DYNAMIC MODELING APPLIED TO DECISION-MAKING IN WATER SUPPLY SYSTEMS IN THE STATE OF BAHIA

Meire Jane Lima de Oliveira[1], Renelson Ribeiro Sampaio[a], Xisto Lucas Travassos[a,b]

[1,a] SENAI CIMATEC, Brazil,
[b] Universidade Federal de Santa Catarina, Brazil

Abstract: universal and equitable access to drinking water is a worldwide concern. Against this backdrop, this article aims to develop a dynamic decision-making model for organizations that operate as water supply operators in the state of Bahia, given the challenges of universalization brought about by the New Legal Framework for Sanitation (99% of the population served by 2033) and the Sustainable Development Goal 6 (SDG 6). To this end, an analysis of the stakeholders network and a systems dynamics model were carried out. The results of the simulation indicated that in order to achieve the target, it will be necessary to invest in increasing the production of treated water while maintaining concern for energy efficiency and the sustainable use of the resource.

Keywords: water supply, system dynamics, stakeholders.

MODELAGEM DINÂMICA APLICADA À TOMADA DE DECISÃO EM SISTEMAS DE ABASTECIMENTO DE ÁGUA DO ESTADO DA BAHIA

Resumo: o acesso universal e equitativo a água potável representa uma preocupação mundial. Diante deste cenário, este artigo tem como objetivo desenvolver um modelo dinâmico de tomada de decisão para organizações que atuam como operadores do abastecimento de água no Estado da Bahia, diante dos desafios de universalização trazidos pelo Novo Marco Legal do Saneamento (99% de atendimento da população até 2033) e pelo Objetivo do Desenvolvimento Sustentável - ODS 6. Para tanto, foi realizada uma análise da rede de partes interessadas e uma modelagem de Dinâmica de Sistemas. Os resultados da simulação indicaram que para atingir a meta será necessário investir para aumentar a produção de água tratada, mantendo a preocupação com eficiência energética e o uso sustentável do recurso.

Palavras-chave: abastecimento de água, dinâmica de sistemas, partes interessadas.

1. INTRODUCTION

The concern to achieve universal and equitable access to drinking water for all by 2030 is expressed in one of the targets of Sustainable Development Goal 6 (SDG 6): drinking water and sanitation [13]. In Brazil, we have the New Legal Framework for Sanitation (NLFS), which, in line with SDG 6, describes the rules of contracts for the provision of public basic sanitation services that should define universalization targets that guarantee 99% (ninety-nine percent) of the population served with drinking water by the end of 2033 [2]. Thus, for organizations that operate water supply systems, there is the challenge of promoting the universalization of water and sanitation services, together with the sustainable management of the resource.

The aim of this article is to develop a dynamic decision-making model for organizations that operate water supply systems in the state of Bahia, given the universalization challenges posed by the NLFS and SDG 6. Due to scope limitations, this work did not cover all stages of the water supply process (catchment to distribution). The reservation and distribution phases were analyzed. The aim is to answer the following question: how can we propose a dynamic decision-making model for the operators of water supply systems in Bahia, given the challenges of achieving universalization targets?

To this end, the stakeholders that influence the water supply service in Bahia were initially identified, and the existing network of relationships was demonstrated using the UNICET software [1]. Stakeholders can be defined as actors who have an interest in the issue under consideration, who are affected by the issue, or who, due to their position, have or can have an active or passive influence on decision-making [3].

A system dynamics (SD) model was then developed to represent water supply (reservation and distribution) and water demand in Bahia. SD helps us push the boundaries of our mental models, generating awareness and responsibility for the feedback created by our decisions. In addition, understanding counterintuitive dynamics requires understanding stocks and flows, time delays, and non-linearities [12]. The model was implemented using Vensim PLE software [14]. The model was used to simulate a scenario that will have an impact on decision-making based on the challenge of universal access to drinking water by 2030.

2. METHODOLOGY

In order to answer the research problem, the methodology adopted involves exploratory and descriptive research [6]. Figure 1 illustrates the methodological approach adopted.

Figure 1. Methodological structure

Source: own elaboration

2.1. Bibliographical research and of secondary data and information

Two search mechanisms were used with the following descriptors: stakeholders and water management; system dynamics and (water supply or water management); and only articles in English and Portuguese were searched. The search in secondary databases was based on queries to approximately 25 websites of government institutions, regulatory, control, and inspection bodies operating on the national scene and in the state of Bahia, financial institutions, basic sanitation companies, and others. The data and information adopted were collected from the National Sanitation Information System [10] and the Brazilian Institute of Geography and Statistics (IBGE) [9].

