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Parsimonious cumulative process-based workflow for early sanitation infrastructure evaluation (CPESI): Case study of Riohacha, Colombia

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ABSTRACT

In small and medium-sized cities from developing countries, the early selection of integrated wastewater management systems is challenging due to the lack or limitations in the availability of basic information and skilled professionals. This study presents CPESI, a cumulative processes-based parsimonious workflow for early evaluation of sanitary infrastructure. CPESI is aimed to provide a simple, objective, and systematic analysis framework at the early stages of development of sanitary systems in underdeveloped nations. CPESI was applied to evaluate sanitation system alternatives for Riohacha (Colombia) in three stages, namely, (1) an initial assessment of citizens acceptability of the alternatives and analysis of basic laboratory testing; (2) a process analysis and technical-economic evaluation of alternatives based on CAPEX and OPEX indicators; and (3) engineering judgment to select the most viable alternative through multi-criteria evaluation. Our results suggest that CPESI could be highly replicable in developing countries and that it has the potential to expedite the alternatives assessment process when compared to data-intensive methods and expert requirements. Several researchers have highlighted the need to develop tools suitable to evaluate SDG 6 in developing nations. We believe that CPESI has the potential to contribute to that end.

1. Introduction

Although globally 80% of wastewater is discharged into the environment without any type of treatment; in developing countries this practice reaches nearly 95% (World Bank, 2020). Thus, these discharges represent a critical societal problem worldwide and, as such, SDG 6 of the UN Water, 2020 Agenda for Sustainable Development defines the targets and their respective indicators to achieve universal and equitable access to sanitation services (United Nations, 2015). To this end, targets 6. a (support developing countries for the expansion of the referred services) and 6. b (support and strengthen the participation of local communities to improve the management of services) are also identified as means of implementation of SDG 6 (United Nations, 2017). Likewise, the Organization for Economic Co-operation and Development, OECD, and the World Health Organization, WHO, are identified as supranational agencies that guard the fulfillment of SDG 6. a and SDG 6. b (Herrera, 2019). Several researchers have highlighted that the main challenges facing developing countries are improving the management of sanitary infrastructure at a subnational level (Herrera, 2019), building capacities to obtain the right amount of highly qualified human resources to improve sanitary infrastructure (Suriyanarayanan, 2015; Leal Filho et al., 2020); and having data in adequate length and resolution for an effective management and decision making on the development of sanitary infrastructure (Guppy et al., 2019; Leal Filho et al., 2020).

Colombia, an upper middle-income developing country, has been a member of the OECD since 2020 and exhibits one of the highest levels of inequality in the world and the second highest in Latin America and the Caribbean (World Bank, 2021). As such, it presents a high disparity in the quality of water and sanitation services. For example, in rural areas only 74% have access to potable water, while in urban areas it reaches 97% (Minvivienda, 2020). Thereby, Colombia has established as a goal to achieve 68% of urban domestic wastewater treatment and reuse 10% of treated domestic wastewater by public water service providers by 2030 (DPS, 2020). Currently, the country has limitations in the elimination of pharmaceutical contaminants from hospital wastewater (Serna-Galvis et al., 2022), management of organic waste from wastewater (Fajardo et al., 2016; Meneses-Jácome et al., 2015), and investing

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approximately US$ 2 billion to close this sanitation infrastructure gap by 2030 (Brichetti et al., 2021) among others.

This contribution presents a parsimonious decision-making methodology (termed herein Cumulative Processes-Based Parsimonious Workflow for Early Evaluation of Sanitary Infrastructure, CPESI) for the evaluation of wastewater treatment alternatives applicable to developing countries. It is based on the well-established Leopold matrix but requires relatively less data compared to other methodologies (e.g., Batelle-Columbus, map overlay, life cycle analysis, etc). CPESI is applied to a treatment plant planned for the city of Riohacha, capital of the department of La Guajira. This department is in the Colombian Caribbean and has one of the lowest human capital indexes in the country (World Bank, 2021)). The city of Riohacha does not currently have a wastewater treatment system and, therefore, municipal wastewater is discharged directly into the sea without any treatment, thus degrading the coastal ecosystem (Invemar, 2008; Findeter, 2019).

To solve the aforementioned problem and reduce pollution in the coastal zone of Riohacha, it is planned to implement a series of environmentally friendly sanitation alternatives (for example, the combined use of clean energy and membrane technologies), to treat wastewater and/or give them a better final disposal or reuse them, following what is indicated in the Colombian regulation such as the 0631–2015 and 1207–2014 resolutions (Minambiente, 2014, 2015). The results obtained allow observing the potential of CPESI as an objective and highly applicable tool in other cities of Colombia or those of countries in the Latin American sphere or other developing countries. Specifically, it seems reasonable to state that the methodology could clearly contribute to decision making in the primary stages of sanitary infrastructure development (i.e., analysis of alternatives and early decision making).

2. Data and methods

2.1. Study area

2.1.1. Geoenvironmental conditions

The study area is located within the geographic limits of the Riohacha district (11° 33′ N, 72° 55′ W), Colombia. This district has an area of 499,400 ha, of which 1500 ha are occupied by a set of rural settlements. The climatological classification of the study area according to the Koppen-Gelger scheme (Fig. 1a) corresponds to a hot arid steppe with average annual radiation of 4.5–6.0 kWhm^{-2}, average annual precipitation of less than 1086 mm, and temperature ranging 30°C–45 °C. Riohacha has an extension of 46 km of coastline (Fig. 1b) with a bathymetric depth of ~4.1 m at ~450 m from the coastline. The study area also exhibits an intermediate seismicity risk (NSR, 2010; UNGRD, 2012).

2.1.2. Socioeconomic conditions

La Guajira is one of the Colombian departments exhibiting the highest monetary poverty, with 67.4% exceeding the national monetary poverty rate (39.3% in 2021), thus positioning it as the second poorest department (DANE, 2018; CCG, 2021; PNUD, 2021; Monroy et al., 2022). The main commercial activities of the District of Riohacha are tourism, livestock, and fishing, showing a monetary poverty index of 56.6%, thereby constituting the second capital with the highest poverty in Colombia (DANE, 2018).

