Developing System Dynamic Modeling for Risk Management in Water Utilities: A Proposal for Framework Based on a Sistematic Review

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This work systematically reviewed articles published between 2019 and 2024 on system dynamics approaches in water resource management, focusing on drinking water supply, seeking to identify advances in models which address risks or risk management in water resources. The aim was to verify whether the models contribute to corporate risk management in companies which provide water supply services. Based on an adaptation of the PRISMA methodology, forty articles published in journals were selected. Main results: all articles presented a case study; only one article presented a water utility as a case study; 20% of the studies entailed risks in modeling and 15% included stakeholders and experts in the formulation of the models; 45% of the studies have adopted both qualitative and quantitative system dynamics modeling; 53% of the studies were produced on the Asian continent, especially in China; 47% of the quantitative models are integrated with other types of modeling; 91% of the models have undergone a verification method. Vensim is the most widely used software in studies. At last, based on these results and identified gaps, a system dynamics model structure was proposed for corporate risk management in drinking water supply companies.

Keywords: Water Resources Management. Water Supply. Risk Management. Stakeholders. System Dynamics.

Water is associated with all aspects of life, such as human health, food security, economic development, and ecological balance [1]. The demand for fresh water is increasing, however, several factors make its future availability uncertain, such as population growth, water pollution, economic progress, changes in land use, and climate change [2].

Decades of misuse, mismanagement, overextraction, contamination of both fresh surface and groundwater affects your supply, thus aggravating water stress [3]. The comprehensive and viable long-term universalization of access to water and sanitation services represents one of the most crucial struggles of the 21st century [4].

The concern to guarantee access to drinking water for all is stated in Sustainable Development Goal 6: drinking water and sanitation, which is defined in its target 6.1: "by 2030, achieve universal and equitable access to safe drinking water for all" [3].

Natural resource scarcity, such as water and food, is among the ten global risks predicted to aggravate over the next ten years. The risk of water scarcity manifests itself as water insecurity on a local, regional or global level. This risk is the result of human overexploitation and mismanagement of critical natural resources, climate change and/or a lack of adequate infrastructure [5].

From a system perspective, risk is inherent and is a function of the states of the system and its environment. Risk can be defined as a measure of the likelihood and severity of consequences, and the vulnerability to hazards and resilience vectors of a system are postulated to be a function of the input, occurrence, and states of that system, which have an impact on the consequences [6].

Urban water supply companies operate in a complex environment, including regulatory, economic (financial), social, environmental issues, and must manage a wide range of risks.

Therefore, water resource managers must manage, for example, environmental risks (floods, water pollution, water scarcity, etc.) and, at the

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same time, improve the quality of the environment, health, and well-being of the population [7].

Evidently, water resource systems are complex and the system dynamics approach has been used to address this complexity, driven by multiple interactions arising from climate change and social-economic stress factors [8]. This enables a holistic understanding of water resource systems [9].

Jay Forester created System Dynamics (SD) in the 1960s. In the 1970s, it was first applied to water resource management. The number of research articles applying SD to water resource management has increased substantially, specially since 2013, and this popularity demonstrates the growing interest of researchers around the world in using the SD modeling approach to manage complex water resource systems [8].

System dynamics-based models for water resources management are intended to evaluate policies or answer the "what if?" questions [2], aiding decision making. In addition, SD models enable the participation of stakeholders from the definition of the scope of the problem to the model validation process [8].

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 [10].

The system dynamics approach allows for the risk assessment, i.e. the impact of different elements (subsystems) on the safety of the system, as well as the achievement of dynamic and quantitative forecasts, thus compensating for the shortcomings of qualitative linear, static, and chain assessment methods [11].

