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Development of a Multi-Methodological Approach to Support the Management of Water Supply Systems

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Abstract: The benefits provided by a model of system dynamics are directly related to its correct construction. One of the main challenges in the process of building such models is that they must be able to effectively represent a specific problematic situation. Thus, the main objective of this study is to develop a multi-methodological approach, adapting the problem structuring method of strategic options development and analysis (SODA) in the initial stage of the system dynamics (SD) model. The role of each of them clearly represents the contribution of this study: the SODA in the structuring (representation) phase of the problem and proposition of alternatives and the SD in the evaluation phase of these alternatives. To illustrate its application, the multimethodological approach developed was used to simulate scenarios considering management strategies, and the various variables affecting a water supply system, including population growth, in order to evaluate more "assertive" water management strategy(s) that could have been adopted to address the water crisis (2012–2017) and analysis future scenarios. The results show that, based on the vision of specialists with enough experience for the case studied, it was possible to structure the problem, and therefore propose a set of strategies (alternatives), which were: water loss control, wastewater reuse, application of more efficient tariffs to reduce water waste, inter-basin water transfer, and awareness regarding the use of water resources. After the survey of alternatives, scenarios were simulated considering these water management strategies. Simulation results showed that actions taken on the demand side would only be effective for a short period of water scarcity, (for example, the impact of the scarcity-based tariff on water consumption reduction). For severe drought scenarios and with a water producing system heavily dependent on rainfall, such action would no longer be efficient. However, water supply management-oriented strategies, e.g., inter-basin water transfers (PISF) and wastewater reuse, are highly effective in securing water supply and preventing water supply collapse in the region. The development of this multi-methodological approach is expected to be useful to support managers in the decision-making and implementation of water management strategies.

Keywords: semi-arid region; water shortage; problem structure methods; strategic options development and analysis; system dynamics; monte carlo simulation

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1. Introduction

According to the United Nations [1], is estimated that 780 million people worldwide do not have access to a minimum acceptable amount of drinking water and 2.5 billion people do not have access to sanitation services. Furthermore, according to the UN, it is estimated that the global demand for water may exceed the annual available resources by 44% by 2050. This scenario is particularly aggravated in arid and semi-arid regions of the world, where the low rainfall indices (arid region: 200–250 mm/year; semi-arid region: 250–600 mm/year) inherent in these regions, together with the effects of climate change will decrease water availability, and it is predicted that water scarcity will more than double in the next 30 years for these regions [2].

In the semi-arid Paraíba State, located in the northeast region of Brazil, the urban water supply systems are almost entirely supplied by surface reservoirs [3]. Thus, water supply depends exclusively on the replenishment of water stocks in surface reservoirs during the short rainy season that occurs annually, lasting from two to six months. This logic leads to increasingly severe drought cycles. However, when drought arrives, the standard experience has been a sequence of levels of water rationing, with increasingly severe restrictions. During the height of the crisis (2012–2017), for example, water rationing policies operationalised by CAGEPA (Paraíba's Water and Sewerage Company) in the 19 cities supplied by the Epitácio Pessoa reservoir, including Campina Grande that is the second largest city in the state of Paraíba, involved the temporary suspension in water withdrawal for industries and irrigation purposes, in addition to suspension policies on human supply, which culminated in 70% of weekly time without water supply at the peak of the crisis in April 2017 [4]. According to Grafton and Ward [5], these water rationing policies, including mandatory restrictions on water use, are demonstrably inferior with respect to economic and social equity. Most of these policies without "pricing" impose additional costs. For example, for households, these costs may be hidden by the need to purchase additional new household tanks [6].

In general, there are two distinct types of strategies that can be used by water managers: increasing water supply (inter-basin water transfer, rainwater recycling and desalination) and managing water demand (water pricing or restrictions) [3]. These two strategies are directly related, since better demand management (e.g., the use of optimal water pricing) can reduce the need to increase supply [7].

In this context, the system dynamics (SD) approach is widely used in water resources planning and decision making [8–10] (see in detail in Section 2.2). However, the benefits provided by SD are directly related to their correct construction. One of the main challenges in the process of building these models is that they must be able to effectively represent a specific problem situation [11]. For the process of structuring the water supply management problem, this requires efforts of understanding for "divergent solutions", as it involves a complex and interrelated structure of several actors involved (government and the multiple users), besides several experts with different visions and proposals of water management solutions, which most of the times are conflicting and divergent [12], in which the decisions taken about the problem have their consequences observed in the long term. It is important to emphasize that decision-making on water management needs to be done with extreme caution and to make sure that all solutions/opinions of different experts are taken into consideration, because making a decision on an unstructured problem can lead to the choice of alternatives that are not the right ones and that in the future can bring problems that were not previously predicted [13].

Thus, the strategic options development and analysis (SODA) methodology becomes an appropriate alternative in the initial stage (problem identification and construction) of the system dynamics model. According to Eden et al. [14], the SODA method is based on the construction of cognitive mapping techniques for structuring problems and developing strategic analyses based on the different and often conflicting points of view of decision makers. In the literature, although it is verified the existence of studies proposing to adapt the SODA method to support the construction of SD models [11,15], the objective, and consequently the contribution of this study is given by the improvement of the junction of both methodologies, so that from these a multimethodological approach is developed, considering the objective of each one, the SODA in the problem structuring phase (construction of alternatives for the resolution of such problem) and the SD in the evaluation phase of these alternatives, especially in the decision-making context of hydric management.

2. Approach

2.1. Case Study

The case study to be investigated refers to the semi-arid region of the state of Paraíba, in which the Epitácio Pessoa reservoir is located (Figure 1). This reservoir has a maximum storage capacity of 411 MCM (million cubic metres) [16], which supplies Campina Grande and 18 other small municipalities. The population of the region under study consists of approximately 650,000 people, with a current and future growth rate of 1% [17].

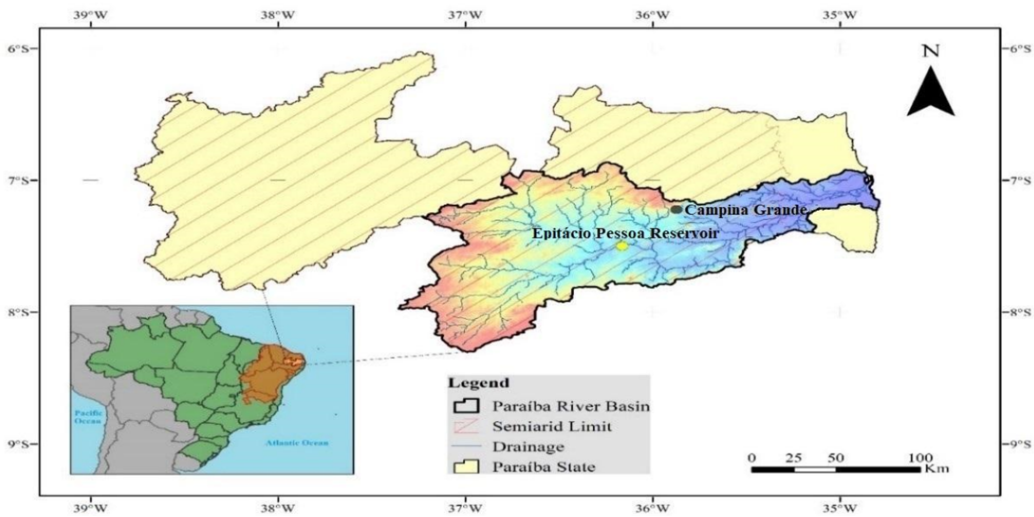

Figure 1. Epitácio Pessoa Reservoir in the Paraíba River basin in Northeast Brazil.

The municipalities that are supplied by this reservoir face several challenges, mainly due to the hydroclimatic aspects of the Paraíba River region, the main source of the reservoir (Table 1) [18,19], in addition, factors related to municipal water management (for example, the high 33% water loss rate) [20]. The water loss considered in this study is a result of real losses (leaks in pipes) and apparent losses (theft, hydrometer with calibration problems). Another worrying factor is the high average water consumption which corresponds to approximately 222 L/p/d (litres per person per day) (131 domestic + 91 industrial/other). These consumption levels were taken from transformations of the average monthly withdrawals from m^3/s to L/p/d from the works of Rêgo et al. [21,22].

Table 1. Hydroclimatic aspects of the Paraiba River region.

Aspects	Values
Drainage area (km^2)	6727.69
Minimum Temperature (°C)	18–22
Maximum Temperature (°C)	28–31
Precipitation (mm/year)	600
Rainfall concentration period (months)	4 (February–May)
Evaporation (mm/year)	2000–2500

In addition, to complement the hydrological balance and perform the simulations in this study, information on inflow and evaporation of the Epitácio Pessoa reservoir was necessary. Therefore, for the inflows, a series of flows between 2004 and 2015 was employed based on daily measurement volume and converted to annual (Figure 2), taken from the ANA reservoir monitoring system [16].

