de decisão para a priorização de critérios técnicos, ambientais, econômicos e sociais, a partir das características das bacias de esgotamento". Por meio da validação do método para as bacias de esgotamento de quatro municípios paraibanos, os resultados mostraram que a tecnologia de *wetlands* construídos ocupa a melhor colocação em 88,9% das bacias. Essa tecnologia se destaca pelas taxas de eficiência de remoção de matéria orgânica e sólidos suspensos, além de não gerar lodo e possuir bom desempenho em relação aos critérios sociais (produção de odores e vetores). As alternativas de tanque séptico e tanque séptico + filtro anaeróbio obtiveram pior colocação no *ranking* das bacias estudadas. A robustez do método e a atribuição de preferência aos critérios para bacias com diferentes classificações, indicam que o modelo é replicável para municípios de pequeno porte. Portanto, o estudo contribui para a otimização da tomada de decisão de sistemas de tratamento de esgoto, propiciando melhor uso dos recursos, redução de vulnerabilidades, bem como o desenvolvimento municipal.
Palavras-chave:
Saneamento ambiental, Modelo multicriterial, PROMETHEE II.

I. INTRODUCTION

The complex dynamics of socioeconomic and cultural elements in today's society create various forms of relationships between human beings and the natural environment, often intensifying environmental impacts. Human occupation in predominantly rural environments or in areas of urban sprawl, with inadequate and irregular growth, brings with it problems related to precarious basic sanitation infrastructure, reflecting in limited health promotion and poor quality of life of the population (SENNA et al., 2023).

Achieving universal access to adequate and equitable sanitation and hygiene by 2030 and improving water quality by the year 2030 are among the Sustainable Development Goals (SDGs) established by the United Nations (UN). In Brazil, it is estimated that only 52.2% of the volume of waste water generated in 2022 was treated (BRASIL, 2023). In 2019, the National Basic Sanitation Plan (PLANSAB) estimated that about R$ 214,999 million would be needed to universalize sewer services in Brazil, and of this amount, R$44,369 million (20.64%) had to be allocated to the expansion/replacement of treatment systems.

In small municipalities, the vulnerability to the effects of the absence of a sanitary sewer system for effective collection and treatment of waste water is greater in rural areas and areas where traditional peoples and communities are established (CRUZ et al., 2019). The increased incidence of Diseases Related to

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Inadequate Environmental Sanitation (DRIES), reduced school performance of children, and reduced performance of workers are some of the consequences, generating losses in the economic, environmental and public health spheres (ROSSONI et al., 2020).

These areas often exhibit characteristics such as low population density, low payment capacity of users, and disorderly disposal of the effluent produced, usually close to water catchment areas for human supply (MORETI et al., 2021). These factors stimulate the search for decentralized sewage alternatives, which provide greater economic and social sustainability of the service based on the use of technologies with low operating and maintenance costs, operational simplicity, satisfactory rates of pollutant removal, and that use materials available in the region where they are to be implemented (MESQUITA et al., 2021; PERONDI et al., 2020; FIGUEIREDO et al., 2019).

However, the large range of sewage treatment processes and technologies make the decision-making process complex and costly. The selection of the most appropriate treatment in each situation should consider social factors, local conditions, the desired efficiency, and the cost/benefit ratio, including operating expenses. In small municipalities, low technical capacity, reduced budget structure, and overlapping employee activities impose the need for effective planning and management, requiring the adoption of methodologies that facilitate the decision-making process (MORETTI et al., 2021; NETO, 2021)

In recent years, multi-criteria methods have been used to solve complex problems. The Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) stands out among these methods for the ease of understanding of concepts and parameters related to the selection, simplifying the preference modeling process and, consequently, increasing the effectiveness of its application. Its use is preferable when criteria weights are defined and the ranking of performance of the alternatives is required (CARVALHO, 2022; ĐURDEVIC et al., 2022; GICHAMO et al., 2020; MAKAN et al., 2021).

Lima et al. (2014) pointed out that the method is robust and provides a perspicuous analysis of potential of alternatives, structuring the decision-making process in sanitation. Goffi (2022), who used the method for the selection of effluent treatment technologies in small communities and urban centers, concluded that PROMETHEE has high potential for reducing subjectivity in the determination of sewage treatment processes.

Several studies on the decision-making processes of sewage treatment technologies have already employed the PROMETHEE family of methods. Among them, those of Gichamo et al. (2020), Goffi (2022), Munasinghe-Arachchige et al. (2020), and Yahya et al. (2020) stand out. However, most of these studies were

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focused on centralized and urban systems. Thus, it is still necessary to search for decentralized alternative solutions in small communities and small municipalities, where there is ethnic and cultural diversity, land conflicts, and a diversified economy.

The objective of this study is to propose a model for the selection of decentralized sewage treatment systems in small municipalities using a multi-criteria analysis based on technical, environmental, economic and social criteria. The model takes into account the peculiarities of sewer basins, allowing its replication in different scenarios and locations. The proposed system will improve the quality of treatment processes by optimizing decision-making by managers and professionals directly or indirectly involved in the planning stages of the sewage treatment system of a municipality, leading to better use of resources and greater investment capacity.

II. Materials and Methods

To achieve the proposed objective, the methodological procedures involved four steps presented in the flowchart in Figure 1 and detailed ahead.