The purpose of this article is to carry out a systematic review of literature, covering the state of the art in the period 2019-2024, works on the application of SD modeling to water resource management, specially works on urban drinking water supply, with an emphasis on models that address risks or risk management. Moreover, to verify whether stakeholders and/or specialists are involved in water resources modeling. Taking into consideration the most recent publications on the problem, the analysis was filtered in the period 2019-2024 as a filter to restrict the sample size. Furthermore, literature reviews with similar themes were identified in periods prior to this work, such as Phan et. al. (2021) [8].

The aim is to answer the following research question: Is it possible to propose a model structure based on the system dynamics approach for risk management in water supply companies?

Thus, this study includes the selection and systematic analysis of studies, characterizing them based on the definition of requirements. At last, the objective is to propose a modeling framework for dealing with risks and their management in the environment of water supply companies.

Materials and Methods

For the qualitative selection of articles, a systematic literature review was conducted, setting a clear purpose, research question, a defined research approach, and establishing inclusion and exclusion criteria for articles [12]. For the systematic review, the research problem was first defined, and then the search terms were chosen, i.e., the keywords, and combinations using the Boolean operators "AND" and "OR." Afterwards, the search period was defined.

The PRISMA 2020 flowchart methodology (Recommended Reporting Items for Systematic Reviews and Meta-Analyzes) [13] was therefore adopted, covering the identification, selection, and inclusion of articles. The journal articles were identified by searching the following databases:

- Portal de Periódicos Capes, on 10/16/2023, with the search terms Risk management AND System dynamics AND (water supply or water management); on 11/29/2023, with the terms risk management AND system dynamics AND (water supply or water management) AND stakeholder, the search was during the period 2019 to 2023;
- Web of Science on 2/01/2024, risk management AND system dynamics AND stakeholder AND

(water supply or water management), the search was during the period 2019 to 2023;

- Science Direct, on 12/10/2023, a random search on the website was conducted, using the search terms risk management AND system dynamics AND (water supply or water management), the search was during the period 2019 to 2023;
- Google Scholar on 05/31/2024, random search on the website using the search terms risk management AND system dynamics AND (water supply or water management), the search was during the period 2019 to 2023.

The filters used in the searches were: journal articles; published from 2019 onward; in English; and peer-reviewed. The search for articles based on keywords was complemented by a snowball sampling strategy, in which additional relevant articles were found in a reference list of articles already included in the sample. Duplicate papers and review articles were excluded.

In the selection stage, the titles, keywords, and abstracts of each of the identified articles were read and analyzed, resulting in an initial selection of scientific articles which were downloaded for reading. The following exclusion criteria were applied:

- Works which did not meet high-quality academic standards, with an impact factor exceeding criteria 1;
- Works which did not involve applications of a SD modeling approach with qualitative and/or quantitative steps; and Works which were not peer-reviewed by a journal.

The Semantic-Analysis Expert (My-SAE) software was used to analyze the most mentioned keywords, journals by year of publication, and the list of journals in which the articles were published.

Results and Discussion

A total of 552 articles were obtained, including relevant publications. Only articles in English, peer-reviewed, and searched in the following search engines: Periódicos Capes, accessed on 10/16/2023, resulting in 405 articles, and on 11/29/2023, resulting in 27 articles; Web of Science, accessed on 02/01/2024, with 101 articles obtained. This research was complemented by a search in Science Direct, with 18 articles manually selected, and Google Scholar, with the selection of 1 article. The flow chart (Figure 1) represents the article search process adopted and adapted according to the PRISMA 2020 guidelines.

Forty (40) relevant articles were included in the systematic review. There was an increase in the number of publications between 2019 and 2023, from 8 publications in 2019 to 9 in 2021; in 2022 there was a further drop; and in 2023, 11 articles were published (Figure 2). This demonstrates the scientific community's interest in this topic.

The 10 keywords or search terms most present in the articles investigated are shown in Figure 4: system dynamics (31.7%), climate change (12.2%) and water resources (9.8%). The terms "water management" and "participatory modeling" reached 7.3%, the same percentage as most of the keywords present in the articles, and the latter represents the presence of modeling which includes stakeholder participation.