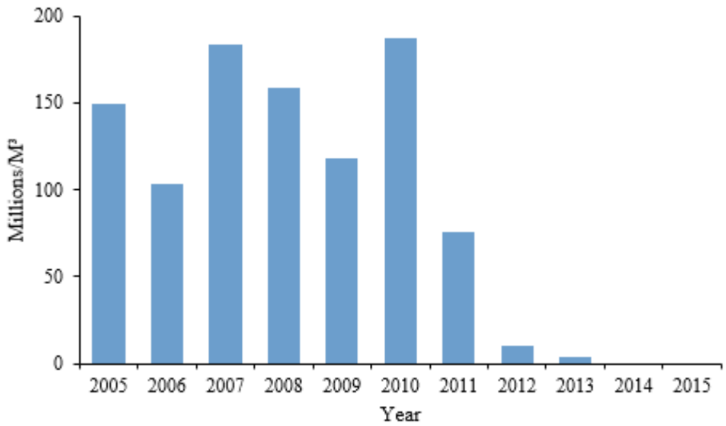

Figure 2. Historical series of inflows for the Epitácio Pessoa reservoir (2004–2015).

Regarding evaporation, there is no measurement of evaporated laminas in the Epitácio Pessoa reservoir. For this reason, monthly average evaporation data collected from a Class A evaporimetric tank of São João do Cariri School of the Federal University of Campina Grande were used. The series is taken as representative because of its proximity to the Epitácio Pessoa reservoir, and the similarities of its climatic, terrain, and vegetation characteristics. The coefficients (Kp) calculated by Nunes et al. [19], were used to correct the values measured in the Class A tank. In the Epitácio Pessoa reservoir, other coefficients besides the frequently employed value of 0.7 are used seasonally, since each season of the year has its own climatic conditions and is unique to each location. The monthly averages of evaporated water used in the simulations can be seen in Figure 3.

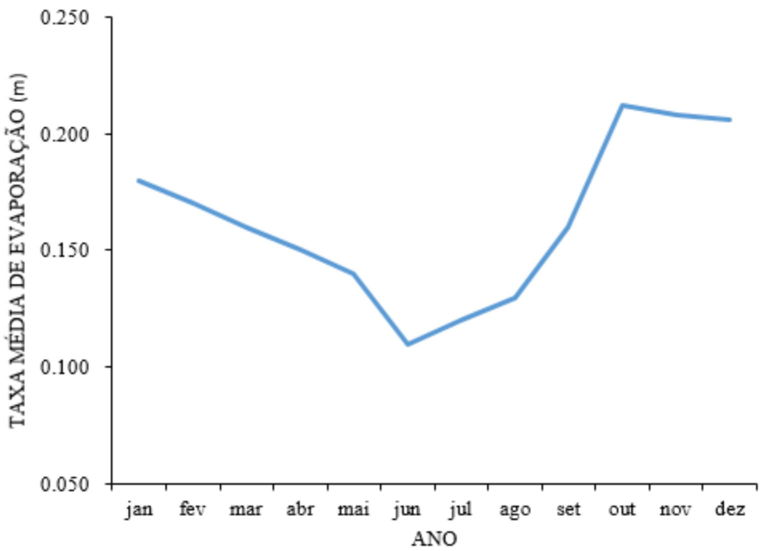

Figure 3. Average monthly evaporation.

2.2. System Dynamics

The systems dynamics approach was created in the early 1960s by Jay Forrester as a modeling and simulation methodology for decision making in industrial management problems. Since then, SD has been applied in several areas, such as urban transportation [23,24], health [25–27], economy [28,29], and natural resources, for energy, rainfall, wind etc. [30], grazing [31], energy [32,33], and water [34–36].

In water resources planning in urban areas, some studies have been observed in the literature using the SD approach. Dai et al. [37] devised an object-oriented system dynamics model to capture the interrelationships between water availability and increased water demand for population growth and industrial consumption located in Manas River Basin, Xinjiang Uygur region. Dawadi and Ahmadi [38] investigated the influence of population increase and the effect of climate change on water availability in the semi-arid Las Vegas Valley, Southern Nevada.

In Sahin's studies [8,39], urban water management models were developed, applying the SD approach. The studies aim to create price adjustments that in turn can generate revenue to invest in desalination plants that can efficiently provide water security in the future. The study was developed in Queensland, Australia. Park et al. [40] sought to create an SD model to predict the long-term effects of developing an alternative water source on Nak-Dong riverbank storage in Busan, South Korea, based on causal feedback relationships inherent in the management of water supply systems. The model simulation results indicated that the key indices of water supply system management, such as water supply rate and water revenue rate, will be improved during the 60-year simulation periods starting from the year 1999.

Huanhuan et al. [41] used SD to analyse future water availability in a coastal region in Longkou, Shandong Province, China. For this study, three different scenarios ("business as usual", economic development and comprehensive protection of water resources) were projected for 50 years. Weil et al. [42] constructed an urban water management model that incorporates the will to conserve. The model was useful for quantifying residents' consumption and the effects of water savings.

Ahmadi and Zargham [43], in their study, addressed water consumption in urban green spaces for the city of Shiraz, Iran, and the main question was whether to look for external water resources (dam construction) or internal resources, i.e., within the city (sewage treatment). For this purpose, a System Dynamics Model was developed to evaluate and compare different scenarios of external and internal water supply until 2025. The study by Tianhong et al. [44], using the entire water cycle of the city of Shenzhen as a case study, aimed to build a system dynamics model to investigate the complex interactions along the water cycle in the socio-economic-ecological system. Water supply and demand in Shenzhen city were simulated from 2015 to 2030. The results show that Shenzhen's water supply and demand will decrease steadily in the coming years, indicating a severe shortage of water resources and conflicts between water supply and demand in this region. Another study that simulated long-term scenarios was developed by Bao and He [10]. The author in that study develops a system dynamics model to simulate the current conditions and future development scenarios of urbanization and water scarcity in the Beijing—Tianjin—Hebei (PTH) urban agglomeration in 2000–2030, examining the interaction and feedback between the six main subsystems: water supply, water demand, water pollution, population urbanization, economic urbanization, and land urbanization. It was found that the South to North Water Diversion Project and the enhanced Reclaimed Water Reuse System can greatly increase water supply. However, the speed of population urbanization and economic growth, spatial structure of urban agglomeration, and water consumption pattern can determine the water demand.

The most recent studies [45,46] have been aimed at developing SD models to assess security at the water–food–energy nexus, considering the ecosystem provisioning services of watersheds.

In the context of all these studies reported above, the interconnected components and complex behaviour of urban water systems make SD an effective approach to deal with such types of problem [47].

2.3. Proposal of the Multi-Methodological Approach SODA/SD: The Rationality

The multimethodological approach proposed in this study aims to support the problem structuring and decision-making process of water supply management. To this end, the SODA method and SD approach will be used in the construction of this multimethodology. The role of each of these clearly represents the contribution of this thesis: the SODA in the problem structuring phase (construction of alternatives for the resolution of such problem) and the SD in the evaluation phase of these alternatives. Figure 4 shows the step-by-step application of this proposed approach:

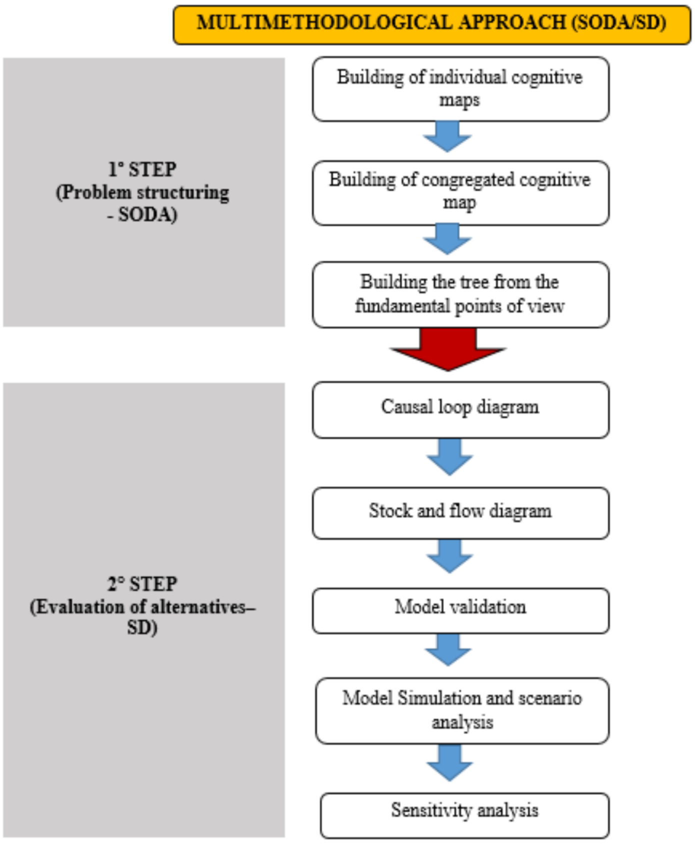

Figure 4. Step-by-step application of the SODA/SD approach.