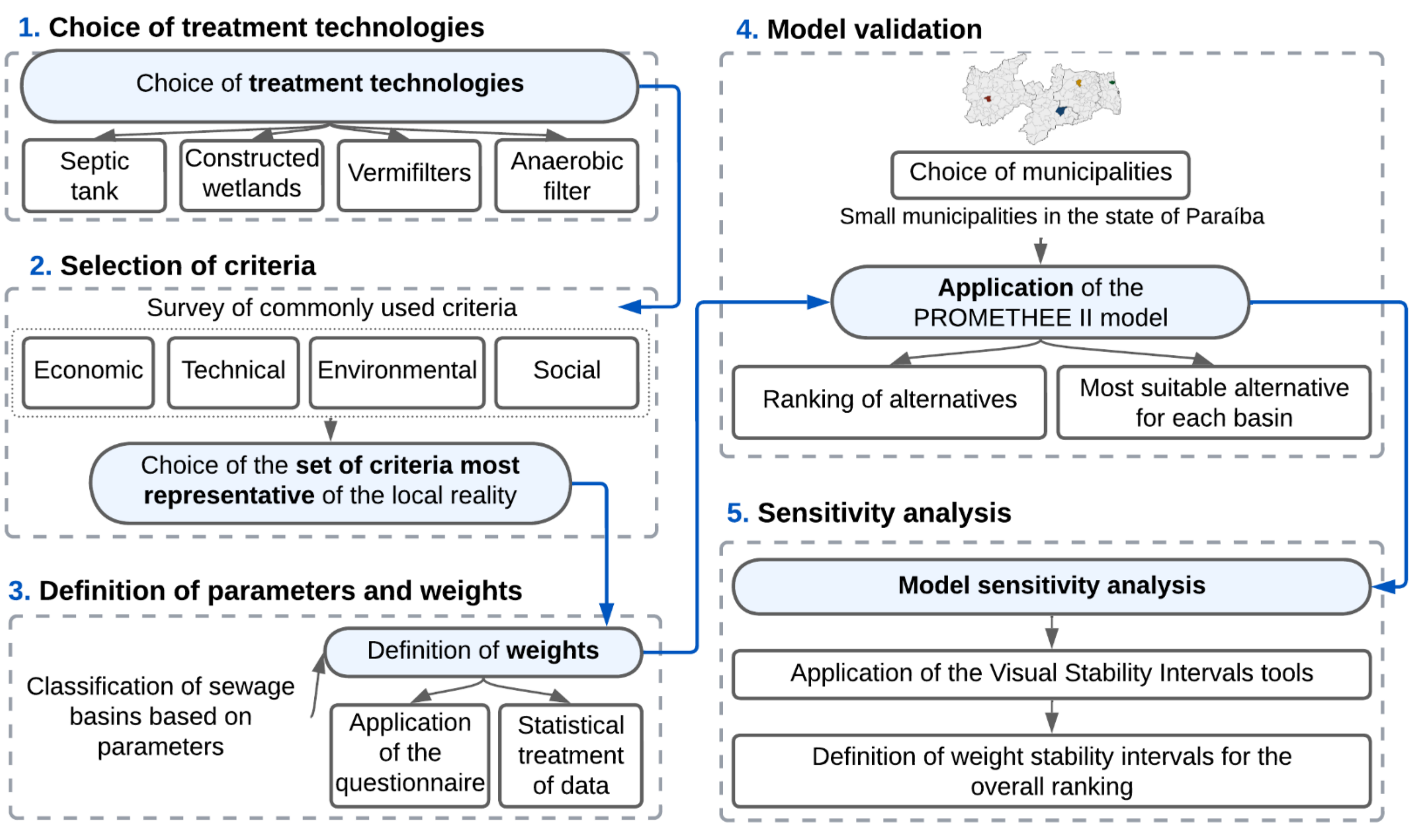

Figure 1 – Synthesis flowchart of the stages of the methodological procedures. Source: The authors (2024)

Choice of treatment technologies

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Based on the studies of Cruz et al. (2019), Tonetti et al. (2021) and Tres et al. (2022), in addition to septic tanks, which is the most common form of treatment used in isolated and rural areas, four solutions stand out with studies and implementation in national and international contexts: constructed wetlands, vermifilters, and anaerobic filter with alternative filter material. Box 1 presents the alternatives of semi-collective/collective treatment systems considered in the study.

Box 1 – Alternatives of effluent treatment systems considered

Alternatives	Treatment system	System description
A1	Septic tank	Community septic tanks are impermeable structures that promote the primary treatment of waste water, separating solid and liquid waste. The sedimentable solids settle at the bottom of the tank where they undergo anaerobic digestion while the clarified liquid is directed to another treatment and/or subsequent disposal. It has a low associated cost, but generates sludge and has low efficiency of removal of organic matter and suspended solids (ANDRADE et al., 2022).
A2	Septic tank + Anaerobic filter with alternative filter material	An anaerobic filter is an upflow biological reactor with a lower chamber and an upper chamber filled by a submerged filter support material onto which the biomass adheres or is retained, forming a biofilm responsible for sewage degradation. With the alternative filling, such as the bamboo rings and green coconut (*Cocos nucifera*) shell, it is possible to reduce the associated costs. This technology should be associated with a primary treatment method such as a septic tank. The limitations of the system are related to sludge generation and low reliability (TONETTI et al., 2021; TRES et al., 2022).
A3	Vermifilter	A vermifilter is a type of aerobic biological filter of downward and intermittent flow, generally composed of three layers: a top layer of organic substrate where detritivorous microorganisms and earthworm species develop; a second layer formed of gravel; and a third layer formed by crushed stone, serving as a support and providing aeration to the system, allowing the drainage of the clarified liquid to the outlet pipe located at the bottom of the reactor. It stands out for not absence of sludge generation, for its versatility, and low required area. However, it has higher associated costs (MADRID et al., 2019; SINHA et al., 2008).
A4	Constructed wetlands	Constructed wetlands consist of an artificial wetland built specifically for the treatment of wastewater, simulating and accelerating natural processes through the relationship between water, substrate, plants, invertebrate animals and microorganisms. Despite requiring very large spaces, they have advantages such as low cost of implementation and ease of construction and operation (PERONDI et al., 2020).

Source: authors (2024)

Selection of criteria

Having small communities and small municipalities in mind, we listed the criteria and weights defined in studies aimed at these sites, presented in Box 2, taking into consideration the adequacy in four axes: economic, technical, environmental and social. It is noted that most of the technologies considered in the older works are conventional. The system of constructed wetlands, which corresponds to an alternative treatment model, is present in all studies we analyzed. Based on literature data and considering the reality of

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small municipalities and the simplicity of measurement, a balanced set of criteria was chosen that allowed a holistic evaluation of the specified effluent treatment technologies.

