The role of agent-based modeling and multi-agent systems in flood-based hydrological problems: a brief review

Jose Simmonds, Juan A. Gómez and Agapito Ledezma

ABSTRACT

Flood problems are complex phenomena with a direct relationship with the hydrological cycle; these are natural processes occurring in water systems, that interact at different spatial and temporal scales. In modeling the hydrological phenomena, traditional approaches, like physics-based mathematical equations and data-driven modeling (DDM) are used. Advances in hydroinformatics are helping to understand these physical processes, with improvements in the collection and analysis of hydrological data, information and communication technologies (ICT), and geographic information systems (GIS), offering opportunities for innovations in model implementation, to improve decision support for the response to societally important floods impacting our societies. This paper offers a brief review of agent-based models (ABMs) and multi-agent systems (MASs) methodologies' applications for solutions to flood problems, their management, assessment, and efforts for forecasting stream flow and flood events. Significant observations from this review include: (i) contributions of agent technologies, as a growing methodology in hydrology; (ii) limitations; (iii) capabilities of dealing with distributed and complex domains; and (iv), the capabilities of MAS as an increasingly accepted point of view applied to flood modeling, with examples presented to show the variety of system combinations that are practical on a specialized architectural level for developing and deploying sophisticated flood forecasting systems.

Key words | agent-based modeling, autonomous, flood forecasting, hydrological related problems, intelligent, multi-agent system

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INTRODUCTION

Nowadays, the severity in the increase of hydrologic-related problems observed worldwide due to changes in environmental conditions are becoming more frequent and constitute major threats to human lives and to economic development (Noji & Lee 2005; Adikari & Yoshitani 2009). In addition, the number of communities affected by climate change and its related disasters is increasing, especially in low- and middle-income countries where the population continues to rise, as well as an increase in industrialization and rapid urbanization (World Bank 2005, 2012).

From a river basin perspective, hydrologic-related problems, especially those induced by floods, have had severe impacts beyond geographical boundaries. For example, in areas like Asia and the Pacific, the floods of 2014 were responsible for damage that caused some 26.8 billion dollars in economic impacts and resulted in 3,559 deaths as reported by the Economic and Social Commission for Asia and the Pacific (ESCAP 2015), and in 2015 comprised two-fifths of all disasters in the region, causing over 11 billion dollars in economic damage (ESCAP 2016).

On a worldwide basis, it can be noticed that the increase in weather-related phenomena, such as global warming, continues to foster the rising temperatures that we observe, and similarly, it is causing river flood risk distribution to

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increase unevenly, throughout regions like Asia, the USA, and Europe (Alfieri *et al.* 2017). Thus, it is evident that water-related disasters are escalating on an exponential level and present serious concerns to governments. It is important to note that flooding is by no means restricted to a specific country or countries and often does not differentiate between the groups of people it affects, as is the case for recent flooding events in the USA, Australia, India, Iraq, Thailand, and Cambodia (Garner 2013). For these reasons, the need for efficient and precise river flow forecasting tools has been growing at a faster pace in past decades. Conversely, the knowledge and understanding of future conditions on surface water resources are valuable assets for the development and management of proper flood risk mitigation and sustainable water resources management. Traditional flood management systems are largely composed of hydraulic structural protection measures such as terracing, floodways, inundation ponds, dams, weirs, levees, barriers, dikes, embankment, and other structures that constitute the most common structural solutions to reduce flood peak, stages, and inundation extent. One concern of structural measures is that although they reduce flood risk, they are expensive and sometimes are not a guaranteed effective solution. Besides, structural measures are not practical for installation in some areas (e.g., inaccessible areas, no access to roads, mountainous regions), may not be effective for all flood processes and can also generate unfavorable environmental effects (Tullos 2008). On the other hand, the non-structural measures are of two types: the first is of an environmental nature (e.g., replanting, soil management, bank stabilization, revegetation, river training, and flood plain restoration and administration). Notwithstanding, measures like these are far-reaching and costly and do not necessarily reduce flood loss. The second group involves implementing river flood warning systems.