Figure 1. Flowchart of the article search process, adapted according to the PRISMA 2020 guidelines

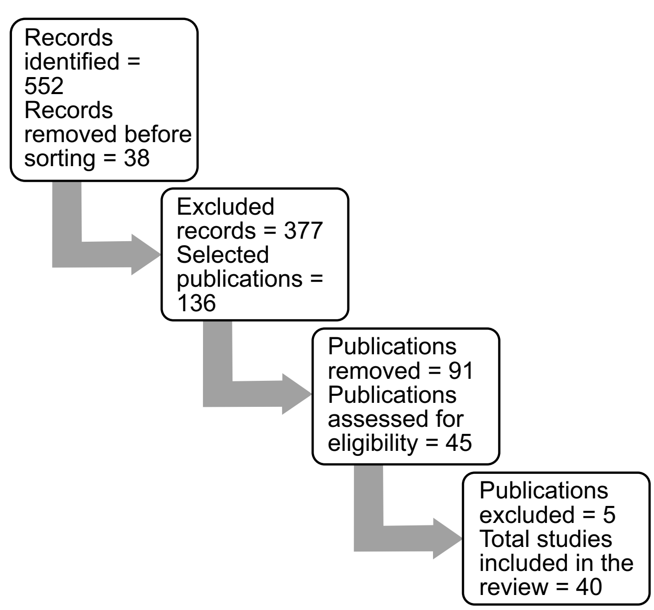
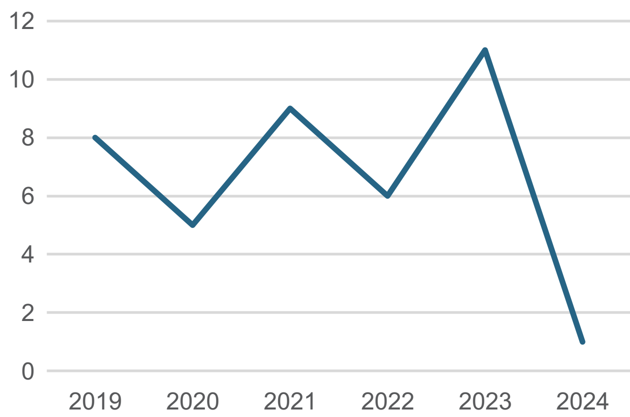


Figure 2. Number of articles per year of publication.



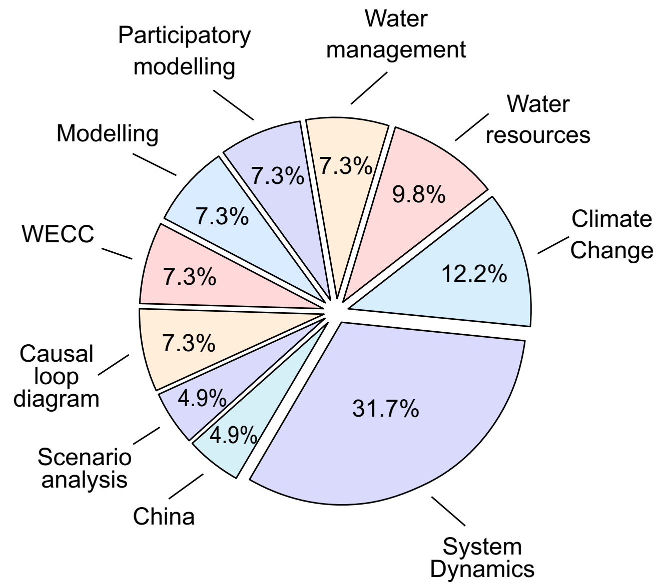
The term "causal loop diagram" also stands out, with 7.3%, revealing the use of qualitative modeling. The term "scenario analysis" appears in 4.9%, highlighting modeling which adopts scenario analysis, and "China" also in 4.9%, revealing that many models were developed for the reality of the Chinese country. The words "risk" and "risk management" do not appear among the most mentioned keywords, which may indicate a gap in the studies (Figure 3).