2.3.1. Step 1: Structuring the Problem

To start the process of structuring the problem of water management strategies during the water crisis (2012–2017) and analyze future scenarios, it was necessary to identify the actors involved in the decision-making process. In the process of choosing the actors, it was considered specialists in the area of water resources and sanitation, which in a way, have experiences in studies and interest in the management of water resources of the Epitacio Pessoa reservoir, besides an expert representing the water and sewage company of Paraiba (CAGEPA). For the latter, it was not possible to schedule an interview. However, testimonies/information/insights in scientific articles and reports were taken advantage of [4,48,49]. This harnessing technique for cognitive map construction was similarly used also by Santos et al. [50]. In the sequence a facilitator was assigned to conduct the process of applying the method. In this study, the author himself assumed the role of facilitator.

Once the actors are defined, the problem's label can be determined. For the case analyzed, the label was defined as "Actions to improve the water supply of cities located in the semi-arid region of Paraiba during the water crisis (2012–2017) and future scenarios".

Building the Individual Cognitive Maps

In this phase of the application of the SODA method, through interviews, the facilitator gathered a compilation of Primary Elements of Assessment (PEAs) for each actor about the water supply problem. From each of these elements a concept was produced, from which the whole produced the cognitive map. The concepts presented in these maps express the understandings, explanations and strategies that reflect, in general, the problematic analyzed. The connections between these concepts are represented by arrows, which indicate how a concept leads to or impacts on another. The meaning of the concept must be partly based on the action the actor proposes, with a current pole (in which it is determined by the decision-maker for present action) and an opposite pole (which exposes the psychological opposite of the action). The two labels are separated by '...', meaning the opposite. In addition, starting from a concept elicited from the actor, a hierarchy is made between two concepts, in which the actor is asked what are the means necessary to achieve them, that is, for which ends it is intended. In most cases, the cognitive map is built obeying the order of means concepts in the bottom position of the page and ends concepts in the top position. The Decision Explorer software was used to make the maps [51].

Building the Congregated Cognitive Map

After the construction of the individual cognitive maps of the actors involved, an aggregated cognitive map will be elaborated coupling all these individual maps and presented to the group of actors so that they can validate, make modifications or inclusions, as well as discuss the state and evolution of the concepts about the water supply problematic of the region studied. This aggregation of all individual cognitive maps is a very difficult procedure, especially when the number of actors involved in the research is more than two and thus there is a large number of concepts. However, for the case studied in this research, several concepts were presented by more than one actor, which made aggregation easier. It is noteworthy that at this stage SODA's "standard" procedure to validate the aggregated map was not followed, i.e., a meeting with all players involved in the study would be impractical. Thus, this process took place by sending emails to all actors containing the aggregated map. This type of validation was also performed in the studies of Santos et al. [11] and Tajra [52] and was quite effective to validate the aggregate map by allowing all actors involved to participate, overcoming all the adversities of geographical distance and time differences for a possible meeting of each actor.

In the next stage, with the presentation and validation of the aggregated map with the actors, the congregated map was generated, which in turn represents the problem according to the vision of all actors.

Construction of the Tree of Fundamental Viewpoints

In the next step, with all the information already available, the facilitator builds the tree of key viewpoints, showing for each necessary action (ends) which alternatives can be implemented (means). In other words, proposals to solve/mitigate the problem of water supply in the water crisis (2012–2017) and in future scenarios.

2.3.2. Step 2: Application of System Dynamics for the Evaluation of Alternatives

Construction of the Causal Loop Diagram

In this second stage, after identifying the proposed alternatives, a Causal Loop Diagram was built to explain the cause-and-effect relationships within the context of the problem. The model elaborated is called "Water in the Semi-arid Region of Paraiba—WSPB-SD" and is presented in Figure 5. The model was developed using the software package Vensim DSS v6.3 [53].

The process of creating the diagram began by using as reference variables the management alternatives defined in the application of the SODA method (inter-basin water transfer; structuring of a new water tariff; wastewater reuse; water loss control; rational and efficient use). After defining these variables in the diagram, it was possible to capture the interactions between these reference variables and several others that influence the model, called auxiliary variables, which were: population growth, investment in the sector, domestic water demand, agricultural water demand, industrial water demand, and surface water supply.

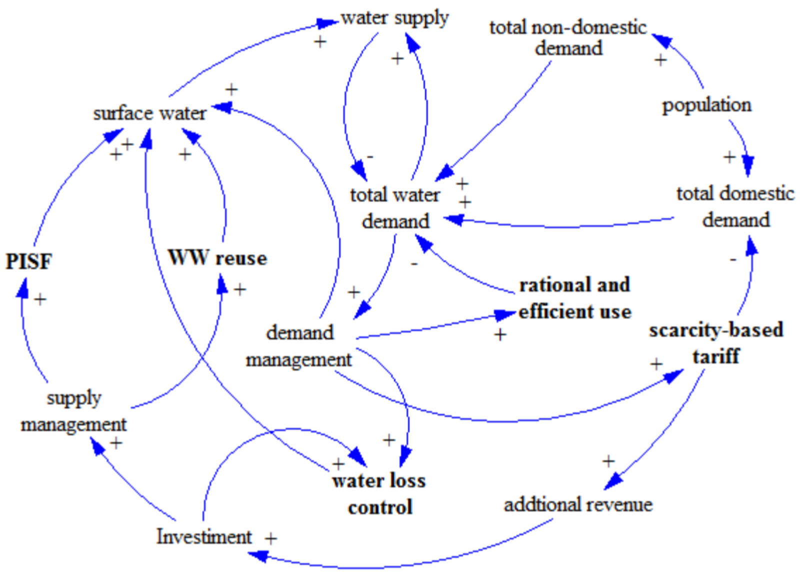

Figure 5. Causal loop diagram to represent the model "WSPB-SD".

Building the Stock and Flow Diagrams

After the construction of the Causal Loop Diagram, which is characterized by a qualitative diagram, sub-models were delimited in order to build, in a detailed way (with parameters, variables and data set), the stock and flow diagram (Figure 6). The proposed diagram consists of five submodels: water supply submodel (surface), population submodel, demand submodel, reclaimed water submodel, and water tariff submodel. To avoid anomalies due to oscillations in reservoir levels, the model will be set up to group monthly volume measurements into an annual simulation volume measurement.

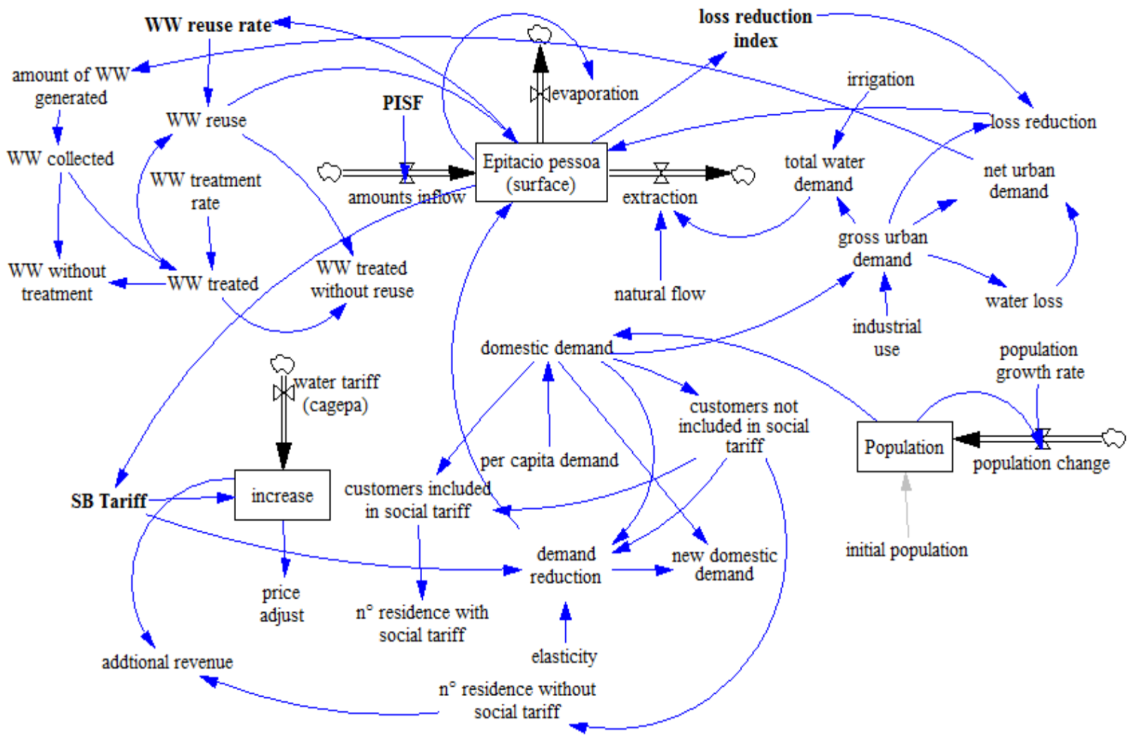

Figure 6. Stock and flow diagram to represent the model "WSPB-SD".