Subsequently, experts (e.g., Gleick 2003; Brooks *et al.* 2009; Opperman 2014; Son *et al.* 2015) suggested shifting from employing structural flood measures to non-structural flood defense measures that ease the hazards of flooding, involving the governance of land development and enhancing flood prediction in densely populated areas specifically at high risk of flooding. A flood event is described as a condition, whether incomplete or complete, in which the flow continuously exceeds the 80% of flows observed during a time period. Floods can be of various categories and dimensions, as such they represent the building blocks for the different types of design and operation of inundation prediction techniques. Flood prediction systems have been put into operation for various scale domains, which include global (Revilla-Romero *et al.* 2015), continental, basin-scale (Azam *et al.* 2017), and urban (Dewelde *et al.* 2014).

Traditionally, flood problems have been treated through the use of rainfall–runoff modeling tools, which are classified into three main categories: (i) empirical (or so-called black-box models), (ii) conceptual (or so-called lumped, semi-lumped, or semi-distributed), and (iii) physically based process models (or white-box models, also known as distributed models) as suggested by Sitterson *et al.* (2017). In this sense, the river flow forecasting applications in water resources engineering are classified into two types with regard to the values and parameters they need: physically based process models and the data-driven types (Wang 2006). Physically based models describe the physics involved in the processes occurring within the catchment by mathematical equations, by connecting empirical and physically based mathematical formulations. In addition, data-driven models do not require knowledge of the governing physical processes, as they rely solely on empirical equations that need lots of data and require on-site data calibration. Generally, the two models differ significantly due to their data requirements and the manner in which they express the physical phenomena (Shrestha & Nestmann 2009).

The number of catastrophic floods that are occurring around the world today is attributed to climate change, which increases the need to develop stronger and ‘intelligent’ flood protection systems to enhance operational flood forecasting and is resulting in many projects for protecting coastal zones from high water surge events that can damage maritime operations (Pousa *et al.* 2013; Alfredini *et al.* 2014; Dong *et al.* 2015; Adam *et al.* 2016; Simmonds *et al.* 2017), urban areas (Elliott *et al.* 2014; Quinn *et al.* 2014; Webster *et al.* 2014; Prime *et al.* 2015), infrastructure, and the population in general (Raber & Ferdaña 2011). These problems call for the design of more sophisticated early warning systems (EWS) and robust databases (DB). Yet, they can be very expensive and one of the most challenging tasks to undertake for flood prevention and disaster management.

An example of tools for implementing EWS is the Urban Flood project, a European initiative that implemented a framework for EWS with the purpose of connecting sensors to real-time models for flood forecasting and warning; however, validation for this system was only done for dikes. Some of the EWS that have been implemented are mostly localized, custom-designed, and need high computational resources (Akhtar *et al.* 2008; Werner *et al.* 2013).

Considering the world we live in is gradually becoming more complex, this means that the hydrological processes in parallel to the changes in the global climate are also becoming more complex; as a consequence, there is a need to develop, investigate, and build models with higher complexities in relation to their interactions with the increasing complexities of the hydrological system. This global increase in complexities could also mean that conventional hydrological models may not be equally relevant to model these complex changes.

The general contributions of the current review paper are to explore and demonstrate the use of agents' technologies in flood problems, specifically agent-based modeling and simulation (ABMS) and the multi-agent systems's MAS(s) applicability as a growing requirement for solving flood-based hydrologic problems and to comprehensively categorize these approaches and list their advanced implementation in hydrologic modeling and forecasting along with their advantages, to enable decision-making of flood warning and forecasting using all recent advances in agent technology theory to cope with the notorious changes in the hydrological system in view of climate change. As this is a recent simulation approach in hydrologic research, this assessment also has the aim to serve as signaling for implementing fresh ideas regarding future research in this area. Nevertheless, this paper is not a revision of the literature on hydrologic modeling methods; for further information on that topic, the reader can peruse the following publications (Yaseen *et al.* 2015; Jain *et al.* 2018; Mosavi *et al.* 2018), in which a comprehensive review of hydrologic modeling with traditional models and artificial intelligence (AI) methods such as artificial neural networks (ANN), machine learning (ML), data mining (DM), soft computing (SC), and their variants can be found.

