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Efficiency Analysis of Water Conservation Measures in Sanitary Infrastructure Systems by Means of a Systemic Approach

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Abstract: The challenges of urban water management and sanitary infrastructure (water supply (WSS), sewage (SS), urban drainage (UDS) systems) are increasingly frequent in Brazilian cities whether as a combined result of overcrowding and/or a lack governmental interest and hence investments, in the sector. Such an increase in environmental pressure reflects directly on population welfare and well-being related to the availability of drinking water, wastewater treatment, and access to effective drainage systems in order to minimize, or at least reduce, the occurrence of urban flooding and associated public health risks. Thus, alternatives with an integrated approach to urban water management are interesting to the reality of countries such as Brazil. The urban water use (UWU) model is a strategic planning tool with integrated way of thinking, which selects measures to mitigate the urban impacts in sanitary infrastructure and buildings. In this sense, the objective of this research is to apply the UWU model in a case study in Curitiba/Brazil to demonstrate the effect of the systematic approach and its intrinsic synergies in the systems in question, promoting water conservation in urban areas. The results are favorable to integrated systems with synergy use, evidencing quantitatively a greater efficiency in them.

Keywords: urban water management; sanitary infrastructure systems; integrated approach; UWU model; strategic planning; synergy

1. Introduction

Brazil has 12% of the planet's freshwater reserves; however, these natural resources are disproportionately distributed. The biggest share of water is concentrated in the Amazonian region, in the northern region of the country, having Manaus as its largest city with a population density of 183.7 inhabitants/km^2; on the other hand, the South and Southeast regions have the smallest availability of water and hold denser cities. São Paulo, the largest city in the country, with a population density of 7904.32 inhabitants/km^2 [1] is located in the Southeast region.

In addition to these conditions related to water distribution, Brazil has historically not had a sufficient basic sanitation structure to serve the population. In order to deal purposefully with this reality, in 2007 federal law number 11,445 [2] was issued establishing the national basic sanitation guidelines for the sanitary infrastructure in Brazil. However, recent data show an unpromising prospect. Regarding the water supply system coverage, for example, only 83.62% of Brazilians are served with drinking water and the network suffers with a loss of 38.45% [3].

Regarding the sewage system, until 2015 access to basic sanitation (a household connected to the general sewage network or septic tank, served from the general supply network and the garbage

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collection and destination by the cleaning services) has increased only 15% reaching the share of 65.30% of all of the country's households [4]. Looking to the drainage system, a total of 47.5% of Brazilian municipalities have at least once declared emergency situation or public calamities due to flooding. These floods affected around 7.7 million people between the years 2013 and 2016, an average of 1.9 million per year [5].

For those reasons, a priority demand in Brazilian cities is to promote the sustainable use and management of water in its cycle, which involves sanitary infrastructure (water supply, sewage and drainage systems) and buildings.

Most agencies, including the World Bank, The United Nations, Education, Scientific and Cultural Organizations (UNESCO), and the World Water Council, have increasingly argued that the solution for complex water management systems is integrated management, involving governmental and public participation. Going further, a water-smart society can be accomplished by developing resilient and sustainable solutions for key water challenges, e.g., a multiple water concept as a holistically integrated system (the right quality and quantity of water, for the right purpose and the right user) [6–9].

A solid understanding of the finite character of water and many concerns have been raised since the end of the 1980s when society started to be aware of environmental issues and sustainable development [10]. Such an era is characterized by intense urbanization which led to the development of several challenging issues for water management [11]. In several parts of society, a larger discussion on how to achieve a balance between environmental, societal, and economic balance has started [12].

Regarding the design of solutions, there is a wide range of possibilities that refer to sustainable practices, but they do not necessarily guarantee success in achieving sustainability. This can be explained by the culture of Western engineering to design isolated technical solutions in an unsystematic manner [13]. Water Europe [6] defines sustainability of a water utility as the ability to access reliable supplies to consistently satisfy current need, make responsible use of supplies, and have the capacity to adapt to future scenarios. Therefore, it is assumed that the systemic approach with synergy to such a cycle can generate a set of integrated solutions whose results enhance the benefits of sustainable water use.

According to Corning, synergy means "the effects produced by wholes are different from what the parts can produce alone" [14]. In 1969, Hermann Haken was the precursor of the synergetics theory, an interdisciplinary science that explains the formation and self-organization of complex systems composed of many individual parts. It was inspired by the laser theory explained only by self-organization phenomena of non-equilibrium systems [15]. The self-organization requires a macroscopic system consisting of many nonlinearly interacting subsystems. Depending on the external control parameters (environment, energy-fluxes) self-organization takes place, and non-equilibrium—that is, an open system—is a prerequisite to the self-organization, since self-organizing is powered by external factors.

Addressing the water use cycle as a system is a complex task since there are several component subsystems which interact with each other and with the environment that surrounds them. The interactions between the subsystems are called internal while those with the environment are called external. Internal interactions in a system may be either linear or non-linear. Linear interactions are those that do not change the final state of the system in terms of its original properties. Nonlinear interactions, however, change the properties of this system, leading it to a different state from the original. In reality, non-linear interactions are synergies that are characterized by the interdependencies between the components and their integration. In this context, synergies can be positive or negative [16].

Synergy is positive when the components act with interdependence, this function being differentiation and integration, so that the result goes beyond the mere sum of attributes and functionalities of these components. It follows, therefore, that the level of positive synergy depends on the degrees of differentiation and integration between the components, as well as the stability between them. That is, the more differentiated (specialized) the components are, and the more they are integrated and stable, the greater the overall functionality of the system [17].

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Negative synergy occurs when the overall result is less than the sum of the parts. This inferior result, for example, can be a loss of quality, efficiency, benefit, among others, of the system [17]. Concerning the origin, a negative synergy may result from difficulties related to differentiation and integration between the parts. In this way, such parts can be so different from each other that they make integration impossible. On the other hand, they can be so similar to each other that it causes the same functionalities to overlap, a condition that does not allow the complementarity of differences.

The consequence is the difficulty of integrating diversities, a fact that leads the system to fragmentation. However, there are also the effects of conflicting relations between the parts resulting from their opposite directions, effects that are more harmful than those related to fragmentation.

External interactions, in turn, are outlined by the relationships between the urban water cycle and the external factors that involve it, such as, for example, the effects of global warming, the economy, and the user's posture. Over many of these factors there is no possibility of human control, which results in a cycle subject to unpredictability as to various aspects.

Therefore, the search for a sustainable use and management of water in urban areas requires attention to the inherent complexity of its cycle. It is important to consider several approaches to better understand it. One of the main approaches is integrated urban water management (IUWM), which understands the cycle of water use in the urban environment as a complex system. According to [18], the IUWM has been used for managing freshwater, wastewater, and stormwater as components of a river basin wide management plan, in order to achieve water sustainability. Other approaches are equally important, such as 'blue-green' [19], 'water sensitive urban design' [20], 'resilient urban water systems' [21], among others.

Finally, in view of this constellation of theoretical approaches and the resulting opportunities for action, it is understood that it is essential to investigate the complexities of the cycle of urban water use to investigate the internal interactions between its components. Therefore, the search for a sustainable use of water in its urban cycle, when based on the systemic view, can be significantly more successful than such a search based on an unsystematic view, since it does not direct enough attention to interactions [13].