After defining the indicators, the reference values were obtained from the analysis of specific works for the chosen treatment technologies. The studies of Cruz et al. (2019), Madrid et al. (2019), Sinha et al. (2008) and Von Sperling (2007), all developed in the context of small municipalities and decentralization of treatment, were taken as reference.

The National Construction Cost Index (NCCI), which corresponds to the annual inflation of construction products, was used for the economic criteria, which are based on different years, in order to standardize the cost values for the base year 2023. Annual NCCI values were obtained from Fundação Getúlio Vargas (FGV). In the case of criteria that do not have a quantitative scale, it was necessary to convert the quality associated with a quantitative score. Thus, qualities classified as low (+), medium (++/+++/++++) and high (+++++) were converted to correspond to scores of 1 to 5 points, respectively.

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Box 2 – Criteria, based on studies, for selection of the treatment systems evaluated

	Criteria/Authors	Margarido et al. (2012)[1]	Kalbar et al. (2012; 2013)[2]	Molinos-Senante et al. (2014)[3]	Molinos-Senante et al. [(4)]	Goffi (2022)[5]	Tres et al. (2022)[6]
ECONOMIC	Implementation cost	x		x	x	x	x
	Operation and maintenance cost	x		x	x	x	x
	Life cycle cost		x			x	
	Need for manpower		x				
	Required land area	x	x	x		x	x
TECHNICAL	Reliability	x	x	x	x	x	
	Durability		x			x	
	Replicability		x				
	Flexibility		x			x	
	Resistance to affluent variations and shock loading	x					
	Dependence on climatic variables	x					
	Soil	x					
	Simplicity of operation and maintenance	x				x	x
	Complexity of construction and operation						
ENVIRONMENTAL	Removal efficiency of organic matter and suspended solids				x	x	
	Organic matter removal efficiency	x		x		x	x
	Suspended solids removal efficiency	x		x			x
	Phosphorus removal efficiency			x	x	x	x
	Nitrogen removal efficiency	x		x	x	x	x
	Total coliform removal efficiency	x				x	x
	Energy consumption	x		x		x	
	Carbon footprint				x		
	Eutrophication		x			x	
	Global warming		x				
	Sustainable behaviors		x				
	Sludge production	x		x	x	x	
	Reuse potential			x	x	x	
	Product recycling potential			x	x	x	
SOCIAL	Odors	x		x	x	x	x
	Noise	x		x	x	x	
	Visual impact			x	x	x	
	Aerosols	x					
	Insects and worms	x				x	x
	Public acceptance		x	x	x		
	Social participation		x			x	

Treatment technologies considered by the studies: [1] Ponds, soil disposal, anaerobic reactors, activated sludge, biological filters; [2] Activated sludge, UASB reactor followed by facultative aerated pond, sequential batch reactor, constructed wetlands; [3] Constructed wetlands, ponds, prolonged aeration, membrane bioreactor, rotating biological contactor, drip filter, sequential batch reactor; [4] Constructed wetlands, prolonged aeration, membrane bioreactor, ponds, rotating biological contactor, sequential batch reactor, biological filter; [5] 41 technologies, including: ponds, constructed wetlands, septic tank, septic tank with anaerobic filter; [6] 11 technologies, including: septic tank with anaerobic filter and constructed wetlands. Source: authors (2024)

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Definition of parameters and weights

The characteristics of the sewer basins were considered for the development of the model, based on the use of associated parameters. According to CETESB (1988), four parameters considered relevant in the characterization of the basins of small municipalities were chosen: area available for the implementation of the sewage treatment plant (STP), urbanization, classification of the receiving body, and use of the water of the receiving body. The methodologies presented in box 3 were used to characterize the sewer basins according to the selected parameters.

Box 3 – Classification methodologies for sewer basins according to the selected parameters

Parameter		Methodology	Classification
P1	Area available for implementation of the STP	The area available for construction of the STP at the main valley bottoms of each sewer basin was determined with the aid of the QGis software and Google Earth satellite images. The available area is classified as high when it is higher than the treatment area with higher space requirements in the basin; and, it is said to be low when the area is greater than or equal to that of the treatment with lower space requirement and smaller than the treatment area with the second lowest space requirement.	▪ Low ▪ High
P2	Urbanization	The forms of occupation of the territory were identified based on the methodology of classification of urban areas of the Brazilian Institute of Geography and Statistics (IBGE), using the QGis software and Google Earth satellite images. Sewer basins with the highest number of buildings and trend of urban sprawl were classified as presenting high levels of urbanization, and those with the lowest number of residences, greater distances between housing lots, and large uninhabited green areas were classified as presenting low levels of urbanization.	▪ Low ▪ High
P3	Water use of the receiving body	The shape file of surface water availability of the National Water and Sanitation Agency (ANA) were superimposed on Google Earth satellite images with the aid of the QGis software and used to identify the name of the river and its uses.	▪ Human use ▪ Agricultural use
P4	Classification of the receiving body as to flow duration	With the help of historical satellite images from Google Earth, it was possible to check whether the water bodies present at the bottom of each sewer basins had a water surface in its course, classifying the river as perennial; or only at certain times, classifying the river as intermittent.	▪ Perennial ▪ Intermittent

Source: The authors (2024)

Through a questionnaire, decision-making agents were able to provide representative weights for each of the parameter classifications of the sewer basins. We opted for the use of decision-making agents who make up the preparation team of the Municipal Basic Sanitation Plans (MBSP) of 49 small municipalities in the state of Paraíba, Decentralized Execution Term number 003/2019, a partnership between the National Health Foundation (FUNASA) and the Federal University of Campina Grande (UFCG), including municipal technicians and members of the UFCG technical team with training in the areas of Civil and Environmental Engineering.

The agents assigned weights to the selected criteria on a scale from 0 to 4, depending on the judgment of the level of importance of the criterion for each classification of parameters. Thus, the value "0" was

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assigned for unimportant criteria; "1" for criteria with low importance; "2" for criteria with medium importance; "3" for criteria with high importance; and "4" for criteria with very high importance.