A summary of this work is as follows: immediately below, the background of agents as a modeling paradigm for complex problem-solving are briefly discussed. Next, a section describes the research methodology and discusses the primary objective of the review. This is followed by a section presenting the theories and concepts of agent-based modeling. Then, a section presents the theories and concepts of multi-agent systems. The applications of ABM and MAS in flood-based hydrologic-related problems with some examples are presented, and the final two sections present the conclusions and future perspectives.

A BRIEF BACKGROUND ON ABM AND MAS

Studies in the agent-based modeling area, although some researchers may also argue that it has its roots in complex adaptive systems (Waldrop 1993; Chan 2001; Borshchev & Filippov 2004; Heath 2010), were initiated with artificial intelligence and computer science with its many forms of one-agent systems, such as intelligent assistants and service robots (Agre & Rosenschein 1996), but nowadays it is being developed in other areas in academic research and industry (see Table 1). In this sense, it should be noted that according to O'Sullivan & Haklay (2000) and Gimblett (2002), the prospective for sociological applications lies in the nature of multi-agent systems. In addition, in fields such as geography, the physical components that entail complex systems like vegetation, fauna and flora, physiography, climate, and hydrological components are often unconnected from the socio-economic factors, such as demography, culture, economy, and policy (Reenberg 2001).

In the 1970s, John Conway built a two-dimensional (2D) cellular automata model for which he coined the term 'Game of Life' (Figure 1). This model architecture consisted of a cell layout with two conditions, alive or dead; in this respect, the condition of one cell depended on that of its neighbor's previous time step. Conway's game was the trigger for the interest in the beginning of complexity from simple instructions.

The evolution of ABMS development continued throughout the 1990s, as can be witnessed through the emergence of diverse means of application, such as Swarm, one of the earliest application tools built for

Table 1 | Areas of agent-based modeling applications (modified from Macal & North 2006)

Field	Applications	Field	Applications
Commercial and institutional	• Industrial processes • Resource chain • Supply chain management • Supply and demand • Customer marketplaces • Manufacturing handling	Society and culture	• Early societies • Civilian insubordination • Associated terrorist attacks • Administrative systems
Economics	• Computational economic marketplaces • Commercial nets • Computational economics • Economical ecology	Military	• Authority and jurisdiction • Enforcement
Infrastructure	• Energy power markets • Transportation • Hydrogen infrastructure • Oil and gas industry	Biology	• Civilian displacement • Natural systems • Ethology • Cellular performance and subcellular developments • Environmental science
Crowds	• Population flow • Withdrawal simulation	Engineering	• Power engineering • Systems dynamics • Control engineering • Water resources engineering • GIS simulations

agent-based modeling and simulation (Minar *et al.* 1996), NetLogo, which was first known as 'StarLogoT' in the mid-1990s (Wilensky 1997), Recursive Porous Agent Simulation Toolkit (Repast) (Collier *et al.* 2003), and AnyLogic with its initial release in 2000 by the former XJ Technologies.

