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Identifying policy options and responses to water management issues through System Dynamics and fsQCA

Stefano Armenia [a], Federico Barnabé [b], Eduardo Franco [c], Francesca Iandolo [d,*], Alessandro Pompei [d], Georgios Tsaples [e]

[a] Università Telematica degli Studi IUL
[b] University of Siena, Siena, Italy
[c] University of São Paulo, São Paulo, Brazil
[d] Sapienza University of Rome, Rome, Italy
[e] University of Macedonia, Thessaloniki, Greece

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ABSTRACT

Poor quality and scarcity of water are some of the most relevant problems for policy-makers and private sector, especially in the face of climate change. A systemic perspective is key to studying complex issues like water management and understanding how systems change in response to various inputs over time. This study aims to create a generalized, highly synthetic, and abstract model that can reproduce the key dynamics that emerge from the response to policies in water management. The characteristics of this model make it applicable independent of a specific local context. A literature review of modelling and simulation, System Dynamics (SD), and fuzzy set qualitative comparative analysis (fsQCA) approaches to water management was performed, and insights were gained to recognize and understand existing gaps. The results were then assessed using fsQCA to investigate the necessary and sufficient conditions that contribute to shaping sustainable water management. A minimum common structure which highlights the common elements and their key interactions in a generic water management system was proposed. Main findings showed that the most negatively influencing dimensions of water management issues were the absence of costs related to water consumption, infrastructure obsolescence, and population growth. Implications for policy-making on sustainable water management were discussed in the conclusion.

1. Introduction

One of the most underestimated consequences of climate change and population growth is (and probably will be) insufficient water resources. Consequent to years of unsustainable policies and overexploitation, more than half of the world's population (57 %) will face severe water shortages (Boretti and Rosa, 2019; European Environmental Agency, 2008) The urgency of the situation can also be seen in the sustainable development goals (SDGs) of the United Nations (UN), in which the water management issue spans several SDGs, such as No.6 (clean water and sanitization), No. 11 (sustainable cities and communities), No. 12 (responsible consumption and production), No.13 (climate action), and No.15 (life on land).

The effects of water scarcity highlight the importance of water. It is estimated that 785 million people lack basic water services.[1] This means that any attempt to achieve sustainable development will have to incorporate sustainable water management, proving its criticality over the next decade.

This indicates an urgent need to improve the quality and quantity of water available without resorting to costly solutions or increasing the pressure on the natural environment. The current scenario in which surface and underground water consumption significantly exceeds the natural recharge and restoration capacity makes it increasingly evident that the disruption of the hydrological cycle and depletion of natural water supplies deplete much faster than expected if they have not been adequately addressed for a long time (Cook and Bakker, 2012; Dinar and Mody, 2004; Gleick and Palaniappan, 2010; Manzano-Solís et al., 2019; Pahl-Wostl et al., 2007; Popovici et al., 2021; Vaux, 2011).

* Corresponding author.
E-mail address: francesca.iandolo@uniroma1.it (F. Iandolo).

[1] https://sustainabledevelopment.un.org/sdg6 (accessed on 30th of January 2021).

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The phenomena aforementioned can lead to full-blown political crises, as was recently the case in São Paulo, Brazil, where a water shortage crisis and miscalculated governmental intervention led to social reactions, often bursting into demonstrations (dos Santos et al., 2019), indicating how the severity of the problem can quickly escalate to a chaotic situation.

The situation can worsen if issues such as the pressure on water resources owing to rise in energy demand (Guerra and Reklaitis, 2018), agriculture, industry, and pollution are considered. As a result, it has become increasingly clear that water management requires a conceptual shift to be relevant to and effective in a world characterized by complexity and uncertainty.

Model-based governance can be an effective solution for such changes (Mureddu et al., 2014). Its fundamental core can bridge management issues with operations research approaches such that complex, unstructured, and dynamic problems, often linked to social aspects such as water management, can be tackled through modelling and simulation, which have inherent mathematical foundations.

Nonetheless, many modelling techniques can lead to discussions regarding which one is the most appropriate for use under different circumstances. These techniques span from mathematical, and hydrological models (Tzabiras et al., 2016) to the use of indicators, either to assess water systems as part of the biosphere (Grizzetti et al., 2016) or specific vulnerabilities (Martin-Carrasco et al., 2013), and include the use of classic decision aid (Chitsaz and Azarnivand, 2017; Srdjevic et al., 2012; Tsakiris and Spiliotis, 2011) and optimization methods (Wu et al., 2015; Zhang et al., 2016).

Recent trends in the research on water management include the use of data-driven methodologies (Eggimann et al., 2017; Safavi et al., 2015), holistic decision support systems (Esgalhado et al., 2020; Pedro-Monzonís et al., 2016; Poff et al., 2016) and lately the use of serious gaming as a learning tool (Savic et al., 2016; Van der Wal et al., 2016).

An important methodology increasingly used in the water management field is agent-based modelling (ABM), which uses computational rules, agents, and interactions to explain complex phenomena (Tsaples and Fancello, 2018). However, agent-based models are data-intensive, limiting their scope when data availability is limited. This can influence the accuracy of the model, meaning that to reflect the dynamics of the real-world situation accurately, an ample parameter space needs to be considered, accompanied by extensive use of data techniques to find the "correct" representation of reality (Ayala-Cabrera et al., 2014).

Consequently, attempts have been made to overcome the limitations of a raw multiagent-based approach by merging it with optimization algorithms, for example, using optimal allocation algorithms obtained from computer sciences (Hadipour et al., 2020) or merging with fuzzy cognitive maps, as found in (Mehryar et al., 2019).

Despite the immense value of all the research in the field of water management (Cosgrove and Loucks, 2015; Sabie et al., 2022; Sivagurunathan et al., 2022), previous works show that the technique used should have some essential characteristics: ease of use and communication to non-experts; adequate representativeness of the problem's complexity (specifically that of water management); incorporation of multiple stakeholders' perspectives; enhancing what-if and scenario analysis; and allowing policymakers to quickly set up a consequence-free environment and thus experiment with potential policies before applying them in real life.

Among the various existing modelling and simulation approaches, system dynamics (SD -(Forrester, 1961) is particularly suitable for the analysis of complexity, as it allows an understanding of the structure and dynamics of complex systems based on rigorous modelling to build formal computer simulations aimed at designing more effective policies and organizations (Sterman, 2000).

Two elements define a system's complexity and behavior over time: feedback loops and delays. Bounded rationality makes understanding these elements difficult, often leading decision makers to make suboptimal choices.

As clarified by Ford (2019, p. 373), a feedback loop is identified "when the effect of a causal impact comes back to influence the original cause of that effect. [Therefore] a feedback loop is a sequence of variables and causal links that creates a closed ring of causal influences". Additionally, a delay is defined as "a phenomenon in which the effect of one variable on another does not occur immediately" (Ford, 2019, p. 372). The synergy between the two aforementioned elements can generate highly nonlinear behavioral patterns in a system that our intuition often cannot anticipate. Systems Thinking (ST) and System Dynamics (SD) can thus help decision makers achieve a better understanding of a system's complexity through the analysis of its variables' interdependencies, thereby developing an early awareness of the likely behavior of the system.

Accordingly, the aim of this study is threefold. First, through bibliographic analysis, we define the theoretical landscape surrounding simulation, SD, and fuzzy set Qualitative Comparative Analysis (fsQCA) approaches to water management to analyze the main trends and gaps. It is necessary to browse and study the scientific literature on water management to clearly place this work within a specific debate. Moreover, bibliographic research has made it possible to clarify the importance of the increasingly studied topic and to identify and describe the scientific strand of the works that would then be considered for the next steps.

Second, we decide to use two different methodologies, SD and fsQCA, for comparison purposes and with the aim to define synergies among the two, by mutual complementation. Through SD, we identify a minimum common structure that can describe the fundamental dynamics of water management issues, thanks to the ability of the SD approach to describe a complex problem with synthetic language that remains rich in meaning. A minimum common structure of the key feedback loops and intrinsic delays that typically shape water management is critical for experimenting with and assessing the responses to policies. Responses may differ widely, depending on the different types of applied policies, different types of local cultures, technologies, and community dynamics. Therefore, identifying the core skeleton of water management dynamics, which is generally always present in any context, can be a useful exercise in which policies under exploration can be leveraged and ultimately designed.

Finally, through fsQCA, we identify the necessary and sufficient conditions that shape and describe the fundamental dynamics of water management issues.

The conceptual model proposed in this study aims to represent the basic structure that determines the essential dynamics affecting various systems responses to water management policies. Said structure is intended to be synthetic, abstract, and generalizable, since it is not context-specific and, at the same time, can be adapted and applied to different contexts and situations without losing its fundamental insights or relevance. Therefore, we aim to identify the key characteristics and relationships that shape the outcomes of various water-related interventions.

By highlighting the key factors that emerge from the analysis and constitute the proposed minimum common structure, the model can, on one hand, help policymakers and practitioners to explore and design more effective and adaptable strategies to address water-related problems; on the other hand, the model could serve as a useful tool to compare and evaluate different approaches to water management in different regions, as well as to predict and anticipate the potential impacts of future changes, such as climate variability, demographic shifts or technological innovations. By providing a systematic and integrative framework for understanding water management dynamics, this model could contribute to more informed and evidence-based decision-making, as well as more inclusive and participatory water governance.

Our main findings show that the most negatively influencing dimensions of water management issues are the absence of costs related to water consumption, infrastructure obsolescence, and population growth.

In this sense, key policy implications suggest that the conservation, proper maintenance, and management of infrastructure could be some of the most effective ways to ensure that water resources remain available to the population, especially in the face of current climate change and unstable weather conditions. Another implication of the findings is that a combination of personal responsibility and state intervention could prove to be a sound policy regardless of environmental uncertainties. Added to these are theoretical implications that fill gaps in the application of systems thinking, modelling, and fsQCA methodologies to water management issues.

The article is structured in the following manner. Section 2 sets forth the theoretical background of our study focusing on the literature review. Section 3 describes the methods, research design, and case selection. Section 4 presents the findings and results of the study. Section 5 puts forward the discussion and implications, and Section 6 submits the conclusions, the limitations, and ideas for further research.

2. Theoretical background

Although there is a considerable research *corpus* on water management, key differences can be found in their overarching models, frameworks, and scopes. To depict the current developmental stage of research in the field, an exploratory literature review was conducted. For this purpose, searches were conducted to reveal how diverse, vast, and multifaceted topics are, although sustainable and integrated. This section contains the results of this exploratory review, showing how it developed over time, and relevant studies on general approaches, system dynamics, and fsQCA for water management.

2.1. Methodology for literature review

The main scientific databases of peer-reviewed literature (Scopus and Web of Science) were searched using a combination of keywords and their derivatives consistent with the aim of the study. These databases were selected because they provide an interface for simultaneously searching across different sources using a common set of search fields to obtain comprehensive results. They cover studies from ACM, EBSCOhost, Elsevier, Emerald, IEEE, INFORMS, MDPI, ProQuest, SAGE, Springer, Taylor and Francis, and Wiley, among many other publishers (Franco et al., 2018). Besides, the "Web of Science" database is also the source for computing the "Journal Citation Report" index (journal impact factor), one of the most used mechanisms for evaluating journals based on citation data.