To ensure the consistency of the weights, the judgments were statistically treated using Kendall's rank correlation coefficient; weights with a significance level (p) of less than 0.05 were eliminated (HATEFI, 2023; GUO et al., 2023). The final weight of the criteria for each sewer basin is given by the sum of the weights assigned to the criteria in each of the classifications of the parameters related to the studied basin.

Model validation

To apply the method, we decided to work with the urban area of the Headquarters District of four small municipalities in the state of Paraíba (Brazil) participating in TED number 03/2019, in which there were no conventional effluent treatment systems, with or without a sewage collection network, as the application of alternative treatment systems could make the current system obsolete.

The map in Figure 2 shows the municipalities selected for the study, namely, Marcação, Casserengue, Cabaceiras, and Igaracy. In order to evaluate areas with different natural and cultural characteristics, municipalities from different mesoregions were considered, according to the regional configuration proposed by the Brazilian Institute of Geography and Statistics (IBGE). It should be noted that 88.10% of the population is indigenous.

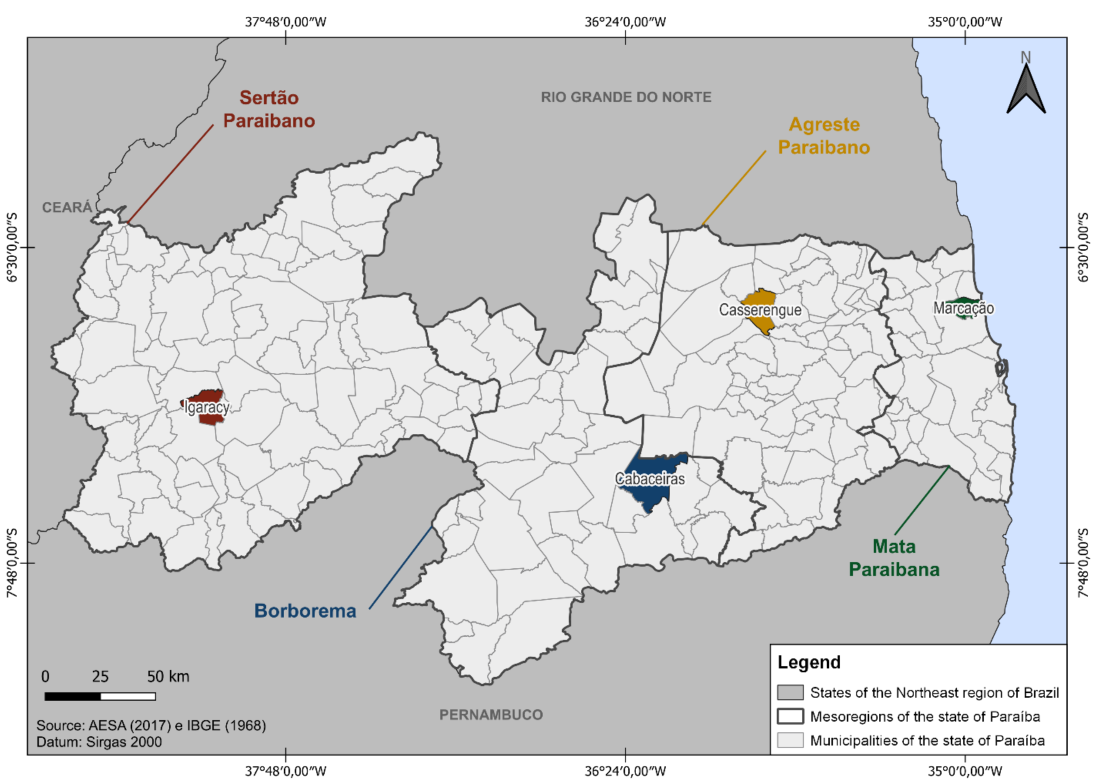

Figure 2 – Location of the municipalities studied in the state of Paraíba (Brazil). Source: The authors (2024)

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According to the technical-participatory diagnosis of the MBSP carried out in 2022, the coverage of the collective sewage collection and transport network in the urban area of the municipalities was 11% in Marcação, 18% in Casserengue, and 43% in Cabaceiras and Igaracy. The waste water collected was sent to large septic tanks or released in open spaces in nature. In areas where there was no sewer basin, households routed their sewage to rudimentary pits with dumping of gray water in the open.

The PROMETHEE II method, based on the methodology expressed by Brans, Vincke and Mareschal (1986), was used to identify the decentralized alternative with the best performance for the different sewer basins of the municipalities analyzed. Using the delimitation of the sewer basins and valley bottoms, available in Product D – Prognosis of Basic Sanitation of the MBSP of the municipalities, the weights were defined and the method was applied with the aid of the Visual PROMETHEE 1.4 - Academic Version software. The preference function of the "usual" type was considered (Goffi, 2022). The final classification of the alternatives was based on the calculation of the net flow *Q(a)*, with the best sewage treatment system being the one that presented the highest positive *Q(a)* value.

Sensitivity analysis

According to Fagundes et al. (2021), weights result from a subjective judgment of decision-making agents, and it is important to perform sensitivity analyses in order to see possible changes in ranking, allowing the decision maker to obtain information about the robustness of the chosen model.

The minimum and maximum values that the weights of each criterion for each sewer basin can assume were calculated, without any changes in the overall ranking. The larger the interval, the more robust is the model. Similar to the study by Munasinghe-Arachchige et al. (2020), the calculation of the sensitivity interval of the criteria weights was performed using the Visual Stability Intervals tool of the Visual PROMETHEE 1.4 - Academic Version software.

III. RESULTS AND DISCUSSION

Definition and weighing of criteria

Among the criteria for selection of effluent treatment technologies presented in Table 2, ten criteria, considered the most relevant in the literature, were chosen, as presented in Table 1. A small number of criteria was established because, according to Real et al. (2021), this simplifies the model and avoids the use of several redundant attributes, hindering the perception of the most significant characteristics of the problem.

