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# Critical review of system dynamics modelling applications for water resources planning and management

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ABSTRACT

This paper systematically reviewed system dynamics applications in water resource management with respect to spatial factors, research aims, modelling sub-systems and model calibration and validation methods. Decision-making context, consideration of climate change, scenarios or management measures were also examined. Results showed that the critical conceptual system dynamics model development phases are often neglected with only 40% of reviewed articles developing causal loop diagrams, and only three studies identifying system archetypes. Most reviewed publications applied scenario-based approaches (82%) to evaluate the effectiveness of management measures, whilst a minority of studies (1.8%) considered water management optimisation. Structure behaviour and behaviour-pattern tests (52%) were mostly applied to evaluate the validity of the model structure and accuracy of the behaviour's pattern, though model validation was not conducted in 12% of the studies. Finally, an integrated system dynamics modelling framework was proposed, exploring opportunities for integration of system dynamics with other modelling tools based on the strengths and limitations of system dynamics modelling; this framework can be used to enhance the simulation and optimisation for future water resource management and planning in the context of climate change and socio-economic development.

## 1. Introduction

Water resources are an integral part of the socio-economic-environmental system, and they have been increasingly affected by challenges driven by the complexities of hydrological cycles, socio-economic factors, diverse stakeholder perspectives and concerns associated with the use of water for various purposes (Tidwell et al., 2004; Langsdale et al., 2007; Sušnik et al., 2013). Understanding dynamic interactions and feedback mechanisms amongst the related hydrological, social, economic and environmental factors is crucial for strategic planning and management of water resources (Zhang et al., 2014; Han et al., 2017; Sun and Yang, 2019). However, nonlinearity, multiple interactions and dynamic feedback between these factors create a high level of complexity and uncertainty, rendering it difficult to understand the potential consequences of decisions (Stave, 2003; Zhang et al., 2008; Simonovic, 2009; Kotir et al., 2016). Traditional linear causal thinking and mechanistic models lack the mental and organisational framework that cannot address such complexity because they treat the interactions and dynamics of different sub-systems in isolation (Sterman, 2000; Mirchi et al., 2012). Consequently, the root causes of the problems are often not understood fully enough to formulate strategic water management policies (Davies and Simonovic, 2011; Gohari et al., 2017).

System dynamics (SD) modelling is a method that facilitates recognition of multiple interactions among the disparate but interconnected sub-systems driving dynamic behaviour of the system as a whole (Sterman, 2000). Consideration of the combined effects of system dynamics can improve management decisions and reduce the possibility of adverse side effects and unintended consequences from policy decisions (Sterman, 2000; Simonovic, 2009). Identifying and capturing feedback loops within water resource systems can provide insight into potential consequences of system perturbations, thereby serving as a suitable platform for sustainable water resource planning and management at the strategic level (Simonovic, 2009; Mirchi et al., 2012). Consequently, many authors have contended that SD modelling provides a holistic view of the magnitude of complex dynamics, feedback processes and interdependencies between hydrological, social, economic and environmental processes for decision-making in water resource management systems (Ahmad and Simonovic, 2004; Gohari et al., 2013; Mirchi and Watkins Jr, 2013; Gies et al., 2014; Bakhshianlamouki et al., 2020).

SD modelling has been widely applied as a decision support tool for

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water resource management and planning (Liu et al., 2009; Davies and Simonovic, 2011; Gastelum et al., 2018; Karimlou et al., 2020). The SD paradigm can incorporate and analyse hydrological, social, economic and environmental components as well as management measures under climatic and non-climatic scenarios in one comprehensive model to understand the dynamic behaviour of complex systems and their responses to interventions over time (Sahin et al., 2015; Phan et al., 2018). SD models assist decision-makers in simulating and/or optimising potential measures for water resource management under different scenarios by answering 'what if' and/or 'which is best' questions (Davies and Simonovic, 2011) through trade-off analysis (Giuliani et al., 2014). In addition, SD modelling facilitates stakeholder involvement from the problem-scoping to model validation processes, thereby increasing consensus for simulation results that can be used to identify effective adaptation options for the modelled system under future scenarios. Therefore, SD can help water managers to identify problematic trends, comprehend their root causes and assess appropriate management measures in a holistic fashion for strategic decision-making (Simonovic, 2009; Mirchi et al., 2012).

As such, the application of SD modelling has become increasingly popular for handling the complexity of water resource systems driven by multiple interactions from climate change and socio-economic stressors. Several papers have reviewed its application in the broad context of water resource management. For example, Chen and Wei (2013) reviewed the application of SD in water security management and classified this into three categories: (i) flood control and disaster mitigation, (ii) water resources security and (iii) water environment security. Mirchi et al. (2012) reviewed the qualitative modelling tools and applications of SD to water resource management and divided them into three types of modelling approaches, namely (i) predictive simulation models, (ii) descriptive integrated models and (iii) participatory and shared vision models. These three types of modelling approaches were further reviewed by Zomorodian et al. (2018). Recently, Mashaly and Fernald (2020) also reviewed these modelling approaches in hydrology and water resources, especially in agricultural water management. These review articles are useful guides to the application of SD to water resource management. However, a substantial gap remains in the literature, with no reviews comprehensively evaluating the applications of SD in water resource management, especially in terms of geographic distribution, model sub-systems, model calibration and validation methods, policy evaluation and optimisation of different decision-making approaches for water-related issues under multiple changes.

This paper aims to conduct a systematic quantitative review of the applications of SD modelling in water resource management. More specifically, research aims, geographical distribution, temporal and spatial scales, modelling sub-systems, model calibration and validation methods were synthesised to identify gaps in the application of the SD modelling approach in water resource management. Decision-making context, consideration of climate change, scenarios and management measures were also examined. Finally, an appropriate modelling tool to address the dynamic, complex, uncertain and spatial water resource systems was proposed based on an assessment of the integration of SD with other modelling tools and analysis of the strengths and limitations of SD in the management of complex and uncertain water resource systems.

The remainder of the paper is organized as follows. Section 2 provides the methodology followed for the systematic quantitative literature review and the reviewing categories. Section 3 describes critical review results evaluating the applications of SD models for water resource management. The last section provides discussion and conclusions about the gaps of system dynamics applications in water resource management. It also proposes an SD modelling framework that was founded on a critical analysis of the strengths and limitations of SD modelling to enhance the simulation and optimisation for future water resource management and planning under climate change and socio-economic stressors.

## 2. Methods

A systematic quantitative literature review (Pickering and Byrne, 2013) was performed to identify and categorise the relevant literature and critically analyse current applications of SD models in water resource management. Scholarly electronic databases (*Scopus*, *Web of Sciences* and *Google Scholar*) were used to identify original research and academic papers published in English-language journals until August 15, 2020. Books, book chapters, review papers, conference papers and theoretical articles lacking any real-world application of SD were not considered in this review.

Relevant articles from these databases were searched using a combination of the following keywords: 'System dynamics*', 'System dynamics modelling approach', 'System dynamics model', 'System dynamics simulation', 'SD model', 'SDM' or 'SD'; and the change-related search terms 'Water*', 'Water resource' or 'Water resource management'. The wildcard '*' was used for 'System dynamics' and 'Water' to match all words around these two keywords. The title, abstracts and keywords of articles were included in these searches. Furthermore, papers were also identified from the reference lists of research papers found through the initial database search. The title and abstract of each article identified via these searches were further screened to confirm a focus on applications of an SD modelling approach in water resource management.

The resulting database of primary research papers reporting on the application of SD modelling to water resource management was then attributed into the database according to the following fields: (1) citation details (i.e. author[s], journal, year of publication), (2) geographic distribution (i.e. continent, country), (3) temporal scale of the study (e.g. short-term (0–5 years), mid-term (6–10 years) and long-term (>10 years) horizontal planning), (4) research aims (i.e. water quality, water supply, water demand), (5) causal loop diagram (CLD) development, (6) modelling sub-systems (e.g. hydrological, social, economic and environmental), (7) decision-making context (i.e. scenario-based or optimisation-based methods or predictive only), (8) model calibration and validation methods (e.g. structure tests or behaviour-pattern tests), (9) participatory model development and validation, (10) consideration of scenarios and measures, (11) consideration of climate change impacts (i.e. sea level rise, rainfall variation), (12) software package used for model development, and (13) coupling with other modelling approaches to deal with complexity and uncertainty as well as identify and optimise potential management measures for water resource systems.