2.2. Data

2.2.1. Limitations of existing environmental data in Colombia

The collection of environmental observations in Colombia is centralized by the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM), a government agency. Most water bodies are assessed by IDEAM once or twice a year (Winton et al., 2022). Therefore, there is a high uncertainty in such observations, especially in remote rural areas (World Bank, 2020). In addition, currently there is no strict regulation for the improvement of the country environmental data quality (Duarte Jaramillo, Mendoza Atencio, Jaramillo Colorado and González Álvarez, 2021). This situation is exacerbated by the existence of small urban areas that do not have basic sanitation services, which do not have data for the provision of sanitation infrastructure as well (Duarte Jaramillo, Mendoza Atencio, Jaramillo Colorado and González

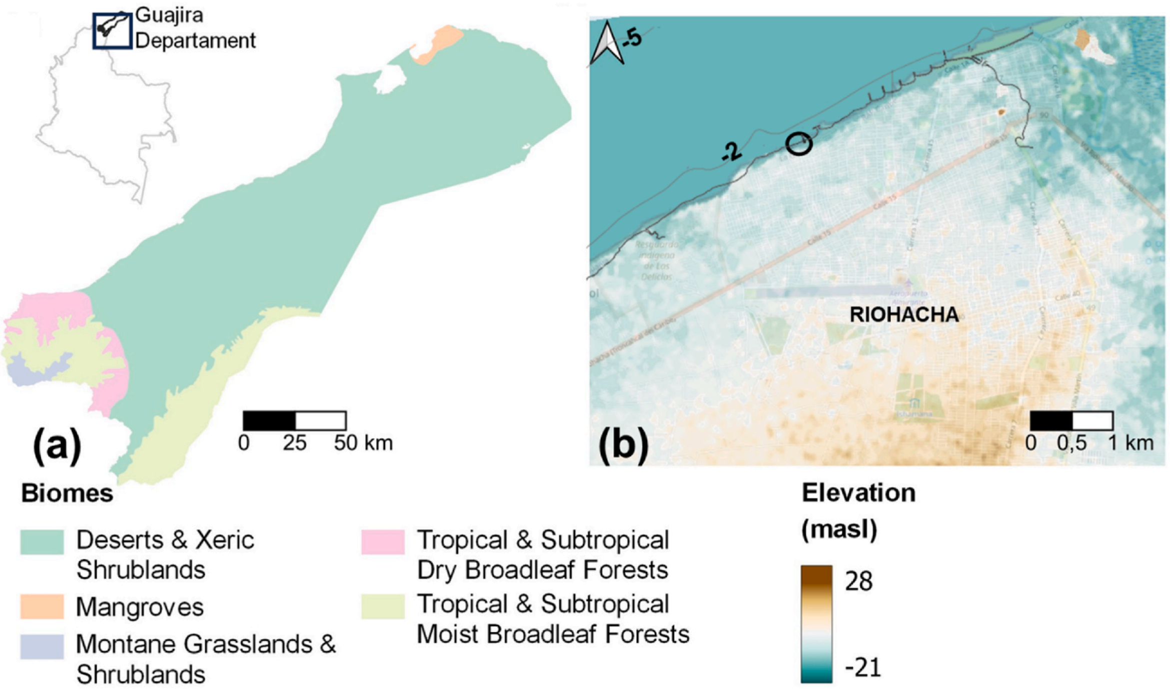


Fig. 1. (a) Location of the study area within the geographical limits of the La Guajira department and the climatic classification according to the Koppen-Gelger scheme (Dinerstein et al., 2017); (b) Inset of the coastal section presenting topographic and bathymetric contours at Riohacha, and the location of the discharge point (black circle) shown at Fig. 2a.

Álvarez, 2021). The environmental data assessment carried out in this study indicates that unfortunately such is the case of the Riohacha District, which lacks sufficient observations, in terms of length and resolution, that may allow for a detailed wastewater analysis.

In these cases, under the Colombian environmental regulation, water quality characterization is conducted using the following metrics: the Risk Index for Drinking Water Quality, IRCA, and the Participatory Action Research, IAP (Martínez-García et al., 2019). These parameters subsequently guide the design of wastewater treatment plants. In smaller urban units such as the District of Riohacha, a minimum number of physicochemical and microbiological parameters (Table 1) must be used to that end.

2.2.2. Field program to obtain the minimum design data

Broader-scale studies show that COD, BOD, and suspended solids indices indicate that seawater in the study area is highly polluted by untreated wastewater discharges (CORPOGUAJIRA, 2019). However, contamination by pesticide residues or metals was not identified in the study area (Invemar, 2019). In addition, a very limited amount of data was provided by the Riohacha sanitation utilities company (ASAA). Therefore, to verify the data provided by ASAA and to obtain primary information, point samples were taken from the discharge site (Fig. 2a) and with the portable pH, conductivity (ORP) and temperature meter these first data were taken in situ following the standard method regulations regarding the correct way to collect, store and transport the samples (Fig. 2b). Subsequently, the samples in question were analyzed in the laboratory of the Universidad del Norte (Barranquilla, Colombia).

3. The CPESI methodology

The Cumulative Processes-Based Parsimonious Workflow for early Evaluation of Sanitation Infrastructure (CPESI) presented herein focuses on the initial analysis of alternatives to help wastewater management for those areas that do not have sufficient information or baselines to allow a more detailed analysis of water quality characteristics and other parameters of interest. Fig. 3 presents the sequence of the main steps that define CPESI and a summary of the related actions when applied to the analysis of alternatives for the design of wastewater treatment plant for the District of Riohacha.

i. Initial evaluation: In this step we strongly recommend conducting a social analysis of the acceptability of the proposed sanitation systems by the community of beneficiaries. It stems from the fact that the participatory approach is essential for strategic planning and implementation of sanitation projects, specially within developing nations (Starkl, M., Brunner, Das and Singh, 2022) To this end, it is advisable to perform online or in-person surveys to map the perspectives of the beneficiaries. In this stage it also necessary to map all the existing basic data of water quality measurements in receiving water bodies and existing sanitation infrastructure, and statistics of sanitation supply that may be embedded in technical reports, printed documents in public agencies libraries, etc. We recommend verifying the measurements of wastewater descriptors (e.g., flow rate, BOD, COD) provided by the public/private sanitation management companies through basic field sampling and subsequent laboratory analysis. Thus, a first iteration to select a set of basic wastewater treatment alternatives can then be carried out.