The keyword combinations used for designing the search string included: "urban," "water resource," "water management," "modelling," "qualitative comparative analysis," "fsQCA," and "simulation." Keywords and derivatives were linked with Boolean operators (i.e., AND/OR), and the resulting search string is shown in Table 1, along with the query results. No limits were imposed within the annual range. Studies that included identified keywords and derivatives in their titles, abstracts, or keywords were selected.

An additional criterion was to consider only documents published in English in peer-reviewed journals. Finally, references were searched for papers that may have been excluded from the databases. The same search string and refinement criteria were used to retrieve publication datasets from both Web of Science and Scopus, which were then merged into a single final result dataset.

Table 1
Search string used for collecting the publication sample and results obtained (asterisk (*) represents any group of characters, including no character).

Search string	Database	Fields	Number of results
("urban" AND ("water resource* management" OR "water management")) AND ("qualitative comparative analysis" OR "fsQCA" OR "simulation")	Web of Science	All fields	859
	Scopus	Article title, Abstract, and Keywords	1037

The workflow of the activities described for collecting publication samples is graphically depicted in Fig. 1.

The final resulting dataset contained 1550 articles published in 358 journals during 1967–2022.

2.2. Synthesis of bibliometric results from the literature review

Although we do not claim that the analyzed literature is exhaustive, several important aspects emerged during the bibliometric analysis. All the analyses shown in the following sections were carried out with the open-source R package "bibliometrix" (Aria and Cuccurullo, 2017).

Fig. 2 depicts the evolution of the published studies over time. The number of yearly publications retrieved by combining keywords related to the topic of the present study has increased consistently, indicating increasing interest from the academic community in the subject. There has been a sharp rise in the number of publications since 2000, which could represent an increasing interest in the research community associated with the growing pressure of water availability and the water management crisis.

Researchers have primarily focused on the effects of water management in the agricultural sector, urban environments, and their intersection. In addition, the areas of application in water management refer to countries, geographical areas, and cities; however, most studies are related to China's water management issues (illustrated in Fig. 3).

Fig. 4 illustrates how the interest in published research has changed over time. The colors represent the years, and each geometric form represents a specific topic, where its area is proportional to the number of publications within a particular timeframe. It is possible to note that various modelling approaches and participatory tools have been increasingly adopted since the start and throughout the analyzed period; in particular, it is evident that socio-hydrological modelling has been increasingly used over the years, while predictive models have been

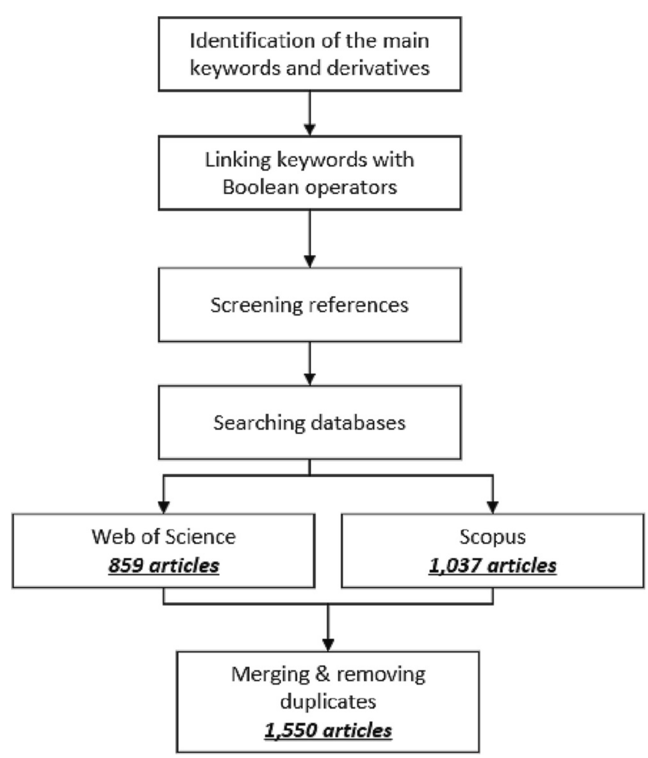

Fig. 1. Literature review rationale.
Source: Authors' elaboration.

Fig. 2. Number of published studies per year.
Source: Authors' elaboration.

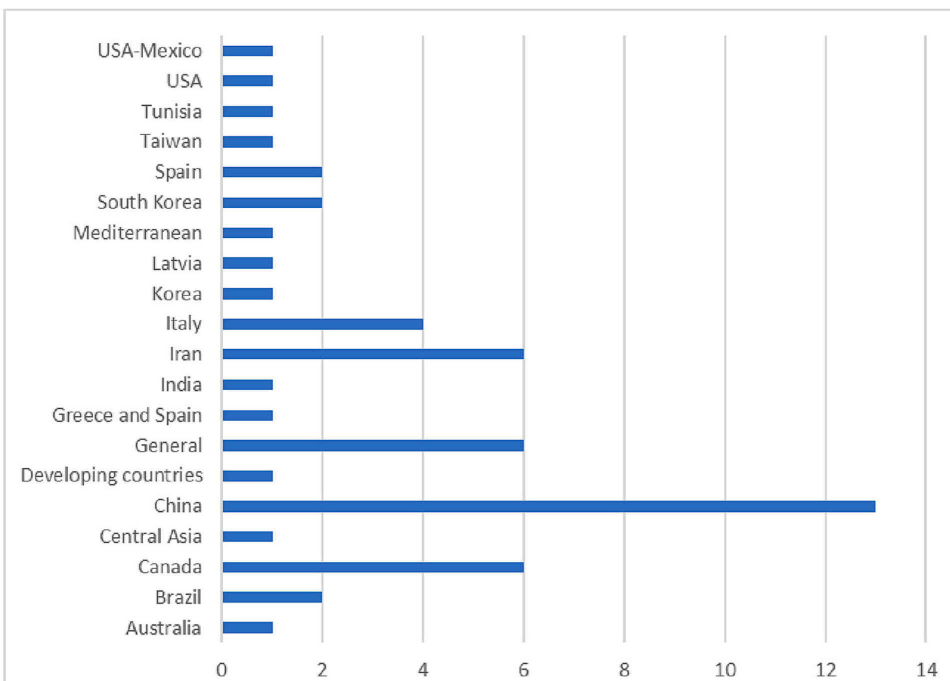

Fig. 3. Frequency of appearance of Countries.
Source: Authors' elaboration.

used less. This highlights the fact that researchers recognize the importance of uncertainty and complexity in characterizing the dynamics of water management, thus favoring approaches such as SD rather than previous predictive approaches, which could appear misguiding and/or wrong.

The following subsections describe the findings obtained from the final search results through comments on the selected papers, and a bibliometric analysis of the retrieved final publication dataset.

2.3. General simulation approaches to water management

The use of analytical and quantitative methods to create complex water resource management models has rapidly expanded in recent years owing to advances in both optimization techniques and computational resources. However, water management remains a challenging field because of problems such as the complexity of modelling, which involves natural processes (complicated by continuous climate change impacts and problems that generally arise in highly complex decision-making contexts). In addition, an appropriate approach to water management requires the maximization of a system's efficiency, which is

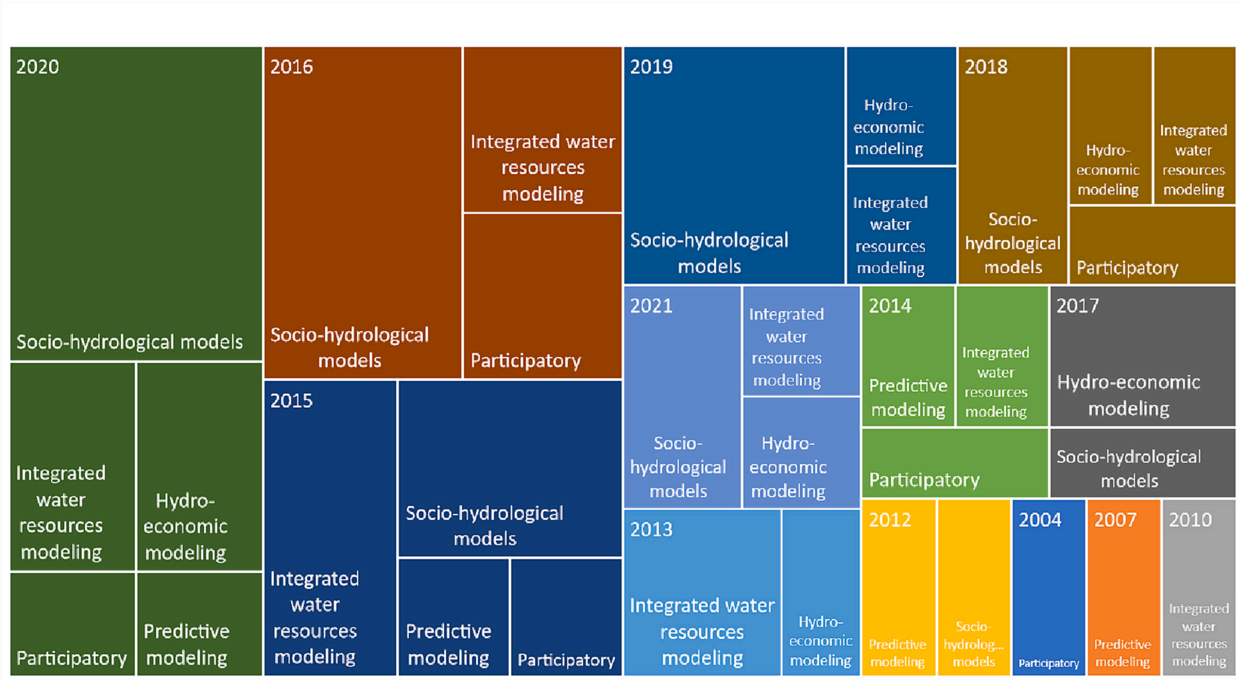

Fig. 4. Topics of interest by year.
Source: Authors' elaboration.

constrained by the availability of resources and cooperative coordination of all involved actors. This is an unreachable target in the real world, in which management sees every single decision maker pursuing their objective(s) with no global view of others' needs, driving the entire system to low efficiency (Madani and Lund, 2012), with no feasible improvement without a common strategy among the players.

Even though a "unification" theory is yet to come, a great effort is being focused on the modelling level for every single cluster of interest. For example, urban water management is often considered independent of river basin issues, although the two fields can be connected (Díaz et al., 2016). This can be attributed to the increasing complexity of the urban environment (Fletcher et al., 2013) and the inherent differences between the water cycles of river basins and urban water resource systems. As a result, building complex water networks have traditionally relied on separating the two (Díaz et al., 2016). Recently, some efforts have moved towards a systemic perspective, joining river basins and urban water management systems (Loubet et al., 2014; Winz et al., 2009); achieving coherence between the two is not easy, but the literature has started moving in that direction (Van den Brandeler et al., 2019). Moreover, various efforts have been made to bridge the gap between different water resource management needs, and between physical and computational modelling and practical applications (Borowski and Hare, 2007).

2.4. System dynamics approach to water management

Based on these considerations, system dynamics has found fertile ground for application in the water management field. A recent comprehensive review of the literature by Zomorodian et al. (2018) identified that many traditional modelling techniques rely on linear and open-loop causal relationships. Consequently, they do not provide an appropriate framework for addressing the complexity of water management problems. The present study aims to complement this perspective by providing additional evidence and insights.