The geographic distribution of research papers was grouped by continent and country. The conventional division of seven continents was used: Africa, Asia (including the Middle East), Australia, Europe, North America and South America. The temporal scale of the research studies was considered to have short-term planning if the simulations were shorter than five years and long-term planning if the simulations were greater than or equal to five years.

In accordance with the Intergovernmental Panel on Climate Change (IPCC) report in 2014 (Noble et al., 2014), the types of scenarios or measures considered in the reviewed SD papers were categorised as follows:

- Institutional and social scenarios or measures (e.g. economic and social instruments, laws, regulations and policies),
- Technological and engineered scenarios or measures (e.g. water-saving technology, desalination plants, wastewater treatment, reservoirs and rainwater tanks),
- Ecosystem-based scenarios or measures (e.g. green infrastructure, forest cover, riparian planting and restoration)

A Venn diagram was drawn using the RStudio program (RStudio Inc.) to consider all possible logical relations between these scenario or measure categories within different decision-making modelling approaches (optimisation-based or scenario-based).

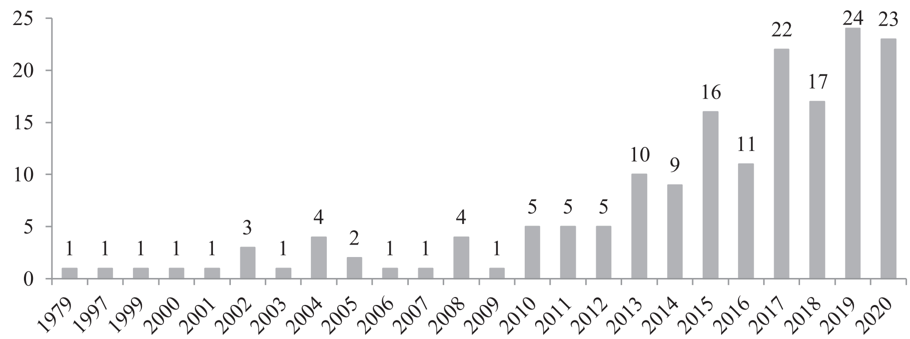


**Fig. 1.** The number of reviewed articles published up to August 15, 2020.

## 3. Results

### 3.1. Overview of reviewed articles

A total of 1053 relevant articles were initially identified from *Scopus*, *Web of Science* and *Google Scholar* after merging and eliminating duplications. However, after checking the titles and assessing the abstracts, 884 of these articles did not specifically discuss the application of SD to water resource management. The remaining 169 articles were then examined in detail to evaluate the application of SD in the management of complex water resource systems. These articles were published in 72 different journals, reflecting the trans-disciplinary interest in the application of SD for complex water resource systems. The majority were published in five journals, including *Water Resources Management* (9%), *Journal of Environmental Management* (9%), *Water* (8%), *Journal of Cleaner Production* (7%) and *Science of the Total Environment* (5%). All other journals were represented by five or fewer articles.

System dynamics modelling has evolved in the 1960s; it was first applied to water resource management in the late 1970s (Picardi and Saeed, 1979). Subsequently, the number of research articles applying SD to water resource management has grown substantially, especially after 2013 (Fig. 1). This popularity demonstrates that the use of the SD modelling approach in the management of complex water resource systems is of increasing interest to researchers around the world.

The application of SD models in water resource management has attracted diverse scholarly interest and attention around the globe. Most studies have been conducted in Asia (57%) and North America (28%). In contrast, few studies have been conducted in South America (2%). Within Asia and North America, research articles have been conducted in 33 countries, of which China (35%), the United States (18%), Iran (10%) and Canada (9%) have the highest proportion of articles. Other countries account for less than 30% of the studies considered.

In this review, most SD models (77%) were developed to understand a long-term perspective of water-related issues for decision-making support. More precisely, 23% of these long-term applications investigated the dynamic behaviour of complex water resource systems for at least 50 years into the future to reflect delays within the system. For example, Dhungel and Fiedler (2016) applied SD models to understand the long-term implications of continued growth in water demand on groundwater-dominant water resources over a 150-year time period in the Palouse region of the USA, with the aim of developing a tool for sustainable water management. Sverdrup et al. (2020) developed an SD model to investigate antibiotics pollution from medical and agricultural uses at various nodes along the Volga River, Russia, over a 150-year simulation to design strategic solutions for preventing antibiotics from contaminating drinking water, rivers and soils. These studies indicate that a long-term simulation is necessary to assess the long-term dynamic behaviour of such systems and the impacts of future scenarios. In contrast, only 14% and 9% of the reviewed studies focused on short-term and mid-term planning for water resource systems, respectively.

Depending on data availability, research aims and the nature of the problem, SD models were developed at different temporal frequencies (hourly, daily, weekly, monthly or annually). Models focussing on short-term operations used daily or hourly simulation time steps to model hydrologic and chemical processes, such as the operation of pumps (Park et al., 2017), nitrobenzene concentration in Songhua River (Zhang et al., 2011) and flood management (Ahmad and Simonovic, 2004). Models focussing on long-term planning—such as reservoir operation (Morrison and Stone, 2015; Jiang et al., 2020), integrated water management (Leal Neto et al., 2006; Sun and Yang, 2019; Liu et al., 2020), evaluation of

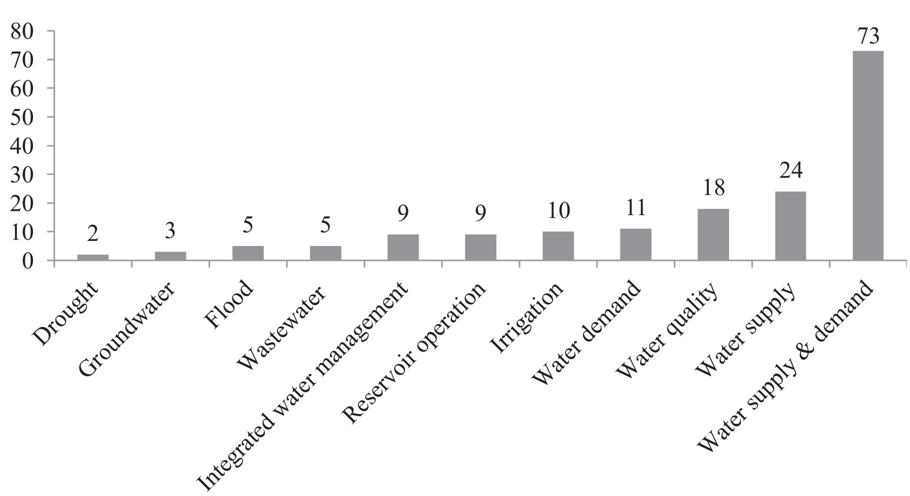


**Fig. 2.** Research aims of the reviewed applications.

**Table 1**
List of reviewed applications of SD modelling approach in water management in the academic literature, published through to August 15, 2020. *H: Hydrological modelling, HS: Hydrological-Social modelling, HE: Hydrological-Economic modelling, HEn: Hydrological-Environmental modelling, HSE: Hydrological-Social-Economic modelling, HSEn: Hydrological-Social-Environmental modelling; HSEEn: Hydrological-Social-Economic-Environmental modelling, SB: Scenario-based approaches, OP: Optimisation-based approaches, SB&OP: Scenario and optimisation-based approaches, PR: Predictive only.*