ii. Process analysis: This step requires conducting an initial environmental analysis (i.e., scoping) to better select the wastewater treatment alternatives—e.g., activated sludge system, submerged membrane bioreactor (MBRs), submarine outfall—based on a matrix diagnostic methodology. An inspection of the potential locations of alternatives may be advisable. In it, the condition of the fauna, flora, air and social demands can also be verified. By applying a decision-making tool, like for instance expert judgment, both negative and positive impacts can be analyzed. At this stage, it is recommended to carry out a technical-economic analysis to verify the feasibility of the wastewater treatment alternatives by means of the CAPEX (i.e, initial investment) indicators resulting from the pre-dimensioning (i.e., quantities of work, materials, and labor) of each alternative and the OPEX (operation and maintenance cost) associated to the surveillance, maintenance of the essential systems and energy cost. In addition, an analysis of the energy system must be carried out. This is important because if there is a deficient and fluctuating energy source, the operation of the system would be negatively compromised. In the study area, for instance, there is a potential renewable energy source of average solar radiation of 6.0 kWh/m^2 (IDEAM, 2018), which could be used to optimize this system and contribute to the environment and technological advancement of sanitation infrastructure supply.

iii. Engineering evaluation based on the CPESI methodology. CPESI focuses on the early identification of environmental, social, cultural, and economic impacts that may induce overheads at the project execution, operations, or closure. It is based on quick and low-cost actions that allow for a comprehensive evaluation of projects from different perspectives. It is based on the combined application of expert evaluations (technical and non-technical), environmental analysis through impact scale processes (i.e., scoping) and a multi-criteria analysis based on basic but relevant information. Thereby, in this step we recommend two alternatives. The first alternative proposes using the experiment design approach, which can potentially provide valid and reliable conclusions regarding the interplay of variables and to minimize the number of viable alternatives or identify the design dominant parameters or processes, i.e., those that may control the analysis outcome. For instance, for an activated sludge system, the experiment design could focus on analyzing the effectiveness of complete-mix, close loop, or plug flow from environmental, economic, and technical performance stand points. The second alternative proposes multicriteria evaluation through, for example, the use of the SWOT (strengths, weakness, opportunities, threats) analysis, which is elaborated in Section 4.2.4. It is important to underline that step iii involves an iterative approach to identify the viable wastewater treatment alternatives.

Table 1
Wastewater characterization parameters.

Type of analysis	Parameter	Unit
Physico-chemical	BOD_5	(mg/L)
	COD	(mg/L)
	Total suspended solids	(mg/L)
	Sedimentable solids	(mg/L)
	Ph	(U)
	Temperature	(°C)
	Total nitrogen Kjeldahl	(mg/L)
	Acidity	(mg/L)
	Alkalinity	(mg/L)
	True color 620 nm	(m^{-1})
Microbiological	Total coliforms	(NMP/100 mL)
	Thermotolerant coliforms	(NMP/100 mL)

4. Application of CPESI to the case study

4.1. Initial evaluation

The initial assessment comprised a primary social, environmental, and cultural analysis. In this part of the methodology, a survey of experts and residents of Riohacha was conducted (virtually) and a total of 113 responses were obtained. This survey allowed to define the acceptance or rejection of the project of the construction of the implementation of a sewage treatment system. Respondents were also asked to define the

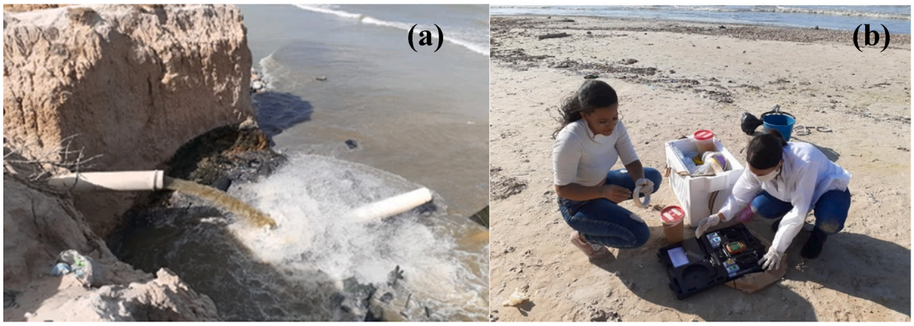


Fig. 2. (a) Point discharge (11°32′30.53″ N and 72°55′58.81″ W) in the coastal section of the study area; (b) In situ untreated wastewater sampling.

