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Dynamic water system modeling: a systematic review

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ABSTRACT

Improving water resource management at a global scale is critical at this time. The risks to which bodies of water are currently exposed, whether due to climate change or anthropogenic conditions, affect water availability and quality in basins around the world. Nevertheless, water management has been revealed as a complex problem. In this light, one of the most promising methodologies is building dynamic simulation models, which may include the largest possible number of variables, not just hydrological. In this way, we may gain a broader perspective on all the natural and social dimensions encompassed in basins and, thus, improve decision making for the benefit of the population. This systematic review seeks to report the most representative results from several authors who have developed dynamic models applied to the management of water resources. Herein, special emphasis is placed on water resource management applied to basin models, decision making, and public policies, as well as on the modeling tools used and on model validation.

Key words: complex system, dynamic modeling, preferred reporting items for systematic reviews and meta-analyzes methodology, water management, water security

HIGHLIGHTS

- Studying and assessing water management as a complex system generates multiple benefits.
- Dynamic modeling is one of the most powerful methodologies used to describe systems and their behavior.
- The dynamic modeling of integrated water resource management is an active field of research.

INTRODUCTION

Water security is one of the main challenges faced by many modern societies today, as has been revealed in the annual Global Risks Report issued by the World Economic Forum, which mentioned water crisis as one of the main risks facing humanity (World Economic Forum 2019; World Economic Forum 2020). The importance of water security is also recognized by several international organizations (i.e. GWP 2000a; UNESCO 2014).

Despite its importance, water management has been deemed a complex problem, since it involves a vast number of different variables, from environmental and hydrological to social, legal, and institutional, among others. In recent decades, this level of complexity has been acknowledged by water management experts, who have developed the concept of Integrated Water Management. This new concept proposes a new approach that comprises the physical, social, economic, and environmental dimensions of this discipline (GWP 2000b, 2009). Within this context, one of the Sustainable Development Goals (SDG 6.5) established by the United Nations is 'by 2030, implement integrated water resources management at all levels, including transboundary basins as appropriate.' Nevertheless, this progress is still extremely limited. Further, the United Nations estimates that only 20% of the countries around the world, most of them developed countries, exhibit high or very high Integrated Water Management rates (UN Environment 2018).

When implementing Integrated Water Management, one of the main problems identified is transitioning from disciplinary approaches to a systemic approach. Up to now, the most popular analysis method has been the Reductionist approach, which basically consists of assessing the problem from a disciplinary approach.

The Reductionist approach, which still predominates in science to this day, is characterized by breaking down natural phenomena into their component parts for their subsequent analysis by any scientific discipline. For example, the same natural phenomenon, such as water management, may be assessed by several branches of science such as hydrology, hydraulics, physics, chemistry, economics, and sociology. However, even when each of these disciplines provides further knowledge in some aspects, none of them can account for the behavior of the whole. This scientific approach has been extremely successful in understanding and modeling isolated phenomena, but it has also proven to be completely insufficient when dealing with complex phenomena, in which the behavior of the system cannot be fully explained in terms of its isolated elements (Meadows 2008; Johnson 2011).

In complex natural phenomena, notably among those involving biological, social, and environmental processes, systems cannot be split into their component parts for their assessment because, once a system has disintegrated, it will no longer exhibit the behavior that actually occurs in the real world. To properly understand and model systemic phenomena, systems must be studied completely. For example, even when equations that model the natural hydrological cycle may be identified, as soon as anthropic interventions occur, the affecting social and human processes, such as water demand, which in turn depends on economic, social, and cultural variables, among others, may not be easily accounted for in these hydrological models.

Due to its own nature, water management is a complex system. Hence, in the last decades, research has been focusing on the application of dynamic modeling without yet establishing a common methodology (Walton *et al.* 2009). One of the main approaches to complex systems is dynamic modeling, which, among other benefits, considers a large number of different variables involved in the system, the structure of the system, including feedback loops, and scenario analysis.

As per the foregoing, this article reports the results from a systematic review focused on the application of dynamic models to water resource management.