| Research aims | Modelling sub-systems | Decision making approaches | Reviewed studies |
|---|---|---|---|
| Drought management | HS | SB | Lee et al. (2012) |
| | HSE | SB&OP | Gies et al. (2014) |
| Integrated water resource management | HSE | SB | Feng et al. (2008) |
| | HSEEn | SB | Leal Neto et al. (2006); Zhang et al. (2014); Han et al. (2017); Sun and Yang (2019); Yang et al. (2019); Zare et al. (2019); Bakhshianlamouki et al. (2020); Liu et al. (2020); |
| Flood management | H | SB | Ahmad and Simonovic (2004); Simonovic and Li (2004) |
| | | PR | Ahmad and Simonovic (2000); Li and Simonovic (2002) |
| | HSE | SB&OP | Turner et al. (2016a) |
| Groundwater management | H | PR | Bates et al. (2019) |
| | HSE | SB | Balali and Viaggi (2015) |
| | HSEn | SB | Barati et al. (2019) |
| Irrigation water management | H | SB | Hosseinzadeh Ghazichaki and Monem (2019) |
| | HS | SB | Tehrani et al. (2013); Pluchinotta et al. (2018) |
| | HSE | SB | K. El-Gafy (2014); Feng et al. (2017a); Gunda et al. (2018) |
| | HSEn | SB | Saysel et al. (2002); Fernald et al. (2010) |
| | HSEEn | PR | Turner et al. (2016b); Feng et al. (2017b) |
| Reservoir operation management | H | SB | Ahmad and Simonovic (2000); Morrison and Stone (2015); Keith et al. (2017); Stojkovic and Simonovic (2019) |
| | HEn | SB | Jiang et al. (2020) |
| | HS | SB | Sun et al. (2002); Hedden-Nicely and Fiedler (2017) |
| | HSE | SB&OP | Gastélum et al. (2010) |
| | HSEn | SB | Ghashghaie et al. (2014) |
| Wastewater management | HS | SB | Jeong and Adamowski (2016); Prouty et al. (2020) |
| | HSEn | SB | Prouty et al. (2018) |
| | HSE | SB | Ganjidoost et al. (2018) |
| | HSEEn | SB | Zhang et al. (2016) |
| Water demand management | HS | SB | Qi and Chang (2011); Wang and Davies (2018) |
| | HE | OP | Faust et al. (2017) |
| | HSE | SB | Aivazidou et al. (2018); Baki et al. (2018); Gonzales and Ajami (2017); Aivazidou et al. (2018); Baki et al. (2018); Park and Lee (2019); Sahin et al. (2017a) |
| | | PR | Gonzales and Ajami (2017) |
| | HSEn | SB | Xiao-jun et al. (2015); Ma et al. (2020) |
| | HSEEn | SB | Gonzales and Ajami (2017); Wang et al. (2019) |
| Water quality management | H | SB | Zhang et al. (2011); Hallas et al. (2020); Wood and Shelley (1999); Xuan et al. (2010); Xuan et al. (2012); Wang et al. (2016); Sverdrup et al. (2020) |
| | HS | SB | Kuai et al. (2015); Hassanzadeh et al. (2019); Bradford et al. (2020) |
| | HE | SB | Bier (2010) |
| | HEn | SB | Sverdrup et al. (2020) |
| | | PR | Wood and Shelley (1999); Xuan et al. (2010); Xuan et al. (2012) |
| | HSEn | SB | Kato (2005); Mirchi and Watkins Jr (2013); Liu et al. (2015); Zhu et al. (2015); Bertone et al. (2019); Nazari-Sharabian et al. (2019) |
| | | PR | Kato (2005) |
| | HSEEn | SB | Berry et al. (2017) |
| Water supply management | H | SB | Dawadi and Ahmad (2012) |
| | | PR | Sehlke and Jacobson (2005); Rusuli et al. (2016) |
| | HEn | SB | Chu et al. (2010) |
| | HS | SB | Picardi and Saeed (1979); Hoekema and Sridhar (2013); Ravar et al. (2020) |
| | HE | SB&OP | Crookes (2018); Xu et al. (2020) |
| | HSE | SB | Rehan et al. (2015); Park et al. (2017); De Stercke et al. (2018); Babamiri et al. (2020); Fernandes et al. (2020); Rubio-Martin et al. (2020) |
| | | SB&OP | Sahin et al. (2017c); Gastelum et al. (2018) |
| | HSEn | SB | Li et al. (2019a) |
| | HSEEn | SB | Chung et al. (2008); Gohari et al. (2013); Gohari et al. (2017) |
| | | OP | Dutta Roy et al. (2011) |
| | | SB&OP | Nasiri et al. (2013); Niazi et al. (2014) |
| Water supply and demand management | HS | SB | Stave (2003); Liu et al. (2009); Qaiser et al. (2011); Sušnik et al. (2012); Dawadi and Ahmad (2013); Wu et al. (2013); Li et al. (2015); Xi and Poh (2015); Dhungel and Fiedler (2016); Kotir et al. (2016); Zarghami et al. (2016); Alifujiang et al. (2017); Dai et al. (2017); Sahin et al. (2017b); Phan et al. (2018); Qin et al. (2018); Huang et al. (2019); Li et al. (2019b); Silva and Teixeira (2019); Joshi et al. (2020); Nguyen et al. (2020) |
| | HE | SB&OP | Gao and Liu (1997); Tsai et al. (2019) |
| | HSE | SB | Yang et al. (2008); Zarghami and Akbariyeh (2012); Sušnik et al. (2013); Wang et al. (2014b); Yang et al. (2015b); Yue et al. (2015); Sahin et al. (2016); Duran-Encalada et al. (2017); Mokhtar and Aram (2017); de Araujo et al. (2019); Dou et al. (2019); Chen and Chen (2020); Karimlou et al. (2020); Li et al. (2020) |
| | | SB&OP | Scarborough et al. (2015) |
| | HSEn | SB | |

(*continued on next page*)

**Table 1** (*continued*)

| Research aims | Modelling sub-systems | Decision making approaches | Reviewed studies |
|---|---|---|---|
| | | | Langsdale et al. (2007); Nikolic et al. (2013); Zhuang and Zhang (2015); Zeng et al. (2016); Chen et al. (2017); Huang and Yin (2017); Wang et al. (2018b); Ahmadi and Zarghami (2019); Dong et al. (2019); Li et al. (2019c); Liao et al. (2020) |
| | | SB&OP | Li et al. (2018a) |
| | HSEEn | SB | Guo et al. (2001); Simonovic and Rajasekaram (2004); Tidwell et al. (2004); Zhang et al. (2008); Wang et al. (2011); Wei et al. (2012); Wang et al. (2014a); Wang et al. (2014c); Xie et al. (2014); Chang et al. (2015); Yang et al. (2015a); Pienaar et al. (2017); Sun et al. (2017); Wang et al. (2017); Jiang et al. (2018); Wang et al. (2018a); Cui et al. (2019); Su et al. (2019); Dai et al. (2020); Tian et al. (2020); Yin et al. (2020) |
| | | OP | Li et al. (2018b) |
| | | SB&OP | Wei et al. (2020) |

infrastructure development (Sahin et al., 2016; Pienaar et al., 2017) and the impacts of climate change and socio-economic stressors on water resources (Wang et al., 2014c; Wang and Davies, 2018; Nazari-Sharabian et al., 2019)—used monthly or annual time steps.

### 3.2. Research aims

The reviewed applications encompassed a wide range of water management or research aims (Fig. 2), with 11 water research domains identified across the 169 reviewed publications (Table 1). Water supply and demand management was the major concern studies addressed (43%), followed by water supply management (14%), water quality (11%), water demand management (7%), irrigation water management (6%), reservoir operation management (5%) and integrated water management (5%). The remaining research aims account for 9% of the reviewed studies.

### 3.3. Modelling sub-systems

The SD modelling approaches can integrate different sub-systems to pave the way for a more holistic approach to strategic decision-making (Simonovic, 2009; Mirchi et al., 2012). Importantly, these models assist decision-makers in better understanding the hydrological, environmental, social and economic feedback structure as well as long-term behaviour patterns and interactions (Zare et al., 2019). In addition, these integrated feedback models are necessary for sustainable water resource management and planning because they facilitate testing and the selection of potential plans and policies under climate change and socio-economic stressors (Gohari et al., 2017; Sahin et al., 2017a). As a result, the integration between three or more sub-systems is increasingly widely applied among scholars for water-related management, appearing in 62% of reviewed applications (Fig. 3). However, SD was also applied to only one sub-system, such as the hydrological (13%), or two sub-systems, such as the hydrological-social (21%) and hydrological-economic (4%).