In summary, this article assumes that the use and management of water, in its urban cycle, promotes a gain in sustainability when designed under the systemic approach. Such a hypothesis would be justified by the possibility of prospecting synergies, and subsequently enhancing the positive ones and mitigating the negative ones, that would provide for the emergence of a more sustainable use of water.

Considering this context, the present work aims to propose and test the hypothesis that in a given urban water cycle a gain in sustainability is achieved when it is systemically conceived and managed, since such an approach allows the identification of synergies which would not be considered in a conventional unsystematic approach.

In this sense, the urban water use (UWU) model [22,23] aims to assist the management of urban waters in an integrated manner, considering measures for urban environmental sustainability. The tool focuses on the selection of measures for urban sanitary infrastructure and for buildings using the strategic plan and system theory.

Therefore, the purpose of this study is to demonstrate the effect of the systemic approach considering theories such as interdependence and synergy in the sanitary infrastructure project with alternative measures, resulting in a more efficient and sustainable system under environmental, social, and economic conditions, when compared to the classical approach. For its development, a comparative analysis was developed through a case study in which the UWU model is applied.

2. Materials and Methods

The urban water cycle system is configured by the building components, water supply system, sewage system, and drainage system. The water flows between these components include both linear and non-linear interactions that characterize the system as a whole. Thus, the greater the

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degree of knowledge of these interactions, the greater the possibility of prospecting for synergies, whether positive or negative. Emerging properties that result in benefits must be explored and enhanced, while those associated with setbacks must be mitigated. Thus, in this item, a case study was conducted in which the measures of sustainable use and management of water were designed, for a given urban water cycle, initially under the unsystematic approach and later under the systemic approach for comparison purposes.

2.1. The Urban Water Use (UWU) Model

The UWU model [22,23] is a decision-support tool that intends to evaluate and rank groups of measures for urban areas considering the water supply systems (WSS), the sewage systems (SS), the urban drainage systems (UDS), and the buildings using the strategic planning technique. In summary, it is necessary to formulate scenarios based on external factors (e.g., population growth rate, economic performance, and climate change), select the indicators by means of which the measures will be evaluated (e.g., water supply system coverage, sewage system coverage, maximal runoff flow), establish the vision and the weight of the indicator, select the measures, and group them. Finally, the evaluation is carried out through the effectiveness index.

UWU uses an integrated urban water management (IUWM) approach to adapt to environmental and social changes currently.

The model has the following stages: (i) Current data input, (ii) vision building, (iii) scenarios building, (iv) defining the best components strategy, (v) selection, equation, and structuring of measures, (vi) simulation equations of the indicators, linking the scenarios, measures, and vision, (vii) outcomes, and (viii) integrated evaluation, as shown in Figure 1.

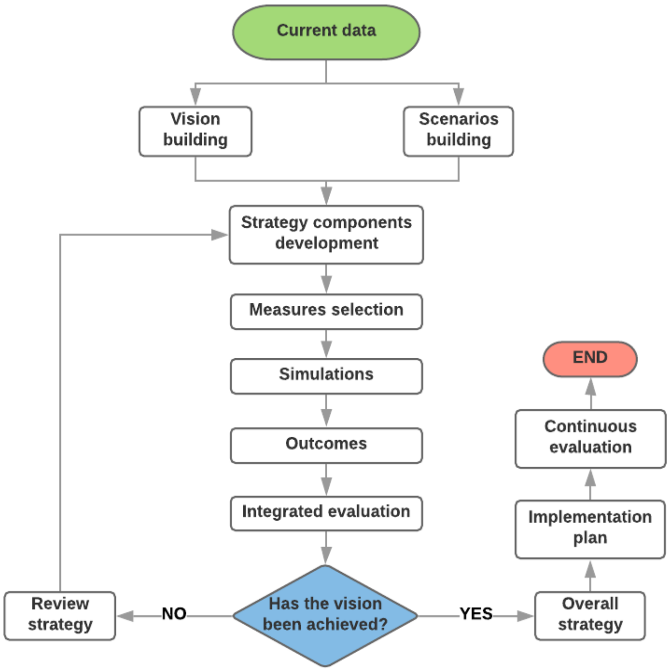

Figure 1. General structure of urban water use (UWU) model.

The vision building stage consists of indicators that represent the community desire for the future in terms of quality of life and sustainable environment. Therefore, to build the vision, it is necessary to choose indicators that should be related to what is desired by the community for that area in the future (in this work, the current values were selected in order to at least maintain the same value of the indicators for future scenarios). After selecting the indicators, it is necessary to quantify them in specific values expected for each scenario, as well as to set weight values for each indicator. The scenarios are

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part of strategic planning and represent uncontrollable changes in the future. Based on this definition, scenarios are constructed considering external factors, which are variables that the decision maker has no control over.

In brief, to run the model it is necessary to elaborate future scenarios based on external factors; establish the indicators; develop a set of measures correlated with the indicators; establish one vision (score to be achieved); establish the weight of each indicator; select the measures and group them; add and classify per the effectiveness index. The evaluation is performed through an effectiveness index.

2.2. Case Study

The method to conduct this investigation was based on a case study approach. It is because this approach allows to work under real conditions. In this way, several steps were developed such as study area presentation, vision building, scenarios building, measure groups elaboration, simulations, and outcomes evaluation. These steps are presented as follow.

2.3. Study Area

The study area selected to apply the tool and evaluate the measure groups' effectiveness in a real projection was the Barigui river basin, since it is the best available to the authors. The Barigui river basin is the biggest in Curitiba, crossing it from the North to the South.

From that basin, the Pilarzinho neighborhood was chosen based on three main criteria; (i) it borders the Barigui river, (ii) it has one of lowest sewage coverage areas, and (iii) it has the highest population density. It makes border with two parks in Curitiba—Tangua Park and Tingui Park—and these are used as a flood attenuation, as shown in Figure 2.

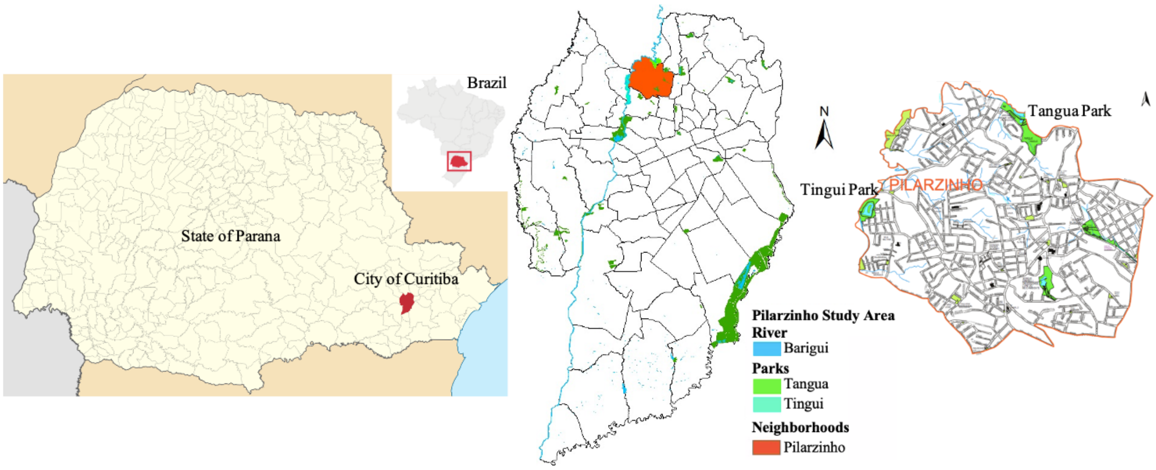

Figure 2. Study area.