METHODS

A systematic review is a comprehensive review driven by synthesis of data focusing on a topic or on related key questions (Enago 2019) that follows an internationally renowned methodology. In this case, the Preferred Reporting Items for Systematic reviews and Meta-Analyzes (PRISMA) methodology was used, as depicted in Figure 1.

As systematic reviews are part of the scientific method, a series of clearly defined steps must be followed for their proper implementation. According to Khan *et al.* (2003), there are five general steps for their development, as listed and explained below:

I. Framing the question.
II. Identifying relevant publications.
III. Assessing study quality.
IV. Summarizing the evidence.
V. Interpreting the findings.

The first step is critical, since it defines the query within the research study. In this case, the problem was specified in the form of extremely clear and unambiguous questions before beginning the review work. The main question in this work is: *What is the current state-of-the-art of dynamic modeling applied to water resources?* and more specifically, *what are the methodologies used?*

The second step, 'Identifying relevant publications,' refers to performing an extensive search in multiple resources available, such as books, scientific articles, databases, and interviews, including printed and physical items.

The search criteria will be previously provided based on the research question defined in the first step. The search criteria or strategy used in this research was: DYNAMIC MODELING (OR DYNAMIC SIMULATION) AND (WATER RESOURCES OR WATER MANAGEMENT). For this search, we used the Scopus database, since it is a renowned extensive database that hosts reliable and updated articles.

After entering the previous sequence, a search query was performed by article title, abstract, and keywords. The first search yielded 227 results and, as is common in these cases, many of these results were not relevant. The exclusion criteria were the following:

1. Duplicate articles were immediately removed.
2. The results were then restricted to articles published from 2000 to 2020 and, thus, the list was reduced to 171.
3. Of these 171, those articles whose title did not clearly reflect our interest (not directly related to dynamic water management modeling issues) were removed from the list. As a result, the total number was reduced to 27.