First, SD was used to address specific issues related to water management in agriculture (Muñoz-Rojas et al., 2019; Pluchinotta et al., 2018; Robert et al., 2018; Thakur et al., 2018). Zomorodian et al. (2018) identified five pillars under which SD models can be used for water management.

1) *Predictive Tools*

Langsdale et al. (2007) used a predictive model to assess the behavior of water supply and demand under different climate change scenarios. Ryu et al. (2012) developed a model for planning the use of available resources. Park et al. (2014) predicted the water quality of wastewater plants under various operational scenarios. Zhu et al. (2015) analyzed the influence of water on vegetation growth. Finally, Wang et al. (2020) used SD with Monte Carlo simulations to test the uncertainty in the water capacity of Fushun City.

2) *Hydro-economic modelling*

Bekchanov and Lamers (2016) and Mokhtar and Aram (2017) examined the environmental costs of groundwater exploitation in the agricultural sector. Dai et al. (2013) and Barati et al. (2019) investigated the economic effects of groundwater management. Feng et al. (2017) studied the agricultural water footprint of the Heihe River Basin in China. Jiang et al. (2020) studied the impacts of reservoir operation, whereas Liao et al. (2020) and Abebe et al. (2021) studied the policies and economic elements concerning regional water management.

3) *Tools for integrated water resources modelling*

Regarding SD models as tools for integrated water assessment, Guest et al. (2010) developed a qualitative model to evaluate different wastewater management options. Mai et al. (2019) developed a conceptual model of a generalized water trade system in the Murray–Darling Basin. Akhtar et al. (2013) and Wu et al. (2013) have investigated the effects of climate change on water resources. Gohari et al. (2014) evaluated different policies and suggested feasible scenarios to avoid future water scarcity and conflicts. Xiong et al. (2015) developed a Decision Support System based on SD models to develop water-supply plans for various subsystems. Walters and Javernick-Will

(2015) used a qualitative approach to understand the dynamic interactions between the most important factors affecting rural water services. Mereu et al. (2016) employed an SD representation of a multi-reservoir system to assess the water management among various demand sources. Duran-Encalada et al. (2017) investigated the effects of climate change on the quality and quantity of water in the US-Mexico transborder area, while Apostolaki et al. (2019) used SD under different scenarios to evaluate how future conditions could affect the sustainability of water resources in Greece and Spain. Keyhanpour et al. (2021) used SD to model sustainable water resource management in Iran, whereas Bakhshianlamouki et al. (2020) attempted to quantify the impact of restoration policies on the Urmia Lake Basin in Iran. Sušnik et al. (2021) explored the impacts of policies on the water-energy-found-land-climate nexus in Latvia.

4) *Tools for participatory processes*

System dynamics can be used to engage different stakeholders (and their perceptions) in building a common framework of analysis and a shared understanding of the problems at stake (and their dynamics over time). Tidwell et al. (2004) applied this principle to develop an interface that could help the general public engage in and understand the decision-making process of water management. Chen and Wei (2014) conducted group model-building sessions on wetland management policies. Wang and Davies (2015) used a serious game model with different demand sectors, which allowed players to evaluate and apply policies in a consequence-free environment. Similarly, Kotir et al. (2016) employed this model as a learning tool for policymakers. Halbe et al. (2018) attempted to institutionalize participatory modelling to develop legal frameworks in Canada. Similarly, Stave (2010) used participatory SD modelling to support stakeholders' learning about the Las Vegas water supply system and build social capital. Finally, González-Rosell et al. (2020) integrated the views of different stakeholders in an SD model to assess the water-energy-food nexus in Andalusia.

5) *Socio-hydrological models*

The top-down representation of a system allows the incorporation of seemingly different subsystems into the same model, resulting in the emergence of socio-hydrological models. Sušnik et al. (2012) assessed water scarcity scenarios by considering human and societal behavioral elements. Sivapalan and Blöschl (2015), and Liu et al. (2015) investigated the parallel evolution of hydrological systems and social processes. Sahin et al. (2015) focused on the finances and economics of water management, and how tariff structures could affect demand levels. Di Baldassarre et al. (2016) employed system dynamics to show how incorrect assumptions in the decision-making process can affect the effectiveness of policies in water management systems. Garcia et al. (2016) investigated how these assumptions and human behavior, in general, affect reservoir management. Wei et al. (2016), Sun et al. (2017), Armenia et al. (2021), and dos Santos et al. (2019) focused on urban environments. Rubio-Martin et al. (2020) studied the impacts of drought on the Jucar River System in Spain, and Jeong and Park (2020) evaluated water management in three Korean regions.

Finally, another important issue that is gaining traction in scientific literature is the security and conflict around water resources (Enteshari and Safavi, 2021; Shao et al., 2020; Yuan et al., 2020, 2021).

Despite the use of system dynamics in several previously published studies on water management, several gaps have been identified in the literature. These include the following.

- The explicit modelling of water management in large, European urban centres is missing.
- In Europe, the focus has been on the Mediterranean region. Central and Northern European applications were almost entirely missing.
- Not much research focused on explicitly modelling aging infrastructure and urban water management.
- Not much research focused on the transportation of water from other areas.
- Lack of models related to the effects and impacts of the water industry on public water management (Papathanasiou et al., 2019).
- Increasing the diversity of the models and including more sectors in the model would be helpful.
- There is a lack of research on combining or hybridizing different analysis (in particular including simulation) paradigms and approaches.

Nonetheless, there is clear evidence that system dynamics and water management complement each other, particularly when sociological aspects are included in the system under study.

2.5. *fsQCA approach to water management*

From the resulting dataset obtained from the two databases (Web of Science and Scopus), only eight of the retrieved publications used fsQCA for topics related to water management and water resources, some of which are discussed below.

This is described in detail in Section 3.4. fsQCA is a comparative configurational methodology based on both set theory and fuzzy logic. By simultaneously adopting qualitative and quantitative approaches, this analysis returns the degree of difference and belongingness of a given configuration (Ragin, 2008, 2009), both by determining which factors are minimally necessary and/or sufficient to achieve the analyzed outcome and by identifying which groups of cases share a particular combination of conditions (Meyer et al., 1993).

Regarding the results of the literature review, Knieper and Pahl-Wostl (2016) applied fsQCA to evaluate data on water management and environmental and socioeconomic indexes. The authors showed that polycentric governance with high per capita income and low levels of corruption is sufficient for good water management practices. However, good water management practices are not sufficient for a good environmental status in river basins; thus, it is necessary to lower human pressure on water usage to achieve sustainable conditions.

Hamidov et al. (2015) identified the necessary and sufficient conditions for successfully managing common pool water resources and irrigation canal maintenance in the rural region of Uzbekistan. The fsQCA showed that to achieve a well-maintained irrigation canal, it is necessary to have sustainable resource appropriation or effective participatory governance.

Jiang et al. (2018) used a fuzzy set qualitative comparative analysis to identify the drivers of high and low percentages of wastewater reuse in water-stressed Chinese provinces. They found that a high percentage of wastewater reuse was driven primarily by water stress and access to urban green spaces. However, they argued that the results obtained may be context dependent and may not be generalizable.

Llopis-Albert et al. (2018) employed fsQCA to analyze the level of stakeholder satisfaction in the public participation process of water resource management in Europe. The results showed that there may be several different causal paths to explain stakeholder satisfaction, including the environmental objectives pursued, the actual capacity to efficiently carry out those objectives, the socioeconomic development of the region, and the level of stakeholder involvement.

Olaerts et al. (2019) analyzed combinations of conditions that influence regular payments for water services in resource-limited communities in Uganda. This study used the fsQCA to determine the combinations of conditions that led to water payment compliance.

Subsequently, by combining the fsQCA and system dynamics acronyms and terms while searching for publications within the two databases (WoS and Scopus), no results matched this search criterion, which indicates that there is a lack of previous studies that explored the combination of the two approaches in the field of water resources and water management.

3. Methods

3.1. Research design/approach (introducing case studies, SD and fsQCA)

To achieve the objectives of the current study, a hybrid approach was followed. First, case studies of system dynamics in water management were chosen based on specific criteria (described in Section 3.2). Second, from these case studies, a minimum common structure was derived that contained the most common and essential stocks, flows, and variables that helped to represent a basic (minimum common) system for water management. Finally, the results from the first two steps of the approach are used (starting from the minimum common model) with fsQCA to investigate the key variables in the context of an urban and peri-urban water management crisis.

3.2. Multiple case studies analysis and case studies selection criteria

This work was based on the analysis and comparison of multiple case studies that attempted to address the same topic (i.e., water crisis management) using a systemic approach to identify and extract commonalities and similar main variables to be included in a common minimal model (Stake, 2013).

The choice of such an approach lies in the effectiveness of a typical multi-case study analysis for the investigation and identification of key factors that have some relevance (in this case, systemic influence) to an outcome of interest in similar contexts (Stewart, 2012). In fact, in such analysis, several different instances of a particular problem (or phenomenon) are brought together for a comparison of their main variables and, with the use of substantive grounded theorizing, it is possible to construct a “rudimentary parsimonious conceptualization” (Guo and Zheng, 2019, p. 39) of the phenomenon.

Following this process, the subsequent use of an analytical method, such as fsQCA, allows the investigation and conceptualization of the main drivers of water crises and the relative points with a greater leverage effect to be considered for effective water management approaches.

The first step in the proposed approach involves the selection of system dynamics case studies that explicitly deal with water management issues. Case studies were selected based on the following criteria.

(1) The selected case studies should contain basic water management structures that are common in almost all modelling approaches (water supply, water demand, storage/reservoir, etc.).
(2) The case studies should represent the system under study using different granular approaches. Thus, it should begin with a generic top-down approach and continue with more detailed models.
(3) At least one case study should contain the social dimension of water management.
(4) The case study selected should allow experimentation with a what-if analysis.
(5) Finally, the last criterion should be the actual availability of the simulation model so that it would be possible to become familiar with the intimate details of the case study model.

Based on the above criteria, the following case studies were chosen:

- the case of Lake Bracciano (Armenia et al., 2021) covers Criteria (1), (4), and (5);
- the water crisis in São Paolo, Brazil (dos Santos et al., 2019) covers criteria (1), (3), (4), and (5);
- the SUSTAIN model includes criteria (1), (4), and (5) (Papathanasiou et al., 2019).

Finally, all case studies met criterion (2). The background and details of the case studies are presented in Section 4.1.

3.3. Structural and causal approach through system dynamics

Following an analysis of the scientific literature, which demonstrates how system dynamics modelling and simulation is a relevant method for addressing the complexity underlying water management issues, we briefly describe the main characteristics of such an approach.

Initially developed in the 1950s (Forrester, 1961), SD is currently used in public and private sectors for policy analysis and design (Forrester, 1971, 1997; Mureddu et al., 2014; Richardson, 1991). In particular, we consider the system dynamics methodology (Sterman, 2000) as the quantitative declination of the systems thinking (ST) approach (Senge, 1990), which is particularly suitable for the identification of systemic relationships among the parts of two or more phenomena.