The neighborhood has a population of 12,232 inhabitants on an area of 305 ha, yielding a density of 40.09 inhabitants/ha [24]. The coverage of the water supply and sewage system is 100% and 69.70%, respectively [25]. The soil permeability coefficient is equivalent to 10^{-5} m/s [26]. Tables 1–3 present additional data sets for the study area.

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Table 1. Data set for study area.

Categories	Input Data	Values	Source
External factors building process	Current population	12,232 inhabitants	[27]
	Current population growth rate	0.76%	[27]
	Minimum population growth rate	0.38%	[27]
	Maximum population growth rate	1.79%	[27]
	Type of population growth	Logarithmic	Statistical analysis
	Current year	2018	-
	Future year	2048	-
	Historic average temperature per year	17.23 °C	[28]
	Historic minimum average temperature per year	13.14 °C	[28]
	Historic maximal average temperature per year	23.43 °C	[28]
	Historic average rainfall	1474.68 mm/year	[28]
	Current average income rate	R$ 3776.22	[29]
	Current minimum income rate	R$ 1653.45	[29]
	Current maximal income rate	R$ 9821.57	[29]
	Return period	2, 5, and 10 years	-
	Time of rainfall	32 min	Calculated
Water Supply System (WSS)	Current WSS coverage	100%	[25]
	Current water per capita consumption	130.40 l/inhabitants.day	
	Water supply network loss index	37%	
Sewage System (SS)	Current SS coverage	69.70%	[25]
	Return coefficient	Calculated	Calculated
Drainage System (DS)	Covered area	3.05 km^2	[24]
	Urban basin length	2 km	[24]
	Number of households	4.917 houses	[27]
	Soil permeability coefficient	10^{-5} m/s	[26]
	Runoff water		
	Biological Oxygen Demand	13 mg/L	[30]
	Total Nitrogen	2.4 mg/L	
	Total Phosphorous	0.42 mg/L	
	Total Suspended Solids	141 mg/L	
	Total Coliforms	5000 MPN/100 mL	

Table 2. Parametrization of daily per capita consumption of water (q_e) input data.

Appliances	Consumed Specific Flowrate	Use Frequency	Use Duration (s)	Persons (inhabitants)	Total of Water Consumption (l/day)
Toilet (valve)	6	5	–	1	30
Toilet (shower)	0.1	1	360	1	36
Toilet (hand basin)	0.1	5	12	1	6
Kitchen (tap)	0.2	3	240	4	36
Garden (tap)	0.2	1	180	4	9
TOTAL (q_e)					130.40

Table 3. Pollutant loads per appliances.

Appliances	BOD (mg/L)	N (mg/L)	P (mg/L)	TSS (mg/L)	Coliforms MPN/100 mL	Source
Toilet (valve)	400	60	15	450	1.00×10^{10}	[31]
Toilet (shower)	165	3.89	0.2	103	3.95×10^{4}	[32]
Toilet (hand basin)	265	6.2	0.6	146	1.35×10^{2}	[32]
Kitchen (tap)	633	14.44	9.1	336	1.47×10^{3}	[32]
Washing machine	184	4.17	14.4	53	5.37	[32]
Garden (tap)	0	0	0	0	0	-

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The estimation of the water per capita consumption was defined for a typical dwelling according to the reality of Brazilian cities [33]. The Curitiba average (130.40 l/inhabitants.day) was adopted according to the local wastewater treatment company data.

2.4. Vision Building

The vision was built for 2050 (next 30 years) and the indicators assumed were (i) water supply system coverage, (ii) sewage system coverage, (iii) maximal runoff flow, (iv) biological oxygen demand (BOD), (v) total nitrogen, (vi) total phosphorus, (vii) total suspended solids, and (viii) total coliforms. The main indicators (water supply system coverage, sewage system coverage, and maximal runoff flow) were selected equally weighted. The polluting loads, in turn, were equally weighted, however, lower than the three main indicators, since the main issues related to sanitation social issues in Brazil are related to these three main indicators. All of them are shown in Table 4 with the respective weights.

Table 4. Indicators and their respective weights.

Systems	Indicators	Weight (W)
Water Supply System	Water Supply System Coverage (%) - C_{WSS}	10%
Sewage System	Sewage System Coverage (%) - C_{SS}	10%
	BOD (kg/day) - $L_{SS,BOD}$	7%
	Total Nitrogen (kg/day) - $L_{SS,N}$	7%
	Total Phosphorus (kg/day) - $L_{SS,P}$	7%
	Total Suspended Solids (kg/day) - $L_{SS,TSS}$	7%
	Total Coliforms (day^{-1}) - $L_{SS,TC}$	7%
Drainage System	Maximal Runoff Flow (m^3/s) - Q_{RF}	10%
	BOD (kg/day) - $L_{DS,BOD}$	7%
	Total Nitrogen (kg/day) - $L_{DS,N}$	7%
	Total Phosphorus (kg/day) - $L_{DS,P}$	7%
	Total Suspended Solids (kg/day) - $L_{DS,TSS}$	7%
	Total Coliforms (day^{-1}) - $L_{DS,TC}$	7%

2.5. Scenario Building

For the scenario building, external factors were defined as (i) the per year population growth rate (λ); (ii) the annual average temperature (T), which helps with previewing the contribution of the human activities to global warming and the behavior of population according to the temperature variation, as [34] highlighted as a variable of climate change effects; (iii) the economic performance (EP), which reflects directly on the social conditions where the community is inserted; and (iv) the rainfall intensity, also highlighted by [34], being the rainfall divided in maximal rainfall intensity to evaluate flow peaks and the average rainfall intensity to evaluate the pollutants loads.

Thus, four scenarios were built (SC1, SC2, SC3, and SC4) with four external factors based on the method called adaptive delta management (ADM) for scenario conception [35], as shown in Figure 3. It is a concept to adapt to the unexpected challenges in the future.

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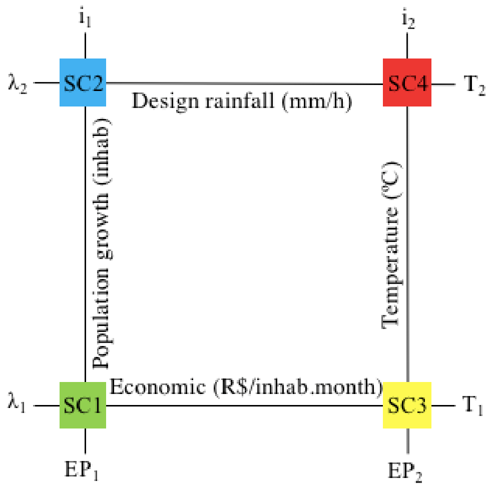

Figure 3. Scenarios building representation [35,36].