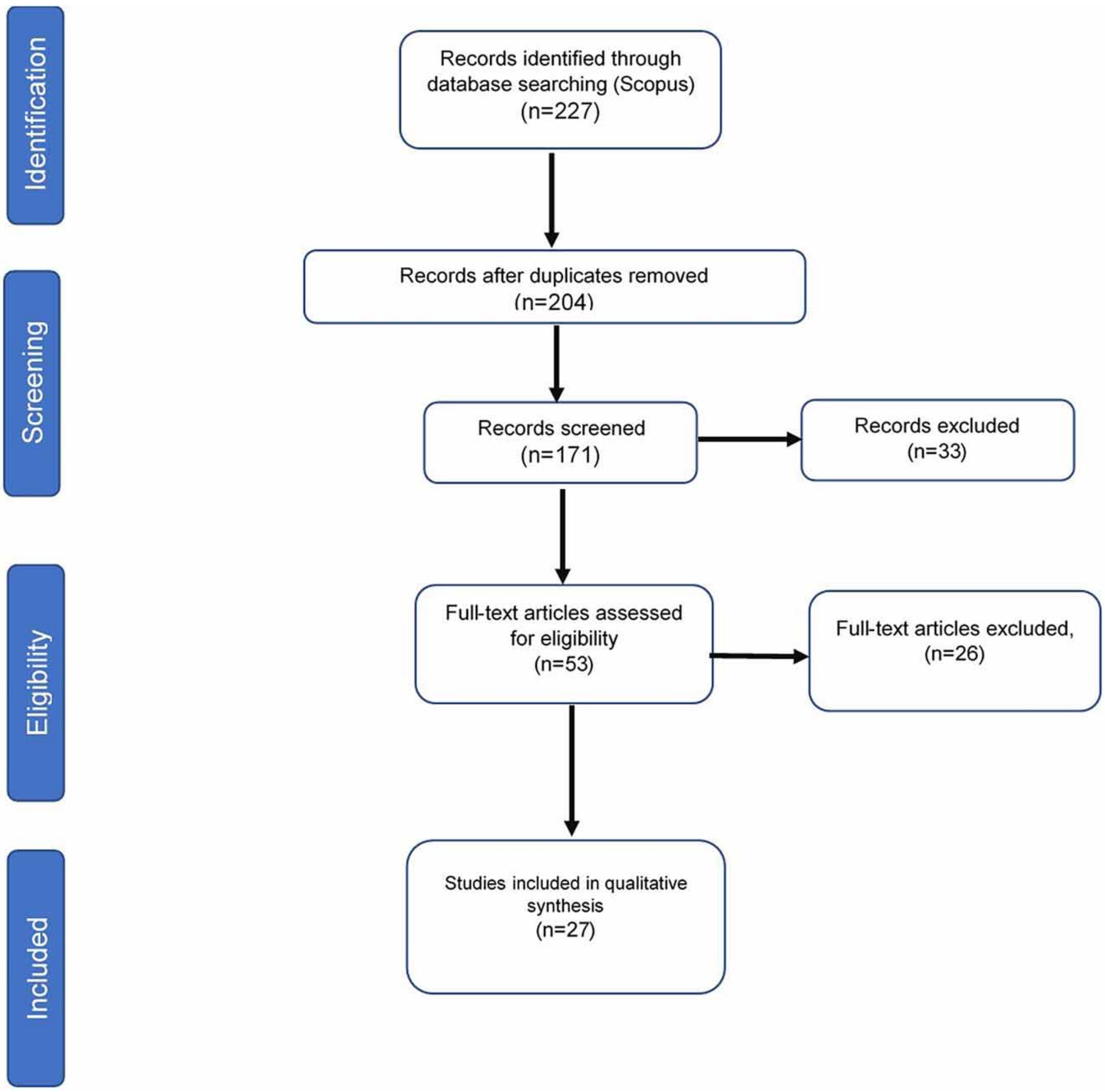

Figure 1 | Systematic Search Flowchart (prepared based on the PRISMA model, www.prisma-statement.org).

4. The existence of similar articles was analyzed; that is, of previous systematic searches. For this purpose, a search was made in the Science Citation Index with the following strategy: 'dynamic modeling AND water management AND systematic review' and no results were found, so it is considered that there are no previous studies with the systematic search methodology such as used in this article.
5. Based on the methodology used, as a first stage, all abstracts were reviewed. Then, all articles whose abstract was found relevant according to our initial research question were selected for a full text assessment.

The third step, 'Assessing study quality,' is relevant to every step of a review. This stage guarantees from the beginning that we are working with recognized sources of information and scientific articles.

Step four of the methodology, 'Summarizing the evidence', is an essential part of the development of a systematic review. Due to the large amount of information managed, any information found relevant must be fully described, as well as the criteria used to determine its relevance. If possible, the approaches used by different authors must be compared against each other.

The final step, 'Interpreting the results', leads to the conclusions achieved by the systematic review, establishes the points of view, in which different authors agree or differ, and suggests appropriate recommendations (Khan *et al.* 2003).

The PRISMA methodology has been recommended as the ideal methodology for performing our systematic review and reporting its results. This methodology is defined as an evidence-based minimum set of items for reporting in systematic reviews and meta-analyses. In fact, one of the PRISMA goals is to help authors improve the report of systematic reviews and meta-analyses. Also, for journal peer editors and reviewers, PRISMA may also be useful for critical appraisal of published systematic reviews, although it is not a quality assessment instrument to gauge the quality of a systematic review (PRISMA 2020).

Table 1 below lists the articles from specialized journals that have been used in this document; the summarized results from the systematic review conducted in Scopus.

RESULTS AND DISCUSSION

Recently, environmental problems have been gaining the attention they deserve due to the negative effects they cause to humanity. For this reason, scientists and researchers are exploring new techniques for better studying this type of phenomena. These techniques often involve a large number of processes that interrelate, transform, act, and interact among themselves to finally constitute what we now know as a 'complex system.'