There are two elements of system behavior, the effects of which our bounded rationality generally does not allow us to grasp, leading decision-makers to make suboptimal choices: feedback loops and delays. By working together, feedback loops and delays can generate highly nonlinear behavioral patterns, which our intuition often cannot anticipate. Systems thinking and system dynamics can help us develop a better understanding of the abovementioned relationships through the analysis of their system interdependencies as well as develop an early awareness of the likely behavior of these phenomena. In addition, the systems thinking & system dynamics approach is endowed with the inherent capability to easily explain complex phenomena (Meadows, 2008). Through a technique known as Causal Loop Diagramming (CLD) (Sterman, 2000) – an easy and straightforward ST concept-mapping approach used to represent causal interdependencies – we can concentrate on the essential processes and dynamics and infer, even qualitatively, the behavior of the system. The ease of use and understanding of these maps (i.e., the causal loop diagrams) are especially useful for policymakers (Diehl and Sterman, 1995).

CLDs’ design relies on participatory modelling sessions (Vennix, 1999): they are (mind-) maps that combine various oriented links (represented as “arrows”) that causally tie together the various relevant aspects (the model variables) of a system. There are two types of causal links: a “positive” link defines a direct causal relationship in which when the independent variable changes (e.g., it increases), then the dependent variable changes in the same direction (e.g., it also increases). Conversely, the “negative” link defines an opposite variation between the independent and dependent variables. Such links can also account for delays between the independent and dependent variables. Closed and circularly connected causal relationships determine “feedback loops.” Feedback loops are basic systemic structures that can be of two types: reinforcing (indicated by “+” or “R” inside the loop and determining an exponential growth/decay) and balancing feedback loops (indicated by “–” or “B” inside the loop, and determining a limited growth/decay, promoting a settling to equilibrium by reducing the effects of possible perturbations).

Generally, a balancing loop begins to dominate only after a certain threshold (carrying capacity) is reached in the system. This contributes to the resilience of a system, and in general, resilience is strictly connected to balancing or reinforcing actions that bring the system back to its normal functions. A system dominated by a reinforcing feedback loop generates exponential growth. If there are no limiting conditions that activate a counterbalancing process (or if the balancing effect in the system is triggered only after a delay, i.e., a tipping point), then the system’s behavior tends to grow more quickly.

Therefore, understanding the system’s structure and related behavior is key to being able to grasp signals of exponential growth even when not evident, and hence, be able to react more promptly.

The CLD method is particularly important, as it supports the mapping of causal relationships among the various parts/aspects of a system, with the possibility of identifying important systemic structures known as system archetypes (Senge, 1990). A system archetype is a structure that displays (n) (arche)typical behavior over time and is mainly characterized by the feedback loops that compose it.

In this work, we use an "enhanced" version of the typical CLDs, by introducing the notation of stocks and flows to better represent certain specific processes. Stocks represent points of accumulation and movement of quantities (from a mathematical perspective, they represent the integrals of their associated flows over time). In turn, flows are continuous values that cause an increase or decrease in stock values.

For all these reasons, we believe that the systems thinking approach, through its elective quantitative modelling and simulation methodology – system dynamics – is particularly suitable for the representation of a complex system (e.g., water management) as a series of interrelated processes whose interdependencies are characterized by circular causality, non-linear relationships, and delays between cause and effect, allowing (through simulation) the extrapolation of information and the discovery of hidden/counterintuitive behaviors over time (Sterman, 2000). Furthermore, system dynamics can be integrated with other methodologies, thereby increasing the potential to retrieve useful insights suitable for designing appropriate policies for a more holistic approach to water management that minimizes the potential for unwanted consequences.

3.4. fsQCA approach

The fsQCA is a comparative configurational methodology based on set theory and fuzzy logic, characterized by the possibility of analyzing the degree of difference and belonging to a given configuration (Ragin, 2008, 2009). Using qualitative and quantitative approaches simultaneously (Ragin, 2009), fsQCA aims to (a) determine which combination of configurations (i.e., factors) is minimally necessary and/or sufficient to achieve a particular outcome, and (b) identify which groups of cases share a particular combination of conditions (Meyer et al., 1993).

The configuration comprises factors or conditions that may be positive, negative, or absent.

A condition is necessary if a particular outcome cannot be achieved without the condition. Conversely, a condition is sufficient if it leads to an outcome without the need for other conditions (Ragin, 2008). This method assumes complex causalities and asymmetric relationships that reveal sufficient configurations to lead to a particular outcome (Kumar et al., 2022; Llopis-Albert et al., 2018). Sufficient or necessary conditions were used for all cases analyzed. However, conditions may be sufficient or necessary when combined with other conditions in a situation known as conjunctive causality. They may also describe only one alternative that applies only to some cases, a situation called equifinal causality. Therefore, this methodology assumes that many configurations can lead to the same results. Moreover, fsQCA overcomes the limitation of managing binary variables because the membership of conditions is not considered dichotomous but based on degrees of membership. This is achieved by defining the outcome and causal conditions as fuzzy sets in which the membership functions must be regularized. First, a calibration procedure must be performed, in which theoretical or content knowledge outside the empirical data is used to transform the data into membership measures of a set. This allows for the categorization of significant groupings of cases (Ragin, 2008). Fuzzy values describe the degree of membership in a given set and range from full membership to non-membership, while the crossover point represents neither the inside nor the outside of the "group".

Second, a truth table is created. This matrix consists of 2^k rows, where k is the number of preconditions, and each column represents a condition. The number 2 represents both the causal condition and its complements. The truth table describes all logically possible combinations of causal conditions and classifies cases according to these logically possible combinations. Each empirical case corresponds to a configuration that depends on the antecedent conditions satisfied by the case (Fiss, 2011). Third, the method attempts to reduce the number of rows in the truth table using the Quine-McCluskey algorithm (Quine, 1952). This algorithm uses Boolean algebra to obtain a set of combinations of causal conditions, where each combination is minimally sufficient to obtain a result. This procedure is based on consistency and coverage (Ragin, 2008). Consistency quantifies the degree to which instances with similar conditions lead to the same results (Ragin, 2008). Thus, consistency measures the degree to which membership in the solution (set of terms in the solution) is a subset of membership in the outcome. Coverage represents the empirical relevance of a solution, and thus measures the proportion of memberships in the outcome that is explained by the full solution. Raw coverage shows the proportion of the outcome explained by a particular configuration (i.e., solution). Unique coverage expresses the proportion of the results explained solely by a particular configuration.

4. Findings and results

The next subsections present the results obtained by following the previously described research design.

4.1. Case studies retrieval and analysis

Building on an analysis of the literature and the previously defined selection criteria, three case studies were retrieved and analyzed:

- Armenia et al. (2021) analyzed a water management issue in Italy, considering natural water resources, sociodemographic aspects, and processes of transporting water from the source to the public;
- in the second one, dos Santos et al. (2019) investigated the water management issues that emerged in Brazil in 2018;
- the third case study analyzed the results of an Erasmus+ Project named SUSTAIN (Papathanasiou et al., 2019) with the goal of exploring and supporting decision-making in complex urban environments (including the issue of water management) using SD modelling principles and tools.

Interestingly, these three studies provide different levels of detail and aggregation, thereby allowing us to explore and investigate how water management issues and policies arise and fit into a larger decision-making process.

Armenia et al. (2021) investigated the urban water reservoir system of Rome, Italy and how it is affected by the hydrological cycle of Lake Bracciano. The authors simulated different scenarios and dynamics of the lake's water level (which suffered from a severe shortage in the summer of 2018) to showcase how the weather (and inherent climate change) can affect the water extraction policy of the organization responsible for supplying the urban water system. The proposed causal structure in the form of a Causal Loop Diagram is shown in Fig. 5.

dos Santos et al. (2019) simulated the effectiveness and impact of various policies applied in the metropolitan area of Sao Paulo, Brazil, to test the overall resilience of the water reservoir system. The authors concluded that "difficult" policies must be applied for a long period (such as supply restrictions) for the system to remain sustainable and resilient to water shortages following droughts caused by climate change. Fig. 6 shows the subsystem diagram of the proposed model, which is qualitative in nature and can thus be assimilated to a causal loop diagram. Indeed, we could consider that an outflow can be represented as a negative link affecting the stock and, likewise, an inflow can be represented as a positive link affecting the same stock.

Finally, the SD model developed for the SUSTAIN project (Papathanasiou et al., 2019) addressed water management issues within an interactive learning environment in which a generic urban environment was simulated. The "water" sector of the model is based on the consideration that any activity in the urban environment consumes water and generates wastewater. Water consumption is accounted for by