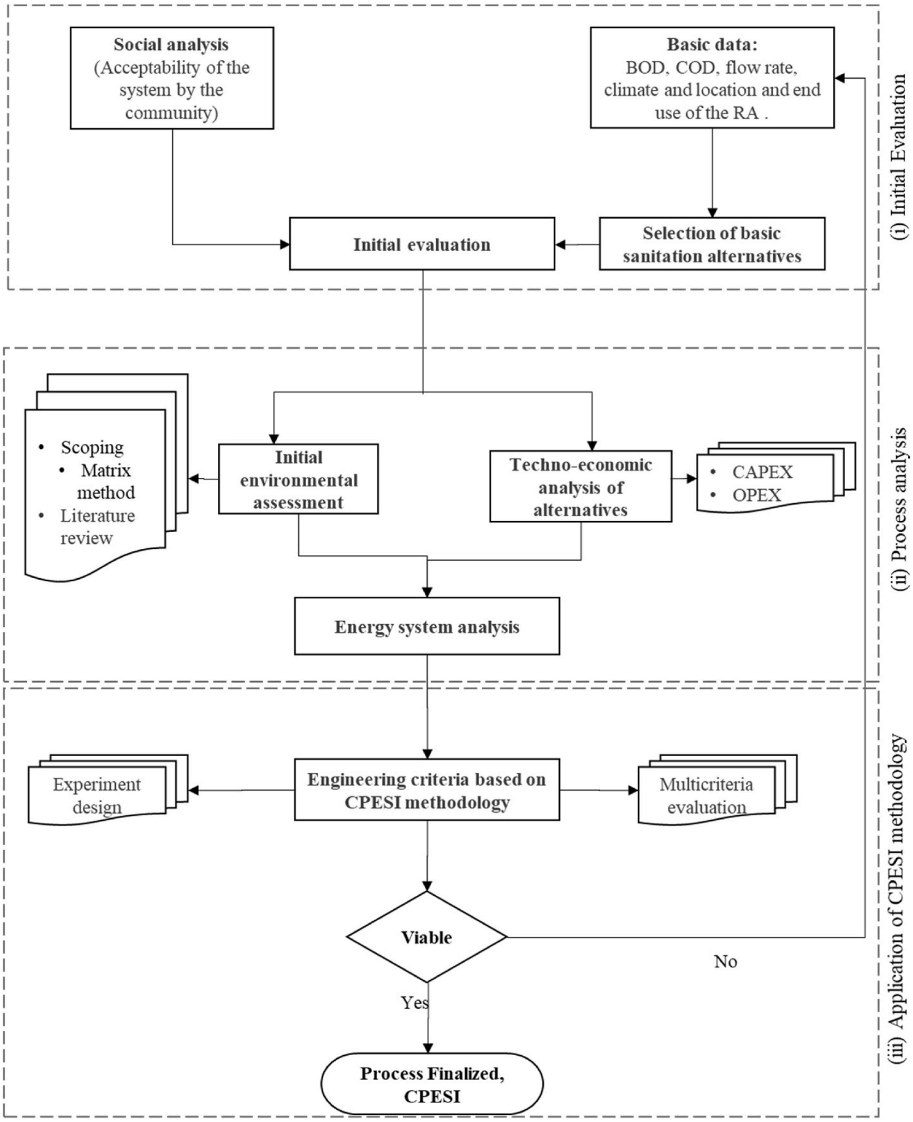


Fig. 3. CPESI workflow.

importance of eliminating the direct discharge into the sea, considering that the health of the neighbors in this area could be affected. It is important underlining that the questions were also related to the use of alternative energy sources for the supply of energy to the wastewater treatment plant. Two examples out of the 16 questions that were part of the questionnaire, and their respective statistical analysis are presented in Table 2.

The main objective of analyzing different alternatives is to find the possible solution and establish which of these is the one that best fits the environmental, economic, technical, and social aspects of the study area. For the selection of the different sanitation systems, the following criteria were considered within the stages of the CPESI methodology process:

Firstly, the physicochemical and microbiological characterization of

Table 2
Main questions of the primary social, environmental, and cultural survey.

Question	Perspectives of the beneficiaries
Is the discharge of wastewater in the coastal zone affecting your quality of life?	68% of the respondents answered that their quality of life is being affected by this problem, while 21% answered that they have not been affected and the remaining 11% do not know/do not answer.
Do you think that implementing a wastewater treatment plant will help improve the economic growth of the district?	87% responded that it will help with economic growth, 11% did not know or did not respond, and 3% said that it will help improve the district's economy.

the domestic wastewater of the District of Riohacha was analyzed. Then, the parameters that mainly contribute to contamination and that are not complying with the maximum permissible discharge limits set forth in the Colombian environmental regulation (i.e, Resolution 883 of 2018 in Chapter V - Article 8) were verified. Likewise, data provided by ASAA consisting on monthly effluent flows discharged to the beach from January to December 2019 were analyzed.

Secondly, to determine the alternatives under study, the type of contamination was analyzed by discerning if it presents organic contamination, heavy metal contamination or mineral contamination, considering that the type of contaminant present in the effluent requires a specific process for its purification, whether by physical, biological, chemical, or combined treatment.

Thirdly, after a literature review, consultations with experts and information related to the experience of other cities worldwide and nationally that have applied different treatment systems with similar characteristics in terms of organic load and climate, three alternatives were selected, namely, activated sludge system, submerged membrane bioreactor and submarine emissary.

Finally, Riohacha climate characteristics were assessed to determine the effectiveness of each treatment process. The assessment focused on temperature variation as high temperatures can accelerate the generation and spread of odors (Markov et al., 2017).

4.2. *Process analysis*

The following is a detailed analysis of the different stages developed in the study.

4.2.1. *Initial environmental assessment*

4.2.1.1. Alternative 1: Conventional activated sludge plant. Through visits to the point discharge area (Fig. 2) and to the possible locations of the treatment plant, an environmental diagnosis was made following the guidelines of the Leopold matrix methodology (Herrera and Pacheco-Bustos, 2024). The Leopold matrices were constructed thanks to the contribution of several professionals (e.g., environmental engineers, environmental specialists, civil engineers, and industrial engineers). These professionals were selected for their familiarity with the case studied, either by having lived in the area of influence or by having conducted a related study, as well as for their technical judgment.

These professionals were contacted by e-mail and face-to-face meetings were held to present the subject and obtain their point of view from different areas of study. In this way, a more consolidated and technical matrix was developed (see Table 3). The environmental diagnosis of the conventional activated sludge plant indicated that the greatest associated damage to the environment are the removal of vegetation and stripping, deep excavations, and the construction of concrete structures due to their large dimensions.

Table A.1 presents the Leopold matrix of the activated sludge system for sanitation. It provides a detailed assessment of the challenges associated with the environmental impacts of this system.

Table 3
Environmental diagnosis of a conventional activated sludge plant.

Activities that cause the most damage	Factors	Total of the activity [a]	Total of factors [a]
Vegetation removal and stripping	Concentration of particulate matter, gases, and odors	−20	−146
	Loss of landscape nature	−30	
	Flora	−20	
Deep excavations >3 m	Concentration of particulate matter, gases, and odors	−30	−206
	Loss of landscape nature	−42	
	Flora	−36	
Construction of treatment structures (inlet channel, sand trap, primary settling tank, aeration tank, secondary settling tank)	Concentration of particulate matter, gases, and odors	−35	−165
	Loss of landscape nature	−36	
	Flora	−36	

[a] Positive values indicate positive environmental impacts and negative values indicate negative environmental impacts.