More specifically, in 2008, in a paper entitled 'Complex Systems: A Contemporary Perspective,' Figueroa Nazuno (2008) asserts that a system may be deemed as complex if it contains a large number of variables that interact among themselves. Additionally, these variable interactions must be non-linear, and despite their extreme simplicity, these problems cannot be solved using current mathematical or theoretical procedures. Finally, the system may be deemed as complex when the knowledge of its component parts must not be sufficient to know and explain its behavior as a whole.

To provide an accurate representation of these systems, models depicting the studied reality, including all of its different elements, are built. Still, dynamic systems are a methodology and not a simple one at that, which is implemented to describe and reproduce the behavior exhibited by a system and assess its performance for decision-making matters. The importance, relevance, and convenience, among many other qualities, of using dynamic models in water resource management is described in a significant number of research articles, books, and conferences.

Researchers such as Mohammad Azmi, Nima Heidarzadeh, Sajjad Ahmad, Ali Mirchi, Kaveh Madani, David Watkins, Sajjad Ahmad, and the renowned Dr Slobodan P. Simonovic all refer to the origin of dynamic systems in their works and recognize Forrester as the first to mention complex dynamic systems in 1958 (Forrester 1968; Ahmad & Simonovic 2004; Mirchi *et al.* 2012; Azmi & Heidarzadeh 2013).

In fact, this methodology continues to be explored in several disciplines and has been used to address issues of multiple nature. For instance, in the 1990s, Simonovic & Fahmy (1999) discussed the matter in water systems in their article 'A new modeling approach for water resources policy analysis,' wherein they laid the foundations for a main branch of dynamic modeling that specifically focuses on issues related to water resources. More than a decade later, Ryu *et al.* (2012) continued studying the advantages that the implementation of these models brought about for the development of water resource management plans and the role they play in decision making.

Historically, the literature provides several examples wherein authors not only denote the advantages of using dynamic models but also extensively describe their virtues. For example, some authors highlight their capabilities for accurately representing water systems, their contributions to better understanding the interactions and relationships among the different variables involved, their abilities for illustrating water management and displaying several water management options and ideas, how they promote citizen participation or even the implementation of policies to mitigate the impacts from the specific conditions of a given basin or region, and the role they play in ecosystem modeling, natural resource management, climate change, or even disaster management (Ahmad & Simonovic 2004; Azmi & Heidarzadeh 2013).

Due to their importance, this systematic review focuses on some of the most relevant papers found in the literature in the hope they will be useful for scholars and other stakeholders interested in the subject.

In this light, system dynamics represents not only the realization of a model *per se* but also a radical change of thought. Building a dynamic model requires a vast previous knowledge of the system being modeled and warrants collaborative and integrative work among multidisciplinary fields.

Given the current challenges facing water management, simpler models that fail to consider population changes, socioeconomic changes, environmental changes, and the impact that they all have on water resources,

Table 1 | Information from specialized journal articles selected in the systematic review