2.2. Study area

The area chosen is the state of Bahia, which is the 5th largest state in Brazil and has an estimated population of 14,136,417 (2022 IBGE census), representing the 4th largest population in Brazil and the 1st in the Northeast region. In 2021, the total population service rate for potable water was 80.97% [10]. The water supply service is carried out predominantly by a regional provider, Empresa Baiana de Águas e Saneamento (Embasa), which serves 88% of the state's 417 municipalities [10].

2.3. Identification and analysis of stakeholders

The stakeholders were identified in the secondary databases and then, based on the Principles of Water Governance - Indicator Framework [8], were classified according to their roles and responsibilities into: a) political and strategic actors: policy makers and implementers; b) regulation and oversight: regulatory and inspection agents; c) financial actors: national and international development and financing agents; d) operational management: operational management of water supply systems; e) users: users of treated water; f) influence and interest groups: technical and scientific circles, academics, trade unions, civil society, others; and g) supply chain: main suppliers. The "supply chain" group, not mentioned in the OECD classification, was included due to the scenario imposed by the NLFS. In this scenario, investments will be required from the providers of treated water distribution services, mobilizing the industry that supplies goods and inputs to this sector, with an emphasis on pipes, equipment, and expenditure on chemical products [4].

An analysis of the stakeholders network was then carried out using UNICET software [1]. To analyze the interrelationships between these actors, different instances of relationships were identified through secondary sources, such as participation in councils, basin committees, basic sanitation plans, etc. Finally, an analysis was made of the network's density and degree centrality metrics, calculated using the UNICET software. Density represents the number of ties in a network in relation to the number of theoretically possible relationships. Its value can vary on a scale from 0 to 1, where 1 represents a highly cohesive network. Degree centrality, in turn, refers to the total number of stakeholders to which a focal node is directly connected [7].

2.4. System Dynamics (SD) Modeling

The SD modeling developed represents the supply and demand sides of water in the reservation and distribution stages. Since the model does not cover the water catchment and treatment stages, a stable supply of water sources was considered. To develop this model and select the relevant variables (table 1) for the reality of Bahia, we used stakeholder analysis and the articles that use SD modeling in water resource management and in water supply systems as references [15, 16, 5, 17]. In addition, we opted for variables that had publicly accessible historical series for research. The modeling was developed using Vensim PLE software [14], and the simulation horizon is up to 2030. The variable names (table 1) were adapted in relation to the historical data sources. The equations adopted were based on the literature cited and on the Vensim system itself. The historical series were taken from SNIS [10] and SIDRA/IBGE [9], from 2005 to 2021.

Table 1. Main dynamic modeling variables

Variables	Equations	Unit	Source of variables
Treated water (stock)	*=INTEG (produced water - water uses, initial value)*	m^3/ Year	Articles; stakeholders (operational management)
Water Uses	*= total demand + distribution losses*	m^3/ Year	Articles; stakeholders (operational, users)
Losses in water distribution	*=treated water*losses index*	m^3/ Year	Articles; stakeholders (operational, regulation)
Per Capita Demand	*=0.03*	m^3/ Year	Articles; stakeholders (operational, users)
Residential demand	*=per capita demand * population served*	m^3/ Year	The same
Total demand	*=non-residential demand + residential demand*	m^3/ Year	The same
Average electricity expenditure	*=spending on electricity/treated water*	R$/$m^3$/ Year	Articles; stakeholders (operational, supply chain)
Average expenditure on chemical products	*=spending on chemical/treated water*	R$/$m^3$/ Year	Stakeholders (operational management, supply chain)
Average investments	*=investments in supply systems/treated water*	R$/$m^3$/ Year	Articles; stakeholders (operational management, policy and strategy financial actors)
Population served	*=total population* population service rate*	People	Articles; stakeholders (operational, policy and strategy, users, influence and interest groups)
Supply-demand x ratio	*= treated water/total demand*	Dmnl/ Year	Articles; stakeholders (operational management)

Variables	Equations	Unit	Source of variables
Water balance	= *produced water - water uses*	m3 /Year	The same

