

Article

A Multi-Criteria Decision Framework for Sustainable Sewer Technology Selection Under Environmental Constraints: An Application in Uruguay

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Abstract

Universal access to sanitation in environmentally constrained and territorially heterogeneous settings demands decision frameworks capable of transcending cost-dominant planning approaches. This study develops a multi-criteria decision framework based on the Analytic Hierarchy Process (AHP) to support sustainable sewer technology selection. The model integrates technical, economic, and socio-environmental criteria within a hierarchical structure, incorporating structured expert judgment with consistency verification. The framework is applied to a real case study in Ciudad del Plata, Uruguay, an environmentally sensitive area with medium–low urban density. Results indicate that when socio-environmental criteria are explicitly prioritized, the Condominial system achieves the highest global score (35.9%), outperforming both the Conventional and Small-Diameter alternatives. Sensitivity analysis confirms the stability of the ranking under moderate variations in criteria weights. Beyond the specific case evaluated, the proposed framework advances sustainable infrastructure governance by providing a transparent, transferable, and replicable decision-support tool for sanitation planning under complex territorial conditions.

Keywords: multi-criteria decision-making; urban sanitation planning; infrastructure governance; socio-environmental assessment; sustainable urban development; environmental risk evaluation; adaptive infrastructure planning

1. Introduction

Access to safe sanitation remains among the foremost challenges of sustainable development. Despite global progress, only 57% of the world's population used safely managed sanitation services in 2017 [1]. The adoption of the 2030 Agenda for Sustainable Development reinforced sanitation as a global priority through Sustainable Development Goal 6 (SDG 6), which calls for universal and equitable access to water and sanitation for all [2]. However, achieving this objective requires not only expanding infrastructure coverage but also ensuring that technological solutions are socially acceptable, economically feasible, environmentally sound and institutionally viable.

Sanitation planning has historically relied on standardized engineering solutions, most notably conventional gravity sewer systems. Although technically robust, such systems frequently entail high capital costs and may pose operational or environmental challenges in low-density areas, environmentally sensitive zones, or territories with unfavorable



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physical conditions. In such contexts, applying a single technological model can lead to inefficiencies, infrastructure underutilization, or financial unsustainability.

From a sustainability perspective, infrastructure planning increasingly requires integrated decision frameworks capable of reconciling multiple, and at times competing, objectives. Environmental protection, public health, economic efficiency, regulatory compliance, and community participation must be evaluated concurrently. The inherent complexity of these interactions renders purely deterministic or cost-based evaluation approaches insufficient for well-informed decision-making.

Multi-criteria decision-making (MCDM) methodologies offer a structured approach to managing this complexity. Among these, the Analytic Hierarchy Process (AHP), originally formulated by Saaty [3], has been extensively applied across infrastructure planning, land suitability analysis, energy systems, health infrastructure prioritization, and public investment evaluation [4–10]. AHP enables the decomposition of complex decision problems into hierarchical structures, supports systematic pairwise comparisons, and facilitates the aggregation of expert judgments within a consistent quantitative framework [3,11]. Its application to sanitation planning provides a transparent mechanism for integrating technical, economic, and socio-environmental dimensions within a unified decision model.

In Uruguay, conventional separate sewer systems have historically been adopted as the default technological solution for urban sanitation. National policies, including the National Sanitation Plan [12], aim to achieve universal coverage by 2030. However, territorial heterogeneity—ranging from dense urban centers to environmentally protected areas and medium–low-density settlements—suggests that a uniform technological approach may not always be optimal. Alternative systems such as condominial sewers and small-diameter systems have demonstrated successful implementation in various international contexts, particularly where cost constraints or environmental conditions limit conventional solutions [13–20].

Despite the availability of these alternatives, technology selection processes frequently remain governed by regulatory inertia or cost-based comparisons, without systematic integration of socio-environmental criteria or explicit weighting of decision factors. This deficiency underscores the need for a replicable and transparent evaluation framework capable of supporting sustainable infrastructure governance at both local and national levels.

The present study addresses this gap by developing and applying a structured AHP-based decision framework for sewer technology selection under environmental constraints. The proposed model integrates three main criteria—technical, cost, and socio-environmental—each decomposed into specific sub-criteria reflecting regulatory compliance, operational feasibility, community participation, environmental risk, and long-term sustainability.

The framework is applied to a real case study in Ciudad del Plata, Uruguay, a locality situated within an environmentally sensitive wetland area. By explicitly incorporating environmental and social considerations into the prioritization process, the study moves beyond cost-dominant planning approaches and contributes to the broader discourse on sustainable urban infrastructure transitions.

The scientific contributions of this work are as follows:

1. The development of a transferable hierarchical decision framework for sanitation technology selection;
2. The integration of expert-based weighting with consistency verification;
3. The real-world application of the framework in a protected territorial context;
4. The demonstration of how decision outcomes vary when socio-environmental criteria are explicitly prioritized.

By framing sanitation technology selection as a multi-dimensional sustainability problem rather than a purely technical optimization task, this study advances integrated decision-making approaches in urban infrastructure planning.

2. Conceptual Framework for Sustainable Sewer Technology Selection

Sewer technology selection constitutes a multi-dimensional sustainability problem encompassing engineering feasibility, economic viability, and socio-environmental externalities. Conventional planning approaches tend to prioritize technical compliance and capital cost minimization, implicitly assuming that standardized infrastructure typologies are universally applicable.

However, under heterogeneous territorial conditions—including environmentally protected areas, low-density settlements, or financially constrained municipalities—technology performance must be assessed through a broader evaluative lens. Sustainable infrastructure governance requires structured decision mechanisms capable of integrating multiple criteria and stakeholder values within transparent evaluation processes.

The framework proposed in this study conceptualizes sewer technology selection as a hierarchical decision problem in which sustainability dimensions are explicitly weighted and systematically compared. This structure enables rigorous trade-off analysis and enhances the replicability of the approach across diverse territorial contexts.

3. Materials and Methods

3.1. Sewer Technologies

Sanitation is defined as the process by which liquid effluents—domestic and/or non-domestic—are managed from their point of generation through to final disposal [13]. During the nineteenth century, unitary systems—conveying both domestic wastewater and stormwater—were introduced, followed subsequently by separate systems (domestic effluents only) and combined systems.