#### 3.3.1. Hydrological models

Hydrological modelling mainly focussed on hydrological processes and performance for a catchment but without linking to economic, environmental or social sub-systems. This type of SD model is developed to understand the future behaviour of the hydrological system, which can be used as a basis for tactical decisions (Mirchi et al., 2012). Hydrological modelling has been applied to a range of different water-related problems, including reservoir operation (Ahmad and Simonovic, 2000; Keith et al., 2017), flood management (Li and Simonovic, 2002; Ahmad and Simonovic, 2015), water supply management (Sehlke and Jacobson, 2005; Rusuli et al., 2016), groundwater management (Bates et al., 2019) and water quality management (Hallas et al., 2020).

#### 3.3.2. Hydrological-environmental models

Hydrological-environmental SD modelling was developed to understand the interactions between ecosystems and hydrological cycles at different spatio-temporal scales. Most environmental hydrology studies reviewed focussed on the relationships between environmental flows and water quality management in the water resource system, such as nitrogen removal (Xuan et al., 2010), metal pollution in constructed wetlands (Wood and Shelley, 1999) and antibiotics pollution in the Volga River (Sverdrup et al., 2020). Environmental hydrological modelling also investigates the interactions between hydrological cycles and other organisms and water environment preservation. For example, Jiang et al. (2020) developed an SD model to understand the impacts of reservoir operation on fish habitats, sediment flushing and landslide stability. In addition, Chu et al. (2010) adopted an SD modelling approach to analyse the relationship between water supply, flood detention and healthy water environment in artificial lakes in Taiwan.

#### 3.3.3. Social-hydrological models

Social-hydrological modelling was developed to understand the relationships between hydrological processes and human impacts on water resources. Hydrological and social sub-systems are strongly related; thus, decisions that impact the hydrological cycle also impact people and vice

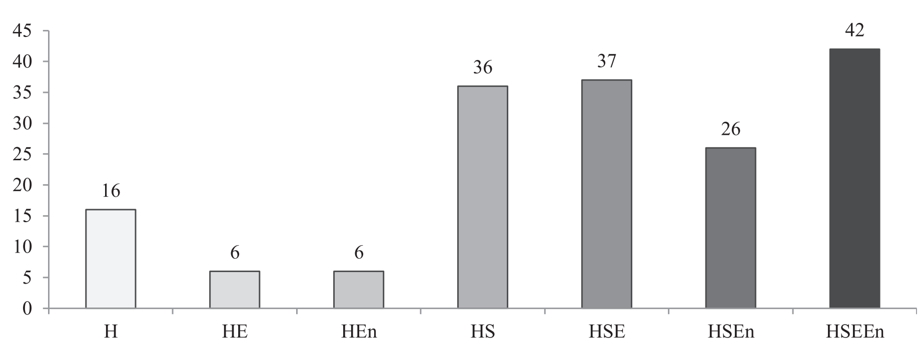


**Fig. 3.** Modelling sub-systems for water resource management.
H: Hydrological modelling, S: Social modelling, E: Economic modelling, En: Environmental modelling.

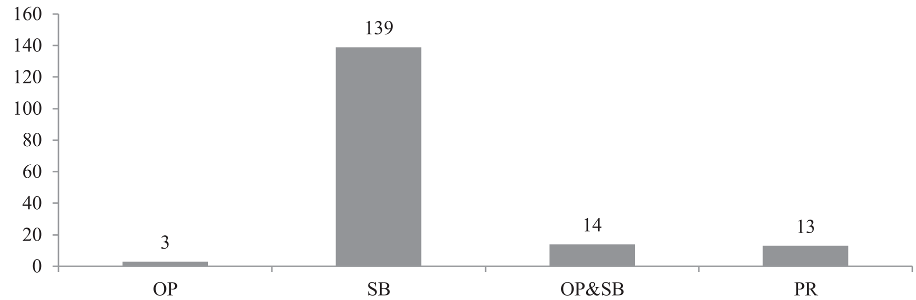


**Fig. 4.** SD models for different types of decision support in water resource management. *OB: Optimisation-based approaches, SB: Scenario-based approaches, OP&SB: Optimisation- and scenario-based approaches, PR: Predictive only*.

versa (Blair and Buytaert, 2016). These interactions between hydrological and social processes are nonlinear and occur on different temporal and spatial scales. For example, people build water infrastructures such as reservoirs, water treatment plants and water transfer projects that—-whilst improving water supply for a community with related social benefits—could significantly change the hydrological processes of a catchment. As a result, these hydrological changes will affect the water supply for human (Sivapalan, 2015).

Traditional models have mainly focussed on hydrological systems for decision-making support without considering social interactions within water resource systems, and they are not capable of simulating the nonlinear dynamics and feedback between these interactions (Zomorodian et al., 2018). However, an SD-based socio-hydrological model presents a useful methodology for decision-makers to understand the process and general trends of socio-hydrological systems and identify the root causes of problems, thereby contributing to the implementation of integrated water resource management (Jeong and Adamowski, 2016). For this reason, this modelling type has been increasingly widely applied to capture the dynamic behaviour of coupled human-water systems for a range of water research aims in recent decades. However, water supply and demand management were mostly applied by this SD modelling type (Dai et al., 2017; Sahin et al., 2017b; Phan et al., 2018) to capture the dynamics emerging from the interactions and feedback between water resources and social processes. More specifically, SD models have considered the impact of population growth (Dawadi and Ahmad, 2013; Dhungel and Fiedler, 2016) and changes in agricultural and industrial production (Nazari-Sharabian et al., 2019; Chen and Chen, 2020) on water quantity and quality.

### 3.3.4. Hydro-economic models

Hydro-economic modelling was developed to understand the dynamic interactions between hydrological and economic sub-systems and to evaluate potential economical options and their outcomes in terms of providing policy insights and revealing opportunities for better management of water-related issues (Harou et al., 2009). These hydro-economic models vary in their modelling approaches to include hydrology models with strong economic analysis incorporating cost-effectiveness or benefit analysis (Scarborough et al., 2015; Crookes, 2018; Xu et al., 2020) and weak economic analysis with economic tools such as water price (Yue et al., 2015; De Stercke et al., 2018; Park and Lee, 2019). However, most of these studies (80%) focussed mainly on hydrological models with weak economic analysis; they accomplished this by incorporating economic tools into the SD models or coupling external economic valuations to simulate and/or optimise management measures of water-related issues.

These models tend to emphasise water allocation and infrastructure development (Turner et al., 2016a; Sahin et al., 2017b), agricultural production (Feng et al., 2017a; Gunda et al., 2018), economic development (Feng et al., 2008), wastewater treatment (Yang et al., 2008; Zarghami and Akbariyeh, 2012) and markets and profits (Bier, 2010). Potential solutions were generally identified by comparing simulated results of scenarios, often contrasting current conditions with one or more changes to conditions. These changes may be physical, such as changes in temperature, precipitation and sea level resulting from climate change projections (Sušnik et al., 2013; K. El-Gafy, 2014), the building of a water storage dam or other infrastructure (Scarborough et al., 2015) or water saving technology (Baki et al., 2018). These changes may also be institutional, such as the development of markets to trade water from one place to another (Gastélum et al., 2010; de Araujo et al., 2019) or water price mechanisms to adjust water demand (Park and Lee, 2019; Babamiri et al., 2020)

A wide range of economic factors were considered, including water price (Bier, 2010; Sahin et al., 2017a; Wang et al., 2018a), water trade (K. El-Gafy, 2014), costs and revenue in agricultural production (Gunda et al., 2018; Bakhshianlamouki et al., 2020) and wastewater treatment costs (Pienaar et al., 2017). In addition, researchers have used SD models to incorporate economic tools to optimise potential options in terms of costs and effectiveness, as in Crookes (2018) study on desalination plants and dam construction in Cape Town, South Africa, and Faust et al. (2017) research into water infrastructure in the United States.

### 3.3.5. Fully integrated models

Water resources decision-making should be based on a holistic view of existing problems because of the multitude of complex, interlinked socio-economic and bio-physical sub-systems within watershed systems (Gohari et al., 2013). The recognition of various feedback mechanisms within a water resource system driven by distinct sub-systems is important for appropriate quantitative and/or qualitative projection of long-run behaviour, providing a basis for quantitative simulation to examine different policies. This integration has been well-recognised and is being increasingly applied in various water-related domains (Fig. 3).