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Table 1 – Criteria selected in the study

	Criteria		Description	Functions by treatment alternative			
				A1	A2	A3	A4
ECONOMIC	C1	Implementation cost (R$/inhab.)	Cost required for the construction of the treatment plant, including machinery, equipment, facilities and pipes.	92.15	241.89	316	149
	C2	Operation and Maintenance cost (R$/inhab.year)	Necessary cost with energy, personnel, chemicals, waste management and maintenance.	4.32	18.43	28.80	7.49
	C3	Required land area (m^2/inhab.)	Physical area required for the construction and installation of the STP.	0.04	0.20	0.02	3.00
TECHNICAL	C4	Reliability	Probability of mechanical failures of operation and process and the impact of failures on effluent quality.	4.00	3.00	4.00	4.00
	C5	Simplicity of operation and maintenance	It takes into account the level of skill and training required of the operator, difficulties involved in routine and emergency operations in the operation and maintenance of the system.	3.00	4.00	3.00	5.00
ENVIRONMENTAL	C6	Organic matter removal efficiency (%)	Ability of the system to remove biochemical oxygen demand (BOD) from the effluent.	32.50	82.50	90.00	85.00
	C7	Suspended solids removal efficiency (%)	Ability of the system to remove suspended solids (SS) from the effluent.	60.00	85.00	92.50	90.00
	C8	Sludge production (m^3/inhab.year)	Amount of sludge by-product produced by the treatment system.	0.24	0.60	0.00	0.00
SOCIAL	C9	Odors	Possibility of not emitting odors in the treatment process by the system.	2.00	2.00	4.00	2.00
	C10	Vectors	Possibility of not generating and attracting vectors (insects and worms) to the system, normally associated with the odor factor.	3.00	4.00	2.00	2.00

*Vermifilters (A3) were considered to be a type of biological filter. Source: Adapted from Von Sperling (2007), Sinha et al. (2008), and Madrid et al. (2019).

During the period from April 19 to May 3, the questionnaire was sent by email to 31 Decision-Making Agents (DMA) who make up the preparation team of the Municipal Basic Sanitation Plans of 49 small municipalities in the state of Paraíba (TED number 03/2019). Fourteen (45.2% of the total) of these questionnaires were answered, corresponding to a participation of 87.5% (7 DMA) of the members of the UFCG technical team and 30.4% (7 DMA) of the municipal technicians selected to participate in the study.

After application of the Kendall test, responses with weak pairwise correlation values and those strongly negatively correlated were eliminated. More than 50% of the decision judgments for criteria C1, C3, C6, C7, C8, C9 and C10 showed satisfactory correlation ($p>0.33$), with the best performance observed for indicator C10, where 14 responses (92.9%) were considered consistent. Criteria C2, C4 and C5 had less than 50% of the judgments with significant correlation ($p>0.33$), presenting a minimum of 5 consistent responses.

The highest number of responses with weak correlation ($p<0.05$) was observed in the questionnaires answered by municipal technicians (35.7%). This may be associated with the financial limitation and low institutional capacity of small municipalities, which have as consequences the lack of technical expertise of

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employees (MORETTI et al., 2021). The final weights of the criteria for each classification of parameters of the sewer basin, obtained after the exclusion of inconsistent values, are presented in Table 2.

Table 2 – Final weights of the criteria for each classification of sewer basins

Criteria/Parameters		Available area		Urbanization		Water use		P4 - Classification of the river as to flow	
		Low	High	Low	High	Human	Agriculture	Perennial	Intermittent
C1	Implementation cost	3.13	3.38	3.38	3.25	3.88	2.38	2.50	2.88
C2	Operation and maintenance cost	3.40	4.00	3.80	3.40	3.80	2.20	2.40	3.20
C3	Required land area	3.67	1.83	2.75	3.58	2.92	2.42	2.58	2.83
C4	Reliability	3.17	3.33	3.17	3.50	4.00	2.67	3.67	4.00
C5	Simplicity of operation and maintenance	3.60	3.20	3.60	3.20	3.40	2.20	2.40	3.20
C6	Organic matter removal efficiency	2.75	2.67	3.00	3.17	3.67	1.92	2.50	3.33
C7	Suspended solids removal efficiency	3.00	2.91	2.82	2.91	3.64	2.27	2.64	3.36
C8	Sludge production	3.40	3.00	3.10	3.40	3.70	2.50	2.80	3.40
C9	Odors	3.58	3.08	2.50	3.58	3.75	2.92	2.75	3.50
C10	Vectors	3.36	3.09	2.82	3.73	3.82	3.00	2.82	3.27

Source: The authors (2024)

In general, the weighting of criteria indicated greater importance for the economic (C1 and C2), technical (C4 and C5) and social (C9 and C10) criteria, as observed by Munasinghe-Arachchige et al. (2020), Lisbôa et al. (2020), and Tres et al. (2022). These results are in line with the study by Maciel et al. (2023), which indicates that treatment solutions in small municipalities must be of low cost, technically simple, and ensure the social well-being of the community.

Among the environmental criteria, sludge production (C8) was highly important in most classifications, due to the costs and complexity of its treatment and environmentally appropriate final disposal, as evidenced by Goffi (2022). In perennial receiving bodies and which are used for agriculture, the criterion has medium importance due to the possibility of reusing the sludge in agriculture.

In basins with receiving bodies classified as having intermittent flow and destined to human use, the environmental criteria (C6, C7 and C8) and the criterion C4 (reliability) were of high and very high importance. In rivers with intermittent flow, the capacity of purification of organic matter is lower, so that the low efficiency in the treatment of effluents affects the quality of water resources and promotes the increase of DRIES (SOARES; SANTOS, 2021). In receiving bodies with use intended for human consumption, treatment efficiency is indispensable to reduce the health risks and costs involved in the treatment of water for human consumption.