- Population sub-model

Equation (1) that will calculate the population size takes into account the current population rate and population change. It is emphasised that the domestic consumption of the population includes both urban and rural users.

$$P = \int (P_{ch})dt + [P_i] \tag{1}$$

where,
P—population
P_{ch}—population change rate (person/year)
P_i—initial population

- Water supply sub-model

In the study region, all water supply for the region derives from the Epitácio Pessoa reservoir, which is a surface water stock. Thus, we used Equation (2) of the water balance adapted to the Epitácio Pessoa reservoir, proposed by Nunes et al. [19]. We consider that all variables will be measured in MCM (million cubic meters).

$$S_{t+1} = S_t + VD_t - E_t - VW_t - NF_t \tag{2}$$

where,
t—the current simulation interval and $t+1$ the next simulation interval;
S_t—volume stored in the reservoir;
VD_t—inflow volume into the reservoir;
E_t—volume of water lost through evaporation;
VW_t—volume withdrawn from the reservoir for consumption;
NF_t—volume of water spilled from the reservoir to the natural flows in the Paraiba River.

A range of observed and meteorological data will be repeated in the future scenario simulations (2016–2025) in order to consider a variety of inflows into the reservoir.

- Water demand sub-model

The total water demand in this study includes agricultural, industrial and domestic uses. Thus, before calculating the total water demand, it was necessary to determine the annual domestic water demand, which used the following Equation (3).

$$DWD_t = P_t \times WD_{pc} \tag{3}$$

where,
DWD_t—represents the annual domestic water demand;
P_t—annual population;
WD_{pc}—water demand per capita.

With the domestic demand already calculated, it can determine total water demand. For this, Equation (4) was used:

$$TWD_t = DWD_t + IWD_t + AWD_t \tag{4}$$

where,
TWD_t—annual total water demand;
DWD_t—domestic water demand;
IWD_t—industrial water demand;
AWD_t—agriculture water demand.

- Water tariff sub-model

The Epitácio Pessoa reservoir provides water for multiple uses (urban, agricultural and industrial consumption). However, for the purposes of this research, the proposed scarcity price adjustment is restricted to domestic use only. The equation that defines the adjustment price is shown in Equation (5).

$$\text{AP} = RT^{*}\ [1 + (SBT)/100] \quad (5)$$

where,

AP—adjusted price;

RT—regular tariff ("*increasing block tariff*"- structure practiced by CAGEPA);

SBT—scarcity-based tariff (percentage increase over the regular tariff).

The SBT applied in this study is defined based on the volume of water available in the reservoir, in which the price can reach a maximum percentage of up to 200% in relation to the regular tariff in its "dead" volume (i.e., 10% of the reservoir's maximum capacity, a level that represents water insecurity for the cities supplied by the Epitácio Pessoa reservoir [54]. On the other hand, if the volume of water in the reservoir increases, the SBT is withdrawn at the same levels. To predict the impact of demand to a change in price, the following basic demand elasticity Equation (6) was applied. The elasticities 0.45 and 0.55, proposed by Medeiros and Ribeiro [55] and Bank of Northeast Brazil [56], respectively, were used to measure how sensitive consumers are to SBT tariff.

$$Change\ in\ demand = WD_{pc}\ \times\ (AP\ /\ RT)^{\mathrm{Ed}} \quad (6)$$

where,

WD_{pc}—per capita water demand;

AP—adjusted price;

RT—regular tariff;

E_d—price elasticity of demand.

- Returned water sub-model

The total volume of water returned to the system will take into account the water recovered as a result of the elimination of water waste through leakage control and the reuse of wastewater. The latter will be returned for agricultural uses. To measure the total volume of water returned, Equation (7) will be used.

$$RW_t = LC_t + WW_t \quad (7)$$

where

RW_t—anual returned water;

LC_t—returned water with loss control;

WW_t—returned water with wastewater reuse.

Model Validation

The process of model validation is critical to the credibility and reliability of the results of any model. Firouzabadi [57] defines model validation as a process that seeks to determine the degree to which a theory, approach or model is a 'good enough' representation of reality from the perspective of the intended uses of the theory, approach or model. In this context, before proceeding with the analysis of the results, the model will be validated for the water balance from 2005 to 2015.

Model Simulation and Scenario Analysis

In this step, the scenarios that will be simulated to identify options for water management instruments considering supply and demand management are delineated. Exploring these scenarios using system dynamics modelling can put water sector managers in a better position to understand the complexity and dynamics of the system, supporting them to manage and make decisions more effectively. Next, a scenario analysis will be conducted to analyse the impacts of possible future events under an uncertain environment on the system performance, taking into account several alternative outcomes, i.e., scenarios, and to present different options to evaluate future choices.

Sensitivity Analysis

After simulating the model and performing the scenario analysis, a sensitivity analysis will be performed. The sensitivity analysis aims to identify which input parameters of a model (or combination thereof) explain, at best, the uncertainties in the model predictions [58].

In this proposed methodological approach, Monte Carlo simulation will be the method used to perform the sensitivity analysis. In applying this method, one of the system parameters is changed by a certain percentage, keeping all other parameters constant, the model is run, and the percentage change of the pre-specified performance indicator is observed.

3. Results

3.1. Stage 1: Structuring the Problem

3.1.1. Construction of Cognitive Maps

Step 1—Construction of the Individual Cognitive Maps

At this stage of the application of the SODA method, the facilitator compiled a compilation of each actor's important points (APPs) about the water supply problem. In other words, the actors were led to reflect on the causes and effects of the problem, seeking suggestions and solutions to the issues presented.

To this end, meetings were held with each actor separately to build the individual cognitive maps. It is pertinent to emphasize that the cognitive map is not a decision model, but a way to support the actor to think in a more structured manner about the problem.

For making the individual cognitive maps, the following primary elements of evaluation (PEAs) were identified in the view of actors "A", "B", "C", and "D":

(A) "improved management of the reservoir's hydrological balance; reuse of wastewater; stimulating water charging through efficient tariffs; control of losses and environmental education for conscious use of water";

(B) "inter-basin water transfer; desalination; loss control; wastewater reuse; efficient pricing models; construction of a new dam and environmental education for conscious water use";

(C) " Expand the control of water losses; rationing water uses; raising water tariffs; conscious use of water resources; reuse of wastewater and transposition of water between river basins";

(D) "improve watershed planning; greater action to control losses; develop tariffs that guide to rational water use and inter-basin water transfer".

After ordering the PEAs for the actions, the psychological opposite is determined and thus concepts are constructed with each actor. In the next stage, the preparation of individual cognitive maps was initiated as of the hierarchization of concepts. Appendix A presents the cognitive maps of actors ("A"—Figure A1; "B"—Figure A2; "C"—Figure A3; "D"—Figure A4).

Step 2—Construction of the Congregated Cognitive Map

In the next stage, with the presentation and validation of the aggregated map with the actors, the congregated map was generated, which in turn represents the problem according to the vision of all actors (Figure 7).