Authors	Title	Year	Source title	Volume, Issue	DOI
Abou-Abdo T., Davis N.R., Krones J.S., Welling K.N., Fernández J.E.	Dynamic modeling of Singapore's urban resource flows: Historical trends and sustainable scenario development	2011	Proceedings of the 2011 IEEE International Symposium on Sustainable Systems and Technology, ISSST 2011		10.1109/ISSST.2011.5936851
Ackerman D., Stein E.D. (Ackerman & Stein 2008)	Evaluating the effectiveness of best management practices using dynamic modeling	2008	Journal of Environmental Engineering	134, 8	10.1061/(ASCE)0733-9372(2008)134:8(628)
Ahmad S., Simonovic S.P.	Spatial system dynamics: New approach for simulation of water resources systems	2004	Journal of Computing in Civil Engineering	18, 4	10.1061/(ASCE)0887-3801(2004)18:4(331)
Azmi M., Sarmadi F.	Dynamic modelling of water resources sustainable development using a mathematical approach	2015	KSCE Journal of Civil Engineering	19, 6	10.1007/s12205-015-0341-0
Bittumon K.B., Ivanov M., Ivanova O., Revetria R., Sunjo K.V.	Modeling for the safe management of complex river basins	2018	Lecture Notes in Engineering and Computer Science	2,238	
Cabo F., Erdlenbruch K., Tidball M.	Dynamic management of water transfer between two interconnected river basins	2014	Resource and Energy Economics	37	10.1016/j.reseneeco.2014.03.002
Carrera-Villacrés D.V., Quinteros-Carabalí J.A., Gómez A.J., Solano E.M., Llumiquinga G.E., Burgos C.A.	Dynamic model for the management of water resource and water aptitude for irrigation of the Togllahuayco gorge in the Guangopolo micro-basin	2019	IOP Conference Series: Earth and Environmental Science	344, 1	10.1088/1755-1315/344/1/012029
Flores M.J., Nicholson A.E., Ropero R.F.	Dynamic OOBNs applied to water management in dams	2016	2016 IEEE International Conference on Knowledge Engineering and Applications, ICKEA 2016		10.1109/ICKEA.2016.7803030
Ghbn N.	Dynamic Modeling for Municipal Climate Change Adaptive Measures and Integrated Watershed Management	2016	World Environmental And Water Resources Congress 2016: Hydraulics and Waterways and Hydro-Climate/Climate Change – Papers from Sessions of the Proceedings of the 2016 World Environmental and Water Resources Congress		10.1061/9780784479872.066
Guo X., Zhou X., Chen Q., Liu J.	Flow field and dissolved oxygen distributions in the outer channel of the Orbal oxidation ditch by monitor and CFD simulation	2013	Journal of Environmental Sciences (China)	25, 4	10.1016/S1001-0742(12)60114-4

(*Continued.*)

Table 1 | Continued

Authors	Title	Year	Source title	Volume, Issue	DOI
Haasnoot M., Van Deursen W.P.A., Middelkoop H., Van Beek E., Wijermans N.	An Integrated Assessment MetaModel for developing adaptation pathways for sustainable water management in the lower Rhine Delta	2012	iEMSs 2012 - Managing Resources of a Limited Planet: Proceedings of the 6th Biennial Meeting of the International Environmental Modelling and Software Society		
Karamouz M., Goharian E., Nazif S.	Development of a reliability based dynamic model of urban water supply system: A case study	2012	World Environmental and Water Resources Congress 2012: Crossing Boundaries, Proceedings of the 2012 Congress		10.1061/9780784412312.207
Karimlou K., Hassani N., Mehrabadi A.R., Nazari M.R.	Correction to: Developing a Model for Decision-Makers in Dynamic Modeling of Urban Water System Management (Water Resources Management, (2020), 34, 2, (481–499), 10.1007/s11269-019-02428-z)	2020	Water Resources Management	34, 8	10.1007/s11269-019-02478-3
Lee M.T., Chang Y.C. (Lee & Chang 2006)	Strategic analysis for sustainable urban river aquatic environment using the system dynamic approach	2006	Water Science and Technology	53, 1	10.2166/wst.2006.003
Lord B., Zechman E., Arumugam S.	A complex adaptive system approach assessing the dynamics of population growth, land use, and climate change for urban water resources management	2013	World Environmental and Water Resources Congress 2013: Showcasing the Future – Proceedings of the 2013 Congress		
Martínez-Austria P.F., Hidalgo A.V., Patiño-Gómez C.	Dynamic modelling of the climate change impact in the Conchos River basin water management	2019	Tecnologia y Ciencias del Agua	10, 1	10.24850/j-tyca-2019-01-08
Martínez-Austria P.F., Vargas-Hidalgo A.	Adaptive dynamic model for urban water management [Modelo dinámico adaptativo para la gestión del agua en el medio urbano]	2016	Tecnologia y Ciencias del Agua	7, 4	
Mashhadi Ali A., Shafiee M.E., Berglund E.Z.	Agent-based modeling to simulate the dynamics of urban water supply: Climate, population growth, and water shortages	2017	Sustainable Cities and Society	28	10.1016/j.scs.2016.10.001
Mhiribidi D., Nobert J., Gumindoga W., Rwasoka D.T. (Mhiribidi *et al.* 2018)	Optimal water resource allocation modelling in the Lowveld of Zimbabwe	2018	Proceedings of the International Association of Hydrological Sciences	378	10.5194/piahs-378-67-2018