The first sewer network in Montevideo was constructed in 1856, at a time when the city concentrated approximately 25% of Uruguay's population. According to [12], 61.8% of the population has access to sewer services and 37.4% to domiciliary sanitation (pit, latrine, etc.).

The conventional separate sewer (SS) is the most widely adopted system for the collection and conveyance of domestic wastewater. It consists entirely of pipes operating under gravity flow, routed along street centerlines or sidewalk alignments, preferably within public rights-of-way. Design criteria are primarily based on minimum pipe diameter and minimum slope or flow velocity requirements to ensure self-cleaning conditions [13,14]. In certain areas, the extension of separate sewer networks entails high capital investment, making the implementation of alternative sanitation systems—technically comparable to conventional systems but at lower cost—a viable option [15,16].

One such alternative is the small-diameter (SD) sewer system, which combines on-site primary treatment at the household level with a collective small-diameter collection and conveyance network [16–18]. These systems are designed to receive only the liquid fraction of domestic wastewater, as settleable solids, grease, and other materials that could cause blockages are retained in household septic tanks upstream. Because of this condition, it is not necessary to meet the self-cleaning design criteria required in conventional systems [19]; minimum diameters can be as small as 75 mm and, exceptionally, pipe sections with horizontal or ascending slopes can be used [17,18].

The condominial sewer (CS) represents another alternative to conventional systems. Originally developed in the northeastern states of Brazil (Rio Grande do Norte and Pernambuco) as a lower-cost option, the condominial system is distinguished by the routing of secondary collectors through the interior of private properties, following natural ter-

rain slopes to avoid deep excavations [18]. It is also common for sewers to be laid along sidewalks or other public spaces to obtain substantial savings in length, diameter and depth [20,21]. The characteristics of each system are shown in Table 1.

Table 1. Summary of Design Criteria by technology.

Parameter	Conventional System	Condominial System		Small Diameter System
		Condominial	Main Network	
Layout	Street centerline	Sidewalk	Street centerline	Street centerline
Minimum diameter	200 mm	110 mm	200 mm	75 mm
Minimum self-cleaning velocity	Yes	Yes	Yes	No
Minimum slope	Self-cleaning criterion: Tensile stress 1 Pa (if $Q \leq 1.5$ L/s $P_{min} = 0.45\%$ for 200 mm)	Self-cleaning criterion: Tensile stress 1 Pa (if $Q \leq 1.5$ L/s $P_{min} = 0.45\%$ for 110 mm)	Self-cleaning criterion: Tensile stress 1 Pa (if $Q \leq 1.5$ L/s $P_{min} = 0.45\%$ for 200 mm)	No minimum slope requirement.
	Constructive: 0.25%	Constructive: 0.25%	Constructive: 0.25%	
Maximum velocity	5 m/s	5 m/s	5 m/s	5 m/s
Pipe material	PVC	PVC	PVC	PVC
Minimum cover	0.9 m	0.9 m	0.9 m	0.9 m
Chamber or manhole	1250 mm	400 mm	1250 mm	Inspection pipe in chambers receiving a single collector. 1250 mm for the rest of the chambers.
Distance between manholes	100 m	50 m	100 m	100 m
Maximum water flow	75%	75%	75%	100%
Infiltration flow rate	No groundwater: 0.3 groundwater: 0.5 (L/s/km)	No groundwater: 0.3 groundwater: 0.5 (L/s/km)	No groundwater: 0.3 groundwater: 0.5 (L/s/km)	No groundwater: 0.15 groundwater: 0.25 (L/s/km)
Connection to the network	5 sidewalk chambers every 100 m, receiving up to 3 household connections and connected to the collector by roadway.	Short connection to the collector on the sidewalk.	5 sidewalk chambers every 100 m, receiving up to 3 household connections and connected to the collector by road.	Long connection to the collector in the roadway.

3.2. Methodology

3.2.1. AHP Structure

Multi-Criteria Analysis Methods (MCAM) originate primarily from the field of Operations Research.

The objective of these methods is to quantify the degree of preference of one alternative over another. To enable meaningful comparison, a common evaluation scale is required, allowing all elements to be assessed within a consistent comparative framework.

This necessitates a methodology capable of relating heterogeneous elements and scales within the decision-making process, without compromising the quality, reliability, or consensus of the results [22]. Methods within this family differ in how individual criteria are evaluated and in the aggregation procedure used to derive an overall assessment.

The Analytic Hierarchy Process (AHP) is among the most widely adopted multi-criteria methodologies with formal mathematical foundations. It is characterized as a discrete-variable, deterministic evaluation method that measures preferences through criteria aggregation, without explicit treatment of uncertainty. Since 1993, AHP has been the most extensively applied and published MCAM method in the academic literature, owing to its versatility in adapting to diverse decision contexts and its compatibility with complementary methods [23]. The method's objective is to establish priorities or weights for the criteria and variables relevant to the problem under analysis. The evaluation proceeds from strategic macro-level criteria representing the overarching objectives, through successive disaggregation, until reaching a level of specification that permits rigorous analysis and comparison of alternatives. The resulting priority vector enables the identification of the most appropriate alternative.

Criteria priorities are derived from pairwise comparison matrices, with consistency verification and sensitivity analysis conducted as recommended steps to ensure the credibility of results [11]. A standardized priority scale is employed to render the method independent of the disparate measurement scales associated with individual criteria (see Table 2). Priorities are established by posing the question: "To what extent does option A contribute more than option B to the attainment of the higher-level objective?" Incorrect formulation of the comparative questions may introduce omissions or biases in the resulting weights [24].

Table 2. Safety Values Scale.

Intensity	Definition	Explanation
1	Equally important	2 activities contribute equally to the goal
3	Moderate Importance	Experience and judgment slightly favor one activity over the other
5	Strong Importance	Experience and judgment strongly favor one activity over the other
7	Very Strong or Demonstrated Importance	Experience and judgment very strongly favor one activity over the other
9	Absolute	Experience and judgment strongly and clearly favors one activity over the other

Human judgment inherently tends toward consistency when establishing relationships between objects or concepts, meaning that individual assessments are mutually congruent. In the context of AHP, consistency entails two specific properties:

Transitivity: If A is preferred over C, and C is preferred over B, then A must be preferred over B.

Proportionality: The relative magnitudes of preferences must be mutually consistent within an admissible tolerance range.

The overall inconsistency of the judgment matrix is quantified by the Consistency Ratio (CR), defined as the ratio of the Consistency Index (CI) to the Random Index (RI).