Source: own elaboration

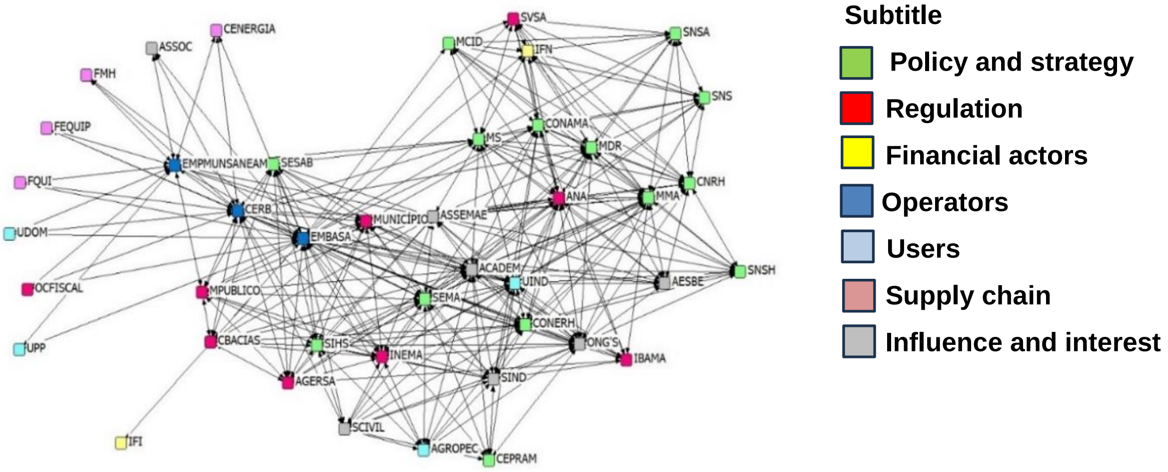
SD modeling is a powerful tool to enable managers to communicate information about the structure of the system to stakeholders and the effects of different decisions [11]. Finally, a simulation was carried out based on the target set by the NLFS of 99% of the population served with drinking water by 2033.

3. RESULTS AND DISCUSSION

3.1. Stakeholder analysis

Stakeholders were identified and classified according to their roles and responsibilities in water management [8] into 7 groups. A total of 43 stakeholders were identified. Figure 2 illustrates the sociogram of the relationships observed between the stakeholders, created using the UNICET software. There were a total of 586 connections, or relationship points. The density of the network was 0.33, which indicates that the number of links observed between the actors in the network represents 33% of the total number of theoretically possible relationships. However, considering that the relationships were obtained through secondary sources without collecting primary information from the stakeholders, the degree of density can be much higher.

Figure 2 – Sociogram of stakeholders in Bahia's water supply.



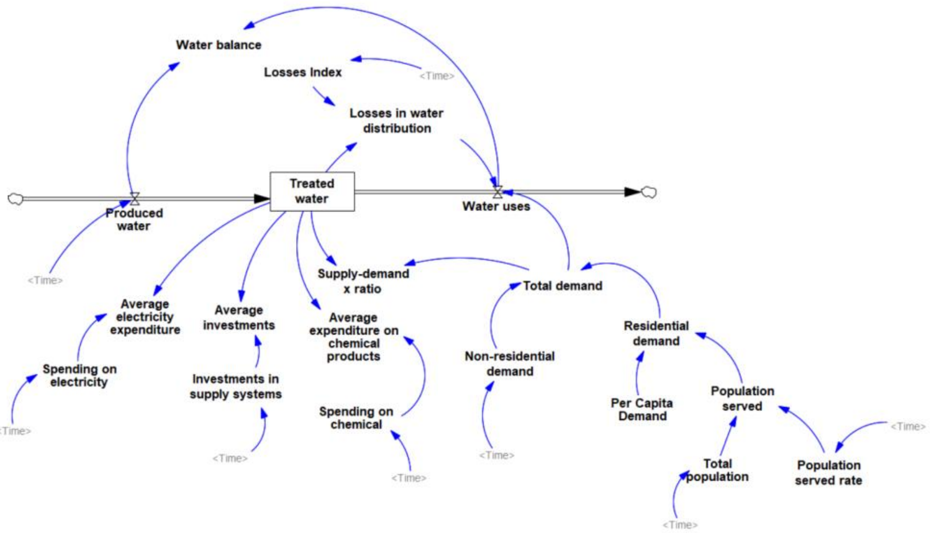
Source: own elaboration using UNICET software.