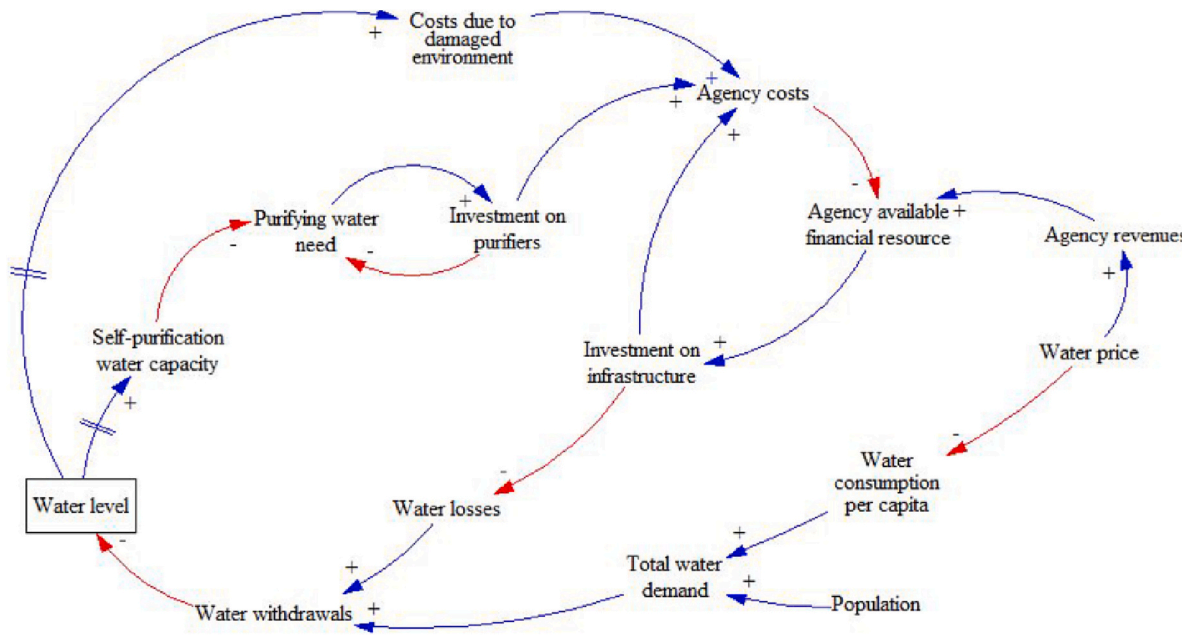

Fig. 5. CLDs from the Bracciano Lake case study.
Source: Armenia et al., 2021

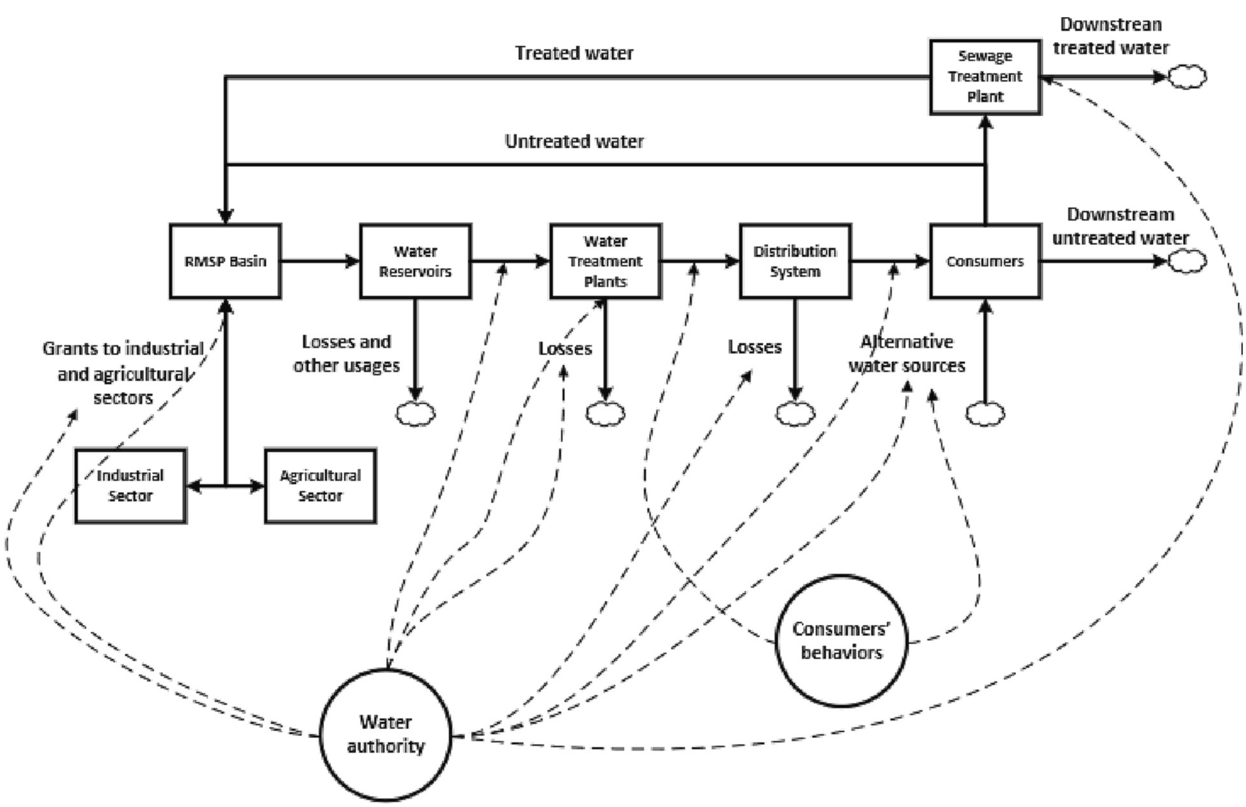

Fig. 6. Subsystem diagram from the São Paulo case study.
Source: dos Santos et al., 2019.

considering the average consumption of water for each specific activity sector (e.g., the "average water consumption per hospital" is multiplied by the total number of hospitals in the city, etc.). In turn, some of the used water creates wastewater that needs to be treated in advanced purification plants. Purified water represents an inflow that feeds back (pure) water into the reservoir of the city and is also increased by rainfall.

Interestingly, this diagram also highlights the linkages between the water management sector and the other key leverage variables. For example, investments in this area are required to maintain the efficiency of purification plants. Therefore, the diagram emphasizes the existence of trade-offs and multiple feedback loops among various sectors of the

SD model (Fig. 7).

Despite geographical differences and different levels of aggregation and detail, in all three case studies, the authors simulated the origins of water, how it is processed to become reusable, and how the behavior of the population drives water usage.

In their most basic form and at the macro-level, all models contain linkages among the following subsystems.

- **Sources of water** included lakes, rivers, and meteorological phenomena. In addition to new water sources, these structures contain variables that stakeholders cannot easily control because they represent natural phenomena. However, they can still invest in preserving and exploring these resources sustainably.
- **Treatment process**. Water agencies pull water from natural sources, process it to become drinkable, and distribute it to the general population. Additionally, purified water can be obtained by recycling the wastewater generated by other activities.
- **Population** data included demographics and water requirements. Additionally, the population demand can be separated into domestic and non-domestic users, who can behave differently. These structures influence the total water demand, which drives the behavior of water agencies towards natural water repositories.
- **Agricultural and industrial infrastructures**: These two structures usually include all the key resources (e.g., fields and plants) contributing to the generation of products and services and, at the same time, demand water. The consumption of these activities is added to the population demand to compute the total water demand.
- **Water economics**. Finally, an essential aspect is the general economics of water, where expenditure for infrastructure repairs and expansions is assessed, water prices are determined, and so on. This is where the various stakeholders' conflicting interests meet and essential policy levers are decided. For example, the water price can be established as a negotiation between the State (and its view on whether water should be considered a right of the population with as low a price as possible), the water agency (with its additional objective of profit), the population (which can implicitly affect the price either by adjusting demand or applying political pressure for lower prices), and agricultural and industrial infrastructures.

These structures can be organized as subsystems, and their macro relationships can be identified. Sterman (2000, p. 99) stated that subsystem diagrams show the overall architecture of a model and are particularly useful because they "convey information on the boundary and aggregation levels in the model. Each major subsystem is shown along with the flows of materials, money, goods, information, etc., coupling the subsystems to one another". Additionally, subsystem diagrams convey information about the endogenous and exogenous variables for the specific domain under investigation.

Fig. 8 presents the common elements, structures, and interconnections among the three analyzed case studies. The final result was depicted as a subsystem diagram constructed during a group discussion session carried out by the authors of the current study with previous knowledge of the studies mentioned above. A narrative synthesis (Popay et al., 2006) was conducted using the agreement criterion (Mill, 2002) to compare cases and identify their commonalities. The authors jointly explored the relationships in the retrieved data and assessed the robustness of the synthesis outcomes. Finally, the resulting logical rationalizations are summarized according to the subsystem

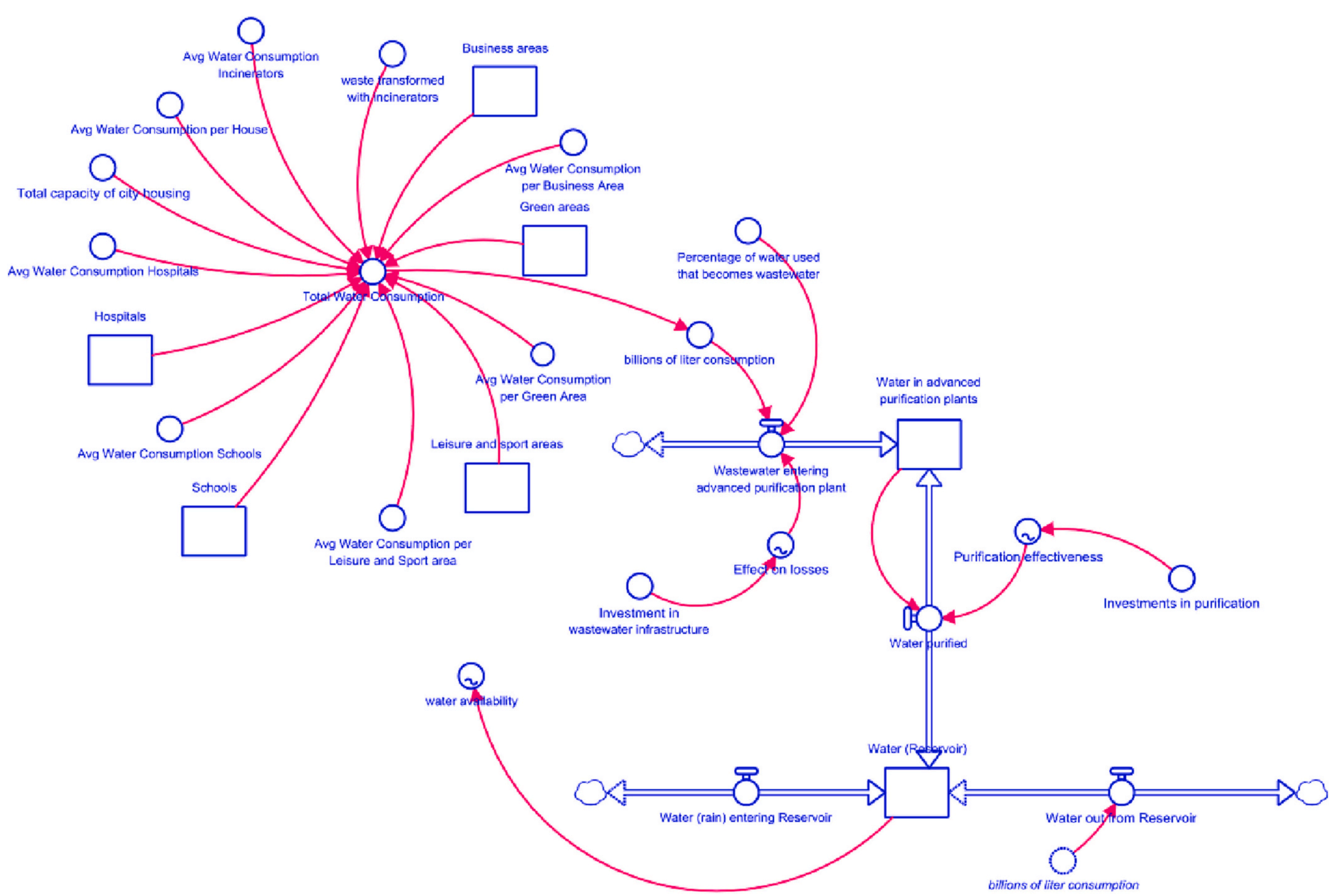

Fig. 7. The water management sector of the model developed for the SUSTAIN Project.
Source: Papathanasiou et al., 2019,

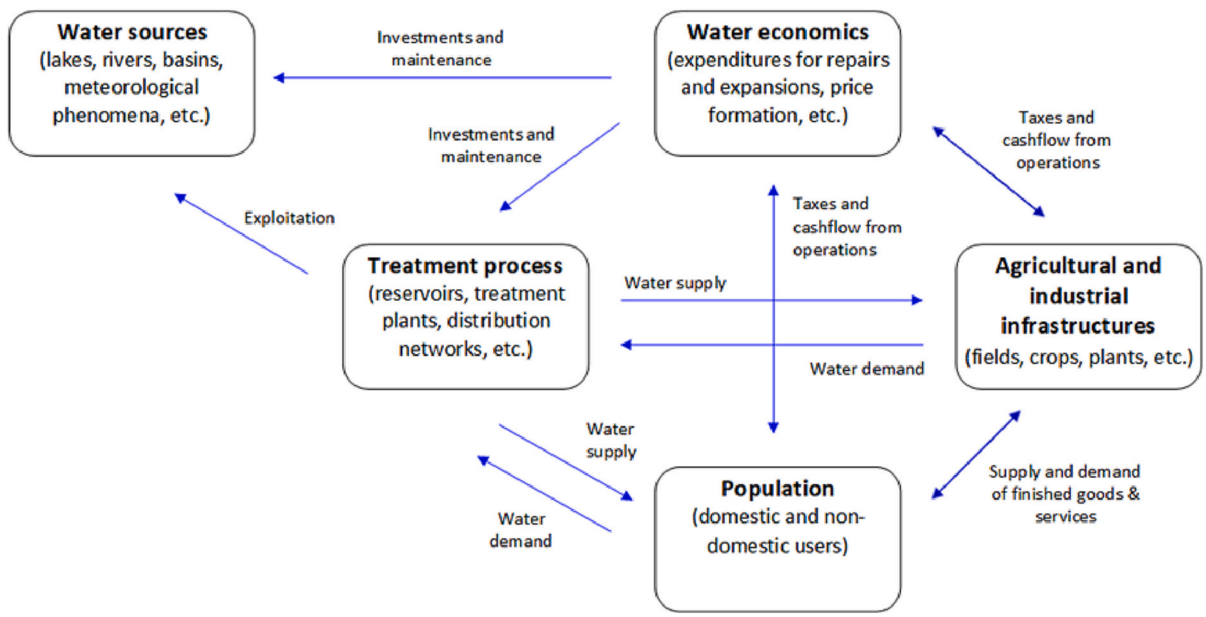

Fig. 8. Case studies common structure depicted as a subsystem diagram.
Source: Authors' elaboration,

diagram.