The Consistency Index measures the degree of deviation from perfect consistency in the pairwise comparison matrix. The Random Index represents the average consistency index of a randomly generated reciprocal matrix of equivalent order, with entries drawn from the same 1-to-9 scale.

The method accommodates the participation of a group of qualified specialists in the evaluation process. Each participant independently constructs pairwise comparison matrices, and Saaty proposes the geometric mean of the individual judgments as the appropriate aggregation measure to synthesize group assessments into a single composite judgment [11].

Although the AHP method formally supports the participation of multidisciplinary expert panels—with individual pairwise comparison matrices aggregated through the geometric mean as proposed by Saaty [11]—the application presented in this study was conducted based on the judgment of a single expert with extensive professional experience in sanitation engineering and infrastructure planning in Uruguay. This approach, while limiting the breadth of perspectives incorporated into the weighting process, is consistent with single-expert AHP applications documented in the literature, particularly in cases where panel composition is constrained by expert availability or the institutional specificity of the territorial context. The judgments reflect accumulated technical knowledge of the design, regulatory framework, and operational characteristics of the three sewer typologies evaluated, as well as direct familiarity with the environmental and institutional conditions of the study area.

The AHP method constitutes a structured decision-support tool that enables practitioners to:

- Define the problem to be solved.
- Identify the evaluation criteria on which decision-making will be based.
- Work with a multidisciplinary team.
- Structure the criteria and sub-criteria according to a hierarchy.
- Determine the importance of each criterion under the same scale and synthesize all this information to make the best decision.
- Reach a consensus result.

The AHP integrates qualitative and quantitative dimensions within a unified analytical process. Its structure allows the incorporation of professional values, experience, technical knowledge, and logical reasoning into a coherent framework, from which an individual or group decision can be derived [11,22]. The criteria employed in the model represent the key dimensions that determine the relative suitability of each evaluated system.

3.2.2. Procedure

To illustrate the procedure, a simplified example is presented in which three criteria are considered—environmental, social, and economic—alongside three alternatives designated I, II, and III.

The matrix “A” of relative importance between criteria (pair matrixes) is generated (See Table 3).

Table 3. Matrix A of relative importance between criteria.

	Environmental	Social	Economic
Environmental	1	1/3	1/5
Social	3	1	1/3
Economic	5	3	1

The matrix is interpreted as follows: the social criterion is moderately more important than the environmental criterion, while the economic criterion is considerably more important than the environmental criterion; conversely, the environmental criterion is of lesser importance than both the social and economic criteria.

Deliberation

As per the matrix “A” defined, the problem is expressed by the following equation:

$$A \cdot w = \lambda_{max} \cdot w$$

where A is the reciprocal pairwise comparison matrix, w is the eigenvector representing the priority weights, and λ_{max} is the maximum eigenvalue. Applying this procedure to the example matrix yields the following priority vector:

$$V = \begin{pmatrix} 10\% \\ 26\% \\ 64\% \end{pmatrix} \Leftrightarrow \begin{pmatrix} \text{environmental} \\ \text{social} \\ \text{economic} \end{pmatrix}$$

In this example, the economic criterion receives the highest priority weight, followed by the social criterion, with the environmental criterion assigned the lowest weight.

Consistency

The consistency of the judgment matrix is assessed through the Consistency Ratio (CR), computed as follows:

$$CR = CI/RI$$

where $CI = (\lambda_{max} - n)/(n - 1)$ is the Consistency Index and RI is the Random Index for a matrix of order n . For the example matrix, $\lambda_{max} = 3.02$, yielding $CI = 0.0115$ and $CR = 1.98\% < 10\%$, confirming the judgments are sufficiently consistent. If CR exceeds 10%, the comparison matrix must be revised.

Alternative Selection

Once the priority weight vector has been established for all criteria, each alternative is scored against each criterion using a defined rating scale. In this example, a 1–3 ordinal scale is applied, where 3 denotes the best-performing and 1 the least-performing alternative, as shown in Table 4.

Table 4. Matrix of comparison of alternatives by criteria.

Alternative	Criteria		
	Environmental	Social	Economic
I	3	2	1
II	2	3	3
III	1	1	2

The resulting rating matrix M is normalized by column and multiplied by weight vector V , yielding the composite score for each alternative.

The alternative with the highest composite score is selected as the preferred option. Applying this procedure to the example yields composite scores of 24.4%, 48.3%, and 27.3% for Alternatives I, II, and III, respectively, identifying Alternative II as the preferred solution.

3.3. Criteria Selection for Model

From the broad universe of criteria applicable to infrastructure projects—and to sanitary engineering projects in particular—a three-category classification was adopted for this study.

Cost criteria account for the principal expenditure components associated with implementing each alternative, recognizing that both the scale of works and the relative significance of individual cost items vary across systems.

Socio-environmental criteria capture the relationship between each collection system and the prevailing social and environmental conditions of the implementation area. The three resulting categories are: technical, cost, and socio-environmental criteria. See Table 5.

Table 5. Selected comparison criteria.

Criteria	Technical	Costs	Socio-Environmental
Sub-criteria	Technical Acceptance	Supply and placement of pipes and manholes	Community participation
	Regulatory Compliance	Pumping stations	Employment Generation
	Coverage	Adequacy of domiciliary installation and connection to sewer	Risk of contamination (soils, groundwater, water bodies)
	Construction work staging	Operation and Maintenance (labor, spare parts, tools, energy consumption, etc.)	Health risk for operators/users

3.3.1. Technical Criteria

- Technical Acceptance: This criterion refers to the degree of acceptance of each system by professionals responsible for its design and regulatory approval, primarily assessed on the basis of compliance with established design parameters such as minimum slope and self-cleaning velocity requirements.
- Regulatory Compliance: This criterion addresses conformance with applicable regulations governing the design and operation of the selected system. In Uruguay, the primary regulatory reference is the OSE Regulations for the Processing and Execution of Projects and Works for Potable Water Supply and Sanitation Services [25], which applies specifically to conventional systems. A regulatory framework for small-diameter systems also exists but is not currently enforced in practice; design parameters for these systems are instead derived from institutional design criteria established by OSE's Sanitation Management [26,27].
- Coverage: This criterion refers to the extent of the population served and the geographic area reached by the implemented system.
- Construction Phasing: This criterion refers to the feasibility of executing the project in stages, accounting for potential future network expansions.