In this review, 25% of the reviewed articles incorporated four different components into one framework to understand their interactions and feedback for integrated water management and planning, such as evaluation of water-carrying capacity in different planning and development schemes (Zhang et al., 2014; Liu et al., 2020), environment-economy-society relationships for sustainable development (Han et al., 2017), and water environment and environmental degradation (Leal Neto et al., 2006). In addition, 37% of reviewed applications considered three sub-systems for water-related issues. Hydrological, social and economic sub-systems were largely considered for integrated water management, such as optimisation of urban water security regulation schemes driven by different industrial development patterns (Dou et al., 2019) and evaluation of benchmarking performance indicators (e.g. infrastructure, social and financial) on sustainable long-term management of water distribution and wastewater collection networks (Ganjidoost et al., 2018). In addition, two sub-systems—such as hydrological-social sub-systems (21%), hydrological-environmental sub-systems (4%) and hydrological-economic sub-systems (4%)—were considered in SD models to understand water demand for both humans and the environment or ecology; these models addressed issues such as alleviation of water shortages for ecological and domestic water demands

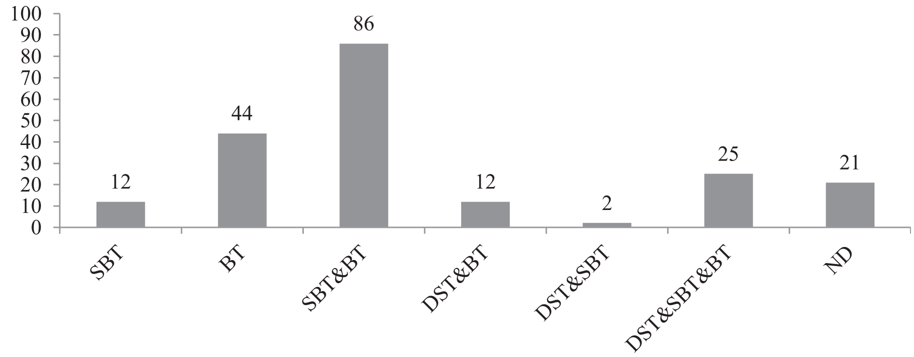


**Fig. 5.** Validation and verification methods for water resource system dynamics models. *DST: Direct structure tests, SBT: structure-behaviour tests, BT: Behaviour-pattern tests, ND: Not discussed.*

as well as agricultural and industrial production due to climate change and population growth (Huang and Yin, 2017). These integrated models help decision-makers to understand the impacts of a range of factors on water resource systems, from climate change to population growth, economic growth, management costs and benefits, and changes in agricultural and industrial production.

### 3.4. Decision-support modelling approaches

SD models were developed to assist decision-makers to simulate and/or optimise potential measures for water related problems under different plausible scenarios through answering 'what if' and/or 'which is best' questions. In this review, scenario-based approaches were most commonly used to simulate the dynamic behaviour of water resource systems under different scenarios or measures, accounting for 82% of the reviewed studies (Fig. 4). Optimisation-based methods were also applied to optimise potential measures (2%). About 7% of the reviewed articles were developed for predictive modelling only (Fig. 4).

Only seven (e.g. Sahin et al., 2017c; Crookes, 2018; Wei et al., 2020) of these optimisation-based studies incorporated economic tools into the SD models to optimise potential management options. Other studies coupled SD models with external economic valuations to optimise the selection of water management measures, including fuzzy optimisation for optimal interventions (Gao and Liu, 1997), an inexact fuzzy-parameter two-stage programming model for water use structure (Li et al., 2018a) and the non-dominated sorting genetic algorithm for optimal reservoir operation (Tsai et al., 2019).

### 3.5. Model validation and verification

In the reviewed articles, direct structure tests, structure-behaviour tests, behaviour-pattern tests, and combinations of these were applied to validate SD models (Fig. 5). Structure tests and behaviour-pattern tests are two main classes of tests, usually applied to assess the validity and usefulness of SD models (Barlas, 1996; Sterman, 2000). Structure tests include direct structure tests (e.g. structure and parameter confirmation and dimensional consistency) and structure-behaviour tests (e.g. behaviour sensitivity and extreme conditions), which are used to determine how well the structure of the model matches the structure of reality and to uncover potential structural flaws (Barlas, 1996). Behaviour-pattern tests determine how consistently and accurately model outputs match real-world behaviour; this type of test can either be based on available time-series data or the correlation of mental models with established reference modes (Sterman, 2000). In addition to these tests, validation and verification of SD models can be undertaken by consultation with a range of experts and stakeholders throughout model development processes.

Of the reviewed articles, a combination of structure-behaviour and behaviour-pattern tests (51%) as well as behaviour-pattern tests only (26%) was most often applied by researchers and modellers to validate and verify their SD models. Some studies (15%) also combined three different methods. However, in 12% of the reviewed papers, the SD model validation was not discussed at all. This omission may reflect the fact that many reviewed cases presented models that were purely conceptual rather than operational, which may be due to a lack of required historical data.

Thirty-nine reviewed papers applied direct structure tests to ensure model structure complying with natural laws and a truthful description of the investigated water system (Barlas, 1996). These tests were conducted by comparing the causal and mathematical relationships between variables with available knowledge on the real system, such as checking both the model structure and dimensional consistency (e.g. Crookes, 2018) or mathematical equations and variable values (e.g. Wang et al., 2019). Building CLDs is considered an important phase for improving understanding of complex water resource systems (Mirchi et al., 2012). However, in this review, only 76 articles (45%) developed CLDs, and only three studies (Ghashghaie et al., 2014; Gohari et al., 2017; Zare et al., 2019) identified systems archetypes to understand the generic systems structure of water resource systems.

Two common methods for structure-behaviour tests applied by researchers in this review were sensitivity analysis and extreme condition tests. Most authors conducted sensitivity analysis by changing values (e.g. 5%, 10%) for several variables to test the structure behaviour of the models (e.g. Phan et al., 2018; Cui et al., 2019; Huang et al., 2019; Yang et al., 2019). The Monte Carlo sensitivity analysis was also conducted by estimating the 50%, 75% and 95% confidence intervals to understand the dynamic behaviour of the studied systems (e.g. Zhang et al., 2014; Baki et al., 2018; Ma et al., 2020). Extreme condition tests were conducted by assigning extreme values of selected variables and comparing simulated behaviour to anticipated behaviour for the water resource systems (e.g. Gohari et al., 2013; Prouty et al., 2018).

The majority of the studies reviewed applied behaviour-pattern tests (82%) to validate SD models for water resource systems. Several statistical methods, including the root mean square error (e.g. Dawadi and Ahmad, 2012; Hallas et al., 2020), mean of the relative error (e.g. Dai et al., 2017; Cui et al., 2019) and the correlation coefficient (e.g. Li and Simonovic, 2002; Faust et al., 2017) were commonly used to compare the behaviour patterns between observed data and simulated data.

In addition to these validation methods, the validity of the SD models was also verified by stakeholders. Stakeholders participating in model validation can enhance understanding and build trust in the results of models, thereby strengthening decision-making support (Mirchi et al., 2012); despite this, there were only nine studies (5%) which involved stakeholders in validating the applications of SD models in water resource management (e.g. Sušnik et al., 2012; Sahin et al., 2016; Phan et al., 2018; Bertone et al., 2019).