For basins with a low availability of area, the criterion 'required area' (C3) was considered very important, being assigned the maximum weight value, while basins with a high available area, the criterion C3

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http://dx.doi.org/10.5380/raega.v61i1.95473

had a lower associated weight. In highly urbanized basins, the reliability (C4), treatment efficiency (C6 and C7), and social (C9 and C10) criteria were of high to very high importance, considering that in these areas the volume of sewage generated is higher and the production of odors and vectors significantly affects the population (SALAMIRAD et al., 2021).

Classification of sewer basins and determination of associated weights

Figure 3 shows the delimitation of the studied sewer basins and Table 3 presents a summary with their classification according to the four characterization parameters. In all basins, the available area (P1) was evaluated as high, due to the availability of space in relation to the area required for the installation of the alternative, which requires large portions of the territory (constructed wetlands).

Table 3 – Classification of depletion basins in the urban area of the municipalities studied

Parameters		Sewer basins								
		Marcação		Casserengue			Cabaceiras		Igaracy	
		A	B	A	B	C	A	B	A	B
P1	Available area	High		High			High		High	
P2	Urbanization	High	Low	High	Low	High	High	Low	Low	High
P3	Water use	Human		Agriculture			Human		Human	
P4	River flow	Perennial		Intermittent			Intermittent		Intermittent	

Source: The authors (2024)

Urbanization (P2) showed significant variation among basins, classified as high in the majority (55.6%). This category was characterized by the presence of commercial and service activities, smaller distance between housing lots, and expansion trends. In basins with low urbanization, there was a greater distance between housing lots, presence of areas with agricultural activities, green areas and uninhabited areas, indicating a rural-urban transition character, according to Gomes et al. (2020).

With regard to water use (P3), it was observed that, with the exception of the municipality of Casserengue, the receiving bodies of the evaluated basins are used to supply water for human consumption. In Casserengue, agricultural use was identified through satellite images (Figure 3); presence of agricultural and cattle raising practices was found near water sources. As for the river flow classification parameter (P4), the evaluation of the satellite images in Figure 3 indicated a predominance of basins with receiving bodies presenting intermittent flow, typical of the Brazilian semiarid region. Specifically in Marcação, rivers were classified as perennial due to coastal geological and geomorphological characteristics, in line with the rainy tropical climate of the region (FUNASA/UFCG, 2022).

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http://dx.doi.org/10.5380/raega.v61i1.95473

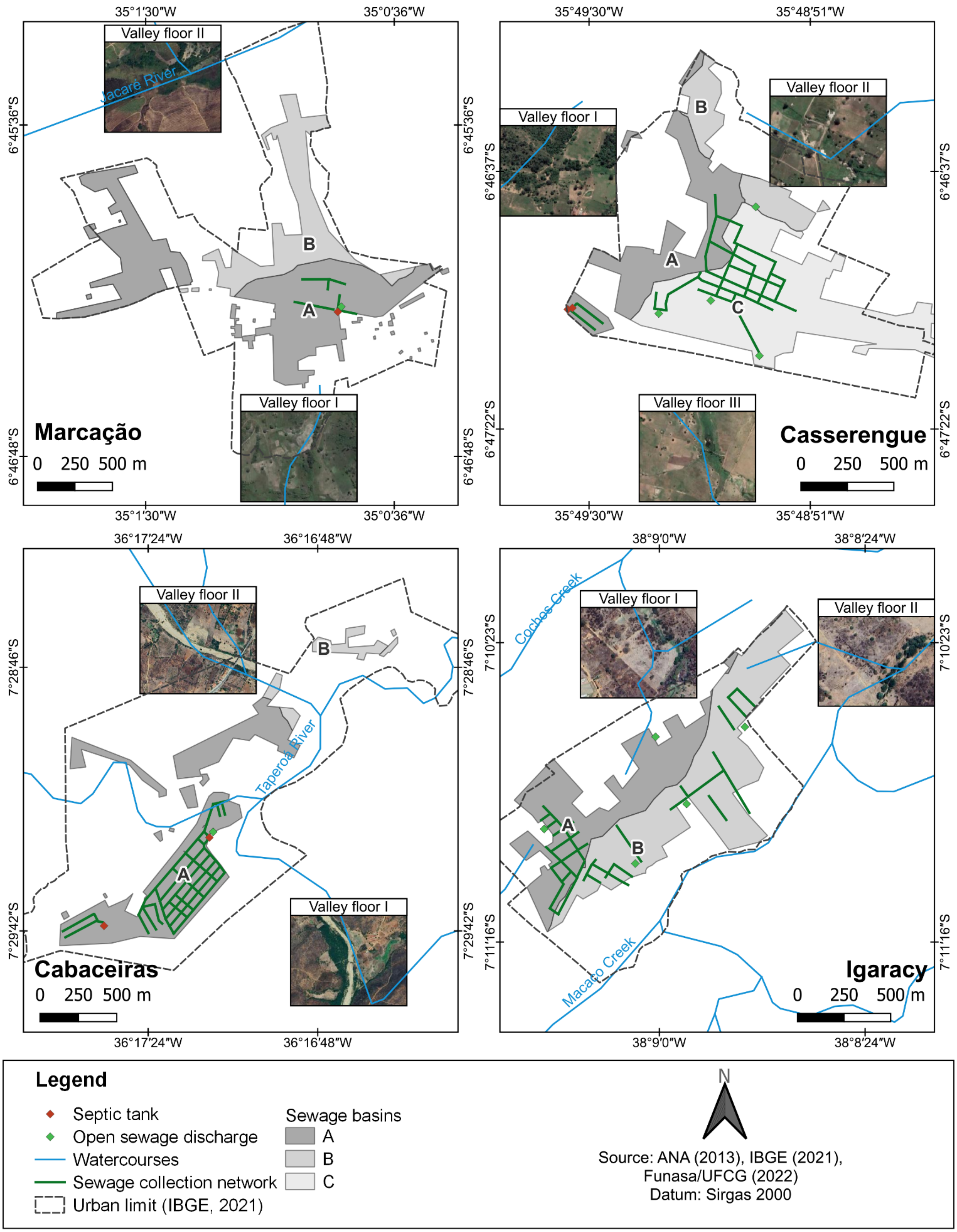

Figure 3 – Delimitation of the sewer basins of the urban area of the municipalities studied. Source: The authors (2024)

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http://dx.doi.org/10.5380/raega.v61i1.95473

Based on the classifications of the sewer basins of the municipalities (Table 3) and based on Table 2, weights were assigned to the criteria, as shown in Table 4.