3.3.2. Cost Criteria

The selected cost sub-criteria correspond to the principal investment components required for the implementation of a sanitation system. For each alternative, a planning-level design was developed sufficient to estimate the costs associated with the following items:

- Supply and installation of pipes and manholes.
- Pumping Stations and pressure pipes
- Adequacy of household installation/connection to sewer
- Operation and Maintenance (labor, spare parts, tools, energy consumption, etc.)

3.3.3. Socio-Environmental Criteria

These criteria are defined in relation to the social and environmental conditions prevailing in the area where the sanitation solution is to be implemented.

- Community Participation: The successful implementation and long-term sustainability of sanitation projects are critically dependent on active community engagement throughout all project phases.

- **Employment Generation:** This criterion refers to the incremental employment opportunities created by each alternative, both during the construction phase and in the subsequent operation and maintenance of collective and individual system components.
- **Contamination Risk (soil, groundwater, water bodies):** This criterion evaluates the susceptibility of each system to generating environmental contamination under conditions of facility misuse, unauthorized discharges, illicit stormwater intrusion, or inadequate maintenance.
- **Health Risk:** This criterion refers to the probability of disease transmission associated with inadequate system management, including risks arising from direct contact with wastewater, system failures, or improper handling of waste and maintenance residuals.

Model hierarchy diagram is shown in Figure 1.

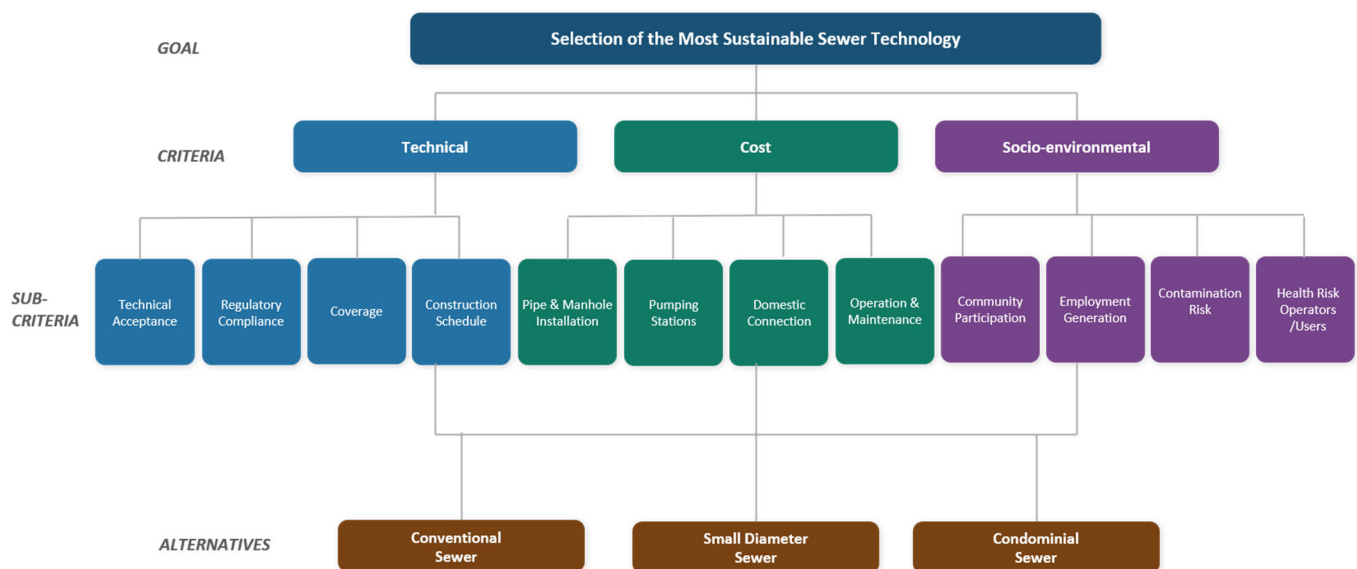


Figure 1. Model hierarchy diagram.

3.4. Limitations

The framework employs deterministic weighting and does not incorporate formal uncertainty modeling. Cost estimates correspond to planning-level design assessments and may vary during detailed engineering stages. In addition, the expert panel reflects national experience, which may limit direct transferability to other institutional contexts.

4. Results

4.1. Project Area Description

The methodology is applied to the sewer infrastructure project for the SOFIMA and Delta del Tigre neighborhoods, located in Ciudad del Plata, Department of San José, Uruguay.

From an environmental standpoint, the project area presents several structural sensitivities. The neighborhoods of Delta del Tigre and SOFIMA are located within the lower basin of the Santa Lucía River, immediately upstream of its confluence with the Río de la Plata estuary. This river constitutes the primary surface water source for the Montevideo metropolitan area, serving approximately 60% of Uruguay's population through the Paso Severino reservoir system. The study area is characterized by flat topography with partially flooded zones, sandy soils with high permeability, and shallow groundwater tables—conditions that significantly increase the risk of contaminant infiltration from deficient sanitation systems. The combination of high hydraulic connectivity between the subsurface and the Santa Lucía River, limited natural attenuation capacity of the soil

matrix, and the ecological and supply-chain importance of the receiving water body justifies the elevated weight assigned to contamination and health risk criteria within the decision framework.

As shown in Figure 2, the study area is characterized by large land parcels with extensive vegetative cover and an estimated residential population density of 39 inhabitants/ha, predominantly comprising medium-to-low-income households.

While limited commercial and industrial activity exists within the area, a significant proportion of the resident population commutes to Montevideo for employment.

Drinking water supply relies on groundwater extraction through boreholes. No collective sanitation infrastructure currently exists; the majority of households rely on permeable septic tanks for wastewater disposal, and the presence of raw sewage in drainage ditches has been documented.

Under strict regulatory application, the prescribed sanitation solution for this area would be a Conventional sewer system. However, OSE may grant exceptions where technically justified, accepting alternative design criteria and construction approaches. The following section presents a structured multi-criteria comparison of the three alternatives to identify the most appropriate solution for this specific context.



Figure 2. Cont.