Those four future scenarios were obtained by a combination of two stages—a minimum and a maximum—for each external factor. At the same time, a current scenario was formulated to compare the results and show the worsening of the indicators over the years as shown in Table 5.

Table 5. Scenarios building.

External Factors	**Scenarios**				
	Current	**SC1**	**SC2**	**SC3**	**SC4**
Population growth (λ)	λ_0	λ_1	λ_2	λ_1	λ_2
Annual average temperature (T)	T_0	T_1	T_2	T_1	T_2
Economic performance (EP)	EP_0	EP_1	EP_1	EP_2	EP_2
Maximal rainfall ($i_{máx}$)	$i_{máx0}$	$i_{máx1}$	$i_{máx1}$	$i_{máx2}$	$i_{máx2}$
Average rainfall (i)	i_0	i_1	i_1	i_2	i_2

Indexes 0: Current value; 1: Minimum value; 2: Maximum value.

The data used in the scenario formulation as population growth, average temperature, economic performance, and rainfall intensity, to current scenario, Scenario 1, Scenario 2, Scenario 3, and Scenario 4, were obtained from reported data by appropriate agencies as shown in Table 6.

Table 6. Scenario data.

External Factors	**Scenarios**				
	Current	**SC1**	**SC2**	**SC3**	**SC4**
Population growth (λ = %)	$\lambda_0 = 0.76$	$\lambda_1 = 0.38$	$\lambda_2 = 1.79$	$\lambda_1 = 0.38$	$\lambda_2 = 1.79$
Average temperature (T = °C)	$T_0 = 17.23$	$T_1 = 14.64$	$T_2 = 26.03$	$T_1 = 14.64$	$T_2 = 26.03$
Economic performance (EP = R$/month) (EP = US$/month)	$EP_0 = 3776.22$ $EP_0 = 906.29$	$EP_1 = 1653.45$ $EP_1 = 396.82$	$EP_1 = 1653.45$ $EP_1 = 396.82$	$EP_2 = 9821.57$ $EP_2 = 2357.18$	$EP_2 = 9821.57$ $EP_2 = 2357.18$
Maximal rainfall ($i_{máx}$ = mm/h) Average rainfall (i_{aver} = mm/year)	$i_{máx0} = 73.46$ $i_0 = 1474.68$	$i_{máx1} = 84.98$ $i_1 = 1548.42$	$i_{máx1} = 84.98$ $i_1 = 1548.42$	$i_{máx2} = 94.88$ $i_2 = 1769.62$	$i_{máx2} = 94.88$ $i_2 = 1769.62$

SOURCE: [24,27,28,30,37].

2.6. Measures Group Selection

The measure group elaboration for 2050 was based on strategies, as well as in [38], however, in this case, it focused on improving the water conservation performance of water supply, sewage, and urban drainage systems. Based on these strategies, the following groups of measures were composed as shown in Table 7.

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Table 7. Group of measures.

Identification	Measures	Quantity	Additional Information
Group of Measures 0 (GM0) Current values	(M0): Without measures	Without measures	It considers that no intervention will be adopted for the study area, it corresponds to a control group of measures and for the establishment of vision value.
Group of Measures 1 (GM1) Without Sinergy	(M1): Rational Use of Water (M2): Use of Rainwater (M3): Network Loss Ratio Reduction (M4): Use of Grey Waters (M5): Distribution Tanks (M6): Permeable Pavement	Reduce 20% of water use Use 30% of rainwater Reduce 50% of the losses Use 10% of grey water A tank of 2 m^3/house 50% of the area using	In GM1 all the measures are calculated separately, that is, without synergy.
Group of Measures 2 (GM2) With Sinergy	(M1): Rational Use of Water (M2): Rainwater Use (M3): Network Loss Ratio Reduction (M4): Use of Grey Waters (M5): Distribution Tanks (M6): Permeable Pavement	Reduce 20% of water use Use 30% of rainwater Reduce 50% of the losses Use 10% of grey water A tank of 2 m^3/house 50% of the area using	All the previous measures from Group of Measures 1, but calculated together interconnected, with synergy.

With respect to Group of Measures 0 (GM0)—the group without intervention measures—its greatest contribution is to understand future scenarios without any mitigation measures being taken, and to serve as a basis value for comparison with other groups. On the other hand, GM1 and GM2 considered measures without and with synergy, respectively, thus allowing to evaluate the impact of it. GM1 consists of six measures to be applied independently in their respective subsystems, with measures M1, M2, M4, and M5 specific to buildings. Measure M3 is designed for WSS and M6 for UDS. GM2 contains the same six measures, however with some applied together to operate the interactions between the subsystems in order to prospect for synergies.

2.7. Simulation Equations

For the indicators estimates, detailed in Table 4, the respective equations are presented next. For this demonstration, only Scenario 1 was chosen, as described in Tables 5 and 6, and the estimates for the other scenarios follow the same logic. Despite the above, the applied measure groups are GM1 and GM2, which reflect concepts with and without synergy, respectively, as presented on Table 7.

For the water supply system coverage, equations are:

$$C_{WSS} = \frac{P_{WSS}}{P_T} \times 100 \tag{1}$$

$$Q_{WSS} = P_{WSS} \times q_t \times k_1 \tag{2}$$

$$q_t = \frac{q_e}{1 - L_{NETWORK}} \tag{3}$$

where:

q_e is the daily effective per capita consumption (consumed at buildings);
q_t is the daily total per capita consumption (including water losses at the distribution network);
$L_{network}$ is the water loss index at distribution network;
P_{WSS} is the population supplied by WSS;
P_T is the total population to be served;
k_1 is the highest consumption day coefficient;
C_{WSS} is the populational coverage by WSS.

In consideration of the variables which modulate C_{wss}, it is observed in Equation (1) that it is possible to act upon q_e and $L_{network}$. Acting upon q_e from GM1, measures M1 (rational use), M2 (rainwater), and M4 (graywater) were chosen, which are specific for edifications and are measures

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linked to residents' initiative. As to the effect of such measures, they are observed in q_e reduction at the edifications, this being the end objective of the inhabitants in order to reduce service costs of WSS. Besides that, M1, M2, and M4 tend to grow the water system coverage (C_{WSS}), a benefit not usually considered by sanitation companies during planning. This way, it is considered that the benefits of M1, M2, and M4 happen only for residents through the reduction of water service costs. Regarding usually planned interventions by sanitation companies, measure M3 has a highlight for loss reduction in the water distribution network. The most common actions taken in Brazil are detection and repair of leaking points and installation of pressure reduction valves. In this context, at the GM1 approach, without synergy, it is not considered the interactions between measures M1, M2, and M4 at edifications and measure M3 at WSS.

At the approach with synergy, to evaluate the impact of GM2 over C_{WSS}, the planning would be under the responsibility of a local water basin committee, which can reflect about the reduction potential of daily per capita water consumption (M1, M2, and M4 in edifications) and the network water loss index (M3 in WSS). Such contemplation of GM2 considers possible integrations between edifications and WSS, which can generate positive synergy.