4.2.1.2. Alternative 2: Submerged membrane bioreactor (MBRs). The MBR system is a wastewater treatment system that uses a combination of microorganism-activated sludge system with the aid of ultra and microfiltration membranes to optimize the treatment process (Judd, 2006). Applying the matrix method, it was determined that the negative effects of this system on the environment (Table 4) would be mainly due to the activities of vegetation removal and stripping, and construction of treatment structures, highlighting that the ecosystem factors that would be most affected are landscaping, Unlike the activated sludge system, this factor would not be so affected in this alternative, since the MBR system, thanks to the membrane filtration process, reduces the size of the tanks and the number of processes needed to decontaminate the water (Judd, 2006).

Table A.2 presents the Leopold matrix of the submerged membrane bioreactor system for sanitation. It provides a detailed assessment of the challenges associated with the environmental impacts of this system.

4.2.1.3. Alternative 3: Submarine outfall. The submarine outfall is a

Table 4
Environmental diagnosis of the submerged membrane bioreactor (MBRs).

Activities causing the most damage	Factors	Total activity [a]	Total factors [a]
Vegetation removal and stripping	Concentration of particulate matter, gases, and odors	−20	−124
	Loss of landscape nature	−30	
	Physical and chemical properties of soil	−18	
Deep excavations >3 m	Concentration of particulate matter, gases, and odors	−30	−200
	Loss of landscape nature	−40	
	Physical and chemical properties of soil	−45	
Construction of treatment structures (inlet channel, sand trap, settling tank, aeration tank, storage tank)	Concentration of particulate matter, gases, and odors	−42	−147
	Loss of landscape nature	−36	
	Flora	−18	

[a] Positive values indicate positive environmental impacts and negative values indicate negative.

pipeline where wastewater is pumped to the sea (Minambiente, 2021). The matrix method was also applied to this system to evaluate the negative environmental impacts it could have on the environment. The removal of topsoil, surface and deep excavation in the ground, excavation and drilling in the seabed are the activities would induce the greatest environmental impact on the terrestrial and marine ecosystem (Herrera and Pacheco-Bustos, 2024). These results can be seen in Table 5.

Table A.3 presents the Leopold matrix of the submarine outfall. It provides a detailed assessment of the challenges associated with the environmental impacts caused by this system.

The results of the environmental analysis (Table 6) show the results summary obtained in the initial environmental diagnosis. The classification of ranges for negative impacts is as follows: moderate when ranging −25 to 40, medium or severe when ranging 50–75 and critical when greater than 75 (Conesa, 2011).

4.2.2. *Technical-economic analysis of alternatives*

After calculating the cost of each element of the system, we proceeded to calculate the CAPEX and OPEX to know how much it would cost to treat and/or dispose of one cubic meter of wastewater through each system evaluated. Table 7 shows what it would cost the District of Riohacha to treat and/or dispose of one cubic meter of RA for each alternative in 2021.

4.2.3. *Energy system analysis*

To solve the high energy consumption of the selected alternative, the use of solar panels was proposed to take advantage of the high energy potential of the Guajira department. Initially, the idea was to invest in renewable energies such as solar panels for this project due to the deficiency of the conventional electrical system in the district. Indeed, the plant would need to have electricity 24 h a day to be in constant movement and help reduce the proliferation of bad odors and guarantee an optimal operation. In addition, this space would be used for research by academic institutions such as universities and other educational institutions located in the city, to expand their knowledge in this area (Herrera Campuzano, 2021).

4.2.4. *Application of CPESI*

A multicriteria assessment approach was followed to objectively select the most viable alternative. To this end, the SWOT (strengths, weakness, opportunities, threats) analysis was utilized for each of the identified alternatives. SWOT matrices describe the technical, economic, environmental, and social dimensions of each alternative and it has been widely used as a decision-making tool in infrastructure development in developing countries (Varma, Evans, da Silva, & Jinapala, 2009; Betancur et al., 2023).

Table 8 presents the SWOT matrix for a conventional activated sludge plant in Riohacha. It details the internalities and externalities that may influence in the performance and viability of the system. For instance, the potential detrimental effect of the sludge plant on the landscaping of the area is highlighted.

Table 5
Environmental analysis of the construction of the submarine outfall.

Activities causing the most damage	Factors	Total activity [a]	Total factors [a]
Vegetation removal and stripping	Concentration of particulate matter, gases, and odors	−8	−69
	Introduction of new structures	−18	
	Loss of landscape nature	−18	
Deep excavations >3 m	Affection to Benton	−20	−82
	Concentration of particulate matter, gases, and odors	−15	
Excavation and drilling on the sea bed	Introduction of new structures	−36	−125

[a] Positive values indicate positive environmental impacts and negative values indicate negative.

Table 6
Results of the environmental analysis [a].

Alternatives	Result	Valuation
Activated sludge treatment system	−621.25	Critic
Submerged membrane bioreactor	−280	Critic
Submarine outfall	−47.5	Medium

[a] See Table A.1, A.2, and A.3 which show detailed information on the justification of the values in column 2.

Table 7
Cost of treating and/or disposing one cubic meter of wastewater by each alternative [a].

Alternative ID	Sanitation system	Costs in US$ per m^3
Alternative 1	Activated Sludge System	0.70
Alternative 2	Submerged Membrane Bioreactor Systems (MBRs)	0.30
Alternative 3	Submarine Outfall System	0.90

[a] See Table A.4, A.5, and A.6 which show detailed information on the justification of the values in column 3.

Table 8
Presents the SWOT matrix for a conventional activated sludge plant in Riohacha.