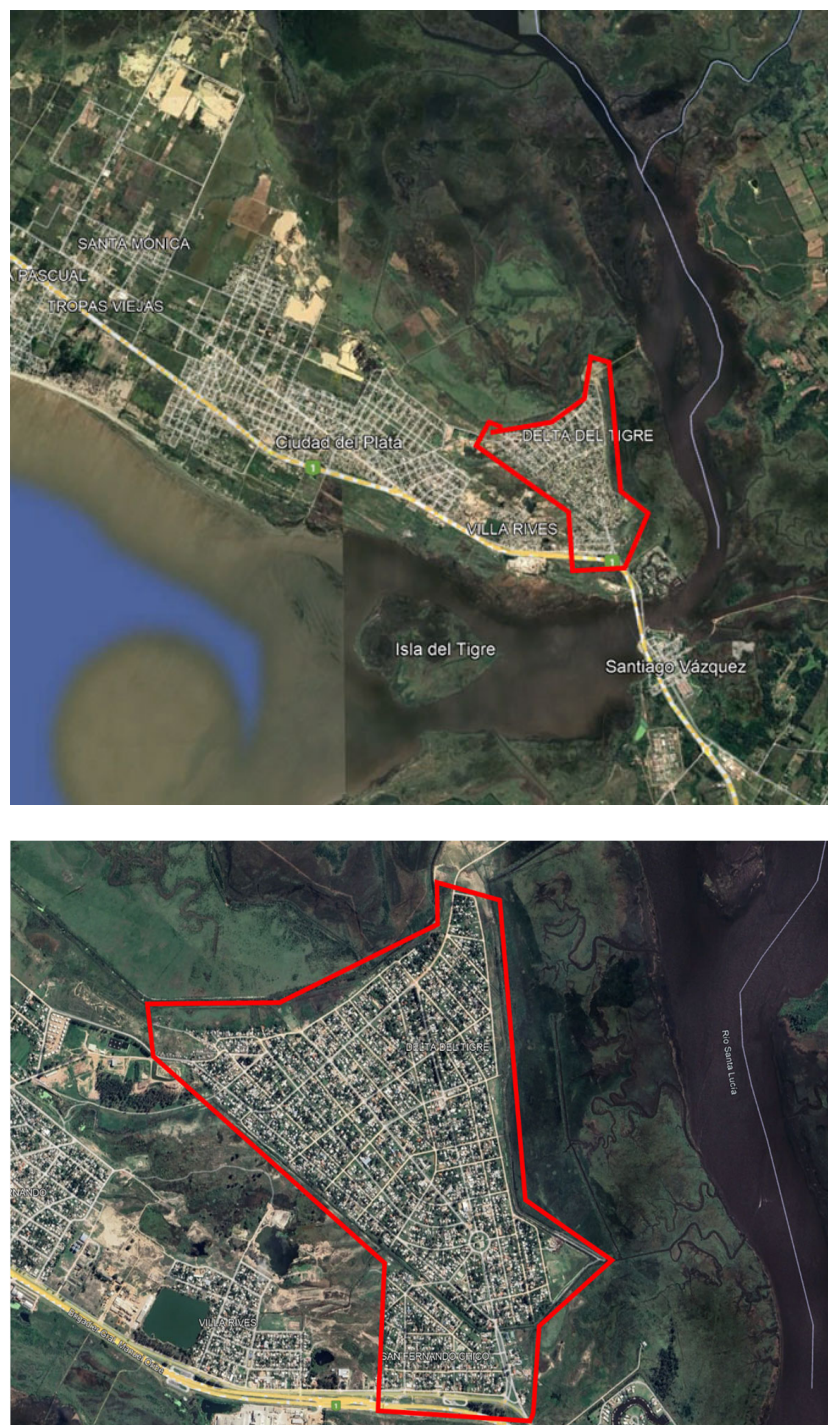


Figure 2. Study area on Google Earth® mapping. **Top:** general location; **bottom:** view of the area to be reclaimed. Image © 2025 Google Earth®.

4.2. Design Hypothesis

The general design and sizing parameters adopted for the comparative analysis of sanitation alternatives in the study area are as follows:

- Urban and demographic projection:
 - o Reference year: 2050
 - o Sanitation coverage by 2050: 100%.
 - o Permanent population in the area: 8000 inhabitants

- Criteria for the projection of wastewater flows to the horizon 2050
 - o Domestic consumption supply: 150 L/inhabitant/day
 - o Sewage Return coefficient: 0.9
 - o Maximum hourly flow coefficient: Harmon's formula (depending on the population considered).

$$k_{\max} = \frac{(18 + \sqrt{(Population/1000)})}{(4 + \sqrt{(Population/1000)})}$$

For population ≤ 1000 inhabitants, the coefficient corresponding to 1000 is taken, which results in a value of 3.8.

- Plumbing and house connection
 - o Adaptation of the domestic plumbing and sanitary installation is assumed for all residential properties.
 - o A single connection chamber per property is adopted as the design standard.
- A single household connection per property is assumed.
- Each alternative is designed in accordance with the technical criteria specified in Section 3.1.

4.3. Description of Alternatives

4.3.1. Conventional Sewer

This alternative comprises a total pipe network length of 25 km, predominantly in 200 mm diameter, with an average installation depth of 2.0 m and localized sections reaching 4.5 m at pumping station inlets.

For this alternative, the service area is divided into 6 basins with pumping stations. A configuration is proposed in which all the effluent collected is received in the main basin and pumped from there to its final disposal or treatment point.

4.3.2. Small Diameter

This alternative subdivides the service area into three drainage basins, each equipped with a pumping station. All collected effluent is directed to a central receiving basin and pumped to the final treatment facility.

The total pipeline length is 23 km, with collectors predominantly in the 75 mm and 110 mm diameter range. The average installation depth is less than 1.5 m, with maximum depths of 2.0 to 3.0 m in selected sections.

4.3.3. Condominial

The basin and pumping configuration for this alternative mirrors that of the Conventional system. Design flow rates are comparable; however, the Condominial alternative exhibits higher infiltration rates, attributable to its substantially longer pipeline network.

The total network length is approximately 45 km, of which 35 km corresponds to 110 mm diameter condominial collectors. The average installation depth is 2.5 m, with localized sections reaching 4.5 m at pumping station inlets.

4.4. Cost Estimation

The Tables 6 and 7 summarizes the principal infrastructure components of each alternative, which served as the basis for cost estimation. The Table 8 summarizes Annual O&M costs for each alternative.

Table 6. Summary of Alternatives—gravity Pipes and Pumping Stations (PS).