For the indicator C_{SS}, the used equation was:

$$C_{SS} = \frac{P_{SS}}{P_T} \times 100 \tag{4}$$

$$Q_{SS} = \frac{P_{SS}}{q_c} \times 100 \tag{5}$$

where:

q_c is the per capita sewage daily contribution;
P_{SS} is the population served by SS;
P_T is the total population to be served;
C_{SS} is the populational coverage SS.

In the approach without synergy characterized at GM1, sanitation companies do not consider the alteration of q_c, according to the application of measures M1, M2, and M4 for the expansion of C_{SS}. In the application of GM2 for positive synergy, it is observed that sanitation companies estimate C_{SS} based on a qc altered qc by M1 and M4, considering thus the interaction between edifications and SS.

For the sewage parameter loads estimate, the following basic equation was considered:

$$\begin{gathered} L_{BOD,N,P,TSS} = 10^{-3} \times P_C \times Q_{SS} \\ L_{Col} = 10^4 \times P_C \times Q_{SS} \end{gathered} \tag{6}$$

where:

$L_{BOD,N,P,TSS}$ is BOD, N, P, and TSS organic loads rates (kg/day);
L_{Col} is Coliforms organic load rate (day^{-1});
P_C is pollutant concentration (mg/L) or (MPN/100 mL);
Q_{SS} is domestic sewage flow (m^3/day).

For the indicators Q_{RF} and L (runoff pollutants loads), both are associated to the measures M5 (distribution tanks in buildings) and M6 (permeable pavements in streets). As previously commented, in GM1, measures M5 and M6 are conceived without synergy while in GM2, they are considered with synergy. Therefore, for the estimate of Q_{RF} in heavy rains the rational method was adopted, as expressed by equation:

$$\begin{gathered} Q_{RF} = \frac{C \times i \times A}{360} \\ A < 5km^2 \end{gathered} \tag{7}$$

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where:

C is runoff coefficient;
i is the maximal rainfall intensity (mm/h);
A is area (ha).

Considering the superficial pollutants flow loads estimate (L), the following basic equation was considered:

$$\begin{gathered} L_{BOD,N,P,TSS} = 10^{-6} \times P_C \times Q_{RFaverage} \times A \\ L_{Col} = 10^{-8} \times P_C \times Q_{RFaverage} \times A \end{gathered} \tag{8}$$

where:

$L_{BOD,N,P,TSS}$ is annual BOD, N, P and TSS load (kg/year);
L_{Col} is annual coliform load (year^{-1});
$Q_{RFaverage}$ is average of annual runoff flow (mm/year);
P_C is pollutant concentration (mg/l) or (MPN/100 mL);
A is area (m^2).

The indicators equation presentation was built just for Scenario 1, as previously explained. For Scenarios 2, 3, and 4, characterized by other external factor arrays, the same mathematical logic is followed for the indicators estimate under consideration. In reality, it is acknowledged that working with scenarios yields a higher complexity to the study. This is observed when evaluating the impact of the measure groups on the indicators; the influence of external factors population growth rate (λ), annual average temperature (T), economic performance (EP), maximal rainfall intensity (i_{max}), and average rainfall intensity ($\mathrm{i}_{average}$), are simultaneously evaluated as shown in Table 5.

Equations which directly or indirectly combine these external factors with the sustainability indicators are associated to the previously described equations. In C_{WSS} case, Equations (1)–(3) present the parameters involved, with highlight for population P, which is a function of the populational growth (λ) and daily effective per capita consumption q_e (multiple linear regression), which in turn is function of the annual average of rainfall (i), temperature (T), and economic performance (EP). Such relations are presented as such:

$$P_g = P_0 \times \left(P_0 \times \lambda_g \times \ln \Delta t\right) \tag{9}$$

$$qe_{EP} = 0.0196 \times (\mathrm{EP}) + 66.3 \tag{10}$$

$$qe_{i,T} = 208.4 - 0.01901 \times i + 2.75 \times T_{max} + 11.31 \times T_{min} - 22.12 \times T_{aver} + 0.2087 \times T_{max} \times T_{aver} \tag{11}$$

For indicators C_{SS}, L (DBO, P, N, Coliform loads) it is considered the same Equations (1)–(3) for C_{WSS}, given that the population P is the same and qc is a direct function of q_e. In other words, C_{SS} and L are function of λ, T, and EP.

Regarding indicator Q_{RF}, Equation (7) presents its direct relation with the external factor i_{max} (maximal precipitation). For indicator L, as per Equation (8), it is a function of Q_{RF}, which is a function of $\mathrm{i}_{average}$ (average precipitation). In sum, Q_{RF} is influenced by the external factor i_{max}, while L depends on external factor $\mathrm{i}_{average}$.

The general structure of these measure groups, indicators, scenarios, and equations that express the subsystems interactions is presented in Table 8. Through such interactions it is possible to probe synergies to evaluate the performance of indicators. Thus, for each scenario, the indicators are estimated for all measure groups without and with synergy. For example, saving water in different ways, such as reducing the water per capita consumption, using rainwater or graywater, implies a reduction of drinking water in buildings and consequently, in an increase of the water supply system coverage (positive synergy). The indirect consequences are the reduction of sewage flow and the increase of pollutant loads in the sewage (negative synergy).

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Table 8. Equations according to scenarios.

Group of Measures	External Factors	Scenarios SCi (i = 1, 2, 3, 4)
GM*k* (*k* = 0, 1, 2)	Water Supply System Coverage (%) - C_{WSS}	$C_{WSSi} = \frac{C_{WSS0} \times Q_{WSS0}}{Q_{WSSi}}$
	Sewage System Coverage (%) - C_{SS}	$C_{SSi} = \frac{C_{SS0} \times Q_{SS0}}{Q_{SSi}}$
	BOD (kg/day) - $L_{SS,BOD}$	$L_{SSi,BOD} = Q_{SSi} \times L_{BOD} \times A$
	Total Nitrogen (kg/day) - $L_{SS,N}$	$L_{SSi,N} = Q_{SSi} \times L_{N} \times A$
	Total Phosphorus (kg/day) - $L_{SS,P}$	$L_{SSi,P} = Q_{SSi} \times L_{P} \times A$
	Total Suspended Solids (kg/day) - $L_{SS,TSS}$	$L_{SSi,TSS} = Q_{SSi} \times L_{TSS} \times A$
	Total Coliforms (day^{-1}) - $L_{SS,TC}$	$L_{SSi,TC} = Q_{SSi} \times L_{TC} \times A$
	Maximal Runoff Flow (m^3/s) - Q_{RF}	$Q_{RFi} = C_i \times i_i \times A$
	BOD (kg/day) - $L_{DS,BOD}$	$L_{DSi,BOD} = Q_{RFi} \times L_{BOD} \times A$
	Total Nitrogen (kg/day) - $L_{DS,N}$	$L_{DSi,N} = Q_{RFi} \times L_{N} \times A$
	Total Phosphorus (kg/day) - $L_{DS,P}$	$L_{DSi,P} = Q_{RFi} \times L_{P} \times A$
	Total Suspended Solids (kg/day) - $L_{DS,TSS}$	$L_{DSi,TSS} = Q_{RFi} \times L_{TSS} \times A$
	Total Coliforms (day^{-1}) - $L_{DS,TC}$	$L_{DSi,TC} = Q_{RFi} \times L_{TC} \times A$