(*Continued.*)

Table 1 | Continued

Authors	Title	Year	Source title	Volume, Issue	DOI
Mohammad Azmi; Nima Heidarzadeh (Azmi & Heidarzadeh 2013)	Dynamic modelling of integrated water resources quality management	2012	ICE Publishing Institution of Civil Engineers	166	https://www.researchgate.net/publication/257271223_Dynamic_modelling_of_integrated_water_resources_quality_management
Oni S.K., Dillon P.J., Metcalfe R.A., Futter M.N. (Oni *et al.* 2012)	Dynamic modelling of the impact of climate change and power flow management options using STELLA: Application to the Steephill Falls reservoir, Ontario, Canada	2012	Canadian Water Resources Journal	37, 2	10.4296/cwrj3702831
Orthofer R., Gebetsroither E., Lehrer D.	Scenarios for a more sustainable water management in the Dead Sea basin	2007	NATO Security Through Science Series C: Environmental Security		10.1007/978-1-4020-5986-5_14
Purnama I.L.S. (Purnama 2020)	Water management model in Bodri River basin, Province of Central Java	2020	IOP Conference Series: Earth and Environmental Science	451, 1	10.1088/1755-1315/451/1/012085
Song C., Yan J., Sha J., He G., Lin X., Ma Y.	Dynamic modeling application for simulating optimal policies on water conservation in Zhangjiakou City, China	2018	Journal of Cleaner Production	201	10.1016/j.jclepro.2018.08.026
Walton B., Nawarathna B., George B.A., Malano H.M.	Future water supply and demand assessment in peri-urban catchments using system dynamics approach	2009	18th World IMACS Congress and MODSIM 2009 - International Congress on Modelling and Simulation: Interfacing Modelling and Simulation with Mathematical and Computational Sciences, Proceedings		
Xiang N., Sha J., Yan J., Xu F.	Dynamic modeling and simulation of water environment management with a focus on water recycling	2014	Water (Switzerland)	6, 1	10.3390/w6010017
Zhu Y., Cao W.-X., Dai T.-B., Tian Y.-C., Yao X.	A Knowledge Model System for Wheat Production Management1 1 Project supported by the National High-Technology Research and Development Program of China (863 Program) (No. 2003AA209030), the National Natural Science Foundation of China (No. 30030090), and the Hi-Tech Research and Development Program of Jiangsu Province (No. BG2004320).	2007	Pedosphere	17, 2	10.1016/S1002-0160(07)60023-X

or that simply consider some factors as independent variables, are no longer adequate due to the complex and dynamic reality of water systems. Continuing to use these models would expose future water resource projections to greater uncertainty. Hence, dynamic models are used to represent dynamic variable interdependencies within a water-related system, since it is an appropriate methodology for modeling complex systems that can accurately predict actual water availability and easily evidence resource management improvements within the basin (Nandalal & Semasinghe 2006; Walton *et al.* 2009).

As a matter of fact, dynamic systems have already been used around the world in different contexts, such as for flood control, to regulate irrigation within a region, for urban water management, in aquifers and, particularly, their implementation has been widely studied at the basin scale (Mirchi *et al.* 2012; Ryu *et al.* 2012; Martínez *et al.* 2019).

Basins play an extremely significant role in water resource decisions. In fact, basins are acknowledged as the basic water management unit, which means that proper strategies and instruments are required for modeling their water resources (in terms of quality and quantity), the variables on which they depend, and their interactions. The following paragraphs will mention some authors who have addressed water resources issues by developing dynamic models at the basin scale.