4.2. SD perspective and minimum common structure

The subsystem diagram in Fig. 8 displays the main interacting subsystems and identifies the key resources that flow from and to each of them and how they are interconnected. Even if aggregated and simplified, the subsystem diagram also indicates the existence and action of several feedback loops among the same subsystems, which are key archetypical structures defining the behavior of the overall water management system in time. Several important insights are obtained from the proposed macrogeneric subsystem.

First, the *Sources of water* are depleted by extraction and restored by several inflows that fill the water basins (e.g., rainfall, rivers, springs, and snow). However, due to climate change and an increase in global temperatures, several countries are facing a shortage of rain and increasing temperatures, a phenomenon that is expected to worsen in the coming years. With demand remaining constant or increasing, these links illustrate what seems to be the root cause of water shortages worldwide. From a systemic perspective, this part of the system does not participate in any feedback loop; thus, no internal mechanisms appear to exist that can reverse the phenomenon, even without extra rain. One area that is potentially subject to being included in some feedback mechanism that could be leveraged thanks to the development of specific water reuse policies is that related to Treatment Processes, which constitutes an interesting (controllable) component potentially feeding back and adding up to the above-mentioned *Sources of water*.

Furthermore, the *Water economics* subsystem participates in the system's main feedback loops because it can determine the behavior of both water agencies (prices, infrastructure investments, etc.) and the population. In theory, an increase in water price would drive demand to lower levels, but because water is essential for life, demand can be considered constant and steady, and it can affect price implicitly through, for example, political pressure or by satisfying demand through other means (bottled water or using non-purified sources). Moreover, one important consideration that several authors (for example (dos Santos et al., 2019) revealed in their research is that much water is lost through inadequate infrastructure and leakages; in our case, among the subsystems themselves. Consequently, agreement among various stakeholders for better infrastructure without a price increase could be a better solution than the business-as-usual scenario.

Finally, one aspect that is not explicitly mentioned in the analyzed papers but illustrates the severity of the problem worldwide deals with importing water from other sources. For example, high prices could lead the population to consider using water from alternative sources (e.g., desalinization of seawater and underground water), which could mean importing water from other countries or areas.

Consequently, the demand in one region could stress another region's water resource system, thus increasing the overall complexity of the system.

Hence, cooperation and better coordination, as well as effective treatment processes, can be relevant solutions for water management as natural replenishment processes continue to deteriorate.

Starting from the subsystem diagram in Fig. 8, we attempted to extract the minimum common structure that determines the overall behavior of water reserves by concentrating on the main and direct influences of other variables that are part of the subsystem diagram.

The minimum common structure we wanted to investigate is the stock of existing water reserves (a stock) and the main aspects determining (adding up to) their increase (inflows) and decrease (outflows), hence constructing a typical "bathtub" exercise analysis (Armenia et al., 2004; Sweeney and Sterman, 2000).

In doing so, we partially neglected some of the existing feedback loops because we wanted to investigate the effective impact of some of the principal aspects that arise from the subsystem diagram on the key variables of the minimum common structure (the main stock and its associated flows).

In particular, we accounted for some key variables for which the three aforementioned case studies displayed relevant data over the course of a few years of analysis. Specifically, we conducted two levels of analysis.

1. **First level**: The analysis of water inflow(s) and outflow(s) on the Water Reserves (this is well known from the System Dynamics Society, so we sought coherence through fsQCA analysis). In this case, the outcome of the analysis (outcome 1) was Water Reserves.
2. **Second level**: We aggregate the data related to the various components that determine the inflow(s), as reported in Table 2. We did so because, notwithstanding the fact that the amount of current water reuse following treatment is an aspect that has a lot of potential for

Table 2
Extraction of main variables out of the subsystems.

Subsystem name (ref. Fig. 7)	Variable name	Coding for fsQCA analysis
Water Sources	● Water Reserves ● Safety Level ● Water Inflow(s) o Precipitation o Tributary Rivers ● Water Outflow(s)	● Outcome 1 ● IN_2.4 ● IN_1.1 ● IN_1.2 = Outcome 2
Treatment Process	● Other Incoming Water o Treatment o Reuse	● Aggregated into the Water Inflow(s) (IN_1.1)[a]
Population	● Relevant Population	● IN_2.2
Water Economics	● Water Price ● Supply Restrictions ● Water Leakage	● IN_2.1 ● Aggregated to IN_2.4 ● IN_2.3
Agriculture and Industrial Infrastructures	● Neglected for the moment	● Not included

Source: Authors' elaboration.

[a] At the moment we have neglected the impact of potential feedback coming from policies in order to limit our analysis to a simpler model, hence postponing further developments of the methodological approach presented in this study to future works. Indeed, this choice also finds a contingent rationale in the fact that the level of water reuse following treatment is still very low worldwide. A recent study from the EC on water reuse (https://ec.europa.eu/environment/water/reuse.htm) reports that: "*At present, about 1 billion cubic metres of treated urban wastewater is reused annually, which accounts for approximately 2.4 % of the treated urban wastewater effluents and less than 0.5 % of annual EU freshwater withdrawals. But the EU potential is much higher, estimated in the order of 6 billion cubic metres – six times the current volume. Both southern Member States such as Spain, Italy, Greece, Malta and Cyprus and northern Member States like Belgium, Germany and the UK already have in place numerous initiatives regarding water reuse for irrigation, industrial uses and aquifer recharge. Cyprus and Malta already reuse more than 90 % and 60 % of their wastewater respectively, while Greece, Italy and Spain reuse between 5 and 12 % of their effluents, clearly indicating a huge potential for further uptake*".

As a further example, consider that all of the water from the Bracciano lake used daily for industrial purposes gets fully poured into the Arrone river, thus currently, sadly, accounting for a 0 % reuse (source: https://www.fidaf.it/wp-content/uploads/2020/07/Salviamo_Bracciano_Finale-2.pdf).

policy feedback, it is still very low, thus still not having particular relevance compared to the magnitude of current natural inflows (see also note 2 in the footer); we have instead considered some of the main components that determine the water outflow(s), as we believe that we can more directly find the main room for policy and social behavior analysis. Hence, in this case, the outcome of our first-level analysis (Outcome 2) was water outflow(s).

Table 2 shows what are the selected variables that we have extracted out of each sub-sector in Fig. 6 (eventually neglecting some, as already mentioned above) and the coding that we have done in preparation for the fsQCA analysis.

In terms of structure, the "minimum common structure" that we have evidenced out of the subsystem shown in Fig. 8 is the model depicted in Fig. 9 below.

Neglecting potential policies connected to water reuse, mainly justified as explained above, also allowed us to keep the minimum common structure as simple as possible in this first stage, in which we propose the use of fsQCA to support SD modelling.

As shown, the water inflow is increased by all three linked variables, whereas the water outflow is increased due to a rising population or to a higher infrastructure obsolescence, but is mitigated by a higher water price (people tend to use less water due to higher bills) or a higher Safety Level (the higher the safety level, the higher the restrictions aimed at imposing planned water shortages due to less usable reserves); thus, both have a balancing effect.

4.3. Application of fsQCA to minimum common structure: data analysis and findings

The fsQCA of the water management case studies proceeded in three steps (Ragin, 2000). First, based on what we learned from the analysis of the presented cases, we studied and established outcome measures and conditions.

Secondly, we codified the cases and calibrated the membership set using a direct method (Kraus et al., 2018; Woodside, 2013). The raw data from each case study used as input for the fsQCA analysis were obtained directly from the corresponding model, as at least one author of the present study was somehow involved in one of the previous studies related to the analyzed cases. Whenever the necessary input was

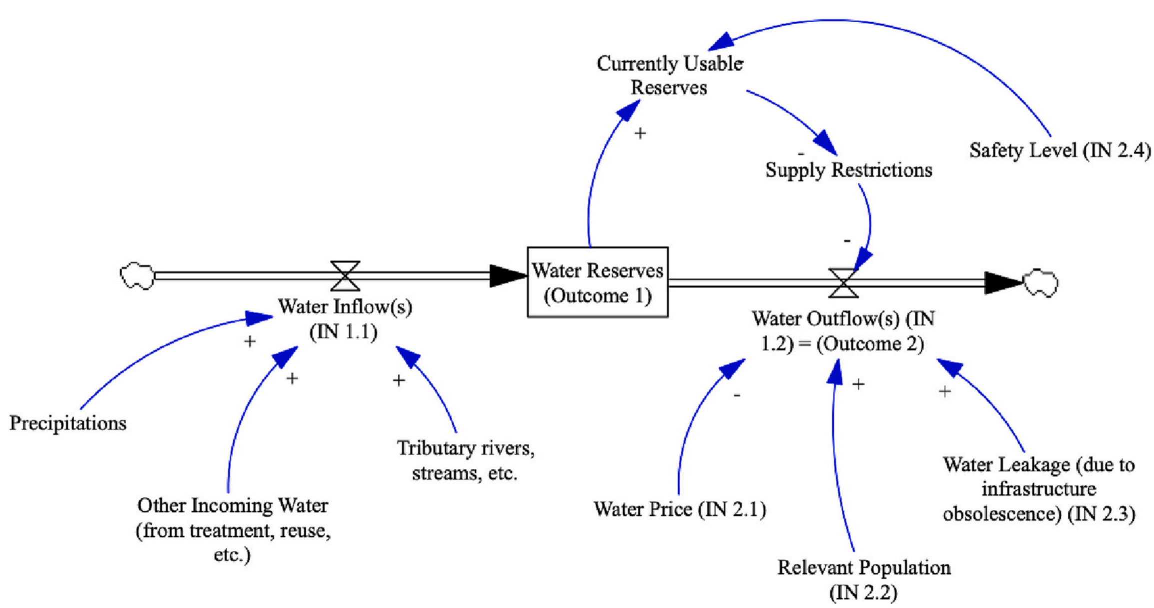

Fig. 9. The underlying "minimum common structure" describing the dynamics of urban water reserves in the absence of specific policy and/or community responses. Source: Authors' elaboration.

unavailable in the model, the author adjusted the current model setting and produced the necessary output as a combination of the available outcomes. After obtaining the required data from all three cases and uniformizing the data, as shown in Table 2, an fsQCA was performed. Accordingly, we have three calibration anchors to denote full membership (0.95), full non-membership (0.05), and the crossover point (0.5).

Finally, the truth tables were created.