With regard to degree centrality, it was found that 11 of the 43 stakeholders have between 20 and 36 links: CONERH, NGOs, ASSEMAE, MS, MMA, ANA, SEMA, CERB, UIND, ACADEM, and EMBASA. The majority (5 of them) are part of the group of political and strategic actors, revealing the influence of those responsible for formulating and implementing policies, including funding, for the sector; 3 of them make up the influence and interest group, representing the municipalities, the population, and academia; and one operator, Embasa, appeared with the highest number of links or degree centrality (36).

3.2. Dynamic modeling

The SD modeling is shown in Figure 3, where the final stages of the supply system (reservation and distribution) are considered. It should be noted that it is possible to analyze a part of a larger system, but there are disadvantages, such as the risk of ignoring the effects of possible events on unanalyzed parts of this larger system. The assumption of a stable supply from the water sources that feed the input of the modeled system was made, and the simulation will take changes on the water demand side as its starting point.

Figure 3 - Schematic Model of Systems Dynamics of Water Supply in Bahia.



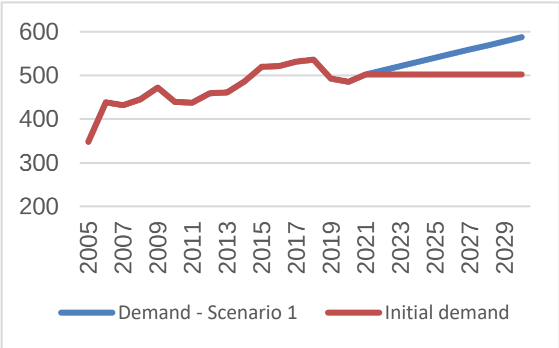
Source: own elaboration

In the model, the stock of treated water decreases as losses in water distribution increase. The increase in water supply requires greater investment in water supply systems as well as greater expenditure on chemicals and electricity, and these variables appear in the model as dependent on the "treated water" variable. The total demand for water, in turn, increases with the increase in residential demand (which grows with population growth) and non-residential demand (economic sectors and others).

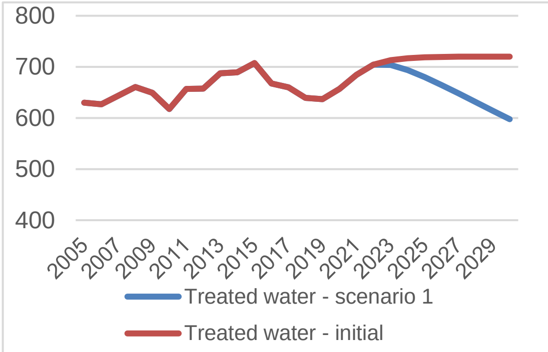
The model was subjected to validation tests. Initially, the structure of the model was observed, which is a test to assess the consistency between the structure of the model and that of the real system [5]. The proposed model represents Bahia's reality in a simplified way. A behavior test was carried out with the model to compare its behavior with the time series of real-world data [5]. A test was carried out on the "total demand" variable with a data series from 2005 to 2015, with the introduction of the "population served rate" for 2021, and the model proved to be reliable.

In order to assess the behavior of the model's variables in relation to the target of 99% of the population served with drinking water, this value was introduced into the historical series of the "population served rate" variable in the year 2030. Graph 1 shows an increase in total demand caused by the increase in the target for supplying the population with drinking water due to the increase in residential demand, which is a population-dependent variable. This increase in total demand has had an impact on the water stock (Graph 2), which has suffered a reduction in its level since the outflow from the system (water uses) has intensified while the inflow to the system (produced water) and losses in water distribution have remained constant. In addition, the ratio between treated water (stock) and total demand fell, so the system was under pressure to produce more water to meet the extra demand.