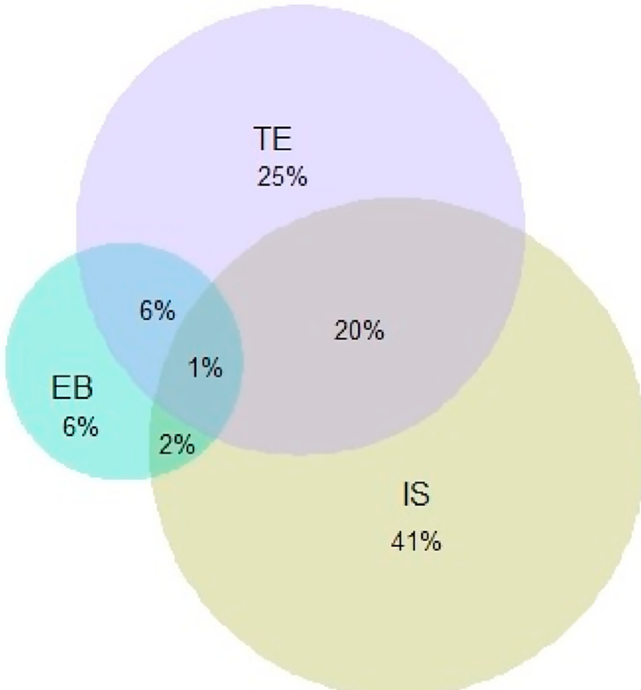


**Fig. 6.** Scenarios and measures considered in the scenario-based approaches in the reviewed studies. *IS: Institutional and social scenarios or measures, TE: Technological and engineered scenarios or measures, EB: Ecosystem-based scenarios or measures*.

### *3.6. Policy evaluation and climate change considerations*

A total of 153 reviewed studies (90%) incorporated scenarios or measures into their SD models to understand the dynamic behaviour of complex water resource systems (Fig. 6). About 64% of these 153 studies considered institutional and social scenarios or measures, while 52% considered technological and engineered scenarios or measures and 15% evaluated ecosystem-based scenarios or measures for complex water resource systems (Fig. 6). About 29% of these 153 reviewed applications considered more than two scenario or measure categories. For example, two studies (1%) evaluated all three categories of scenarios or measures, and 40 studies (28%) in total considered two categories of scenarios or measures for water resource management (Fig. 6).

Although water resource management faces considerable challenges associated with climate change, only 59 studies (35%) were explicitly designed to explore the potential impacts of climate change on the water resource systems. The research aims of these studies addressed water supply and demand management (e.g. Sahin et al., 2017b; Yin et al., 2020), irrigation water management (e.g. K. El-Gafy, 2014; Alifujiang et al., 2017; Gunda et al., 2018), reservoir operation (e.g. Keith et al., 2017; Stojkovic and Simonovic, 2019) and water quality management (e.g. Prouty et al., 2020). In addition, climate change impacts, such as the impacts of sea level rise on coastal freshwater systems through salinity intrusion (e.g. Nguyen et al., 2020), of declined precipitation and increased temperature on river discharge and evaporation (e.g. Hoekema and Sridhar, 2013; Gunda et al., 2018), and of severe drought events on water supply systems (e.g. Li et al., 2015; Rubio-Martin et al., 2020) were considered in reviewed studies,. These studies highlighted that climate change (e.g. sea level rise, altered precipitation) has increased the frequency of extreme events and changed temporal and spatial availability of water resources in different regions. For example, the combined effects of sea level rise and upstream flow decline have caused high levels of salinity intrusion along estuaries in the Da Do basin in Vietnam (Phan et al., 2018). In addition, both precipitation and groundwater level have faced significant decreases over the last two decades, greatly affecting the water supply sources for the Shiraz plain in Iran (Ahmadi and Zarghami, 2019). Streamflow was also predicted to decrease by 3% until 2035, significantly affecting water supply in the Colorado River basin in the USA (Dawadi and Ahmad, 2012).

### *3.7. System dynamics software*

A wide range of SD software packages was found to be used for constructing CLDs and stock and flow diagrams and to capture the feedback for water resource systems, with 11 software packages used across the reviewed papers. Vensim was the most commonly used package, appearing in 57% of the reviewed studies, followed by STELLA (24%). These two software packages were commonly used because they have friendly graphical user interfaces and data management systems to input, manage and display graphics and tables through animation and controls. Other software packages such as Powersim, Dynamo, iThink, Anylogic, Goldsim, NetLogo and Simile were also used. Matlab (Sun and Yang, 2019) and Microsoft Excel (Bates et al., 2019) were also used to understand dynamic behaviour. However, 25 reviewed studies did not indicate which software was used for their research.

### *3.8. Integration of system dynamics models with other modelling tools*

In this review, 20 of the 169 reviewed articles integrated SD models with other modelling tools to assess and manage water-related issues. Optimisation models (Gao and Liu, 1997; Li et al., 2018b) were coupled with SD models to optimise the potential management options for the water resource system under multiple stressors. Hydrological models (Simonovic and Li, 2004; Liu et al., 2009; Gies et al., 2014) were developed to understand the river flows that were used to calibrate the SD models. Agent-based models (Faust et al., 2017; Han et al., 2017) were combined with SD models to understand the multiple interactions from different entities (e.g. environment, economy and society) related to water resource management. General circulation models (Zarghami et al., 2016) were used to investigate the possible impacts of climate change on runoff. Bayesian networks (Wang et al., 2016; Bertone et al., 2019) were also coupled with SD models to simulate and diagnose water quality.

Integration with Geographic Information System (GIS) tools is one of the most promising approaches to analysing spatial temporal characteristics of a water resource system. The SD model is especially useful for temporal modelling with a limited capacity for spatial representation, but GIS is useful for spatial modelling with a limited capacity for temporal representation (Ahmad and Simonovic, 2015). However, in this review only three of the reviewed studies explored links between SD models and spatial data to understand spatial and temporal changes in water resource systems. For example, Ahmad and Simonovic (2015) combined the SD model with GIS to model the spatial and temporal dynamics of flood risk in Red River, Canada. Similarly, Zhang et al. (2011) constructed a conceptual GIS-SD framework to simulate the temporal-spatial changes of pollutant concentration in Songhua River, China.

A simulation game theory in SD models is also a useful policy tool to model economic, political, biological and social situations in water resource management. For example, Bier (2010) developed a simulation game in SD modelling to help relevant stakeholders understand the structure, dynamics, benefits and drawbacks of thermal water quality trading markets. The integration also allows exploring potential market dynamics under different scenarios and policy designs, thereby enhancing understanding of potential uncertainties and their consequences in water quality trading.

## 4. Discussion and conclusions

### *4.1. Findings and gaps in SD applications to water resource management*

A comprehensive literature review on the application of SD modelling on water resource management was performed to identify the application's trend, gap and modelling capacity. This review found that SD modelling has been widely and increasingly applied in the management of water resource systems with many aims. These include understanding the dynamic behaviour of the systems, predicting the current and future changes of systems under different scenarios, evaluating the performance of management measures, conducting trade-off analysis for selecting an optimal management measure, and informing and supporting decision-making.

A broad range of water research aims and interlinked sub-systems indicates that SD has the capacity to be applied to an incredibly wide variety of water-related problems. However, water supply and/or demand management, water quality management and irrigation management are the domains upon which the majority of SD models currently focus. In contrast, groundwater management is less frequently considered by scholars. Groundwater is one of the most important and vital resources for agriculture, urban areas, industry, and ecosystems, but this resource is increasingly threatened by increasing water demand, pollution and climate change (Bates et al., 2019). Nonetheless, only three studies mainly focussed on groundwater management. Modelling and simulating groundwater is challenging because it is difficult to map, quantify and evaluate or to predict its future availability given changes in precipitation (Balali and Viaggi, 2015; Barati et al., 2019).

A wide range of scenarios or management measures—encompassing engineering and technological measures, institutional and social measures and ecosystem-based measures—can be incorporated into the SD models to help decision-makers understand dynamic behaviour and evaluate the effectiveness of these measures for water resource management. Institutional and social scenarios or measures (40%) were found to be the most frequently assessed category of management measure; this could be due to the fact that this category includes a range of scenarios or measures, such as water pricing (e.g. Ahmad and Simonovic, 2015; Park and Lee, 2019), socio-economic development (e.g. Nasiri et al., 2013; Balali and Viaggi, 2015; Baki et al., 2018), operating rules of reservoirs (e.g. Chu et al., 2010) and climate change scenarios (e.g. Keith et al., 2017; Phan et al., 2018; Prouty et al., 2020). It was also observed that the performance of institutional and social measures was more often evaluated by scenario-based models rather than by optimisation-based models. However, the performance of technological and engineering scenarios or measures was mainly evaluated by optimisation models. This may be because it could be much more straightforward to estimate implementation costs for engineered and technical measures, such as the construction of desalination plants (e.g. Turner et al., 2016a; Crookes, 2018) and rainwater tanks (e.g. Gies et al., 2014; Wei et al., 2020), than to estimate societal costs arising from institutional and social measures, such as water right transfers (Gastélum et al., 2010).