During that same period, Epstein & Axtell (1996) implemented Sugarscape, an AI agent-based social simulation model (ABSS), which adapts the fundamental concepts of social sciences. This prototype was composed of a system of naive procedures which formed the basis for the creation of other procedures that enhanced supplementary remarkable outcomes. Sugarscape is an example that presents in what way basic procedures might produce composite organization in a bottom-to-top approach, with local instructions being at the bottom and ascending to adaptive behaviors and system performance right up to the top. At the end of the 1990s, the power of computers

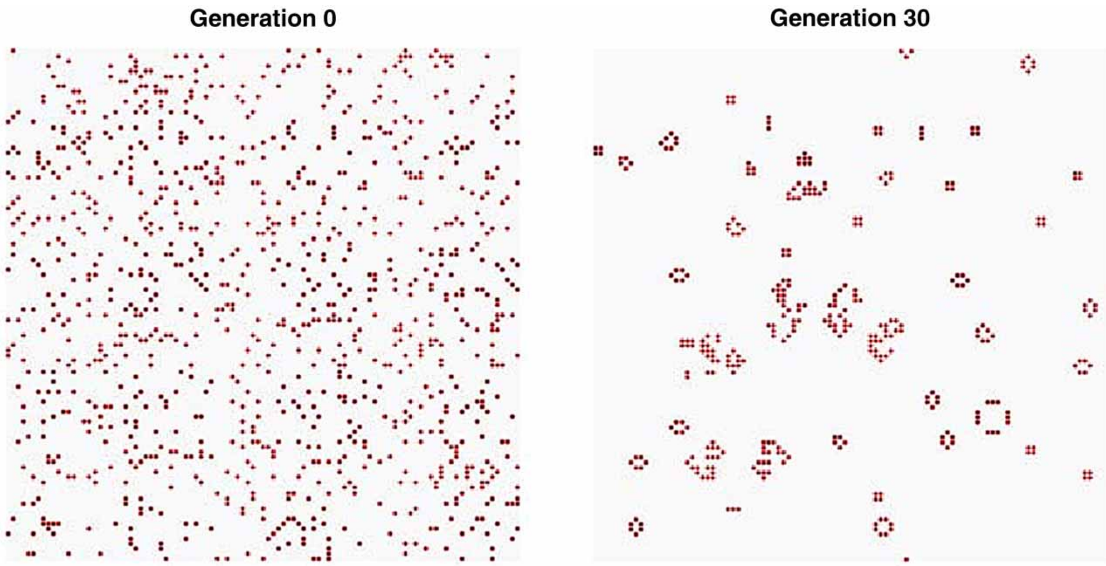

Figure 1 | The 'Game of Life' by Conway, a cellular automata example (*source*: Macal & North 2008).

progressed considerably, and agent-based models became well-known.

When dealing with agent technology we must keep in mind that agent-based modeling is known throughout the literature by names such as agent-based systems (ABS), individual-based modeling (IBM), and multi-agent systems (MAS). In the sections 'The agent-based modeling and simulation concepts' and 'The multi-agent systems concepts', the ABM and MAS concepts, respectively, are addressed in-depth.

RESEARCH METHODOLOGY

The present review uses several articles related to ABM and MAS paradigms that are used to assess and solve problems in the hydrological field. These include the implementation of flooding safety and planning policies, flood control and management, flood warning, and in general, water resources management and its implications under the impact of hydrological natural phenomena (e.g., severe rainfall and floods) and man-made activities leading to hazardous effects on the civilian population, environment, economy, and infrastructures. The purpose of this information is to make a particular use of the agent prototype to encourage the advancement and performance of stream-flow, and flood forecasting. To conduct this survey, we relied on a careful selection of scientific articles from scholarly resources, journals, and magazines like ACM, IEEE, Springer, PLOs, ScienceDirect and the Google Scholar website, with outstanding Impact Factor, as specified by the Journal Citation Reports (JCR), and from respected international conferences proeedings. This review is intended to encourage research and specialization in flood forecasting systems grounded on agent technologies, specifically the MAS methodology, and to improve the agents' methodologies and their experimental performance and strength in coupling with other computational systems.

According to the findings in the literature, ABM and MAS show scarce research on stream-flow and/or flood forecasting, with ABM being less implemented for the task, compared to the MAS and other AI approaches for solving the problems.