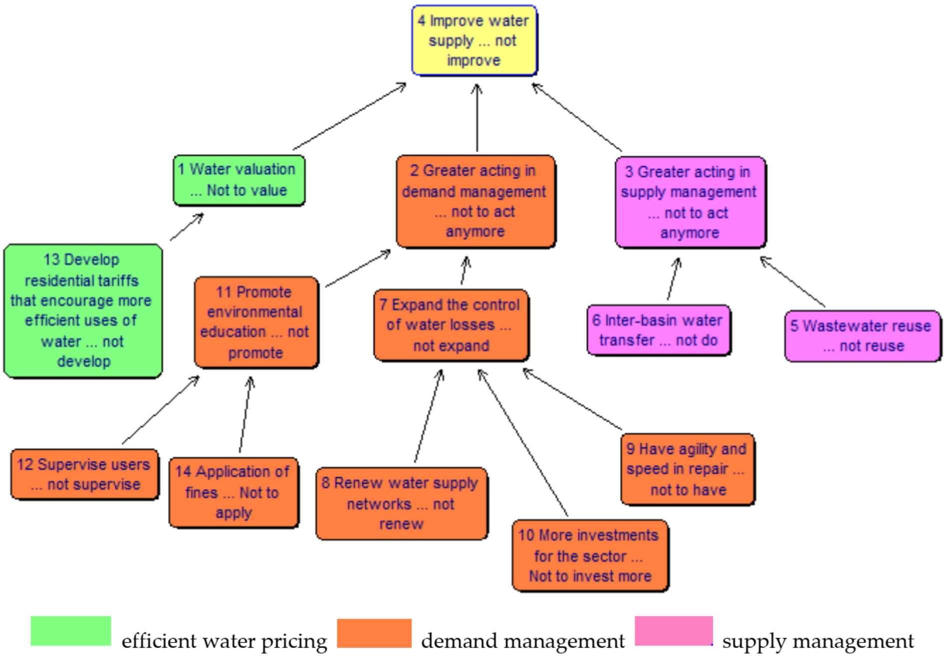

Figure 7. Congregated map of actors.

The analysis of the congregated map was done in the traditional way. In this way, the following items were verified:

- **Hierarchy of means-end concepts**: Observing the congregated map, one can notice a relationship of influence between the concepts, where in the lower part of the map are located the "means" procedures, i.e., how it will achieve the objectives, and in the upper part are located the "ends" elements, which are the objectives;
- **Concepts "heads" and "tails"**: As can be seen, the map has only one concept "head", represented by the number 4, located at the top of the map. This concept was proposed as a central objective that seeks to improve the water supply for the case studied. The "tails" concepts are congregated in the map and are represented by the following numbers: 13, 12, 11, 14, 7, 8, 6, 5, 10, and 9. These concepts "tails", as described in the theoretical framework, are called means to reach the strategic and fundamental objectives of decision makers;
- **Feedback loops**: No feedback loop has been verified on the map;
- **Clusters**: The map shows the presence of three clusters, namely: efficient water pricing, demand management and supply management. The clusters are highlighted with different colours on the map (Figure 7).

3.1.2. Construction of the Tree of Fundamental Viewpoints

Finally, with the information contained in the congregated map, the facilitator built the tree of fundamental viewpoints or decision tree of the problem (Figure 8), presenting management alternatives to solve/mitigate the water supply problematic in the water crisis (2012–2017) and in future scenarios.

The construction of the tree of key viewpoints of all actors selected for this study seeks to provide a set of actions that could be implemented to improve water supply. Thus, at the end of this procedure, the problem is structured.

The structuring of the problem in an interactive and democratic context with various actors (specialists in the theme of water resources management) provided a better understanding of the problem, enabling the determination of actions and goals to be achieved in order to facilitate decision making.

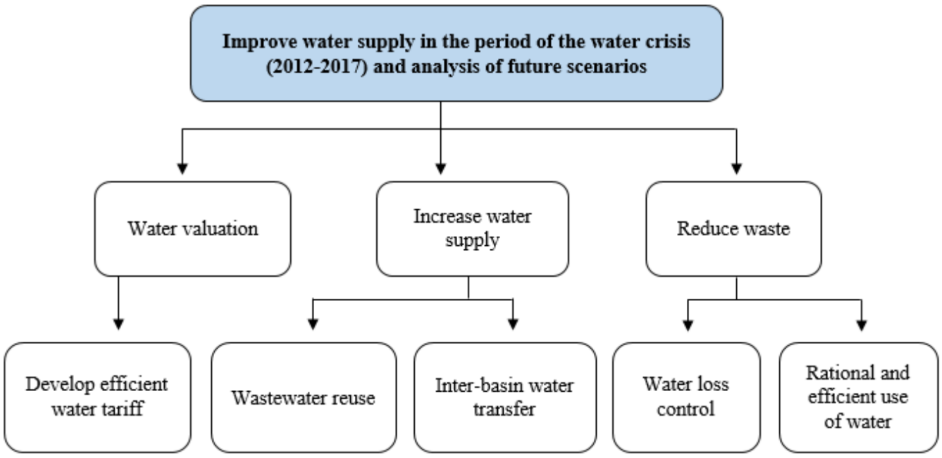

Figure 8. Tree of key stakeholder views.

3.2. Stage 2: Evaluation of Alternatives

3.2.1. Model Validation

The model was validated through direct structural tests that assessed the validity of the model's structure in relation to the real system, as proposed by Barlas [59]. To this effect, it was verified whether the model possessed all critical variables to be investigated.

The model performance was also validated using the Mean Absolute Percentage Errors (MAPE) for the hydrologic balance between the years 2005 and 2015, in which an error of 2.8% between simulated and real data was verified. Thus, a satisfactory model performance can be affirmed, and therefore a good estimate to represent well the real behaviour of the reservoir (Figure 9). The model validation was useful for reproducing the future hydrological balance between the years 2016 and 2025.

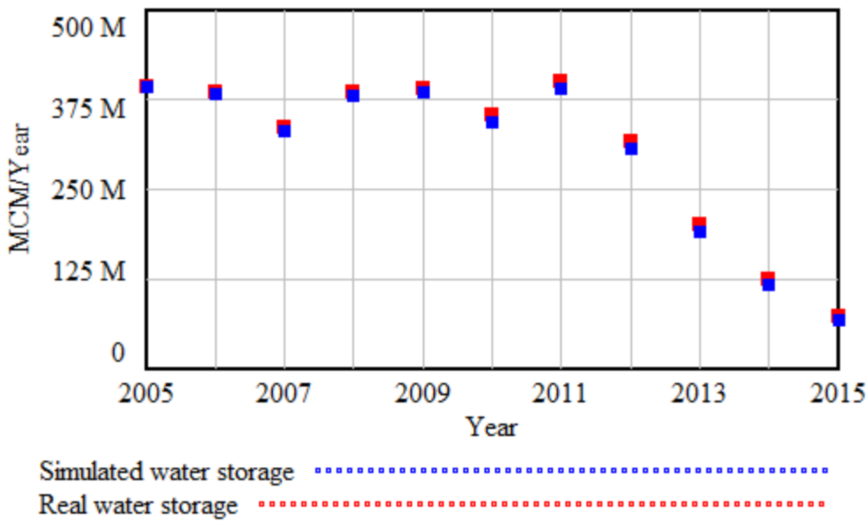

Figure 9. Comparison between real and simulated water storage in the Epitácio Pessoa reservoir.

3.2.2. Model Simulation and Scenario Analysis

Five scenarios will be simulated together with the Status Quo scenario, as defined by the actors through the SODA problem structuring method. Table 2 summarizes the scenarios defined.

Table 2. Input parameters for the simulation of the scenarios.

Scenarios	Scenario Description				Wastewater Reuse (No/Yes)	PISF (No/Yes)
	Population Growth (%)	Water Use (L/P/D)	Loss Control (LC) (No/Yes)	SB Tariff (No/Yes)		
Status Quo	1.0%	Varying	No	No	No	No
SC1	1.0%	222	No	No	No	No
SC2	1.0%	22	No	Yes	No	No
SC3	1.0%	222	Yes	No	No	No
SC4	1.0%	222	No	No	Yes	No
SC5	1.0%	222	No	No	No	Yes

Note: SC1: scenario without restrictions; SC2: scenario without restrictions + scarcity-based tariff; SC3: scenario without restrictions + loss control; SC4: scenario without restrictions + wastewater reuse; SC5: scenario without restrictions + PISF scenario; Combining scenarios: scenario without restrictions + wastewater reuse + scarcity-based tariff.

Simulation Results

- Status Quo versus Scenario 1

The first simulated scenario was a comparison of the Status Quo with scenario 1 (Figure 10). For the simulation made of the Status Quo and occurred in the actual scenario, through these rationing measures it was possible to guarantee the water supply until April 2017 with a volume of approximately 13.7 MCM (3%). However, such measures would no longer be efficient and, in fact, would cause a water deficit of approximately 4 MMC and 15 MMC in 2018 and 2019, respectively. At the end of the simulated period, the reservoir would have a stock of 97 MMC.