Where: C_{WSSi} is water supply system coverage in scenario i (%), C_{WSS0} is current water supply system coverage (%), Q_{WSS0} is current water supply system flow (l/day), Q_{WSSi} is water supply system flow in scenario i (l/day), C_{SS0} is current sewage system coverage (%), C_{SSi} is sewage system coverage in scenario i (%), Q_{SS0} is current sewage system flow (l/day), Q_{SSi} is sewage system flow in scenario i (l/day), Q_{RFi} is maximal runoff flow in specific scenario i (m3/day), C_i is runoff coefficient in scenario i, i_i is rainfall intensity in scenario i (mm/year), A is study area (m2), $L_{i,BOD,N,P,TSS,TC}$ is pollutant loads in scenario i (kg/day), Q_{SSi} is sewage system in scenario i, $L_{BOD,N,P,TSS,TC}$ is pollutant loads from sewage or runoff flow (mg/L).

2.8. Outcomes

After these simulations, the effectiveness of each measure group is evaluated through the effectiveness index (EI), which is the value obtained through the sum of the weight given to the indicators multiplied by the number of scenarios where the vision was achieved, similarly to the Water for Development Planning Index (WDPI) mentioned in [12]. The EI formulation is presented in Equation (12), as follows.

$$EI_k = \sum_{i=1}^{n} N_i x W_i \tag{12}$$

where:

EI_k is the Effectiveness Index k of the Group of Measures k (GMk);
k is the selected Group of Measures number;
n is the selected indicators number;
N_i is the number of scenarios in which the indicator i achieved the vision;
W_i is the indicator i weight.

Thereby, the greater the number of scenarios in which an indicator reached its reference value (vision) and the greater the weight of this indicator, more effective is the group of measures. Therefore, to measure the EI a schedule was built in which the effectiveness values can vary among 0 to 4 (the maximal value variate according to the number of scenarios adopted) as shown in Table 9.

Table 9. Effectiveness index scale.

Categories	Variation Range
Excellent	3.20–4.00
Good	2.40–3.20
Reasonable	1.60–2.40
Insufficient	0.80–1.60
Poor	0.00–0.80

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In this context, it is important to note that the integrated evaluation is a different value from the indicator performance which are different in each group of measures and each scenario. It is possible to change the measures anytime and have new output values, it is always in a constantly and integrated evaluation.

3. Results and Discussion

The outcomes from the GM0 simulations are presented in Table 10 and GM1 and GM2 in Table 11.

Table 10. Indicators outcomes according to GM0 in SC1, SC2, SC3, and SC4.

Groups of Measures	Indicators	Scenarios				Vision
		SC1	SC2	SC3	SC4	
GM0 Current Values	WSS Coverage (%)	103.73	67.77	63.23	41.42	100.00
	SS Coverage (%)	72.30	47.24	44.07	28.87	100.00
	BOD (kg/dia)	471.11	474.37	772.84	776.10	548.03
	Total of N (kg/day)	86.79	87.39	142.37	142.97	100.96
	Total of P (kg/day)	14.15	14.25	23.22	23.31	16.46
	Total of SS (kg/day)	372.20	374.78	610.58	613.16	432.96
	Total of Col. (day^{-1})	6.05×10^{19}	6.13×10^{19}	1.63×10^{20}	1.63×10^{20}	8.18×10^{19}
	Max Runoff Flow (m^3/s)	33.06	40.74	36.92	45.49	27.21
	BOD (kg/dia)	77.25	95.18	88.28	108.78	70.04
	Total of N (kg/day)	14.26	17.57	16.30	20.08	12.93
	Total of P (kg/day)	2.50	3.08	2.85	3.51	2.26
	Total of SS (kg/day)	837.82	1032.33	957.50	1179.81	759.69
	Total of Col. (day^{-1})	2.97×10^{12}	3.66×10^{12}	3.40×10^{12}	4.18×10^{12}	2.69×10^{12}

Table 11. Indicators outcomes according to GM1 and GM2 in SC1, SC2, SC3, and SC4.

Groups of Measures	Indicators	Scenarios				Vision
		SC1	SC2	SC3	SC4	
GM1 Without Sinergy	WSS Coverage (%)	167.74	109.59	102.25	66.99	100.00
	SS Coverage (%)	80.64	52.69	49.16	32.20	100.00
	BOD (kg/dia)	472.53	475.80	775.17	778.44	548.03
	Total of N (kg/day)	87.38	87.98	143.34	143.95	100.96
	Total of P (kg/day)	14.17	14.26	23.24	23.34	16.46
	Total of SS (kg/day)	372.48	375.06	611.04	613.62	432.96
	Total of Col. (day^{-1})	6.05×10^{19}	6.13×10^{19}	1.63×10^{20}	1.64×10^{20}	8.18×10^{19}
	Max Runoff Flow (m^3/s)	19.75	26.08	23.61	30.82	27.21
	BOD (kg/dia)	42.49	52.35	48.55	59.83	70.04
	Total of N (kg/day)	5.70	7.03	6.52	8.03	12.93
	Total of P (kg/day)	0.87	1.08	1.00	1.23	2.26
	Total of SS (kg/day)	0.00	0.00	0.00	0.00	759.69
	Total of Col. (day^{-1})	2.97×10^{12}	3.66×10^{12}	3.40×10^{12}	4.18×10^{12}	2.69×10^{12}
Groups of Measures	**Indicators**	**Scenarios SC1**	**SC2**	**SC3**	**SC4**	**Vision**
GM2 With Sinergy	WSS Coverage (%)	280.64	183.36	171.07	112.07	100.00
	SS Coverage (%)	151.20	99.34	92.17	60.38	100.00
	BOD (kg/dia)	381.39	384.03	625.65	628.29	548.03
	Total of N (kg/day)	70.54	71.03	115.72	116.20	100.96
	Total of P (kg/day)	11.44	11.52	18.76	13.81	16.46
	Total of SS (kg/day)	333.70	336.01	547.42	549.74	432.96
	Total of Col. (day^{-1})	3.87×10^{19}	3.92×10^{19}	1.04×10^{20}	1.05×10^{20}	8.18×10^{19}
	Max Runoff Flow (m^3/s)	19.51	25.77	23.16	30.27	27.21
	BOD (kg/dia)	39.86	48.33	44.24	53.25	70.04
	Total of N (kg/day)	5.35	6.49	5.94	7.15	12.93
	Total of P (kg/day)	0.82	0.99	0.91	1.09	2.26
	Total of SS (kg/day)	0.00	0.00	0.00	0.00	759.69
	Total of Col. (day^{-1})	2.79×10^{12}	3.38×10^{12}	3.09×10^{12}	3.72×10^{12}	2.69×10^{12}

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It is worth remembering that GM0, GM1, and GM2 mean, respectively, group without measures; with measures without synergy; and with all measures with synergy; and SC1, SC2, SC3, SC4 mean, respectively, from best condition to worst condition. The measures are M1 (rational use of water), M2 (rainwater use), M3 (network loss ratio), M4 (use of grey water), M5 (detention tank), and M6 (permeable pavement).