AGENT-BASED MODELING AND SIMULATION

The agent-based modeling and simulation concepts

Before introducing the notions of ABMS as a promising technique used in the development of many composite applications for assessing and providing solutions in hydrologic-related problems, it is necessary to introduce its definition. Therefore, ABM can be defined fairly as a novel methodology for simulating complicated domains comprising cooperating, independent agents, that can exist in space and time (Holland & Miller 1991; Macal & North 2010). Many authors in the research community claim that ABM represents a new paradigm for simulation (Davidsson 2000); however, they disagree among themselves on how to define the agent concept as there are many points of view (Franklin & Graesser 1997; Wooldridge 1999; Jennings 2000; Luck 2001; Riley 2002; Macal & North 2005). So, what is an agent (Figure 2)? As said previously, the definition of an agent is not clear, since an agent could be any components forming part of a system when different objectives in different paradigms are studied. For example, some would regard it as any type of notable part integrating a model, a system, or a subsystem in a given program

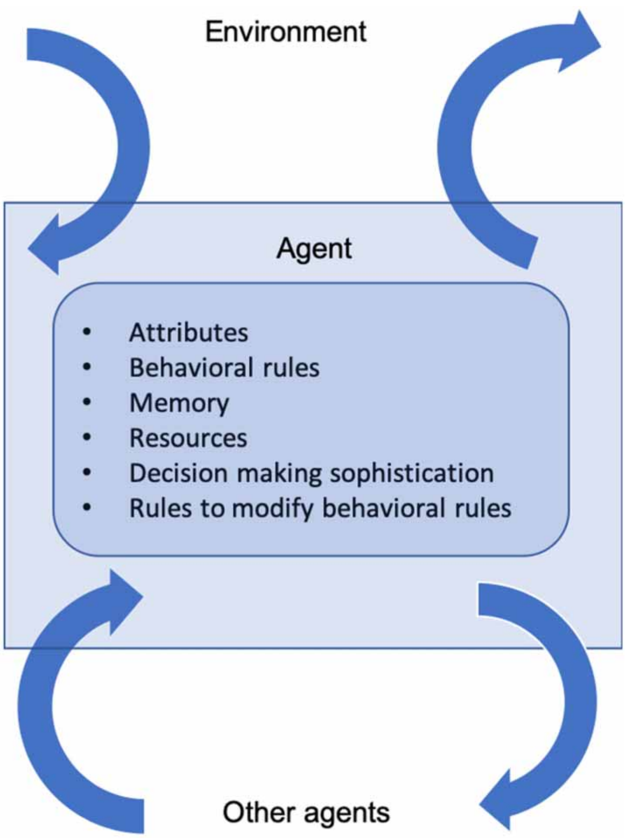

Figure 2 | A characteristic agent (modified from Macal & North 2006).

environment. Likewise, an agent could be considered as any class of autonomous entity, such as an organization, institution, or an individual person. As the idea of an agent is crucial for the understanding and implementation of the ABM systems, most researchers point to the following characterization by Wooldridge (1997) for ABM as they find it useful. ABMs are computer simulations for modeling the behaviors and collaborations between agents which display some sort of autonomous behavior in assessing their cooperation on a system. Additionally, they integrate features from other computational simulation paradigms and schemes. For instance, to introduce repeated randomness into a system, computational algorithms like the Monte Carlo methods are used. According to Volker & Railsback (2005) in an ecological concept, ABMs are known as individual-based models (IBMs). A review by Niazi & Hussain (2011) shows the applications of ABMs in non-computing domains (e.g., biology, ecology, and social science).

Another particular property of ABMs is that they can be displayed as a microscale model (Gustafsson & Sternad 2010), in which the synchronized procedures and relationships of several agents to replicate and forecast the appearance of complicated trends is modeled. Therefore, the process would be one of the developments from a micro- to a macro-level system. As a result, a significant concept is that from simple behavior rules more complex behavior can be generated. Another key principle is the synergy displayed among agents working together as one. Individual agents are usually portrayed as a reasoning entity, acting with independence, and having behavior rules varying from basic reaction decisions to more complex adaptive artificial intelligence (AI) (Macal & North 2006). Bonabeau (2002) argued that in ABM, agents are autonomous entities that may experience 'learning', adaptation, and reproduction.