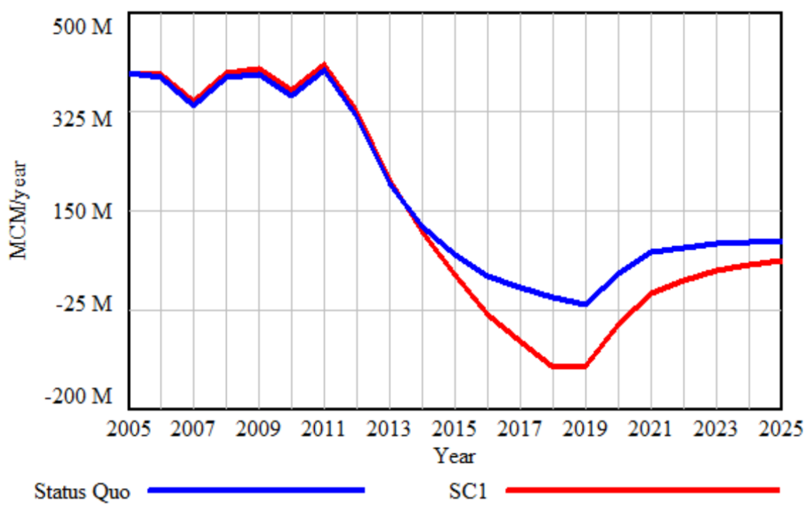

Figure 10. Comparison between the status quo and the scenario without rationing.

For Scenario 1, assuming no changes in the patterns of urban water uses and irrigation over the simulation period in the study, the municipalities supplied by this water-producing system would already have no water at the beginning of 2016, consequently accumulating a water deficit of more than 120 MCM by the end of 2018. At the end of the simulated period, the reservoir would have a water stock of 60 MMC, a volume that represents water insecurity for the region.

- Scenario 2 (Impacts of Scarcity-Based tariff on water conservation)

In this scenario, the impact of the SBT on the water storage level during the simulated period was analysed (Figure 11). According to the simulations, it can be stated that the scarcity-based tariff is an efficient strategy to encourage a reduction in water demand, however, for the case studied it would not prevent a water collapse in the region for the years 2017, 2018 and 2019. For example, in 2017 the water deficit would be 28 MCM and in 2019 the deficit would be 59 MCM. This represents a percentage reduction in the water deficit of 65% in 2017 and 51% in 2019, compared to scenario 1. By the end of the simulated period, 2025, despite a water stock of approximately 138 MCM in the reservoir, this level still represents water insecurity for the region's supply.

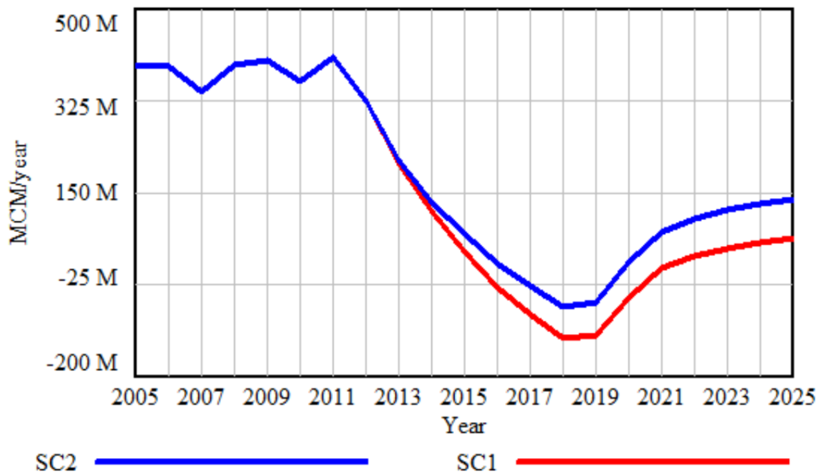

Figure 11. Impact of the Scarcity-Based Tariff on water conservation.

- Scenario 3 (Impacts of leakage control on water conservation)

In this third scenario, the influence of a loss reduction policy on water conservation was analysed, without considering rationing measures in water consumption. Thus, three scenarios were proposed with loss reduction rates of 15%, 20% and 25%. The average loss rate of the region under study is approximately 33%.

As Figure 12 shows, with the implementation of a loss reduction policy at the onset of drought, this could only briefly delay water collapse in the region (in scenario 1) and reduce the water deficit for all loss control scenarios over the simulated period. For example, for a 15% efficiency in loss reduction, from the current 33%, the water deficit would be reduced to 61 MCM in 2017 and 100 MCM in 2019. This represents a percentage reduction in water deficit of 25% in 2017 and 18% in 2019, relative to scenario 1. In 20% efficiency, the water deficit would be reduced to 54 MCM in 2017 and 92 MCM in 2019, a reduction of 34% and 24%, respectively, in relation to scenario 1. For a scenario with a 25% loss reduction, from the current 33%, the water deficit would be reduced to 47 MCM in 2017 and 85 MCM in 2019. Such volumes represent a percentage reduction of 42% and 30% in relation to scenario 1, respectively. For these three loss control efficiency scenarios, the accumulated water stock at the end of the simulated period is approximately 100 MCM. The volume of water stored also represents water insecurity for the region.

However, it is verified that no matter how efficient the control of losses in water distribution networks is, the drought period of more than six years did not prevent a water collapse in the region between the years 2016 and 2019.

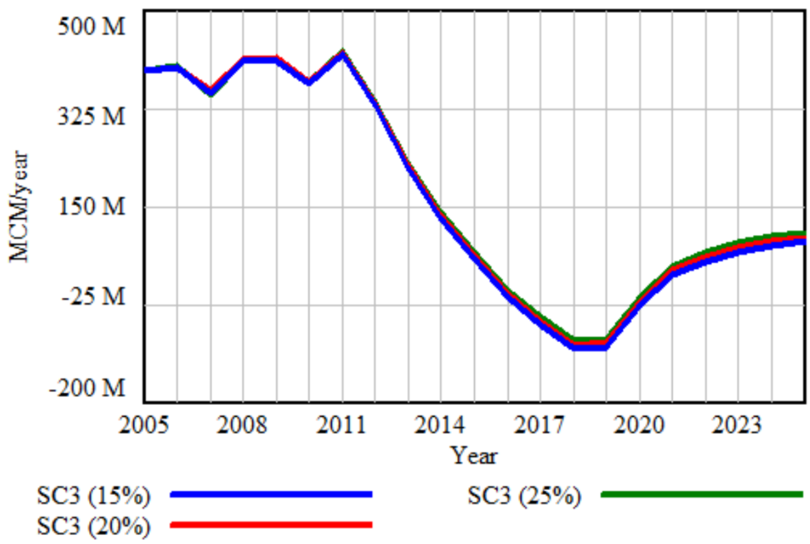

Figure 12. Impact of leakage control on water conservation.

- Scenario 4 (Impacts of wastewater reuse on water supply)

In this scenario, the impact of wastewater reuse on the region's supply will be simulated. For this, reuse indicators in an amount of 60%, 80%, and a more optimistic scenario of 100% will be used as parameters to estimate these scenarios.

Analyzing Figure 13, it can be seen that although water reuse does not prevent a water collapse for the years 2017 to 2019, such policy would already be sufficient to maintain a constant water supply from the year 2020 until the end of the simulated period, even at a level of water insecurity due to the low level of water stock in the reservoir. For example, if for a scenario without rationing measures (SC1) and without any implementation of management strategies, the water deficit is 126 MCM in 2018, for a scenario of 80% reuse of wastewater, this deficit would be 70 MCM, which represents a percentage of water deficit reduction of 44% compared to scenario 1. In 2025, the reservoir would have a positive water storage stock of 127 MCM.

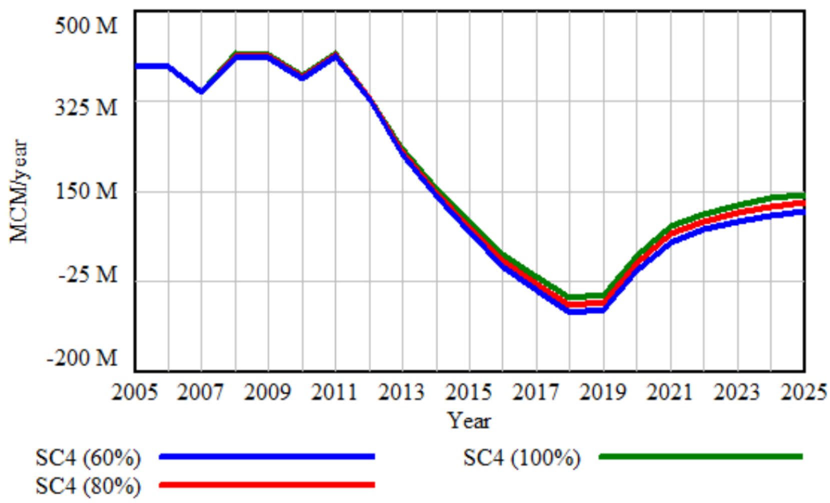

Figure 13. Impact of wastewater reuse on water supply.