SWOT Matrix: Activated Sludge System	Positive	Negative
	Strengths	Weaknesses
Internal origin	Technology widely used worldwide Simplicity in Operation It has the possibility of expansion depending on the need that arises over the years. Either by increase of the flow and/or population	Large area requirements for its construction. High energy consumption Requirement of 4–8 h as aeration time. It would substantially affect the environment due to the large size of the tanks required for the treatments. It reacts negatively to extreme variations in organic and hydraulic loading. Requires maintenance of diffusers and pumps. In the initial start-up (2–3 months) the removal is only slightly higher than that of the primary treatment.
External origin	**Opportunities** Large volumes of organic material that can be used for composting activities and benefit farmers in the area. In addition, it can be a complementary source of income to help cover part of the investment and operating costs of the plant.	**Threats** Rejection by the community because it would affect the landscaping of the area.
	It would increase tourism and the District's economy.	Difficulty on the part of the municipality for its implementation.

Similarly, Tble 9 presents the SWOT matrix for the MBR system. It underlines the inherent strengths and weaknesses of the system in Riohacha. It stands out the potential rejection of the population and public officer to reject the alternative as they may not be familiar with this relatively advanced approach.

Similarly, Table 10 presents the SWOT matrix for the submarine outfall system in Riohacha. The main limitation of this system is that

Table 9
SWOT matrix for the MBR system.

SWOT Matrix: MBR treatment system.	Positive	Negative
	Strengths	Weaknesses
Internal origin	Excellent quality effluent for reuse. Easy to automate	Membranes must be ordered from another country. Membrane maintenance is required to control fouling and periodic replacement is required.
	Reduced land requirements: Due to shorter hydraulic retention times, and the possibility of eliminating secondary settlers and reducing the volume of the aeration tank thanks to the membranes. Reduced sludge generation Initial capital cost savings Low concentration of bacteria, TSS, BOD and phosphorus in the effluent, facilitating high levels of disinfection. Better odor control.	High energy cost compared to the other two systems (activated sludge and outfall).
External origin	**Opportunities**	**Threats**
	The treated water coming out of the plant can contribute positively to the water shortage in the municipality. This system eliminates 99% of COD, BOD, and 98% of suspended solids and allows the water to be reused. An agreement can be made with farmers and the mayor's office so that this water can be used for irrigation of crops, city gardens, and car washing, among others. This would reduce the amount of potable water used for these purposes.	Rejection by the community for not being a non-conventional system.
	The sludge produced by the plant can be sold to composting companies and can be a complementary source of income to help cover part of the plant's investment and operating costs. It has the flexibility for future expansion to increase capacity. It would increase tourism and the District's economy.	Governmental officers do not want to invest in an innovative system that is unknown to them, such as MBRs.

Table 10
SWOT matrix for the submarine outfall.

SWOT Matrix: Subsea Outfall	Positive	Negative
	Strengths	Weaknesses
Internal origin	Easy operation.	Very high construction costs
	Low energy requirement.	Uses additional treatments to meet discharge standards.
	Low environmental impact: Minimal alteration of the ecosystem, low visual impact, minimal volume of soil removed.	The possibility of reusing the discharged water is lost.
	Flexibility and control of operation.	Construction requires modern equipment and specialized personnel.
	Minimal land area	The piping system needs to be imported.
	Immediate start-up of this system.	Modern equipment and specialized personnel are needed.
	It does not generate as much noise compared to other treatment systems.	
External origin	**Opportunities**	**Threats**
	It would increase tourism and the District's economy.	The lack of long-term perspective in decision makers may affect the project implementation. There is not room for infrastructure update after the design population or discharge is reached, which may require building another submarine outflow line or adopting another wastewater treatment system.

there is virtually no room to extend the functionality of the system through renovations or extensions once the outflow reaches is maximum flow capacity.

5. Discussion

5.1. Limitations in data availability

Although reliable and representative observations of water quality are scarce in a vast majority of countries around the world (Biswas and Tortajada, 2019), it appears that developing countries still face enormous challenges in implementing systematic programs to collect such observations (Kirschke et al., 2020). For this reason, it is of great research interest developing methodologies that represent this condition and that can be applicable in developing countries. A relevant body of evidence also highlights the urgency of changing the bad practice of implementing sanitation infrastructure without evaluation in these countries (Institute of Medicine (US), 2009). Moreover, the need for sanitation projects to be monitored and evaluated using metrics representative of the need, design, use, impact, and sustainability of the project (Institute of Medicine (US), 2009), which can then form metadata that can inform regulatory decisions at the regional or national scale (Mensah, 2020) In developing countries, when developing a sanitation system, there are not only data limitations but also resources (e.g., financial, technical, and human resources). Likewise, in the field of technology and infrastructure, these countries lack advanced technologies and sophisticated sanitation systems that can be taken as a reference (Mattar and Cuervo, 2017).

The development of sanitary sewage systems requires conducting measurements in the receiving water bodies. These measurements are very scarce in small or medium size receiving water bodies. For instance, water quality measurements in the Cesar River (310 km^2, 280 km long)—which runs across the departments of La Guajira and Cesar—, shows that water quality is measured through a low-density monitoring network that only provides a maximum of three samples per station per year of five specific parameters, i.e., pH, TP, TN, DO, TSS (Vega et al., 2024). This is the specific situation in the Cesar River even though it is one of the largest tributaries of the lower Magdalena (the largest river system in Colombia) and houses the Valledupar city (567,000 inhabitants).

The data associated to the supply of sanitary infrastructure in small towns (such as Riohacha) in the Colombian territory is very limited because of the lack of trained personnel to carry out the necessary measurements (Wright et al., 2014). According to the JMP (Joint Monitoring Programme for Water Supply, Sanitation and Hygiene) water supply service classification scheme, most small towns in the study area lack water supply services; likewise, the existing systems mostly comprises surface water, unimproved, and limited systems (Doria Argumedo, Lopez Torres and Deluquez Viloria, 2018). In addition, most small towns exhibit very low proportions of population having wastewater services (Doria Argumedo et al., 2018).

In developing countries like Colombia, the lack/limitations of technical information (e.g., operational and maintenance costs, specifications, performance metrics) of referential operating sanitary systems using advanced technologies prevent the adoption of new technologies in public sewerage treatment infrastructure. As a ripple effect, this makes it difficult to implement advanced solutions that could be replicated in other cities in the same country to adequately address sanitation needs.