In the literature review, the use of ABMs is shown to have become increasingly popular in social sciences, given its elegance and explicitness to show objects, environment, and relations between them (Resnick 1997; Jacques 1999; Epstein 2006; Gilbert 2008; Treuil *et al.* 2008; Railsback & Grimm 2011). In spite of many agent-based models having been built to simulate complicated urban and social phenomena, a few are being developed for stream-flow or flood forecasting.

Another important aspect of ABMs is their consideration as experimental tools for theoretical research on complex social experiences for understanding the interactions of the agents and a given environmental scenario. Therefore, as a new approach for analyzing complex systems that emerge through interactions among autonomous agents (Macal & North 2010), and the trends observed in ABM in the manner in which it simulates the system in a bottom-up approach, it suggests patterns, structure, and behaviors that can be perceived.

In respect to their structure, an agent-based model involves three basic components: agents, the agent's association with other agents, and the agent's setting (e.g., 'objects' and the surroundings). In other words, agents denote the active part of the system, the objects are represented by passive elements, and the agent's environment represents the interactions among the different components in the systems.

To offer an intellectual validation, specifically why ABM methodologies are appropriate for solving complexities in computational domains, a qualitative analysis on the topic can be seen in a paper by Jennings (2000). Hence, the reasons why today this idea is largely accepted among researchers in the ABM society is that the technology proposes innovative and often new applicable directions for building complex procedures, particularly accessible and active environments (Luck *et al.* 2004). Briefly shown under this section, we introduced the ABM as a useful intelligent and complex software system that can have many interacting components and parts. Therefore, agents are a useful perspective and appropriate for modeling, as they reduce the time in coupling various systems given the encapsulation provided by independence, and are also robust, reactive, and proactive (Padgham & Winikoff 2005: p. 4).

Agent-based modeling architectures

In the planning and developmental stages of an ABM, an assembly of agents is needed for the complex system during the planning phase. Thus, often times it is required to combine various AI methods and several agents. On the other hand, since diverse methods can simply be coupled into a hybrid system using a connecting type of agent frame, various complicated glitches are resolved within a smaller length of time. Likewise, given the diversity of complementary techniques and approaches to deal with these problems, these become coalesced, and solutions of higher quality have resulted from such schemes. Of course, it is notable that every one of these smart systems has its potential and disadvantages, and they do not represent the norm for solving every difficulty. Many investigations on this subject are addressed further in the following sub-sections.

The MIX multi-agent architectures

This approach was introduced by Hilario *et al.* (1994) and Iglesias *et al.* (1995). This architecture is aimed at developing plans and kits for combining neuronal and representative pieces of knowledge. The testing skills of this architecture is done on the basis of an allocated procedure on multiple systems composed of collaborating diverse agents. The MIX architecture involves a multi-agent toolbox with a basic agent array, facilities, and rules for agents to be able to communicate. Hence, the development of agents is explicit for diverse sorts of neuronal arrangements unlike other tasks such as reasoning systems. A similar attempt is the 'Predictor' system.

The Predictor system architecture

Scherer & Schlageter (1994) detailed how an allocated system of AI methodologies can be used by coalescing neuronal and knowledge methods.

To present this system, the authors have argued that such a design is centered on a slate construction and is validated in the financial and prediction area. The researchers developed this method with the aim of offering solutions to forecasting problems in the financial system. A glimpse of this design can be seen in Figure 3, and a detailed description of how this architecture is characterized and how it works can be reviewed in the reference above.