In a more optimistic scenario, that is, considering 100% reuse of the effluents generated, this deficit would be approximately 56 MCM (55% reduction) in 2018 and an accumulated positive water stock of 143 MCM in 2025.

- Scenario 5 (Impacts of inter-basin water transfer on water supply)

In scenario 5, the impact of water transposition between hydrographic basins was simulated on the region's water supply. In this case, the PISF (São Francisco River Integration Project) was considered to carry out the simulations. It is noteworthy that two assumptions were assumed in this scenario: The first is that the increase of PISF waters in the Epitácio Pessoa reservoir occurs as of 2015. The second is in relation to the flows considered to simulate the two scenarios (2 m^3/s and 4 m^3/s).

The results of the simulations carried out for this scenario (Figure 14) show that both flow rates (2 m^3s and 4 m^3s) supplied by PISF would eliminate the risk of a hydric collapse in the region, in addition to maintaining a high level of water volume and no risk of water shortage by the end of the simulated period.

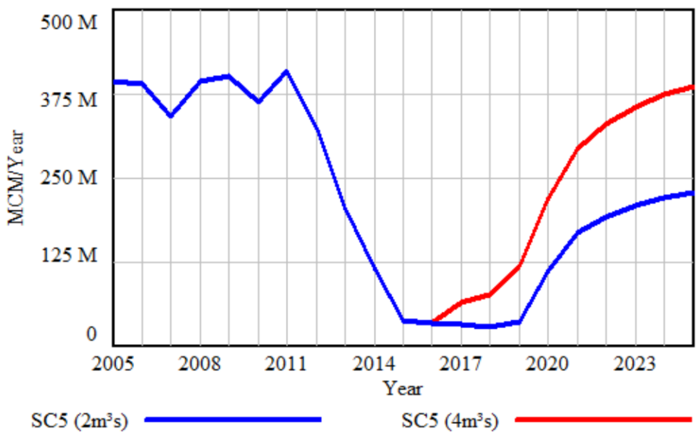

Figure 14. Impact of inter-basin water transfer on water supply.

- Combining different scenarios

In order to present the aggregate influence of water management strategies, two scenarios were simulated. These two scenarios maintained throughout the analyzed period the irrigation and urban consumption patterns, i.e., without any type of rationing in water uses, but are divergent in:

- Efficient management: In which three types of management strategies were added, SBT, the reuse of wastewater for a scenario of 100% reuse and a control of losses with an index of 25%.
- Inefficient management: No management strategy was taken into consideration.

According to Figure 15, it can be seen that, with efficient management, that is, considering various hydric management instruments, it is possible to avoid a hydric collapse during the period of water crisis analyzed (2012–2017), in addition to maintaining water stocks above 150 MCM in the reservoir from 2020 until the end of the simulated period. Otherwise, the region would run out of water starting in 2016, generating socioeconomic problems in the region.

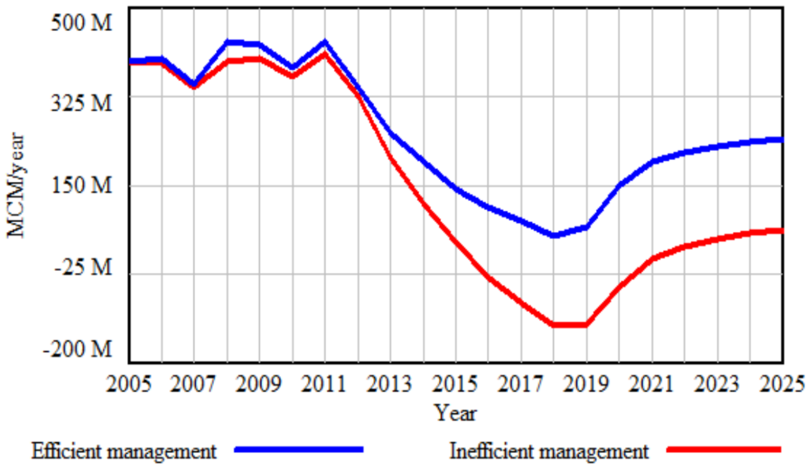

Figure 15. Combining different scenarios.

3.3. Uncertainty Simulation by Monte Carlo Simulation

A sensitivity analysis was performed on each scenario using the Monte Carlo method in order to verify which input parameters have the most influence on the WSPB model. The parameters in this study have uncertainties and therefore significantly affect the WSPB model (Table 3).

Table 3. Parameters used in the sensitivity analysis.

Parameters	Initial Value	Sensitivity Test Range
Loss control coefficient	0.15	[0.1, 0.3]
Scarcity-based tariff	1	(0, 3)
Rate of reuse of wastewater	0.6	[0.1, 1]
Population growth rate	0.01	[0.001, 0.04]
Domestic demand per capita	48	(40, 55)
Water transfer rate between basins	2	(1, 4)

In Figures 16–18 only the parameters that most impacted on the model were exposed, in which were the Scarcity-Based Tariff (Figure 16), the reuse of wastewater (Figure 17) and the transposition of water between basins (Figure 18), here considered the PISF. The latter is the parameter that most strongly influences the WSPB model.

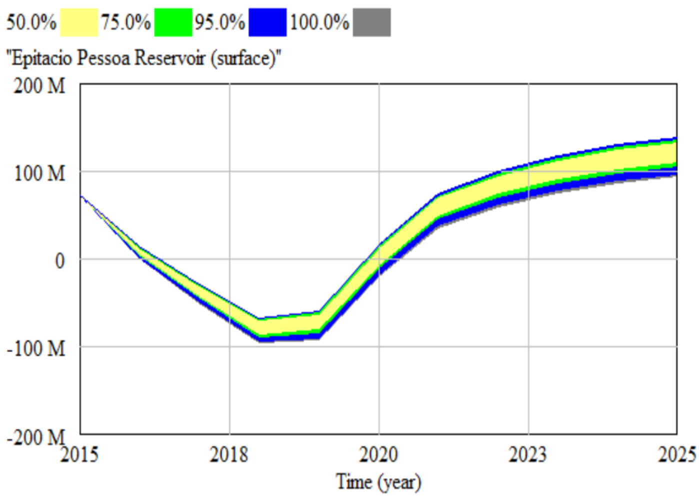

Figure 16. Monte Carlo simulation result for Scarcity-based tariff.

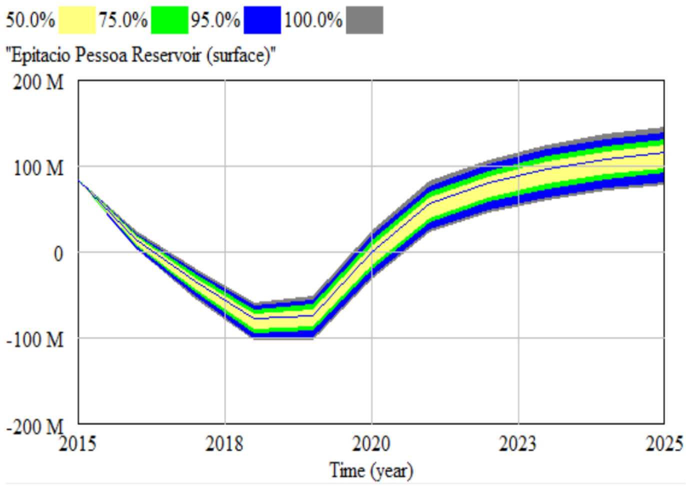

Figure 17. Monte Carlo simulation result for reuse wastewater.

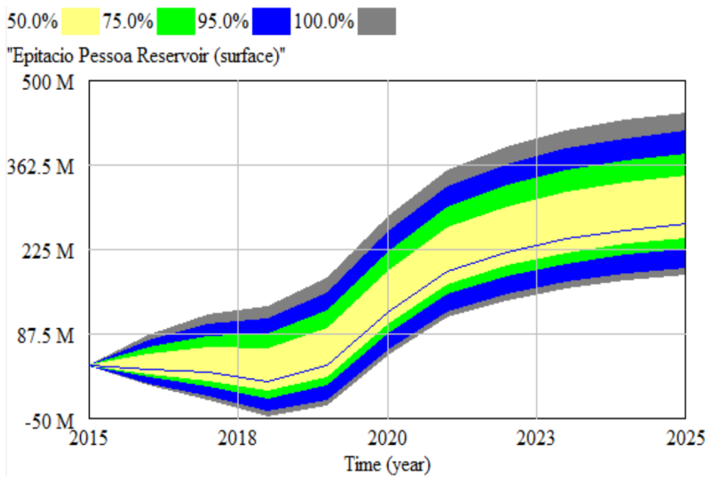

Figure 18. Monte Carlo simulation result for transposition of water between basins.