System	Total Length of Gravity Pipes (km)	Amount of PS	Total Power. (kw)	Depth Range PS (m)	Total Length of Pressure Pipes (m)
Conventional	25	6	81.3	3 to 6.5	2900
Decanted Effluents	23	3	38.3	3.5 to 5.5	2100
Condominial	45	6	79.1	4.7 to 7	2900

Table 7. Sewer system investment costs (×1000 USD).

Component	Conventional	Small Diameter	Condominial
Supply and installation of gravity pipes and manholes.	6430	4350	6750
Pump Stations and pressure pipes	4100	1980	4440
Adequacy of domiciliary installation/public sewer connection	11,440	12,100	8600
Total Investment	21,970	18,430	19,790

Table 8. Annual O&M costs (×USD 1000).

Component	Conventional	Small Diameter	Condominial
O&M Networks and force mains	75	101	80
Septic tank sludge removal	N/C	22.5	N/C
O&M Pumping stations	106	56	170.5
Energy Pumping stations	181	179.5	250.5
Total O&M	362	359	501

The lower total investment cost of the Condominial system compared to the Conventional system, despite its significantly longer pipe network (45 km vs. 25 km), is explained by the combined effect of smaller pipe diameters (predominantly 110 mm vs. 200 mm), shallower excavation depths along condominium sections (which follow property slopes rather than street centerlines), and the absence of sidewalk chambers at regular intervals. These design characteristics substantially reduce unit construction costs per linear meter. Additionally, the Condominial system requires no adaptation of the household domiciliary installation, as the condominium collector is brought closer to each property boundary, reducing the connection cost component. The apparent counterintuitive result thus reflects a structural difference in the cost drivers of each typology rather than an error in estimation.

4.5. Weights Calculation of Criteria and Alternatives

4.5.1. Criteria Hierarchization

Given the deficiencies in existing sewage disposal, the potential for groundwater contamination, and the environmental sensitivity of the study area, socio-environmental criteria were assigned the highest priority weight relative to technical and cost criteria. With respect to the technical dimension, this criterion was prioritized over cost on the basis that the selected solution must achieve the highest feasible technical performance, irrespective of investment level (See Table 9).

Table 9. Main Criteria Comparison Matrix—Application Case.

Criteria	Technical	Costs	Socio-Environmental	VP
Technical	1	3	1/3	26%
Costs	1/3	1	1/5	11%
Socio-environmental	3	5	1	63%
Lambda Max	3.06	UR	0.58	
CI	0.03	CR	5%	CR < 10%, OK

4.5.2. Hierarchy of Sub-Criteria

Technical Sub-Criteria

The most important criterion proposed, “coverage”, was assigned the highest priority, reflecting the objective of maximizing the population served. “Technical acceptance” was ranked second, given the importance of securing professional consensus around the selected alternative. “Construction phasing” was considered more relevant than “regulatory compliance”, as no phased expansion is foreseen for this project given its geographic boundaries. “Regulatory compliance” was assigned the lowest weight within this group, consistent with the National Sanitation Plan’s emphasis on innovation and openness to alternative approaches. The results are presented in Table 10.

Table 10. Technical sub-criteria comparison matrix—Application Case.

#	Sub-Criterion	1	2	3	4	VP
1	Technical Acceptance	1	5	1/3	3	26%
2	Regulatory Compliance	1/5	1	1/9	1/3	5%
3	Coverage	3	9	1	5	58%
4	Construction schedule	1/3	3	1/5	1	12%
	Lambda Max	4.11	RI	0.9		
	CI	0.038073928	CR	4%		CR < 10%, OK

Cost Sub-Criteria

Within the cost criteria, “adequacy of domiciliary installation” was assigned the highest weight, reflecting the significance of household-level adaptation given the current sanitation conditions and property configurations in the study area. “Operation and maintenance” was ranked second, in recognition of the importance of long-term financial sustainability. The remaining cost sub-criteria were assigned lower and equivalent weights. The results are presented in Table 11.

Table 11. Cost sub-criteria comparison matrix—Application Case.

#	Sub-Criterion	5	6	7	8	VP
5	Supply and installation of pipes and manholes.	1	1	1/5	1/3	10%
6	Pump Stations	1	1	1/5	1/3	10%
7	Adequacy of domiciliary installation/public sewer connection	5	5	1	3	55%
8	Operation and Maintenance (labor, spare parts, tools, energy consumption, etc.)	3	3	1/3	1	25%
	Lambda Max	4.07	RI	0.9		
	CI	0.0234	CR	3%		CR < 10%, OK

Socio-Environmental Sub-Criteria

Within the socio-environmental criteria, contamination risk and health risk sub-criteria were assigned equal and dominant weights, reflecting the primacy of environmental protection and public health in the evaluation. Community participation was ranked above employment generation, given its direct influence on project sustainability and social acceptance. The results are presented in Table 12.

Table 12. Comparison matrix of socio-environmental sub-criteria—Case of Application.

#	Sub-Criterion	11	12	13	14	VP
11	Community Involvement	1	3	1/3	1/3	14.3%
12	Employment generation	1/3	1	1/7	1/7	5.4%
13	Risk of contamination (soil, groundwater, bodies of water)	3	7	1	1	40.1%
14	Health risk to operators/users	3	7	1	1	40.1%
Lambda Max		4.01	RI	0.9		
CI		0.00363	CR	0.4%	CR < 10%, OK	

The final Hierarchy of sub-criteria are shown in Table 13.

Table 13. Hierarchy of sub-criteria.

#	Sub-Criterion	Local Weighting	Weighting Criterion	Global Weighting
1	Technical Acceptance	26%	26%	7%
2	Regulatory Compliance	5%	26%	1%
3	Coverage	58%	26%	15%
4	Construction schedule	12%	26%	3%
5	Supply and installation of pipes and manholes	10%	11%	1%
6	Pumping Stations	10%	11%	1%
7	Adequacy of domiciliary installation/public sewer connection	55%	11%	6%
8	Operation and Maintenance (labor, spare parts, tools, energy consumption, etc.)	25%	11%	3%
9	Community Involvement	14%	63%	9%
10	Employment Generation	5%	63%	3%
11	Contamination risk (soil, groundwater, water bodies)	40%	63%	25%
12	Health risk to operators/users.	40%	63%	25%

The three sub-criteria with the highest global weights are: Contamination risk (soil, groundwater, and water bodies), Health risk to operators/users, and Coverage.