This review also found that different sub-systems (e.g. hydrological, social, economic and environmental) were incorporated into the SD applications to understand their interactions in water resource systems. However, mainly three different sub-systems (37%) were combined, followed by two different components (28%) and four different components (25%). The different sub-systems incorporated into one modelling framework are necessary for sustainable water resource management and planning because they both 1) capture various elements and 2) better understand the feedback structure and long-term behaviour patterns driven by these sub-systems, thereby assisting decision-makers to test and select appropriate plans and policies under climate change and socio-economic stressors. That said, the different sub-systems incorporated into SD application add more complexity and uncertainty to the modelling systems. As a result, 12% of reviewed articles involved SD models coupled with other modelling tools with respect to the management of complex and uncertain water systems (Ahmad and Simonovic, 2004; Faust et al., 2017; Li et al., 2018a; Nazari-Sharabian et al., 2019), improving the capacity of dealing with space and time in complex systems and describing complex interactions among system understanding (Kelly et al., 2013).

SD modelling has proven an effective tool for promoting shared vision planning, participatory modelling and common learning opportunities for diverse groups of relevant stakeholders and decision-makers (Langsdale et al., 2007). However, it is surprising that only 14% of the reviewed studies co-developed SD models with relevant stakeholders for water-related issues, and most of these studies were integrated water modelling approaches with three or more sub-systems (e.g. Turner et al., 2016b; Sahin et al., 2017c; Karimlou et al., 2020). Integrated and dynamic water modelling can strengthen the impact of its work by improving collaboration with a range of local experts and practitioners (Harou et al., 2009; Mirchi and Watkins Jr, 2013; Kotir et al., 2016). The participatory modelling approach can increase understanding of the scope and complexity of the problem as well as deepen consensus on and trust of model results and proposed policies (Stave, 2003; Tidwell et al., 2004).

A major finding in this review is that researchers have not utilised the full capacity of qualitative tools and thinking phases in SD modelling. Similar to any modelling technique, SD modelling should start with the essential steps of two modelling phases: qualitative and quantitative (Sterman, 2000; Zare et al., 2019). The end goal of the first phase is to develop conceptual models (e.g. CLDs and system archetypes) that visualise dynamic interactions of variables in the system and gains further insights into system behaviours. The end goal of the second phase is to formulate a model that simulates the dynamic interactions among key variables identified in the first phase for the system. The conceptual model development in the first phase are critically important tools for improving understanding of multiple interactions in complex water resource systems and enhancing the accuracy of the simulation models (Mirchi et al., 2012). Particularly, Zare et al. (2019) applied a series of conceptual modelling techniques to support integrated water assessment in the Gorganroud-Gharesu Basin, arguing that conceptual model development provided insight into the problem boundaries and model structure, thereby furnishing basic knowledge to develop quantitative models. In addition, Sušnik et al. (2012) applied both phases of SD applications for the Kairouan region, stating that the development of qualitative conceptual models have assisted in understanding the causal processes in a system, leading to a basic model structure and reflecting the desired level of detail and complexity of the system, thereby supporting the decision-making process. Coyle (1999) also indicated that conceptual model development is an important step in the model structure optimisation process, which is modified and improved iteratively through changing variables and assessing causal relationships in the studied system. However, only 40% of reviewed articles developed CLDs, and only three studies (Ghashghaie et al., 2014; Gohari et al., 2017; Zare et al., 2019) identified system archetypes to fully understand the interactions between variables in the studied systems.

Another important finding from this review is that SD models were mostly applied for scenario-based approaches (82%) to help decision-makers or modellers understand the dynamic behaviour of water resource systems and answer the question 'what if?' by evaluating the effectiveness of management measures in different scenarios. Optimisation-based approaches (2%) were also applied but less frequently. The outcome of optimisation models was designed to help decision-makers understand water-related systems and answer the question 'what is best?' by conducting trade-off analysis to identify the optimal management options with/without exploring different scenarios. The less frequent application of optimisation models may be driven by implementation constraints and complexity in quantifying the costs and economic effects of management options, particularly institutional and social measures.

Calibrating and validating integrated water systems with high levels of complexity and uncertainty is challenging because of discrepancies between the scales of sub-systems and limited data for all variables; this is an issue particularly when social, economic and political sub-systems are included as they are far more difficult to predict than physically based sub-systems (Blair and Buytaert, 2016). Therefore, more than one testing method (62%) was applied to evaluate the validity of the model structure and accuracy of a behaviour's pattern. However, model validation was not conducted in about 12% of the reviewed studies, and 52% of these non-validated models featured integrated modelling approaches with three or more sub-systems in the SD models (e.g. Dutta Roy et al., 2011; Balali and Viaggi, 2015; Babamiri et al., 2020). In addition, almost all reviewed articles validated only one or two key variables in the SD models of complex water resource systems to ensure that the models reflected the real conditions and processes in the studied systems (e.g. Chang et al., 2015; Berry et al., 2017). This implies that modellers faced difficulties in the data collection for all variables of the complex water systems driven by multiple interactions from climatic and non-climatic changes.

The optimisation approaches for both calibrating the model structure and policy design are rarely applied in the current applications of SD models in water resource management. Simulation and optimisation in SD applications are complementary approaches to enhance the performance of the model as well as identify the robust policies for the system (Coyle, 1999; Duggan, 2008). Especially, the optimisation process helps identify the best combination of parameter values, based on a specific objective function through repeated simulation, where sets of parameters are passed through the optimizer, and then the payoff function value will be achieved, thereby evolving simultaneously both the system structure and its parameter values (Duggan, 2008; Chen et al., 2011). Several optimisation algorithms (e.g. Wolfe-Powell method, The Steepest descent method) have been used to optimise the model structure and policy in SD modelling approaches. These methods aim to determine a set of optimal parameter values and optimise the objective function (Chen et al., 2011). Although the existing optimisation approaches have ability to adjust to include several nonlinear systems in parallel or series with different constraints, they have inability to deal with the stochastic patterns of system parameters (Zomorodian et al., 2018) or difficulty to search optimal solutions and define objective functions (Coyle, 1999). Recently, several evolutionary algorithms (e.g. genetic machine-learning approaches) have been applied to enable decision makers to vary policy equation structures in beer games by agent-oriented SD models (Duggan, 2008), and to optimise both the system structure and its parameter values in World Dynamics model by neural networks-based SD models (Chen et al., 2011). These evolutionary algorithms would be a useful direction for examining both simulation and optimisation processes in SD applications – a current issue for SD modellers in the management of complex water systems.

### 4.2. Challenges and limitations of system dynamics applications for water resource systems

Although SD models have proven an effective modelling tool for a range of sub-systems, expansion of system boundaries to include hydrological, social, economic and environmental sub-systems introduces more complexity than when each system is considered separately. This complexity is typically driven by different time and spatial scales and multiple interactions among the factors of various sub-systems. Therefore, modellers faced difficulties in the development of conceptual models, calibration and validation of a complex water resource system - a result of discrepancies between scales and complexity. As a result, this review found that most of reviewed studies that included CLDs were rarely considered for four sub-systems, especially for the systems that include cultural or political sub-systems because cultural or political variables cannot easily be conceptualised in both qualitative and quantitative aspects.

A high level of uncertainty and dynamic complexities due to nonlinearities, feedback and delays are inherent in water resource management systems, which create challenges for decision-makers. In addition, water resource systems have spatial and temporal characteristics, and thus patterns in time and space need to be examined together to understand the dynamic behaviour of the system as a whole (Ahmad and Simonovic, 2004). However, SD models have inherent limitations in dealing with uncertainties and spatial dynamics in water resource systems, especially under the drivers of climate change impacts, because SD is not well suited to incorporating the qualitative perspectives which these uncertainties often derive from (Kelly et al., 2013). To deal with uncertainty in climate change impacts, several modellers have developed plausible scenarios in a different range of values, as well as conducting sensitivity analysis to produce a broader range of reasonable modelling results and to reveal parameters or model components with the greatest effects on the outcomes. For example, Gohari et al. (2017) developed three different climate change scenarios based on 25%, 50% and 75% probability percentiles under A2 and B1 emission scenarios, comparing the effectiveness and flexibility of different policies and indicating that these three scenario ranges help to deal with uncertainty in climate change assessment. In addition, Kotir et al. (2016) conducted a sensitivity analysis by individually offsetting $\pm$ 10% of key variables to evaluate how changes in uncertain parameters affected model behaviour and to systematically minimise the potential influence of uncertainties in the model output.