Thus, water resource management planning considering SBT, the reuse of wastewater, and inter-basin water transfer play a crucial role in reducing water scarcity in the semi-arid region of Paraíba, the focus of this study.

4. Conclusions

The multi-methodological approach proposed in this study was developed as part of an effort to involve water experts and policy makers in the broad policy choices that could be used to influence water use and supply behaviour. To this end, the SODA method and SD approach were used in the construction of this multi-methodology. The role of each of these clearly represents the contribution of this paper: SODA in the problem structuring phase (construction of alternatives for solving such problem) and SD in the evaluation phase of these alternatives.

The results of the research suggest that, in scenarios such as the PISF, the reuse of wastewater together with the elaboration of tariff structures that encourage the rational use of water should have been implemented in order to avoid the water supply between the years 2016 to 2019, and reduce the risk of future water collapses in the region. In summary, significant changes in the management of water demand and supply are evident for the region.

Some important contributions in this study are highlighted:

- The elaboration of system dynamics models considering the SODA method in the problem identification and structuring phase can be an alternative for the construction of these system dynamics models, which are unable to provide a broad understanding of the problem considering its controversies and multiple decisions about the water management problem.

- The use of the insights generated from the interviews with the experts (construction of the cognitive maps of the SODA method) to assist the facilitator in the preparation of the causal and stock and flow models of the system dynamics, provided a greater understanding and ease when building these models.
- Another important contribution in this study was the development and application of a water tariff structure method, called here scarcity-based tariff (SBT), which encourages the rational use of water based on its availability in the reservoir, which in turn can increase revenue in times of low water stock levels and support investment in other water management strategies.

It is suggested that the results of this research can be used as a starting point for future research addressing the complexity of water management and policy planning. Furthermore, although the SD approach has significant advantages, it is subject to some limitations. For example, the SD method is not able to find the optimal (non-dominant) decisions by design. Another limitation is that uncertainty modeling is a challenging task using SD. Thus, to deal with these types of problems, it is suggested to combine SD with other simulation or optimization methods (e.g., game theory, analytical hierarchy process, fuzzy logic techniques, or with the adaptive Backcasting management methodology developed by van der Voorn et al. [60]), which can produce more valuable, improved methods while being easy to understand and dynamic.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Individual Cognitive Maps

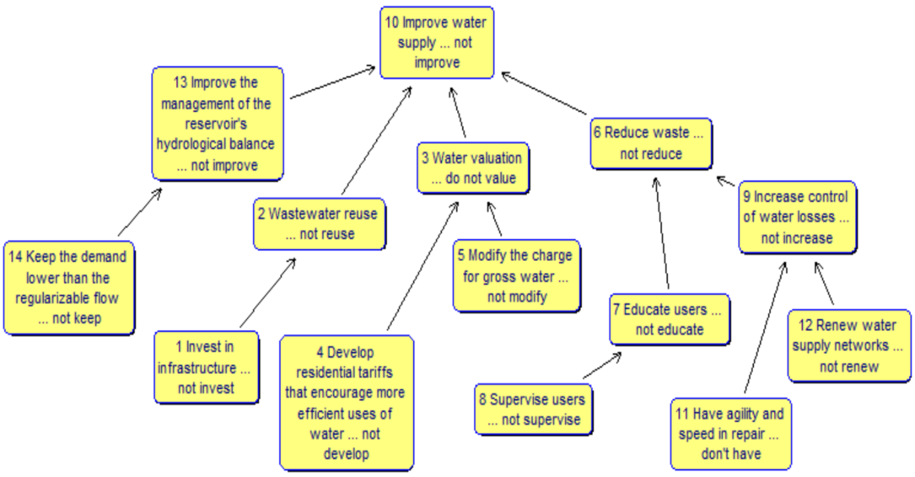

Figure A1. Individual Cognitive Maps of Actor A.

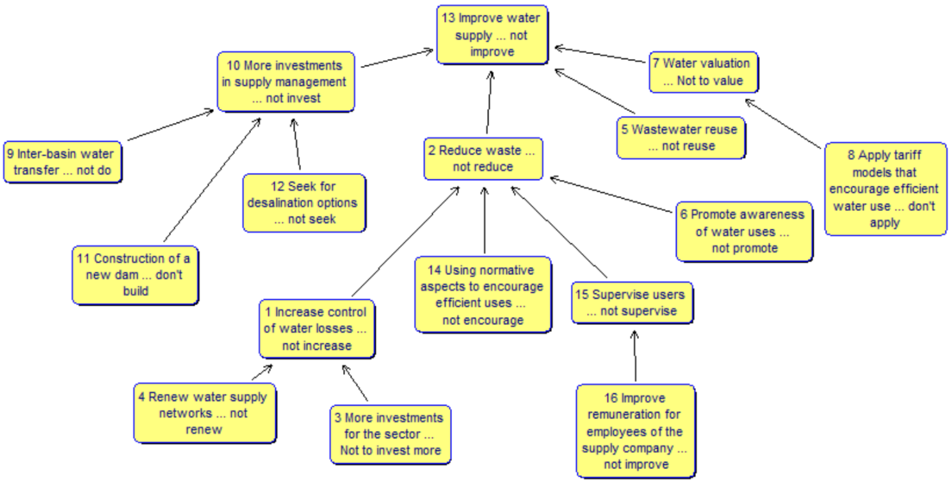

Figure A2. Individual Cognitive Maps of Actor B.

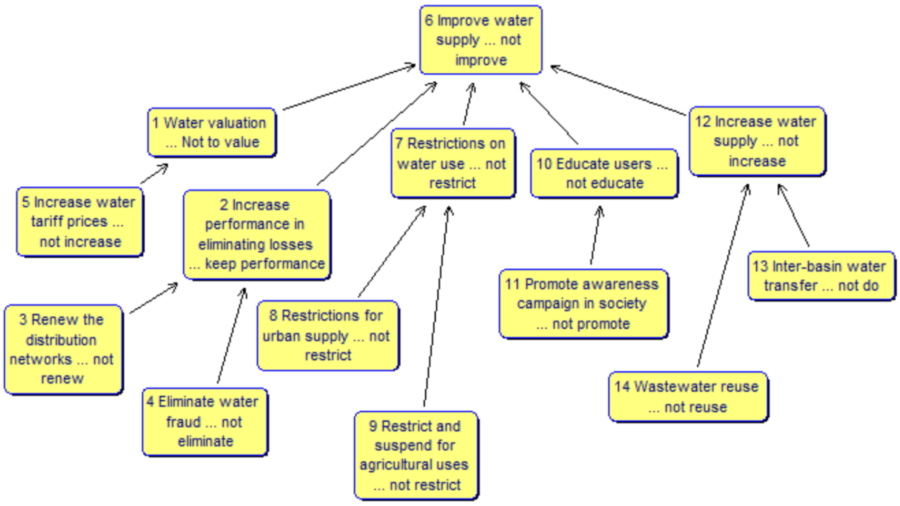

Figure A3. Individual Cognitive Maps of Actor C.

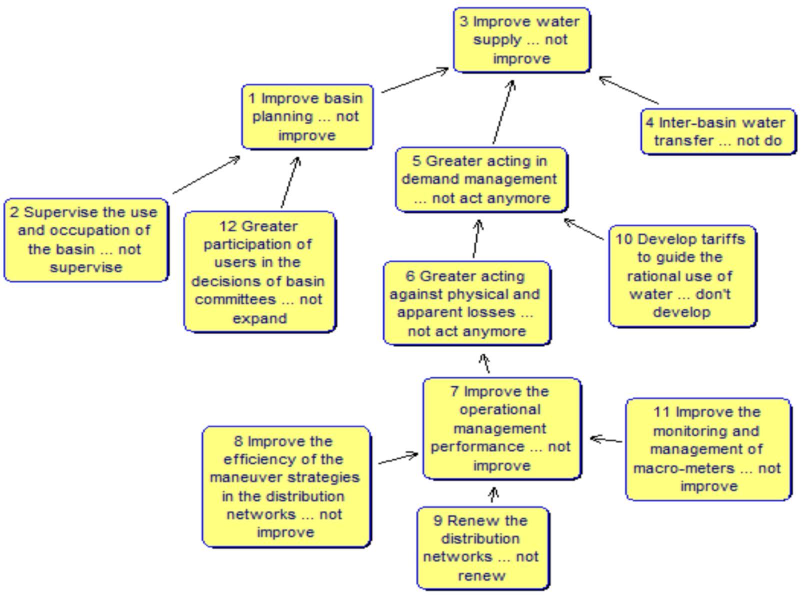

Figure A4. Individual Cognitive Maps of Actor D.

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