Guo *et al.* (2001) conducted a research study at the Erhai Lake basin, where some dynamic simulation models were performed. Their work consisted in assessing deterioration in water quality due to a growing socioeconomic development in that area. Seeking to improve water resource management planning, dynamic models were used to find better ways to leverage the resources available. Herein, the authors consider that these models provide an important advantage because 'such models are capable of synthesizing component-level knowledge into system behavior simulation at an integrated level.'

In 2018 the article 'Modeling for the Safe Management of Complex River Basins' was published; the article points out how a good control strategy can generate benefits in electricity production (hydroelectricity) and irrigation. They developed a model for the management of dams in a hydrographic basin considering the energy production required, minimizing the risks of flooding and maintaining a certain level of water in the basin. In general, the implementation and use of the model can be used to optimize decisions regarding plant management (Bittumon Ivanov Ivanova Revetria & Sunjo 2018).

In their study, Martínez *et al.* (2019) built a dynamic model for the Conchos River basin, which is affected by population growth, the effects from climate change, and water stress, to which the basin is currently subjected. This model intended to assess the time-dependent change in the water balance because of the changes observed in the different variables – governance, population, temperature, and water supply and demand. For these purposes, the authors executed three different scenarios with different conditions, which contributed to a better understanding of the basin.

Also in 2019, an article called '*Dynamic model of water resource management and water aptitude for irrigation of the Togllahuayco stream in the Guangopolo micro-basin*' was published and also presented at the V International Conference on Water Resources and the Environment. In this document, the authors emphasize the importance of the study of water management, which is an important pillar in the areas of water security, which is affected by the degradation that exists in the hydrographic basins derived mainly from the agricultural sector (due to erosion problems and reduction of water resources). They studied the availability of water volumes, which year after year decrease considerably due to an increase in the population rate, closely related to food security and a good part of income in developing countries. The authors used the model as a tool that will help to determine the amount of water available in a crop and the adaptation capacity due to future conditions of climate change and also growth in water demand; all this was simulated until the year 2040 (Carrera-Villacrés *et al.* 2019).

Public policies

Due to the vital importance of water, health protection is also a critical aspect that must be considered. Protecting people from possible harmful effects, coupled with an adequate management of water quality and quantity, are elements that must be regulated through the implementation of appropriate water resource management policies. Consequently, another important number of researchers have targeted their dynamic models toward this interesting topic, as described below.

Simonovic & Fahmy (1999) mention that the implementation of public water resource management policies is a difficult, slow, and expensive process. However, the implementation of dynamic simulation models improves the visibility of the existing alternatives for decision makers.

Furthermore, this systematic review revealed some similarities in the different models used. For example, special attention must be paid to how authors segregate water information into consumptive uses, such as industrial, urban, irrigation, livestock, and other minor uses. They also consider population, including time-changing growth rates and surface irrigation data, since the latter usually represents an important use of water. Additionally, the available models are commonly divided into small subsystems. This way, an organized and clean model may be built to better understand the behavior of the whole system and avoid confusion for the reader or user, which is also an important strategy.

Guo *et al.* (2001) and Ahmad & Simonovic (2004) further agree that system dynamics is a useful methodology for water resources processes, because the behavior of the variables involved changes over time and engages several processes triggered by the different system components, thus favoring the application of a dynamic simulation system. This methodology can also provide a holistic understanding of the main environmental concerns.

Ahmad & Simonovic (2004) claim that there are three major modeling paradigms, which may describe dynamic processes in terms of time and space – geographic information systems, cellular automata, and system dynamics. These three paradigms can be used to represent systems that involve processes in terms of time and space and factors that may generate different conditions that change how the system works. In their paper, these authors suggest a new approach, which they call 'Spatial Systems Dynamics.' This new approach has the potential to improve other models in many application areas, as long as their behavior is expressed in terms of time and space.

Haasnoot *et al.* (2012), as well as Karamouz *et al.* (2012), Xiang *et al.* (2014), Martínez-Austria & Vargas Hidalgo (2016) and Mashhadi *et al.* (2017), agree that population growth, climate change or the rise in sea level, contribute to the problems raised around water management. The authors point out that one of the main challenges is to achieve strategies that are solid and at the same time flexible so that they can adapt to the conditions that may arise. By carrying out their dynamic model, they had as result 'adaptation pathways' that allow them to provide support for decision-making and thus be able to achieve sustainable water management.