The analyzed studies in this article developed SD models in the field of water resources. As indicated in Table 1, 15% of the studies are purely qualitative and present the Causal Loop Diagrams (CLD); 40% develop quantitative analysis with the Stock and Flow Diagram (SFD); 45% of the studies developed qualitative and quantitative modeling, has developed CLDs and the SFD, defining the corresponding equations, which allows the tools of the system dynamics approach to be explored more widely.

SD models integrated with other modeling tools were identified in 47% of quantitative modeling, which may indicate a way to deal with the possible limitations found when using the SD model alone. Approximately 53% of the studies were carried out in Asian countries, particularly China.

The studies that analyzed modeling using subsystems represented 60% of the total, which may be associated with the complexity of the case studies. Scenario analysis was adopted in

Figure 3. Keywords.



around 85% of the quantitative studies. Around 91% adopted some method to test the models (validation, calibration, and or sensitivity analysis tests), revealing the importance of testing the model before performing the simulations, ensuring greater reliability in the results. The judgment of experts and stakeholders was also found in model testing.

The most used software in the studies was Vensim, even for calibrating, validating, and analyzing the sensitivity of the models. Approximately 68% of the quantitative modeling indicated the unit and time horizon of the simulations, with the majority of the time units used being the annual, and of these models, half were carried out over a long-term horizon of more than 30 years.

Few articles have dealt with water supply companies, and only one article has stated that it had one of these companies as a case study, which may indicate a gap given that organizations also represent systems which have exogenous and endogenous complexities at different levels.

The subjects covered in studies dealing with sanitation companies included water supply failures and emergency measures to address the problem; the Life Cycle Assessment (LCA); Water resource management policies; leaks in the distribution network or real losses and apparent

Table 1. Studies analyzed.

Causal Loop Diagrams – CLD (15%)	Stock and Flow Diagram – SFD (40%)
Mai and colleagues (2019) [14]; Tantoh; Mckay (2021) [15]; Bross; Krause (2021) [16]; Sundar; Narayan; Scholten (2022) [17]; Ntajal and colleagues (2022) [18]; Asif and colleagues (2023) [19].	Hassanzadeh and colleagues (2019) [20]; Tsai and colleagues (2019) [21]; Pagano and colleagues (2019) [22]; Rubio-Martin and colleagues (2020) [9]; Giordano and colleagues (2021) [23]; Youzhi; Alexander; Ping (2021) [24]; Ignjatović and colleagues (2021) [25]; Hu and colleagues (2021) [26]; Lindqvist and colleagues (2022) [27]; Wang and colleagues (2022) [11]; Yuan and colleagues (2022) [28]; Dai and colleagues (2022) [29]; Shiu and colleagues (2023) [30]; Cotera et al. (2023) [31]; Tang and colleagues (2023) [32]; Wang; Fu (2023) [33].
CLD AND SFD (45%)	
Ahmadi; Zarghami (2019) [34]; Barati; Azadi; Scheffran (2019) [35]; Malisa; Schwella; Batinge (2019) [36]; Correia; Oliveira; Sahin (2019) [37]; Babamiri and colleagues (2020) [38]; Xu; Yao: Chen (2020) [39]; Gallagher and colleagues (2020) [40]; Elsayed and colleagues (2020) [41]; Pluchinotta and colleagues (2021) [7]; Shen and colleagues (2021) [42]; Mazzoleni and colleagues (2021) [43]; Urban; Nakada; De Lima (2023) [44]; Zuluaga-Guerra and colleagues (2023) [45]; Wang; Dong; Sušnik (2023) [46]; Barati; Pour; Sardooei (2023) [47]; Shahsavari-Pour and colleagues (2023) [48]; Zhou and colleagues (2023) [49]; Kotir and colleagues (2024) [50].	

losses; operating costs and revenues; water production, distribution, and treatment activities.