We then reduced the number of rows in the truth tables based on the minimum acceptable solution frequency and minimum acceptable consistency to produce simplified combinations. To do this, we used the fsQCA software (3.0) (Ragin and Davey, 2016), which, by calibrating the cases into sets, revealed all possible configurations associated with the outcomes of interest.

Hence, as mentioned in the previous paragraph, we identified two outcomes and mapped them onto a hierarchical perspective (Fig. 10).

- outcome 1 represents the stock of water reserves available in a given water basin;
- outcome 2 represents the outflow of water from the given water basin.

Outcome 1 depends on two input conditions: water inflow level (Input 1.1.) and water outflow level (Input 1.2.). Outcome 2 depends on four input conditions: level of costs associated with water consumption (Input 2.1.), level of growing or decreasing population (Input 2.2.), level of safety of the quantity of water present in a certain water basin (Input 2.3.) and degree of obsolescence of water infrastructure (input 2.4.). It is observed that Input 1.2. and Outcome 2 were represented by the same variables, which allowed us to perform two fsQCAs to achieve better results. Table 3 summarizes the outcomes and conditions considered in fsQCA.

Each condition was analyzed in terms of consistency and coverage. The conditions are necessary if their consistency is at least equal to 0.9 (Schneider and Wagemann, 2010). However, the conditions were considered sufficient if the value of their consistency or a combination thereof was at least 0.75. According to the fsQCA method, the presence of combinations of conditions is expressed using Boolean algebra, which is based on the conditions of coexistence or exclusion (AND/OR).

The results of the analysis conducted for the three case studies are presented in detail below. Table 4 summarizes the configurations of the three analyzed case studies. Necessary conditions are indicated by a black circle (•), sufficient conditions are indicated by an open circle (°), blank spaces indicate the absence of the specific condition.

4.3.1. Lake Bracciano

There were no necessary conditions regarding the stock of water present in a basin (Outcome 1). Regarding sufficient conditions, both the complex and parsimonious solutions indicated the presence of an inlet flow condition (C1.1) and negative outflow (C1.2). The presence of sufficient conditions had a consistency of 0.8 with coverage equal to one-third of the sample considered. There were no necessary conditions for the outflow of water (Outcome 2). As for the sufficient solution, however, it tells us that to have a high output flow there must be no costs associated with the use of water, there must be no population growth and the infrastructure must not have a certain degree of obsolescence.

Table 3
Definition of outcomes and conditions for the fsQCA.

Outcomes	*Conditions*
Stock-water reserves (O1)	Water inflow (C1.1)
	Water outflow (C1.2)
Water outflow (O2)	Water costs (C2.1)
	Population growth (C2.2.)
	Safety level (C2.3.)
	Infrastructure obsolescence (C2.4.)

Source: Authors' elaboration,

Table 4
Summary of the configurations of the three case studies.

	Lake Bracciano	Sustain	São Paolo
Stock-water reserves (Outcome 1)			
Water inflow (C1.1)	°	•	°
~Water inflow (C1.1)			
Water outflow (C1.2)		°	
~Water outflow (C1.2)	°		
Raw coverage	0.326531	0.703297	0.572204
Unique coverage	0.326531	0.703297	0.572204
Consistency	0.8	1	0.946106
Water outflow (Outcome 2)			
Water costs (C2.1)		°	
~Water costs (C2.1)	°		•
Population growth (C2.2.)		•	
~Population growth (C2.2.)	°		
Safety level (C2.3.)		•	
~Safety level (C2.3.)			
Infrastructure obsolescence (C2.4.)			•
~Infrastructure obsolescence (C2.4.)	°		
Raw coverage	0.478261	0.765625	
Unique coverage	0.478261	0.765625	
Consistency	0.785714	1	0.916390

•: necessary condition.
°: sufficient condition.
blank space: none of the previous.
Source: Authors' elaboration.

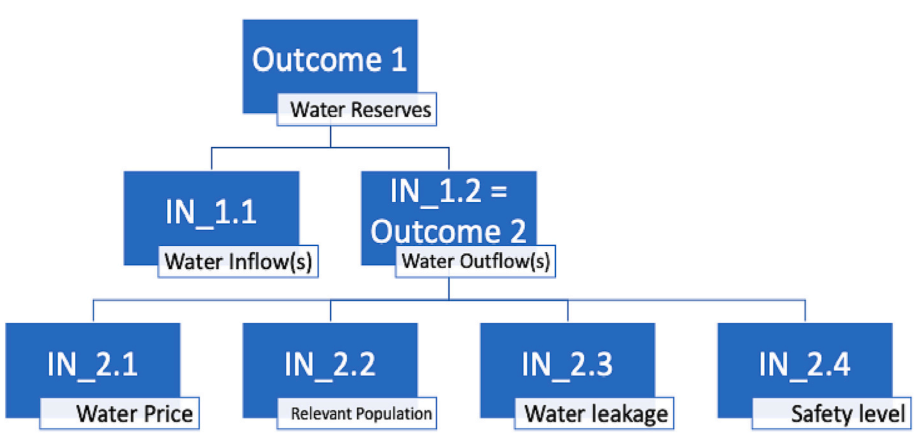

Fig. 10. Hierarchy of outcomes and related input variables.
Source: Authors' elaboration.

4.3.2. Sustain

Regarding the stock of water present in a basin (Outcome 1), the necessary condition that has consistency at least equal to 0.9 is the presence of an incoming water flow. Under sufficient conditions, the solution indicated the presence of an outflow (C1.2). The presence of sufficient conditions had maximum consistency, with coverage greater than 0.7 of the sample considered. With regard to the outflow of water (Outcome 2), two conditions exceeded the consistency level: a high population level and the presence of a safety level. However, for a sufficient solution to have high output flow, there must be no costs associated with the use of water.

4.3.3. São Paulo

With regard to the stock of water present in a basin (Outcome 1), the necessary and sufficient condition that has consistency at least equal to 0.9 is the presence of an incoming water flow. The presence of sufficient conditions has maximum consistency, with coverage equal to more than half of the sample considered. With regard to the outflow of water (Outcome 2), two conditions exceeded the level of consistency: the absence of costs associated with the consumption of water, and the obsolescence of the water infrastructure. For a sufficient solution, however, none of the conditions reach the minimum consistency level to be considered in the configuration.

5. Discussion and implications

5.1. Discussion on SD-based case studies

In the previous sections, we showed how water management is a complex issue because it comprises different interdependent elements and stakeholders with diverse needs, priorities, and types of information. Furthermore, as a complex socio-technical issue, quantification is not always possible or trivial. The quantitative aspect is a relevant issue in decision-making (Akter et al., 2019) and hence requires an intertwined set of decisions to be taken in an environment (whether climate-wise or as a social system) that is intrinsically prone to change over time.

This high degree of complexity makes water management systems characterized by nonlinear relationships among their subsystems, as well as by disconnection between cause and effect in time and space, that is, disturbances to a water system can have serious consequences in different parts of a system and at a very distant point in the future.

In addition, previous studies have shown that water management economics could be driven by human behavior as well as by water agencies' management strategies. Infrastructure and its adequacy play essential roles in ensuring water safety and sustainability. Finally, qualitative analysis showed that cooperation and coordination among different areas can significantly affect how water systems are managed. Building on the gaps identified in the literature search, a cross-analysis of the selected case studies revealed the existence of a common descriptive framework for water management in urban centers. This includes explicitly modelling aging infrastructure and urban water management, as well as the transportation of water from other areas and the effects and impacts of the water industry on public water management (Papathanasiou et al., 2019).

Increasing the diversity of models and including more sectors in the generic subsystem diagram would be helpful.

Consequently, we believe that any methodology used for water management necessarily needs to offer the possibility of representing the interdependencies among many variables in such a complex environment. Therefore, simulations appear to be suitable for analyzing water management systems. In particular, as evidenced in the various studies analyzed in this study, system dynamics can offer all the previously mentioned characteristics, particularly when sociological elements and multi-stakeholder perceptions need to be incorporated into the analysis.

Overall, the generic subsystem diagram presented in Section 4 could be used to increase awareness of the issues at stake for the specific case of an urban (and/or peri-urban) water crisis, thus making such issues much clearer when it comes to policy and political communication. Hence, the value of using SD in water management is clear, given its nature as both a quantitative tool for analysis and an argumentation instrument for communication and awareness (thereby being employed as a qualitative aid).

Additionally, the minimum common structure shown in Fig. 9 lends itself to explains the main behavioral dynamics underlying the water management system. This result is consistent with the outcomes of the literature results analyzed in Section 2. Indeed, the SD model presented above, which we define as the minimum common structure, can be used

1) as a predictive tool: as it is a simulation model, it can be adapted and used to forecast the overall dynamics of a water management issue;
2) for hydro-economic modelling: it can be used to join the dynamic hydrological perspective to its related economic dynamics;
3) as a tool for integrated water resources modelling: it can capture the various water resources through the integrated view of its associated inflow;
4) as a tool for participatory processes: given its intrinsic ease of use and intuitive approach, and being based on systems thinking and system dynamics, which inherently lend themselves to being used in participatory modelling processes (Vennix, 1999);
5) as a socio-hydrological model, given its capability to grasp the social dynamics driving end-user behavior and the potential impacts on such variables from policies aimed at water waste reduction and management of water shortages.

5.2. Discussion on fsQCA results

From the analysis, the following configurations emerge with empirical significance (Ragin, 2006, p. 200). Regarding water reserves, in the first case analyzed, the presence of water inflow and the absence of water outflow were sufficient conditions. This was consistent with the assumptions made in the analysis part of the case study. The conditions that are also sufficient and affect the second outcome, water runoff, point to the absence of consumption-based costs, negative population growth, and outdated infrastructure as the main factors. These conditions are likely related to the fact that the sample was not highly populated, which may have affected the correct identification of the actual trend. Moreover, the simulation results suggest that the first result is always regressive and depends on the production flow, which is mainly determined by high obsolescence. These findings are consistent with those of previous studies, as discussed in Section 2.4 of the literature review. In particular, for Jiang et al. (2018) the main factors that determine water stress conditions are mainly infrastructural, in the same way as the context-specific results make policy-tailored interventions even more necessary.

The second case partially confirmed what was described for the first case. As far as stock water reserves are concerned, the first condition, the presence of water inflow, is necessary in this case, whereas it is sufficient that there is water outflow. For the second outcome, the necessary conditions are the presence of a growing population and an established level of security. The presence of costs associated with water runoff, on the other hand, is considered sufficient.

Finally, in the third case, water inflow was considered a sufficient condition for the existence of water reserves. In terms of water discharge, the necessary conditions are the absence of costs associated with water consumption and the obsolescence of infrastructure.

Based on the configurational approach, more detailed discussions and conclusions can be drawn when considering all dimensions as a whole, focusing on combinations of the mechanisms considered (Misangyi et al., 2017). The following conclusions were drawn from the analysis: The second case analyzed had the highest unique coverage and highest possible consistency for both outcomes considered. In this case, a high stock of water resources is provided by the presence of inflows and outflows, whereas outflows depend on population growth, security level, and the costs associated with water consumption. In terms of policy, this configuration suggests that the conditions that most influence water runoff are population growth and the level of security. Consistent with the results presented in Section 2.4, especially those of Knieper and Pahl-Wostl (2016), anthropogenic impact was one of the factors that most affected water consumption and water stress.