Based on our experience, these limitations are rather significant in small/medium size cities, which commonly lack fundamental observations to design sanitary systems as depicted in Table 8. For instance, they lack historical data to characterize wastewater and quantify the variation of the volume and concentration of pollutants. Thus, there are large uncertainties in the design of sanitation systems.

As shown in Table 11, there is insufficient primary observations (e.g., water quality, air quality, biodiversity, topographic information) and baseline information on previously implemented sanitation systems to conduct accurate environmental impact assessments. Moreover, the limited available information is not centralized and, consequently, it is usually very difficult to access them. Thus, for example, the Battelle-Columbus method could not be applied as it requires experienced evaluators who have a deep knowledge of sanitation infrastructure and copious baseline information on the affected environment (Arboleda González, 2008; Novoa Orjuela, 2017). As previously stressed, unfortunately these resources are not commonly available in small and medium-sized cities from developing countries.

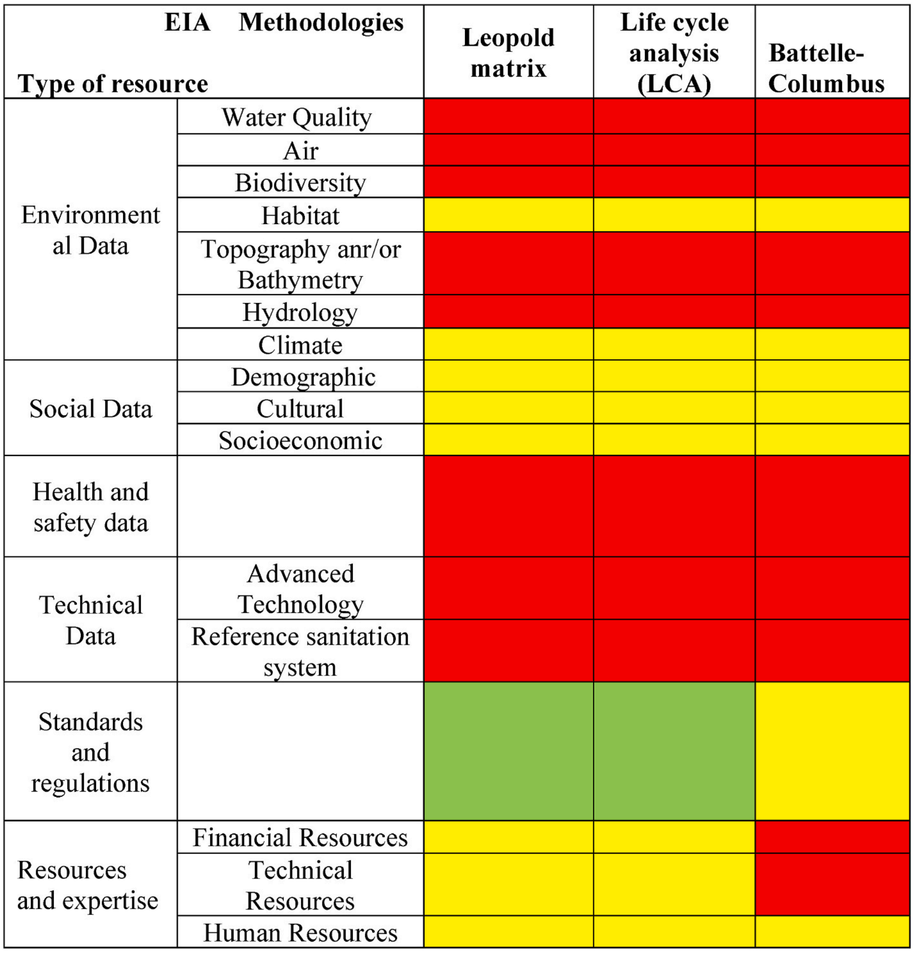
Our experience also indicates that the institutional mechanisms for the design and/or construction of sanitation systems in developing countries commonly demand of long processes and the onerous use of economic/human resources. These idiosyncratic limitations in in small/medium size cities lead, in many instances, to poor technical decisions during the pre-feasibility or feasibility stages.

Therefore, there is a need to implement parsimonious, objective, and agile methodologies—based on a realistic view of the availability of fundamental information—for the design of sanitation systems in developing countries. These methodologies may not be needed in developed countries. However, based on our experience, they are utterly necessary and urgent in developing countries. In this regard, the CPESI methodology presented in this contribution, aims to provide an objective technical frame to evaluate the development of sanitary infrastructure.

Table 11 shows that the methods commonly used for Environmental Impact Assessment (EIA) face difficulties at the time of implementation, as obtaining essential data such as water quality, air quality, biodiversity and topographic information is complicated by the lack of appropriate technologies and tools for this purpose. In addition, baseline information on previously implemented sanitation systems is not available, making it difficult to conduct a more accurate analysis. It is important to note that in developing countries there is no single place to look for baseline information, making it difficult to find primary information to use in design.

For example, the Battelle-Columbus method is recommended for

Table 11
Map of resource availability for the design and/or construction of sanitation systems. Red = hardly available or lacking; yellow = data partially available or having the technical capacity to conduct measurement; and green = commonly available data.



EIA Methodologies Type of resource		Leopold matrix	Life cycle analysis (LCA)	Battelle-Columbus
Environmental Data	Water Quality	🟥	🟥	🟥
	Air	🟥	🟥	🟥
	Biodiversity	🟥	🟥	🟥
	Habitat	🟨	🟨	🟨
	Topography anr/or Bathymetry	🟥	🟥	🟥
	Hydrology	🟥	🟥	🟥
	Climate	🟨	🟨	🟨
Social Data	Demographic	🟨	🟨	🟨
	Cultural	🟨	🟨	🟨
	Socioeconomic	🟨	🟨	🟨
Health and safety data		🟥	🟥	🟥
Technical Data	Advanced Technology	🟥	🟥	🟥
	Reference sanitation system	🟥	🟥	🟥
Standards and regulations		🟩	🟩	🟨
Resources and expertise	Financial Resources	🟨	🟨	🟥
	Technical Resources	🟨	🟨	🟥
	Human Resources	🟨	🟨	🟨

projects related to water resources, but it requires experienced evaluators who have a deep knowledge of the project and requires a solid information base on the affected environment (Arboleda González, 2008; Novoa Orjuela, 2017), which is not available in small and medium-sized cities in the aforementioned countries.