Song *et al.* (2018) made a model that will help water conservation with the premise of sustainable economic development. The model succeeded in simulating the complex interrelationships between water resources and the social economy and exploring optimal policies. The results showed that an annual reduction of chemical oxygen demand emissions was possible; noting that the implementation of these models combined with the optimal policies managed to increase the supply of recovered water, facilitate the exploitation of groundwater and optimize the structure of the industries and the demand for water.

Modeling tools

Regarding the tools used to develop the models, there are several programs that help implementing this methodology in a simple way and without requiring specific programs for each case. Some of the most commonly used tools for the development of both qualitative and quantitative dynamic models are Stella, PowerSim, and Vensim (High Performance Systems 1992; Powersim Corporation 1996; Vensim Ventana Systems 2020).

Each one of these programs features their own dynamic model design tools, although they are actually similar. Still, among these three tools, Vensim has been widely used by several authors, such as Goncalves & Giorgetti (2013), Pourfallah *et al.* (2015), Vilchis-Mata *et al.* (2018), Qin *et al.* (2019), Martínez *et al.* (2019), and Karimlou *et al.* (2020), among others.

Model validation

Due to the complexity of dynamic systems, the same calibration used for simple problems is often not possible, which gives way to the concept of model validation. Validating a dynamic model is paramount for verifying its effectiveness as the validation process allows the model to be acknowledged as a useful and realistic tool for the management of water resources. By validating the model, the authors will be able to observe whether the equations used and the model structure and the variables involved provide a proper response to the reality they claim to represent.

The most frequently used validation techniques are model replication, sensitivity analysis, verification based on previous data, validation from system experts, unit consistency, and subsystem evaluations, among others (Guo *et al.* 2001; Ahmad & Simonovic 2004; Mirchi *et al.* 2012; Martínez *et al.* 2019).

At this juncture, we must also emphasize the critical importance of only feeding the most realistic and reliable information possible into the model as the model will feature the same quality as the data it has received.

CONCLUSIONS

Dynamic systems, of which water management is a relevant case, are characterized by featuring different interacting components, exhibiting feedback loops, and being non-linear, adaptive (their governing rules change over time), counterintuitive (causes and effects are distant in time and space), and resistant to external effects; in short, they are resilient (Sterman 2000).

Based on the systematic review conducted, this study concludes that dynamic modeling is indeed a methodology capable of reproducing the complexity evidenced by water systems. Nevertheless, dynamic modeling has not been widely used yet and its applications, thus far, are basically limited to basins and aquifers. Additionally, its potential for assessing water quality variation scenarios and, in general, for decision making and public policy development, must also be noted.

One of the findings of the present systematic investigation has been the almost total absence of papers regarding to the water quality modeling. Most of the selected articles refer to the modeling of water balances. The article by Azmi & Heidarzadeh (2013) explicitly dedicated to basin modeling stands out as an exceptional case, and in which the coupling of integrated water management models (IWRM) with water quality models of reservoirs (WQMR) is discussed. Without a doubt, the dynamic modeling of water quality in bodies of water (lakes, reservoirs or rivers) is a pending task. Furthermore, since it is relatively recent, it is an active research field, in which major questions, such as the validation of dynamic models, still remain open.

In their article, on using water management scenarios coupled with dynamic models, Qin *et al.* (2019) discuss the urgency of implementing technology capable of saving water in the industrial sector, with special emphasis on the effects that climate change will undoubtedly bring about; all of these will be useful when developing water management strategies in the North China Plain region.

Within this context, Guo *et al.* (2001) understand the need to create effective environmental management regulations or policies, wherein they suggest a comprehensive understanding of the entire system, identifying all contributing parties to the problem, and using a dynamic model to predict how the system will react to the implementation of the proposed policies.

DATA AVAILABILITY STATEMENT

All relevant data are available online.

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