We found that 30% of the analyzed studies understand the importance of involving stakeholders and experts in SD models, either directly or indirectly. Some of the authors use the term "participatory modeling" and emphasize the benefits of this type of method, as well as the challenges and difficulties faced. Among the benefits are the possibility of integrating stakeholder knowledge into the modeling process, greater understanding, and engagement of strategic stakeholders with the modeling results for decision making.

The techniques used to extract knowledge from stakeholders involved workshops, surveys, semi-structured interviews, and focus groups. The use of social network analysis and the identification of new agents using the snowball technique were mentioned in the papers.

Studies dealing with risks in modeling accounted for 20% of the total and had as their scope of analysis the operation of dams, reservoir systems, annual and monthly changes in water supply at the basin scale, water transfer projects and Water Environment Carrying Capacity (WECC). Only 3 studies explicitly used risks as variables in CLDs and SFD models, which may represent a gap.

Overall, the risks arising from climate change and socio-economic development were analyzed in particular. These risks, alone or together, can affect the supply of water from river basins, underground springs and, in turn, affect urban and rural water supply, with consequences for the service provided by water supply companies.

However, no studies were identified in the selected sample that developed models to deal with these and other risks at the organizational level. In some studies, risks that could affect sanitation companies were mentioned, such as operational and maintenance risks, i.e., those associated with infrastructure resilience.

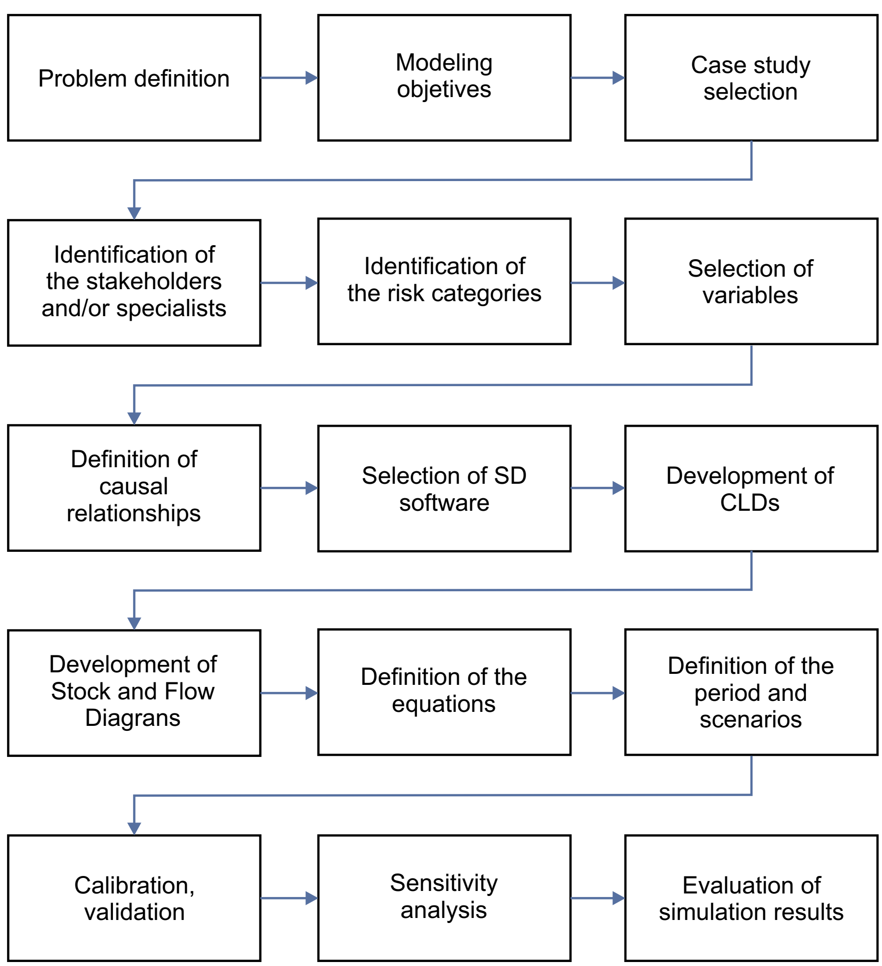
Companies which provide water supply services carry out water catchment, treatment, and distribution activities to guarantee a supply of drinking water that meets the demands of the population, economic sectors, and the public sector. As such, their actions involve the operation of infrastructure such as dams, water treatment plants, water distribution networks, reservoirs, and others, as well as commercial activities in direct contact with end users. They must meet the targets of SDG 6, as well as the applicable legislation.