Intelligent multi-agent systems with hybrid distributed architecture

The architecture introduced by Khosla & Dillon (1997) is a computer design known as IMAHDA (Intelligent Multi-Agent Hybrid Distributed Architecture). In IMAHDA, the

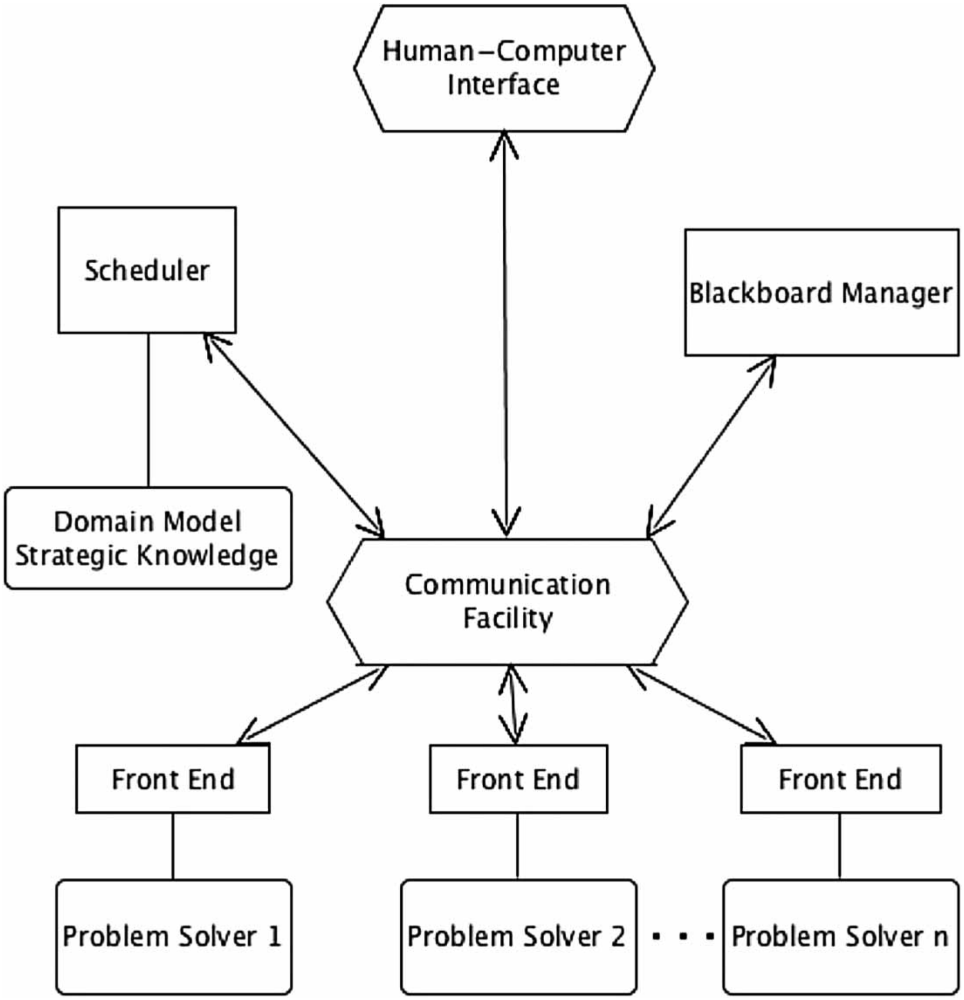

Figure 3 | The Predictor architecture (modified from Zhang & Zhang 2004).

arrangement of the execution of its functioning and knowledge base is composed of four levels. These levels are: objects, computer agents, intelligent agents, and agents for the resolution of problems. This system can be built from general-purpose agent software, standard smart agents, and from other general AI systems.

Multi-agent and fuzzy modeling architecture

This architecture is a more recent attempt and was introduced by Delgado & Gómez-Skarmeta (1999). In this methodology, the authors have proposed a hybridized knowledgeable prototype which is an amalgamation of fuzzy logic techniques and MAS. The arrangement of this type of system allows the participation of several agents with their own tasks within a context of fuzzy logic for the solutions of specific problems. The prototype involves four types of agents, namely, service, which acts as a directory, classifier agents, resources, and finally, those that control tasks.