Table 4 – Final weights of the criteria for the sewer basins of the urban area of the Headquarters District of the municipalities studied

Criteria		Sewer basins								
		Marcação		Casserengue			Cabaceiras		Igaracy	
		A	B	A	B	C	A	B	A	B
C1	Implementation cost	3.20	3.13	3.04	2.97	3.04	3.34	3.27	3.27	3.34
C2	Operation and maintenance cost	3.19	3.11	3.05	2.97	3.05	3.34	3.26	3.26	3.34
C3	Required land area	3.16	3.06	3.03	2.93	3.03	3.31	3.21	3.21	3.31
C4	Reliability	3.23	3.14	3.08	2.99	3.08	3.39	3.30	3.30	3.39
C5	Simplicity of operation and maintenance	3.16	3.07	3.03	2.94	3.03	3.33	3.24	3.24	3.33
C6	Organic matter removal efficiency	3.18	3.05	3.05	2.92	3.05	3.35	3.22	3.22	3.35
C7	Suspended solids removal efficiency	3.23	3.08	3.12	2.97	3.12	3.38	3.24	3.24	3.38
C8	Sludge production	3.29	3.10	3.21	3.02	3.21	3.44	3.25	3.25	3.44
C9	Odors	3.33	3.08	3.27	3.02	3.27	3.48	3.23	3.23	3.48
C10	Vectors	3.36	3.14	3.27	3.05	3.27	3.48	3.25	3.25	3.48

Source: The authors (2024)

Application of PROMETHEE II

For the selection of sewage treatment systems, the values of criteria C1, C2, C3 and C8 were minimized because technology improves as the values of these criteria decrease. The values of the other criteria were maximized. The ranking of alternatives by sewer basin along with the associated net flow *Q(a)* is shown in Table 5.

Table 5 – Ranking of alternatives by sewer basin

Ranking		Sewer basins								
		Marcação		Casserengue			Cabaceiras		Igaracy	
		A	B	A	B	C	A	B	A	B
1st	Alternative	A4	A3	A4	A4	A4	A4	A4	A4	A4
	Q(a)	0.1961	0.1616	0.1946	0.1982	0.1946	0.1976	0.2015	0.2015	0.1976
2nd	Alternative	A3	A4	A3	A3	A3	A3	A3	A3	A3
	Q(a)	0.1015	0.1333	0.1049	0.0986	0.1049	0.1025	0.0970	0.0970	0.1025
3rd	Alternative	A1	A1	A1	A1	A1	A1	A1	A1	A1
	Q(a)	-0.0335	-0.0285	-0.0364	0.0313	-0.0364	-0.0350	-0.0307	-0.0307	-0.0350
4th	Alternative	A2	A2	A2	A2	A2	A2	A2	A2	A2
	Q(a)	-0.2640	-0.2664	-0.2631	-0.2655	-0.2631	-0.2652	-0.2678	-0.2678	-0.2652

Source: The authors (2024)

The data in Table 5 indicates that the alternative A4 (constructed wetlands) presented the best placement in the ranking in the basins studied, with the exception of basin B of the municipality of Marcação, where the alternative A3 (vermifiltro) ranked first. Both technologies stand out for the absence of sludge production and for their efficiency in the removal of biochemical oxygen demand (BOD) and suspended solids (SS). Similar to what was observed by Gichamo et al. (2020) and Tres et al. (2022), the good performance of

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wetlands in the ranking is associated with their low cost, simplicity of operation and maintenance, and good performance in relation to social criteria (production of odors and vectors). Although this solution has the larger area required for installation, all the basins studied presented large areas available for implementation of the STP.

Despite the better ranking of the alternative A3 (vemifilters) in the sewer basin B in Marcação, the net flow value associated with alternatives A3 and A4 was very close, which actually indicates a good placement of both solutions in the ranking. The alternative A3 presents better treatment efficiency values, important for receiving bodies which are used for human supply, and lower chance of generating odors. However, the use of vermifiltration requires greater investments associated with the implementation, operation and maintenance of the system.

The Resolution number 430/2011 of the National Environmental Council (CONAMA) determines that the minimum removal of removal of BOD and SS has to be equal to at least 60% and 20%, respectively, which indicates that the technologies A3 and A4 comply with the legislation. According to the United States Environmental Protection Agency (USEPA, 2012), the effluents treated by these two alternatives, after disinfection, could be used for irrigation of commercially processed food crops, orchards, non-food crops, pastures for dairy herds, cereals, fibers and grains. The reuse of effluents in agricultural areas near the studied sewer basins ensures an increase in water supply for other activities and the recycling of nutrients, in addition to bringing socioeconomic benefits for the community.

Septic tanks (A1) occupy the third place in the ranking of all sewer basins. According to the National Basic Sanitation Survey (IBGE, 2010), 33.3% of municipalities in Paraíba that have sewage treatment use septic tanks, being the most adopted solution in the state. Although this alternative presents the lowest costs, it generates more odors and has lower effluent treatment efficiency. Due to its difficulty in satisfying effluent discharge standards (GOFFI, 2022), septic tanks do not perform well in most basins, where there is a predominance of receiving bodies with intermittent flow and whose water is destined for human consumption.

In the sewer basin A of the urban zone of Marcação, Casserengue and Cabaceiras, there are septic tanks installed. In these places, effluent treatment can be complemented by associating technology with the option placed in the first position in the ranking (constructed wetlands), promoting higher pollutant removal efficiency.

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The worst performance was found for the alternative A2 (septic tank + anaerobic filter). The high production of sludge, greater possibility of generating odors, and lower reliability compared to other technologies are factors that contributed to the low placement of this alternative in the ranking. Reduced reliability is associated with the risk of clogging the support medium (CRUZ et al., 2019). Furthermore, due to the need to remove sludge, the technology has additional transport and treatment costs associated, which becomes a problem in small municipalities where the financial resources are limited and users have low payment capacity (MORETTI et al., 2021).