### 4.3. Development of a SD modelling framework for complex water resource systems

All of these limitations point to the fact that developing fully integrated water resource models remains a challenging task that requires multi-disciplinary skills and knowledge, data and participatory approaches that can deal with all factors and feedback in complicated water resource systems. Although the SD method has proven to have the capacity to model multidisciplinary problems, this alone would be unable to capture the high level of uncertainty and dynamic complexities in water resource systems (Zomorodian et al., 2018; Zare et al., 2019). In addition, a single modeller would not have comprehensive knowledge for developing an integrated SD model that covers all factors and feedback in complex and uncertain water resource systems. Thus, an integrated modelling framework, such as the integration of SD with GIS or Bayesian networks, is required to compensate for these deficiencies; capture dynamic feedback processes in time and space (Ahmad and Simonovic, 2015). It is also necessary to intensively engage relevant stakeholders, including hydrologists, social scientists, and economics and environmental experts as well as other relevant experts to integrate multidisciplinary perspectives for developing conceptual models, and understanding and reducing uncertainties in water resource systems under climatic and non-climatic changes. Particularly, the multi-disciplinary knowledge assists in assessing causal and feedback relationships from different components in the system, and validating the models for the complex water systems.

The integration of SD with the other modelling tools found in this review has some advantages in dealing with complex and uncertain water systems. For example, Ahmad and Simonovic (2015) indicated that coupling SD with hydrodynamic models provides powerful tools for understanding the dynamic characteristics of flood risks and their spatial variability, thereby enhancing the modelling capabilities of river flood risk management. Xi and Poh (2015) also suggested that a combined SD and analytic hierarchy process method helped decision-makers to quantify the priorities of various development plans for integrated water resource system in Singapore. Xu et al. (2020) proposed an integrated model combining a bi-objective mathematical model with the SD method to balance a trade-off between the risk of an increasing future supply-demand imbalance and current water adequacy, thereby identifying a sustainable planning period. Li et al. (2018b) also argued that a hybrid SD and optimisation approach provides a strong reference for decision-makers to optimise water allocation by weighing the cost of the water system, the water distribution target and system risk. In addition, Bertone et al. (2019) indicated that coupling SD modelling with Bayesian networks can help deal with uncertainties, missing data and non-linear behaviours for sustainable long-term water resources management under uncertain conditions.

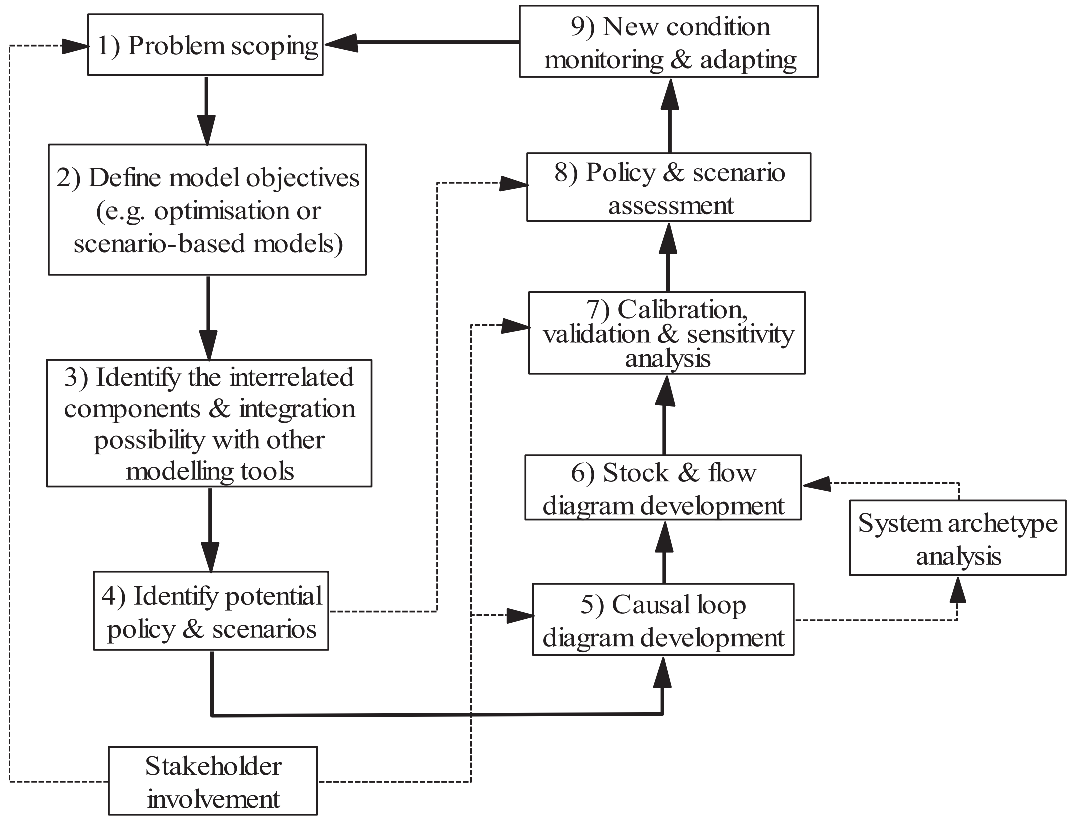


**Fig. 7.** A SD modelling framework proposed for the management of complex and uncertain water resource systems. Solid arrows are suggested information flows.

A traditional SD modelling framework consists of four phases: problem scoping and structuring, model conceptualisation, model implementation and testing and scenarios analysis (Sterman, 2000). However, to manage complex and uncertain water resource systems, an integrated SD modelling framework with nine phases is proposed to model complex, uncertain and spatial water resource systems, as illustrated in Fig. 7 and further explained below.

(1) Define challenges confronting the management of water resource systems by collecting and analysing information and data to understand problems in the systems and identify stakeholders to involve in the modelling process.
(2) Identify the type of the model (e.g. optimisation models to optimise the management measure or scenario models to evaluate the effectiveness of management measures under different scenarios).
(3) Identify interrelated components by conceptualising and quantifying relationships among factors in the system and considering the integration of SD with other modelling tools to compensate for the deficiencies of SD application (e.g. uncertain and spatial characteristics) in water resource systems.
(4) Identify potential policy and scenarios with relevant stakeholders for the studied water resource systems.
(5) Develop CLDs and identify system archetypes by identifying important variables that improve understanding of complex water resource systems (e.g. problem boundaries and model structure) and enhance the accuracy of simulation models.
(6) Develop stock and flow diagrams by incorporating essential variables from the CLDs and findings from historical data analysis to understand the dynamic behaviour of the system over time.
(7) Calibrate and validate the models and conduct a sensitivity analysis to increase the credibility and validity of the SD applications as well as to reveal parameters or model components with the greatest effects on outcomes.
(8) Assess potential scenarios and policies for a range of values to manage uncertainties in scenarios and policy assessment so that decision-makers can better understand dynamic behaviours and management options for challenging water resource problems.
(9) Monitor performance of the implemented management measures and adapt models and management measures to reflect changing conditions and management priorities.

### 4.4. *Future research directions*

Furthermore, two future research priorities are also suggested to enhance the application of SD in water resource management. (i) Optimisation models of potential management options should be prioritised to study water transfer, re-operations, wastewater treatment and water use efficiency rather than seeking new supply water sources or infrastructure development because of climate change and socio-economic stressors. (ii) Climate change impacts and adaptation strategies are another priority to enhance understanding of their impacts and to help develop better adaptation policies for challenging water resource systems. Importantly, these impacts and strategies should be assessed based on a holistic view of dynamic processes and interactions within water resource systems, accounting for the system's socio-economic and environmental dimensions along with hydrological attributes.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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