4.6. Ranking of Alternatives

The following section presents the performance scoring of each alternative across all sub-criteria for the study scenario. An ordinal scale with minimum (1), intermediate (2), and maximum (3) values is employed.

A score of 3 is assigned to the alternative that best satisfies a given criterion in the context of the case study, while a score of 1 is assigned to the least favorable alternative. Equal scores may be assigned to two or more alternatives when no meaningful performance differential exists with respect to a particular criterion. The justification for the ranking of each alternative in each criterion is presented in Table 14, and the numerical results in Table 15.

Table 14. Hierarchy of Alternatives—Comments.

#	Sub-Criteria	Comments
1	Technical Acceptance	The conventional system is the least debatable, since there is experience in its application. Small Diameter has reported good results, although it is currently in disuse. The condominial system is the most resisted given there is no experience in the country.
2	Regulatory Compliance	Conventional is designed with current regulations. Small Diameter also have regulations in force, although they are not applied. The condominial system is designed under regulations for the main network, while there are no regulations for condominial sections.
3	Coverage	The condominial system, due to its conception, has a greater scope of coverage, since it can have a free layout. Small diameter and conventional, as they are laid along the street centerline, limit the scope of service.
4	Construction schedule	Small Diameter does not allow for expansion, while the other systems do.
5	Supply and installation of pipes and manholes	Small Diameter is the cheapest, followed by Conventional.
6	Pumping Stations	Small Diameter is the cheapest, followed by Conventional.
7	Adequacy of domiciliary installation/public sewer connection	Condominial is the cheapest, followed by Conventional.
8	Operation and Maintenance (labor, spare parts, tools, energy consumption, etc.)	Condominial and Conventional have similar annual costs; Small Diameter has a lower cost.
9	Community Involvement	Condominial requires significant community participation as it has to allow the routing of condominial pipes through private properties, both during construction and operation. Small Diameter promotes community participation in the construction site for sanitary modification, and then in the maintenance of the domestic septic tank during operation. Conventional only allows participation in the modification of the sewage system; after connection, participation is less.
10	Employment Generation	Small Diameter, since they are simpler works, allow the use of unskilled labor, and can also generate employment opportunities in cleaning pits and through waste management. As for condominiums, a niche of employment is generated in the cleaning of condominium networks. Conventional does not generate employment in a different way to the other alternatives.
11	Contamination risk (soil, groundwater, water bodies)	The number of sewer overflows and stations presents risk of environmental contamination. On the other hand, the decanted effluent network is also vulnerable if it is not used correctly. Small Diameter is considered one point above conventional and condominial.
12	Health risk to operators/users.	Conventional, being the most robust solution and having no link with the user, is the best rated in this case. Condominial can generate risks to users due to blockages in condominial collectors. In Small Diameter, poor pit management can generate problems in households and downstream network.

Table 15. Hierarchy of alternatives.

Alternative/Criteria	1	2	3	4	5	6	7	8	9	10	11	12
Conventional	3	3	1	2	2	2	2	3	1	1	1	3
Small Diameter	1	2	1	1	3	3	1	2	2	3	3	1
Condominial	2	1	3	3	1	1	3	1	3	2	1	2

The elevated weight assigned to health risk (sub-criterion 12) reflects a foundational sanitary engineering principle: the primary purpose of any wastewater collection system is the protection of public health through the safe management of domestic effluents. From this perspective, a technology's performance regarding disease transmission risk—whether through direct contact with sewage, system failures, or poor maintenance practices—constitutes a non-negotiable dimension of evaluation. The equally high weight of contamination risk (sub-criterion 11) is specifically motivated by the environmental characteristics of the study area. Ciudad del Plata is located within the lower basin of the Santa Lucía River, the primary water supply source for the Montevideo metropolitan area. The presence of shallow groundwater, sandy soils with high permeability, and hydrological connectivity with sensitive water bodies makes contamination risk a structurally dominant criterion in this territorial context, where any failure of the collection system carries direct consequences for regional water security.

4.7. Result

The matrix product of the sub-criteria weight vector and the normalized alternative scoring matrix yields the following composite scores shown in Table 16:

Table 16. Final result.

Alternative	Score
Conventional	31.9%
Decanted effluents	32.2%
Condominial	35.9%

Based on this analysis, the Condominial system emerges as the preferred alternative for the Delta del Tigre–SOFIMA sanitation project.

4.8. Sensitivity Analysis

To assess the robustness of the results, a sensitivity analysis was conducted by systematically varying the weights assigned to the three main criteria: technical, cost, and socio-environmental.

Given the environmental characteristics of the study area, the baseline scenario assigns a weight of 63% to socio-environmental criteria. Two additional scenarios were evaluated:

- Scenario A: Reduction of socio-environmental weight to 50%, redistributing 13% proportionally between technical and cost criteria.
- Scenario B: Increase of socio-environmental weight to 70%, reducing technical and cost criteria proportionally.
- Scenario C: Increase of cost criteria weight to 50%, adjusting the weight of the technical criteria to 17% and socio-environmental criteria to 33%.

The results show that:

- In Scenario A, the Condominial alternative remained ranked first (37.4%), although the difference with the Conventional system (32.4%) increased.

- In Scenario B, the Condominial alternative (34.8%) decreased its advantage over the other options (33.3% Small Diameter, 32% Conventional).
- In Scenario C, the Condominial alternative (36%) decreased its advantage over 34.4%. Conventional, and Small Diameter decrease its rank to 29.6%).

These results demonstrate that the model is robust under moderate variations in criteria prioritization, consistently ranking the Condominial alternative first across all tested scenarios and thereby reinforcing the validity of the decision outcome.

5. Discussions

Sewer networks constitute socio-technical systems in which technical design, user behavior, institutional capacity, and environmental context interact dynamically and must be addressed as an integrated whole.

The results of this study confirm that sewer technology selection outcomes are highly sensitive to the explicit prioritization of decision criteria. When socio-environmental dimensions are assigned substantial weight, alternative systems such as the Condominial solution demonstrate superior overall performance relative to conventional gravity sewers, even in contexts where the latter has historically constituted the default planning choice.