The second configuration, which has a higher degree of uniqueness, is the third configuration, in which inflows affect water resources. Regarding water discharge, the conditions that must occur together are the absence of costs and the obsolescence of infrastructure. This solution allows for policy considerations. The sustainable use of resources to reduce water consumption is one of the main elements to be considered in these configurations, as theorized by Hamidov et al. (2015). Moreover, the presence of low costs related to water consumption has a positive impact on consumption, which is related to the presence of a water distribution infrastructure that, when obsolete, has a negative impact on water runoff from the analyzed watershed.

6. Conclusions, limitations and future work

This study is part of the research field related to the main drivers that can act on water crises and highlights the configurations that can most favor positive water management models. Our results have numerous implications, including theoretical contributions to government policies and governance models.

From a theoretical point of view, this study contributes to the literature on the application of complex methodological approaches to issues related to water management using a blended approach of systemic (system dynamics) and configurational nature (fsQCA). In this way, the study confirmed, through the fsQCA, the validity of the "minimum model" developed via SD. Indeed, the study also paves the way for the joint use of fsQCA as a support for SD modelling, especially when determining the effective impacts that certain variables, initially identified through a causal-loop modelling approach, may or may not have on others, thus supporting the refinement of the causal loop diagram and ultimately supporting the identification of relationship relevance in the stock and flow diagrams to be simulated.

Theoretical insights form the basis for deriving implications for practice, policy, and governance. The literature review reveals how interest in published research has changed over time, with greater use of socio-hydrological modelling than predictive models.

Regarding its contribution to practice and management, we present a generic subsystem diagram to display the main interacting structures involved and how they are interconnected. Although aggregated and simplified, the subsystem diagram captured several feedback loops among the main subsections involved, providing an understanding of the overall system structure and offering clues for determining the elements accountable for the water management system's overall and commonly observed behavior over time.

From the subsystem diagram in Fig. 8, we extracted a minimum common structure that captured the main dynamics of water management issues. Such a minimum common structure (see Fig. 9) is capable of capturing the overall behavior of water reserves by concentrating on the main and direct influences provided by variables that can be found inside the subsystem diagram; hence, it can help describe several water management issues owing to its archetypal nature. In identifying and extracting such an archetype, we have inevitably introduced some limitations by partly neglecting some of the feedback loops that can be found inside the subsystem diagram: as already explained, we did this to investigate the effective impacts that such a minimum common structure (the stock and its associated flows) has on some of the key variables arising from the subsystem diagram. This allows the model to be used as a useful tool for preliminary decision evaluation and policy, as it also highlights that system dynamics has the potential to move from the analytical and quantitative realm to that of policymaking and law (Armenia et al., 2014). Specifically, owing to its communicative effectiveness, which facilitates the explanation of complex simulation outcomes, SD can help policymakers explain their managerial and governance decisions, thereby creating awareness and consensus among relevant stakeholders.

The main results of the fsQCA analysis showed a significant impact on the outflow of water with regard to the absence of costs linked to water consumption, infrastructure obsolescence, and population growth. While the presence of adequate inflows to feed water basins is the variable that mainly positively affects the creation of water reserves. From a policy perspective, preservation and appropriate infrastructure maintenance and management are among the most effective ways to ensure that water resources remain available to the population, particularly in the face of current climate change and unstable weather conditions. In addition to the capability of the identified elements of human behavior, the analyzed studies demonstrated that a combination of personal responsibility and state intervention could prove to be a robust policy, regardless of environmental uncertainties.

Our study emphasizes that a systemic and integrated approach is needed to develop sound policies capable of impacting such goals, conceptualizing and identifying where those policies must be directed, and the levers to manage them successfully. The developed conceptual model is intended to be abstract, generalizable, and non-context-specific as it aims to identify the key characteristics and relationships that shape the outcomes of water-related management issues. This model can help policymakers and practitioners develop effective and adaptable strategies to address water-related issues and serve as a useful tool for comparing and evaluating different approaches to water management and predicting the potential impacts of future changes. Ultimately, the model can contribute to informed decision-making and inclusive water governance by providing a systematic and integrative framework for understanding water management dynamics.

From the above, it can be deduced that the required governance role also requires anticipatory actions aimed at guiding water management actions towards overall sustainability objectives, stimulating the involvement of a multiplicity of actors. In this sense, policy governance can be characterized by preventive protection and conservation of specific areas, and tailor-made strategies for defining management methods. In this latter perspective, it can be said that a potentially coherent role of governance is that which refers to polycentric modalities (Barile et al., 2021; Brodnik and Brown, 2018). This modality lies in the ability of policymakers to direct their actions towards the support of water management practices or policies that can act on the identified outcomes (water reserves and water outflow) or, alternatively, improve their existing characteristics. In this way, it is possible to limit the disconnect that exists between the potential of certain actions concerning water management methods and the effective implementation of short-term government actions and policies, which often prefer top-down governance methods and policymaking to collaborative governance and participatory models.

In this sense, it is possible to provide examples of water management practices that see the active and participatory involvement of both policy makers and communities and foster participatory discussion, sensemaking, and policymaking.

The first example, concerning the remunicipalization of water infrastructure, supply, and sanitation, involves a city or other municipality not renewing or terminating a contract with a private company to return the management of these services to municipal authorities. This water management practice can contribute to an improved definition of water leaks identified in the minimum common structure (Fig. 9) as Input 2.3.

Another example of participatory discussions translating into water management practices is community-led management. This practice consists of providing legal entities to residents to promote cooperation with unplanned neighborhoods, thus enabling the planning, construction, and maintenance of water services to become self-organized and co-managed through them. Again, this defines not only the elements of the Input 2.3. and the variables affecting Input 1.1. such as the water used for treatment and water reuse.

However, it is worth noting that the component of the inflow related to the Treatment Process, feeding used water back to IN_1.1, would characterize a feedback situation that would have largely increased the complexity of the fsQCA analysis. Therefore, for the sake of simplicity, we have decided to limit our scope to a 1-st level (stocks and flows) fsQCA analysis and a 2-nd level fsQCA analysis, which currently only includes the direct policy-related components adding up to the IN_1.2 outflow. Adding the impact of policies to IN_1.1 would increase the complexity of our analysis beyond the scope and aims of this study, but presents an opportunity for further developments.

Again, a further context-specific element that could be used to replicate the model concerns so-called community science. It consists of a community-led water quality monitoring program in which citizens contribute to filling a large data gap on contamination levels and water quality problems. For example, this would allow data concerning water inflow to be entered (Input 1.1.) and quality analysis of Outcome 1.

Our study has some limitations. Although the variables were calibrated using objective criteria wherever possible, some elements of subjectivity remained. Ragin (2009) also emphasized these elements concerning the definition of thresholds, mainly regarding the theoretical and substantive knowledge of researchers. Therefore, although fsQCA identifies the necessary conditions for the proposed configurations, Dul (2016) demonstrated how Necessary Condition Analysis (NCA) can identify additional necessary conditions and determine the level of conditions required for a given outcome. In this sense, further quantitative applications of the results of this study could be based on the application of NCA to gain further insight into the necessary conditions.

Future work could develop a more comprehensive analysis by explicitly evaluating water infrastructure, population characteristics, and human behavior and incorporating them into simulation models. Additionally, more research is needed to confirm the validity of the proposed approach, which considers fsQCA as a viable support for confirming the existence (and relevance) of causal relationships in the system dynamics model. Further research could focus on specific local socio-political conditions that can affect the obsolescence of water infrastructure and the costs associated with water consumption. Furthermore, through comparative longitudinal studies, future research could investigate how different water management models favor the efficient use of water resources. Finally, case studies and cross-case analyses could be used to exploit the analytical potential of the results.

CRediT authorship contribution statement

Conceptualization: Stefano Armenia, Francesca Iandolo; **Methodology (Literature Review)**: Eduardo Franco, George Tsaples; **Methodology (fsQCA)**: Stefano Armenia, Francesca Iandolo; **Methodology (SD):** Stefano Armenia, Alessandro Pompei, Federico Barnabè; **Data and case studies selection:** Eduardo Franco, George Tsaples, Alessandro Pompei, Federico Barnabè; **Writing and Editing**: all; **Supervision**: Stefano Armenia, Francesca Iandolo.

Data availability

Data will be made available on request.

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Stefano Armenia, PhD, is Tenure-track Assistant Professor of Organization Studies at Università Telematica degli Studi IUL Italy. He has a degree in Computer Engineering and Automation (Sapienza University, 1998), a MSc in Business Engineering (Tor Vergata University, 2002), a PhD in Business & Management Engineering (Tor Vergata University, 2004). He applies Systems Thinking and System Dynamics in various research areas, i.e. management of policies/strategies in complex organizations, evaluation of social impacts, development of new decisional framework in dynamical environments. Since 2002, he is member of the International System Dynamics Society (USA), for which he is VP Chapters & SIGs. Since 2015, he is president of SYDIC, System Dynamics Italian Chapter.

Federico Barnabé, Ph.D., is Professor in Business Administration at the Department of Business and Law, University of Siena (Italy). Previously, Federico was a visiting researcher at the University of Bergen (Norway) and Roehampton University (UK). His main research interests include management accounting, performance measurement, accounting history, and simulation & gaming. He published in several international journals on these topics. He was Co-Editor of the Rivista di Contabilità e Cultura Aziendale, and Guest Editor for the journals Kybernetes, Journal of Modelling in Management, and Journal of Simulation.

Eduardo Franco Graduated in Electrical Engineering from the University of São Paulo (2003), Master in Electrical Engineering from the University of São Paulo (2007), and a double Ph.D. degree in Computer Engineering at the University of São Paulo (2020) and in Operations Research at Sapienza University of Rome (2020). His interests rely on topics related to the operation, maintenance, sustainability, and evolution of software and information systems from the perspective of complex systems, employing several modeling and simulation paradigms (discrete events, systems dynamics, and agent-based modeling). He has experience in software engineering, management of large-scale software systems development & maintenance projects, innovation, finance, fund-raising, and entrepreneurship.

Francesca Iandolo, PhD, is Tenure-track Assistant Professor of Management at the Department of management, Sapienza University of Rome, qualified as Associate Professor in Management (Italian ASN). She graduated in Accounting and holds a PhD in Management with a dissertation thesis on Viable Systems Approach (vSa), value creation and sustainability. Her research interests concern the application of systems theories to corporate sustainability and the role of technology diffusion within digital platforms and new business models. She participated in several national and international conferences as a discussant and published in national and international journals.

Alessandro Pompei received his master's degree in Management Engineering at Sapienza University of Rome in 2017 and subsequently PhD in Industrial and Management Engineering in 2021 at the same university. Since 2021 he has been a research fellow at Sapienza University of Rome for quality assessment and monitoring within CIVIS - A European Civic University (Erasmus+). He is the author of several articles published in international scientific journals including Sustainability, Futures, Business Strategy and the Environment. Alessandro Pompei carries out research on issues relating to project management and sustainability. Other research topics concern modeling and simulation based on systemic approaches.

Georgios Tsaples is a researcher at the University of Macedonia, working on problems of Operational Research. He graduated from the Aristoteleion University of Thessaloniki and a Master's degree (MsC) in Engineering and Policy Analysis from Delft University of Technology, where he was introduced to simulation (especially System Dynamics and Agent-Based Modelling) and Decision Analysis (Multi-Criteria Decision Analysis). He has worked as a Researcher at the Sapienza University of Rome, and at the Hellenic Institute of Transport.