Graph 1 - Total demand (1.000^2 m^3)



Graph 2 – Treated water (1.000^2 m^3)



Source: own elaboration

4. CONCLUSION

This research developed a SD model to analyze the decision-making environment of the organizations that carry out the water supply service in Bahia, taking into account the stakeholders involved. Given the complexity of the analysis, which covered an extensive geographical area, it was not possible to delve into the regional particularities of the state. As a result, other variables could have been included, such as personnel costs, targets for non-intermittency in water supply, and others; despite this, the analysis was not prejudiced. A constant water supply was assumed for the modeling. A simulation was carried out based on the scenario imposed by the target of 99% of the population served with treated water. The results of the simulation showed that, with the flows of water production and losses in water distribution remaining unchanged, the increase in service expected for 2030 will require investments in new water supply systems and the expansion of existing ones, as well as increased spending on chemicals and energy (variables analyzed in the model). Thus, this scenario indicates that the joint and assertive action of stakeholders is relevant to the design of strategies to meet the universalization targets associated with the sustainable use of water. In addition, there is a concern with energy efficiency since the water supply process is energy intensive and with reducing losses in water distribution. It is suggested that future research should extend the modeling to include all stages of the water supply system, deepen the analysis of the stakeholders network, and choose a local water supply system that allows for in-depth analysis, identification of the particularities of the system, and analysis of the risks involved.

5. REFERENCES

[1] BORGATTI, Stephen P.; EVERETT, Martin G.; FREEMAN, Linton C. Ucinet 6 for Windows: Software for social network analysis. **Harvard, MA: analytic technologies**, v. 6, p. 12-15, 2002.

[2] BRASIL, Lei 14026, de 15 de julho de 2020. Atualiza o Marco Legal de Saneamento Básico. Disponível em: https://www.in.gov.br/web/dou/-/lei-n-14.026-de-15-de-julho-de-2020-267035421. Access at. 21/05/2023.

[3] BRUGHA, Ruairí; VARVASOVSZKY, Zsuzsa. Stakeholder analysis: a review. **Health policy and planning**, v. 15, n. 3, p. 239-246, 2000.

[4] ERMAKOFF, Eduardo Delmont et. al. Novo marco legal do saneamento: impactos na cadeia de fornecedores. 2022

[5] GHASEMI, Alireza; SAGHAFIAN, Bahram; GOLIAN, Saeed. System dynamics approach for simulating water resources of an urban water system with emphasis on sustainability of groundwater. **Environmental Earth Sciences**, v. 76, p. 1-15, 2017.

[6] GIL, Antonio Carlos et al. **Como elaborar projetos de pesquisa**. São Paulo: Atlas, 2002.

[7] HU, Xiao et al. Stakeholder collaboration on policymaking for sustainable water management in Singapore's hotel sector: A network analysis. **Sustainability**, v. 11, n. 8, p. 2360, 2019.

[8] OECD. PUBLISHING. **Implementing the OECD Principles on Water Governance-Indicator Framework and Evolving Practices**. OECD Publishing, 2018.

[9] SIDRA - Sistema IBGE de Recuperação Automática (2023). Banco de tabelas estatísticas. Pesquisas – população – projeção da população. Disponível em: https://sidra.ibge.gov.br/pesquisa/projecao-da-populacao/tabelas.

[10] SNIS - Sistema Nacional de Informações sobre Saneamento (2023). SNIS – Série Histórica. Disponível em: http://app4.mdr.gov.br/serieHistorica/.

[11] STAVE, Krystyna A. A system dynamics model to facilitate public understanding of water management options in Las Vegas, Nevada. **Journal of Environmental Management**, v. 67, n. 4, p. 303-313, 2003.

[12] STERMAN, John D. All models are wrong: reflections on becoming a systems scientist. System Dynamics Review: **The Journal of the System Dynamics Society**, v. 18, n. 4, p. 501-531, 2002.

[13] UNITED NATIONS (2022). The Sustainable Development Goals Report 2022. disponível em https://www.un.org/development/desa/dspd/2022/07/sdgs-report/. Access at 20/05/2023.

[14] VENSIM, P. L. E. Software; Ventana Systems. **Inc.: Harvard, MA, USA**, 2006.

[15] WANG, Xiao et al. Water resources planning and management based on system dynamics: a case study of Yulin city. **Environment, development and Sustainability**, v. 13, p. 331-351, 2011.

[16] WEI, Tong et al. A system dynamics urban water management model for Macau, China. **Journal of Environmental Sciences**, v. 50, p. 117-126, 2016.

[17] XU, Zhongwen; YAO, Liming; CHEN, Xudong. Urban water supply system optimization and planning: Bi-objective optimization and system dynamics methods. **Computers & Industrial Engineering**, v. 142, p. 106373, 2020.