Several studies have applied MCDM methods to sanitation-related decisions, though most focus on wastewater treatment technology selection rather than on the upstream choice of sewer network typology. For instance, Cetkovic et al. (2023) [28] applied AHP to select among wastewater treatment plant configurations in a municipal context, prioritizing technical efficiency and financial parameters as dominant criteria. Similarly, Ventura Matos et al. (2021) [29] developed a multi-criteria framework for city-wide sanitation solutions in coastal Angola, integrating onsite and offsite alternatives through geographic and decision analysis tools, where environmental suitability and coverage emerged as key differentiators. In contrast to these approaches—which take collection systems for granted, focusing on treatment endpoints—the present study addresses the selection of the collection system itself, where engineering typology, territorial conditions, and socio-environmental externalities interact before any treatment stage is defined. This upstream framing responds to a recognized gap in sanitation planning practice, particularly in Latin American contexts where regulatory inertia and cost-dominant criteria tend to predefine technology choices without systematic evaluation of alternatives.

This finding is consistent with a broader body of international research indicating that cost-dominant infrastructure planning systematically undervalues environmental externalities and long-term sustainability considerations [4,6,9]. Multi-criteria approaches have been increasingly advocated as instruments to redress these limitations by explicitly incorporating environmental risk, community participation, and institutional feasibility into infrastructure decision-making.

Within the field of urban water management, numerous studies have demonstrated the applicability of AHP and other MCDM methods for prioritizing water supply investments, wastewater treatment technologies, and watershed management strategies [7–10]. However, the majority of published applications focus on treatment technologies or macro-scale planning decisions. The present study contributes to this literature by applying AHP specifically to the selection of sewer network typologies under environmentally constrained urban conditions—a decision stage that has received comparatively limited attention.

From a governance perspective, the results reinforce the argument that sustainable infrastructure transitions require adaptive planning frameworks capable of integrating multiple values and objectives, rather than defaulting to standardized engineering templates. Conventional sewer systems remain technically sound solutions; however, their

uniform application is unlikely to be optimal across heterogeneous territories characterized by wetland environments, low population densities, or binding financial constraints.

The sensitivity analysis further demonstrates that explicitly incorporating socio-environmental criteria does not produce radical reversals in the alternative ranking under moderate variations in criteria weights. This stability strengthens confidence in the methodological validity of the framework and supports its potential replicability across diverse planning contexts.

Beyond the specific case evaluated, the proposed model contributes to the broader discourse on sustainable infrastructure governance by demonstrating that technology selection outcomes are significantly influenced by the explicit prioritization of socio-environmental criteria. This finding challenges the cost-dominant planning approaches that have traditionally governed sanitation expansion programs in the region.

The choice of the classical AHP formulation over alternative MCDM approaches warrants brief justification. Methods such as fuzzy AHP [30] extend the standard formulation by incorporating linguistic uncertainty into the pairwise comparison process, allowing decision-makers to express judgments as fuzzy numbers rather than crisp values. While this increases flexibility under conditions of significant data uncertainty, it also introduces additional complexity in weight elicitation and interpretation, which may limit accessibility for practitioners in institutional planning contexts. TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and hybrid AHP-TOPSIS approaches [31] offer robust ranking capabilities but require the definition of ideal and anti-ideal solutions and are generally more sensitive to the normalization method applied. The classical AHP was selected in this study on the grounds of its methodological transparency, well-established consistency verification procedure, and widespread acceptance among infrastructure planning practitioners—factors particularly relevant in institutional contexts where decision reproducibility and stakeholder communication are priorities.

Future research may extend the framework by incorporating formal uncertainty analysis, fuzzy AHP approaches, or lifecycle cost and environmental assessment integration, thereby further enhancing the capacity of the model to support decision-making under conditions of data scarcity and planning complexity.

6. Conclusions

Achieving universal sanitation coverage will inevitably require the expansion of the technological portfolio currently deployed in planning practice.

Even where design standards are met, inadequate operational practices will compromise system performance and ultimately lead to failure. It is therefore essential that the selected solution be fully understood and accepted by the responsible operator, who should actively contribute to the evaluation process to ensure that operational requirements are properly accounted for.

Equally, non-compliance with established operational guidelines by end users will undermine the functional integrity of the system.

User participation throughout all project phases is a critical determinant of long-term success, encompassing informed awareness of available technological options, active engagement in the definition of collector routing, and a clear delineation of responsibilities and obligations.

Analogous challenges have been documented across Latin America, Sub-Saharan Africa, and Southeast Asia, where rapid urbanization and environmentally sensitive territories create sustained demand for adaptive sanitation solutions. The framework proposed in this study offers a structured and replicable mechanism applicable beyond the Uruguayan context, scalable to metropolitan planning scales and adaptable to diverse regulatory

environments, provided that criteria hierarchies are appropriately redefined to reflect local conditions.

The principal contribution of this study lies not in the methodological novelty of AHP itself, but in its application to a decision stage that is frequently bypassed in sanitation planning practice: the structured, pre-design selection of sewer network typology. In Latin American institutional contexts—where technology decisions are often constrained by regulatory defaults, professional path dependency, and the absence of multi-dimensional evaluation frameworks—the proposed model provides a transparent and replicable mechanism to explicitly integrate technical, economic, and socio-environmental criteria before engineering design begins. The case study demonstrates that when socio-environmental criteria are given appropriate weight, alternatives that are routinely dismissed on cost or regulatory grounds may in fact offer superior overall performance. The framework is scalable to metropolitan planning scales and adaptable to different regulatory environments, provided that criteria hierarchies are contextually redefined. Future applications may incorporate uncertainty modeling, fuzzy weighting approaches, or lifecycle cost analysis to further strengthen the robustness of the decision outputs.

The systematic application of structured decision-support frameworks of this nature yields significant improvements in the quality and transparency of infrastructure planning decisions.

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Abbreviations

The following abbreviations are used in this manuscript:

AHP	Analytic Hierarchy Process
WHO	World Health Organization
SDGs	Sustainable Development Goals
UN	United Nations
OSE	Administración de Obras Sanitarias del Estado
IM	Intendencia de Montevideo
PNS	National Sanitation Plan
MVOTMA	Ministerio de Vivienda, Ordenamiento Territorial y Medio Ambiente
U.S. EPA	United States Environmental Protection Agency
OPS-CEPIS	Organización Panamericana de la Salud—Centro Panamericano de Ingeniería Sanitaria y Ciencias del Ambiente
CONAGUA	Comisión Nacional del Agua
MAMC	Multicriteria Analysis Methods

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