Sensitivity analysis

The stability ranges by criterion and sewer basin are shown in Table 6. In general, the intervals had an overall amplitude between 0 and 33.84 (0.00 to 100.00% of the sum of the criteria weights) and an average amplitude of 0.50 to 11.92 (1.58 to 37.26%). In the study by Makan et al. (2022), the intervals were considered sufficiently wide, with a percentage of weights above 18.84%. The widest range found by Munasinghe-Arachchige et al. (2020) was of 0.00% to 34.90%. Thus, the results obtained in this study indicate the robustness of the model.

Table 6 – Stability intervals of criteria weights

Criteria	Stability intervals by sewer basin for the overall ranking								
	Marcação		Casserengue			Cabaceiras		Igaracy	
	A	B	A	B	C	A	B	A	B
C1	0.97-5.04	0.00-3.71	1.01-4.89	0.80-4.61	1.01-4.89	1.00-5.30	0.79-5.02	0.79-5.02	1.00-5.30
C2	0.96-5.03	0.00-3.69	1.02-4.90	0.80-4.61	1.02-4.90	1.00-5.30	0.78-5.01	0.78-5.01	1.00-5.30
C3	0.00-4.48	2.66-6.08	0.00-4.24	0.00-4.20	0.00-4.24	0.00-4.69	0.00-4.66	0.00-4.66	0.00-4.69
C4	0.00-32.33	0.00-30.96	0.00-31.15	0.00-29.78	0.00-31.15	0.00-33.84	0.00-32.47	0.00-32.47	0.00-33.84
C5	1.40-8.63	0.07-3.54	1.43-8.23	1.23-8.03	1.43-8.23	1.49-9.04	1.29-8.84	1.29-8.84	1.49-9.04
C6	1.07-6.81	1.81-10.39	0.92-6.39	1.05-6.41	0.92-6.39	1.10-7.15	1.22-7.18	1.22-7.18	1.10-7.15
C7	0.00-10.71	1.84-10.41	0.00-10.23	0.07-9.94	0.00-10.23	0.00-11.20	0.14-10.91	0.14-10.91	0.00-11.20
C8	0.00-32.33	0.00-30.96	0.00-31.15	0.00-29.78	0.00-31.15	0.00-33.84	0.00-32.47	0.00-32.47	0.00-33.84
C9	0.06-5.25	2.47-30.96	0.00-5.03	1.31-4.88	0.00-5.03	0.00-5.50	0.13-5.35	0.13-5.35	0.00-5.50
C10	0.00-6.81	0.00-7.02	0.00-6.72	0.00-6.12	0.00-6.72	0.00-7.15	0.00-6.56	0.00-6.56	0.00-7.15

Source: The authors (2024)

Criteria C4 (Reliability) and C8 (Sludge production) had the largest stability interval (0.00 to 100.00%), which indicates that they can be altered without changes in the overall ranking. The other criteria were more sensitive to changes in their weights, particularly the economic criteria C1 (Implementation cost), C2

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http://dx.doi.org/10.5380/raega.v61i1.95473

(Operation and maintenance cost) and C3 (Required land area), which are more important according to the weighting attributed by the decision-making agents. Only in basin B of the municipality of Marcação did the criterion C9 (Odors) assume a wide interval, ranging from 2.47 to 30.96 (7.99% to 100.00%), due to its importance in the classification of the alternatives of this basin.

When the model was applied, constructed wetlands led the ranking in most criteria. However, outside the stability intervals of the criteria weights, this alternative remains in first place only for criteria C5 (Simplicity of operation and maintenance) and C7 (Efficiency of removal of suspended solids), for which the wetlands present excellent performance in relation to the other treatments (Table 1). The technology septic tank led the ranking in the criteria C1 and C2, in view of the lower cost associated with it, while the alternative A4 (septic tank + anaerobic filter) assumed better positions in the criterion C10 (Vectors). Finally, the alternative A3 (vermifilter) was first placed in the criteria C3 and C9 due to the smaller area required and the reduced emission of odors.

IV. Conclusions

Based on the economic, technical, environmental and social criteria selected and weighted according to the characteristics of the sewer basins in the municipalities, it was determined that the technology constructed wetlands (A4) presented the best overall performance. The criteria of costs, simplicity of operation and maintenance, and minimization of odors and vectors contributed significantly to this result. Alternatives A1 (Septic tank) and A2 (Septic tank + anaerobic filter) held the worst placements in the ranking due to high sludge generation rates and lower treatment efficiencies. In view of the existence of septic tanks in the urban area of Marcação, Casserengue and Cabaceiras, the association of technologies can be considered a way to promote the improvement of treatment efficiency.

The work developed here can be replicated in any sewer basins of small municipalities, taking into account the differentiated weighting according to the classifications of parameters that characterize the basins. Moreover, the sensitivity analysis indicates that the developed model is robust.

With the application of this selection model, it is possible to promote the optimization of decision making by managers, leading to better use of resources, expanding the investment capacity, ultimately contributing to reduce poverty and improve the health of the population and the quality of the environment. The model can be improved by adding other sewage treatment technologies applicable to small municipalities

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http://dx.doi.org/10.5380/raega.v61i1.95473

and by including other recurring social and environmental criteria, such as public acceptance, the possibility of reusing the treated effluent, and the financial gains from the production of biogas.

Acknowledgments

The authors thank the technical and financial support of the State Superintendence of the National Health Foundation (FUNASA) of Paraíba, based on the Decentralized Execution Term number 03/2021, a partnership between FUNASA and the Federal University of Campina Grande entitled "Technical training and preparation of the draft of the Municipal Basic Sanitation Plans (PMSB) of 50 selected municipalities in the state of Paraíba".

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https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.61, n.1, p. 69 – 91, 12/2024
http://dx.doi.org/10.5380/raega.v61i1.95473