In all groups of measures, the indicator performance in the scenario formulation (SC1, SC2, SC3, SC4) decreases as the external factor conditions are getting worse. As an example of decrease, the values of water supply system coverage and sewage system coverage are decreasing, which means that there are less people receiving water and sewage services in their houses. The opposite happens with the maximal runoff flow, since its value is increasing which means that the likelihood of floods increases.

Regarding the other indicators from the sewage system, as biological oxygen demand, nitrogen, phosphorus, total coliforms, they are increasing as the external factor conditions are getting worse (SC1, SC2, SC3, SC4).

Among the groups of measures there are different behaviors, e.g., GM0 has less pollutant loads than GM1. This happens because GM1 uses the measure of graywater use (M4), after treatment, increasing the pollutant loads since it does not use drinking water for some purposes. GM2 is the group that has less pollutant loads than the others, since it uses measures such as rational use of water (M1), use of rainwater (M2), and use of graywater (M4), after treatment.

To the drainage systems the behavior is different, the maximal runoff flow indicator has a relative decrease from GM0 to GM1 and GM2, showing that detention reservoir (M5) and permeable pavement (M6) are effective measures to attenuate flow peaks and pollutant loads as well.

Now, from GM1 to GM2, the difference is a slight decrease in the maximal runoff flow and a decrease in the pollutant loads in GM2, due to the use of rainwater (M2) in the buildings. Thus, under this criteria, the best option is GM2.

The three main indicator performances (water supply system coverage, sewage system coverage, and maximal runoff flow) distributed by group of measures and scenarios are shown respectively in Figures 4–6.

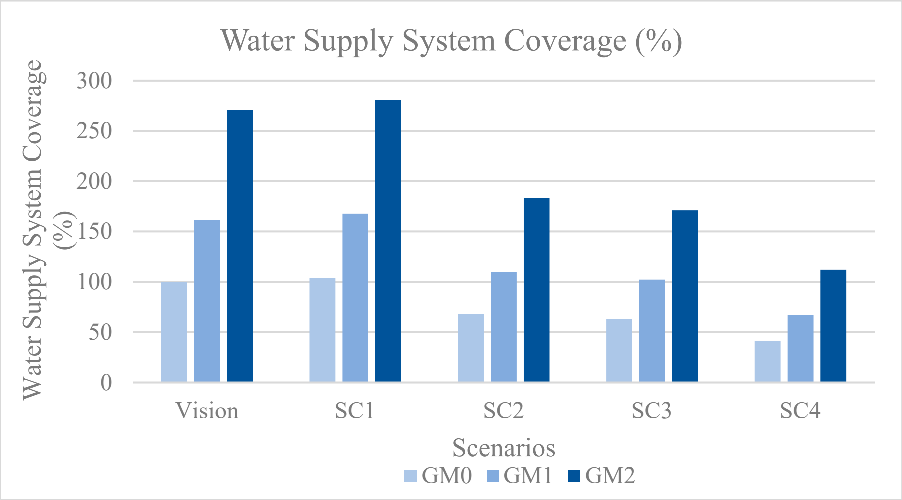

Figure 4. Water supply system coverage outcomes according to GM0, GM1, and GM2 in SC1, SC2, SC3, and SC4.

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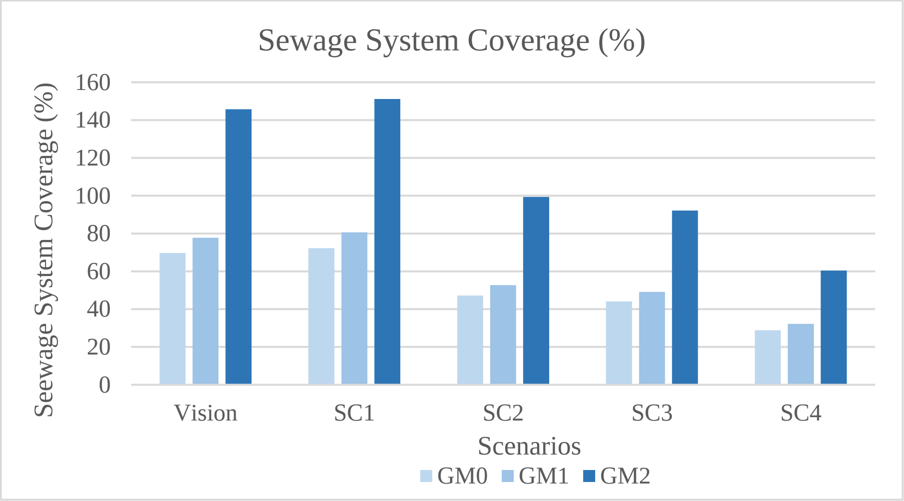

Figure 5. Sewage system coverage outcomes according to GM0, GM1, and GM2 in SC1, SC2, SC3, and SC4.

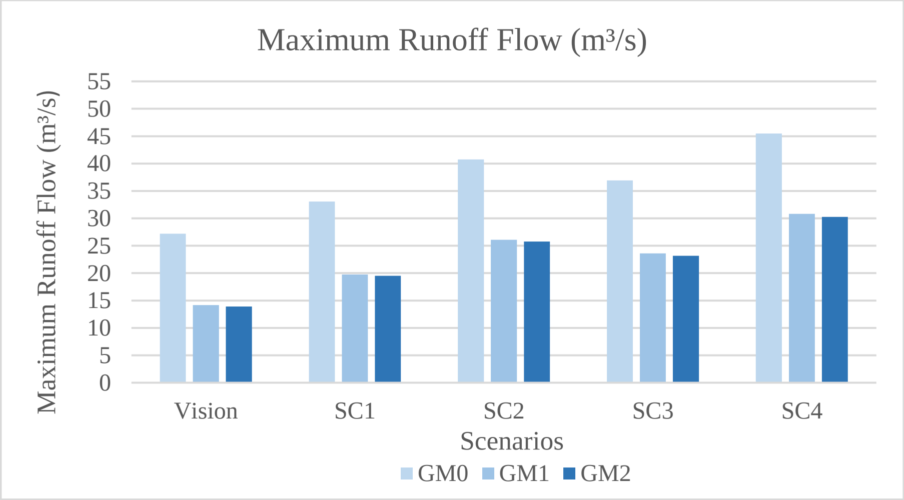

Figure 6. Maximal runoff flow outcomes according to GM0, GM1, and GM2 in SC1, SC2, SC3, and SC4.

According to the first and the second graphs, the water supply system coverage, and the sewage system coverage, respectively, it is possible to notice a decrease of the performance indicator according to the scenarios (SC1, SC2, SC3, and SC4).

In each scenario, as the measures are being implemented (GM1 and GM2), all values have better performance than GM0, particularly in the group GM2. This is a representative result, as it means that simple measures acting together in synergy could help the whole system to work better and produce more efficient results, without any infrastructure intervention.

It is worth mentioning that implementation of GM1 and GM2 in each scenario aids in the mitigation of the deterioration of sanitary conditions, however it does not solve the whole sanitary system issue in Brazil that has been occurring for years.