The environment in which these companies operate includes external challenges such as climate change, water pollution, poor land use and planning, which can affect surface and underground water sources; changes in the legal and regulatory environment, and others. And internal challenges such as operational issues, such as deteriorated infrastructure, which increases leaks in distribution networks; financial and economic issues such as setting tariffs, that cover operational and administrative costs and do not harm consumers; deciding on new investments in infrastructure or new technologies; optimizing the water balance, among others.

This indicates that they operate in complex environments marked by uncertainties, making it necessary to carry out an adequate risk management process with the view of achieving organizational objectives within the scope of their governance actions.

As such, SD represents a promising approach to dealing with these issues. Based on the results obtained in this work, a framework was proposed to develop a SD model for risk management in water supply companies, whether or not they already adopt risk management. The framework is detailed in Figure 4.

Figure 4. Framework for developing SD modeling for risk management in water utilities.



Some of the limitations of the scope of this work include the time available for research, the number of researchers involved, and the number of databases of articles accessed. The use of the search terms and Booleans chosen may also have restricted the selection of other articles.

For future research, we suggest expanding the search database and using other search terms, as well as selecting articles in other languages.

Conclusion

From the results of this work, it can be concluded that water resource management presents major challenges and complexities that cover different levels, including environmental, climate, economic, social, and hydrological factors.

Thus, studies in this area cover issues associated with freshwater sources, whether from rivers, river basins, or underground springs, such as the impoundment of the water in dams and reservoirs and its management, water imports, and issues that cross borders between countries and regions. They also involve the challenges faced in the operation of sustainable urban water systems, which cover the water catchment, treatment, and distribution processes to guarantee universal access to drinking water for the various users, as well as defining the price of the use of the resource.

In the management of water resources, the studies indicate actions on the demand side, such as raising awareness of the rational use of water and the use of tariffs to restrict the increase in consumption, and on the supply side, actions such as the possibility of exploring alternative sources of water to meet the growing demand, including the use of wastewater treatment technologies, rainwater harvesting, desalination, and others.

The challenges posed by climate change, especially socioeconomic and other factors, make the management of water resources even more complex. For companies operating water supply systems, the challenges are many, and they operate in environments marked by uncertainty and complexity. This requires an appropriate risk management process.

To address this complexity, the common point in the selected studies was the use of the system dynamics approach in the management of water resources, alone or in conjunction with other approaches. There was a tendency to develop participatory modeling with the participation of stakeholders and experts.

In the sample of analyzed articles, few studies dealt with risks or risk management in the context of water resources based on system dynamics. The identified articles focused on the operation of dams and reservoir systems, annual and monthly changes in water supply at the basin scale, water transfer projects, WECC, and none assessed risks at the organizational level in companies operating water supply systems. This may reveal a gap. To this end, this paper presents a proposal for a model based on system dynamics to address risk management from the perspective of water supply companies.

The scope of this study was limited, which may have excluded relevant studies in the analyzed period from the analysis. As a proposal for future work, we suggest extending the analysis period and the search bases and reviewing the filters used.

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