5.2. CPESI as a decision-making tool

In recent years, the need for a change in management to comply with the scope of SDG 6 in Latin American and Caribbean countries has been underlined by (Sparkman & Sturzenegger, 2018). They argue that (1) an objective evaluation of alternatives is needed before investing resources in an alternative solution, whether innovative or conventional; (2) strategies and tools applicable to the reality of the region need to be developed; (3) sanitation infrastructure must be tailored to the needs of a particular project; (4) significant investment is required in sanitation infrastructure that by default adopts circular economy practices, but whose justification is based on the environmental impact analysis of conventional infrastructure; and (5) the participation of beneficiaries in the design and implementation of sanitation infrastructure must be encouraged.

In line with these needs, the CPESI methodology we propose is a tool that allows early technical, social, and environmental analysis of sanitation infrastructure projects. In this contribution, its application is reported in the selection of alternatives for a basic sanitation system that includes conventional (e.g., activated sludge plant and submarine outfall) and non-conventional (e.g., MBRs submerged membrane bioreactor system) systems in the early stages of design maturity, in which there has been a participation of the beneficiary community.

CPESI has been conceived as an objective tool in contexts where there are limitations of information, data, or economic resources to make a thorough assessment in the first instance. Such is the case of small populations in developing countries. We believe that with this methodology, technical bodies identifying a sanitation project in such geographic contexts can objectively filter a set of alternatives to determine which of them could be subsequently analyzed in greater detail.

The main limitation of CPESI is that its reliability is dependent upon the quality of the input data, e.g., field observations, water quality measurements in receiving water bodies, supply of sanitary infrastructure, local/regional statistics of the performance of sewerage treatment systems, costs of energy supply, maintenance and insurance costs, availability of skilled personnel for operation and maintenance of the system, etc. Although CPESI could provide an objective decision framework within the context of limited data, it still requires observations that may minimally describe the dominant engineering solicitations of an evaluated sanitary system. In the absence of these observations, it is necessary to collect data from secondary or tertiary sources or conduct preliminary technical assessments and field surveys. In any case, a good practice in the application of CPESI may demand a transparent approach to embedding all the input information related to the assessed sanitary system. On the other hand, it is important mentioning that our research has not examined the extent of CPESI as an intuitive decision-making process derived from the application of CPESI by users who were provided with little guidance on the use thereof. Likewise, we believe that the standardization of CPESI may require building a best practice guidance information, which unfortunately at this point is not available.

The social constraints that basic sanitation projects may face are: Cultural resistance, in some communities, traditional practices may conflict with new technologies or sanitation methods. Resistance to change established habits may hinder the adoption of improved sanitation systems. Lack of Education and Awareness, lack of knowledge about the benefits of proper sanitation may lead to less community participation. Social and Political Conflicts, tensions and conflicts within communities or between different groups can hinder planning and implementation of sanitation projects. Local governance and political stability are critical factors for the success of these projects.

Environmental Limitations that this type of project could have been: Availability and Quality of Water. Geographical and climatic conditions, difficult terrain, such as mountainous areas or unstable soils, can hinder the construction of sanitation infrastructures. Extreme weather conditions, such as droughts or floods, can also affect the functionality of the systems.

In addition, some sanitation systems can have negative effects on the environment, such as contamination of water bodies or inadequate management of solid and liquid waste, and the construction and operation of sanitation infrastructure can negatively affect local biodiversity and ecosystems. It is essential to design solutions that minimize these impacts, which is the basis for the analysis of different alternatives as proposed in this methodology.

5.3. Replicability of CPESI

Regarding target 6. a (expand capacity-building support to developing countries in water and sanitation-related wastewater programs), considering our results, we consider that CPESI can be used to train the technical bodies that must identify and propose a sanitation project in small localities, such as the one reported in this contribution. We consider that CPESI could be adopted as a tool to standardize the preliminary evaluation of early-stage sanitation projects in Latin America, and by extension, in developing countries. In this way it can contribute to (1) making efficient use of economic and human resources in these countries; (2) generating data and disseminating information for optimal decision making and evaluation of sanitation infrastructure; and (3) reducing the asymmetry in access to information and technology and the capacity gap. These elements represent some of the pending challenges to accelerate the achievement of SDG 6 targets in developing nations (UN Water, 2020).

6. Conclusions

The present research describes the role of the limitations of free availability of primary information for the development of sanitation infrastructure in developing countries and presents the CPESI methodology as a tool for early decision making. CPESI aims to provide an objective framework for the analysis of pre-feasibility studies for the selection of the most sustainable alternative. That is, to identify the best alternative from a range of alternatives based on a systematic economic, social, and technical evaluation. The application of CPESI for the evaluation of alternatives in the case study (Riohacha treatment plant) allowed the selection of the best alternative among the following alternatives evaluated: activated sludge system, submerged membrane bioreactor and submarine outfall. The social, environmental, and cultural evaluation was carried out by means of virtual surveys to the population in which a total of 113 responses were obtained. CPESI allowed an agile and objective evaluation of the alternatives and made it possible to select the use of the submerged membrane bioreactor with the use of renewable energies (solar energy) as the best alternative. This selection also allowed us to define inputs for the subsequent evaluation of the project at a higher level of detail. Considering the results obtained, we consider that CPESI potentially has a high replicability for the evaluation of projects with the characteristics of the one described in this study, but that it could be easily adapted to larger projects. Thus, CPESI can possibly be used to standardize the evaluation of sustainable health infrastructure in developing countries.

CRediT authorship contribution statement

Yamileth C. Herrera: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ronald R. Gutierrez:** Writing – review & editing,

Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Carlos Pacheco-Bustos:** Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Input data associated to this contribution can be accessed from https://data.mendeley.com/datasets/4hk72jxx32/1.

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Appendix A. Supplementary data

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