There are more complex systems involved within these processes, such as public policies, governmental priorities, and general management processes. Table 12 shows the outcomes through the effectiveness index (EI).

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Table 12. The effectiveness index outcomes and ranking.

Group of Measures	Indicators	Outcomes			Effectiveness Index Σ(N×W)
		Number of Scenarios which Achieved the Goal (N)	Vision Weight (W)	N×W	
GM0 **Current values**	Water Supply System Coverage (%)	1	0.10	0.10	0.80 Poor
	Sewage System Coverage (%)	0	0.10	0.00	
	BOD (kg/day)	2	0.07	0.14	
	Total Nitrogen (kg/day)	2	0.07	0.14	
	Total Phosphorus (kg/day)	2	0.07	0.14	
	Total Suspended Solids (kg/day)	2	0.07	0.14	
	Total Coliforms (day^{-1})	2	0.07	0.14	
	Runoff Flow (l/s)	0	0.10	0.00	
	BOD (kg/day)	0	0.07	0.00	
	Total Nitrogen (kg/day)	0	0.07	0.00	
	Total Phosphorus (kg/day)	0	0.07	0.00	
	Total Suspended Solids (kg/day)	0	0.07	0.00	
	Total Coliforms (day^{-1})	0	0.07	0.00	
GM1 **Without Synergy**	Water Supply System Coverage (%)	3	0.10	0.30	2.35 Reasonable
	Sewage System Coverage (%)	0	0.10	0.00	
	BOD (kg/day)	2	0.07	0.14	
	Total Nitrogen (kg/day)	2	0.07	0.14	
	Total Phosphorus (kg/day)	2	0.07	0.14	
	Total Suspended Solids (kg/day)	2	0.07	0.14	
	Total Coliforms (day^{-1})	2	0.07	0.14	
	Runoff Flow (l/s)	3	0.10	0.30	
	BOD (kg/day)	3	0.07	0.21	
	Total Nitrogen (kg/day)	4	0.07	0.28	
	Total Phosphorus (kg/day)	4	0.07	0.28	
	Total Suspended Solids (kg/day)	4	0.07	0.28	
	Total Coliforms (day^{-1})	0	0.07	0.00	
GM2 **With Synergy**	Water Supply System Coverage (%)	4	0.10	0.40	2.69 Good
	Sewage System Coverage (%)	1	0.10	0.10	
	BOD (kg/day)	2	0.07	0.14	
	Total Nitrogen (kg/day)	2	0.07	0.14	
	Total Phosphorus (kg/day)	3	0.07	0.21	
	Total Suspended Solids (kg/day)	2	0.07	0.14	
	Total Coliforms (day^{-1})	2	0.07	0.14	
	Runoff Flow (l/s)	3	0.10	0.30	
	BOD (kg/day)	3	0.07	0.21	
	Total Nitrogen (kg/day)	4	0.07	0.28	
	Total Phosphorus (kg/day)	4	0.07	0.28	
	Total Suspended Solids (kg/day)	4	0.07	0.28	
	Total Coliforms (day^{-1})	1	0.07	0.07	

The effectiveness index is used to hierarchize the results and to facilitate the understanding of the results. As described before, the EI varies between the 0.0–0.8 (poor), 0.8–1.6 (insufficient), 1.6–2.4 (reasonable), 2.4–3.2 (good), and 3.2–4.0 (excellent).

For the GM0 (without any measure), the poor classification shows that the traditional system of service provision is not sustainable in the long-term, while for GM1 the EI value was reasonable, where the application of all the measures without synergy shows better results than the group without any measures.

However, the group of measures that better reached the vision was GM2, whose EI was good, demonstrating that measures integrated with synergy are more effective than the other groups.

Besides that, some care must be taken into account with the effectiveness index since it only has a punctual result, leaving out the evaluation of growth and evolution of the indicators from one group to another.

4. Conclusions

The lack of urban water management and sanitary infrastructure are predominant challenges in developing countries as a result of mainly external factors such as population growth, economic

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performance, and climate change, and internal factors like the lack of effective public policies with strategic planning.

The article's main contribution is to improve interactions among the systems in order to evaluate synergy relations with the application of alternative measures in an integrated environment with strategic plan, aiming at the sustainable rational use of water. The UWU model contributes to an environment with strategic planning, selecting the best group of measures providing a rational and integrated use of water in urban areas.

The main step is vision building, that is, the desired indicators and their value performance; this discussion should be taken by the stakeholder and the community involved, determining the priorities to the area. In this work, the current values were considered. Then, considering current estimations and the desired future for the study area, the main indicators have to be selected, developed, and their weights have to be set. The indicators selected and their weights were water supply system coverage, sewage system coverage, pollutant loads from sewage and drainage system (biological oxygen demand, total nitrogen, total phosphorus, total suspended solids, total coliforms), and maximal runoff flow.

Next is the scenario formulation step, in which projections made by appropriate agencies and organizations should be taken into account. The external factors selected to compose the four scenarios were population growth rate, annual temperature, economic performance, and the design of the rainfall with maximal runoff flow and average runoff flow.

The next step is to locate, plan, and pre-design measures that could be implemented in the area. Again, the community engagement is overriding because they will be directly affected by the measure implementation. The alternative measures were chosen by system and classified according to the group GM1 or GM2, meaning, respectively, group with measures without synergy and group with measures with synergy. The measures are M1 (rational use of water), M2 (rainwater use), M3 (network loss ratio), M4 (use of graywater), M5 (detention tank), and M6 (permeable pavement).

Finally, simulations can be performed in order to rank the groups of measures and provide guidance to the decision-making process. In the simulations, as the measures are being implemented in the scenarios (GM1 and GM2), all values have better performance than GM0, particularly the GM2. This is a representative result, meaning that simple measures acting together in synergy could help the whole system to work better and produce more efficient results.

The best group of measure is the one that has the greatest EI. With the results of the simulation, it can be concluded that among the groups of measures addressed (GM0, GM1, and GM2), the one that obtained the best performance in the effectiveness index was the third group of measures (GM2), the conservation group of the water, with measures acting together and with synergy among systems and environment.

Results support application of the systemic approach and the search for synergies between water conservation measures when planning the sanitary infrastructure. For example, instead of increasing the capacity of the water supply system through investment in pipes, storage tanks, and water pumps, it could be more attractive to invest in water conservation measures in buildings to reduce demand. The consequence would be to serve more people without increasing the capacity of the WSS. It is possible to obtain the same consequence for the SS capacity, because the reduced water demand in buildings will reduce the generation of wastewater which will require an increased capacity. Thus, it is understood that these characteristics distinguish the UWU model as a decision support tool for the management of the urban water cycle because it allows public participation, it applies principles of strategic planning, and allows a systemic approach to seek synergies between water conservation measures that can achieve higher levels of sustainability.

Just as mentioned by Loucks, D.P. [39], "how well we manage our natural resources today will determine just how well these resources will serve our descendants and us. Hence, we care much about the management of these resources, especially our water resources." For that reason, sustainability

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frameworks are an important tool that guide planning and management practices in order to avoid economic losses originated both in the internal and in the external environment.

A perspective of future work includes a risk assessment, which can concern the water supply system coverage using risk matrix methods e.g., as presented in [40].

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