The generic architecture for hybrid intelligent systems

Jacobsen (2001) suggested a standard agent-based design for a mixed platform of intelligent agents that was built on the framework already introduced by Russell & Norvig (1995). Consequently, two abstractions typical of this mixed platform were shown, on the one hand, a reinforced-architecture linked to fuzzy logic and, on the other hand, in conjunction with knowledge-based systems and neural-fuzzy techniques, the designs were experimentally validated.

In summary, a thorough insight into the proficiencies and limitations of these five agent-based hybrid platforms or systems can be found in Zhang & Zhang (2004: pp. 38–39).

MULTI-AGENT SYSTEMS

The multi-agent system concept

Just like ABM, a multi-agent system (MAS) (Hon Lim *et al.* 2009; Rogers *et al.* 2009) is also part of AI. It is a methodology that aims to couple artificial intelligence techniques with distributed systems and software engineering in a single discipline system. Generally, MASs are composed of autonomous agents grouped and share the same ordered environment (Weyns *et al.* 2004). They are displayed as a network that interact with each other with the aim of accomplishing common goals (Lesser 1995). An agent can be viewed as a software component that contains coding instructions and data (Parrott *et al.* 2003). Within MASs, the agents that compose the network are likely incapable of solving the assigned problems on their own (Flores-Mendez 1999).

Agent communications in a given environment are performed while they are working autonomously and are in coordination with their peers. Then, in a collaborative society, each agent is equipped with a series of skills that are their own and that together allows them as a team to solve problems. In this sense, the messaging that occurs between agents is feasible thanks to the language protocol for agents provided by the Agent Communication Language (ACL); they can exchange information and demand assistance among themselves in a negotiable manner (Parrott *et al.* 2003).

The most useful ACL protocol among agents is the 'Knowledge Query and Manipulation Language' (KQML). This consists of a communication level that involves a low-level layer of variables like send, recipient, and identify. The messaging level is the one that specifies the performative and the interpretation procedure and the information about the performative is at the content level (Flores-Mendez, 1999). The coordination between agents is imperative since the couriers are given over relays and these messages are not dispatched at regular intervals between the agents. From there, the coordination will depend on the architecture of the system which determines that the flow of information will flow smoothly (Parrott *et al.* 2003). The most simple architecture is a P2P network, in which agents speak openly to each other. This is effective at solving situations in which immediate solutions are needed without creating conflicting situations. There are two other platforms that are shared between the multi-agent systems, the related agent and the so-called black-boards. An associated agent network is one that facilitates an agent as a mediator among other agents, while a network of black-board agents is integrated as a central coordinator who directs the actions of coordination of the activities of data sharing (Parrott *et al.* 2003). Following the conceptual and historical notions of multi-agent systems, it is worth mentioning the paradigm of 'game theory' (GT) (Myerson 2013), which is a mathematical modeling paradigm in which a cooperative environment is simulated between non-thinking and thinking agents where the agents interact among themselves to resolve conflicts. An illustration using GT to address a hydrological related problem can be found in Lai *et al.* (2015).

In an investigation performed by Montalvo *et al.* (2014), an integrated MAS architecture was proposed with an optimization algorithm approach, as an attempt to solve the problems of improvements in drinking water distribution systems. The approach, the authors comment, is apt to train managers and decision-makers when offering proposals for improvements to facilities.

There are various areas in which MAS techniques have been applied (Sycara 1998). Recently, MAS has been shown to have a place in the assessment of ecosystems (Bousquet & Le Page 2004; Borri *et al.* 2005; Nikolic *et al.* 2013; Elsawah *et al.* 2015). Some of these examples also include rangeland management (Gross McAllister *et al.* 2006), fish farming (Batten 2007), urban catchments (Pahl-Wostl 2005), and irrigation farming systems (Barreteau Bousquet *et al.* 2004). The approach of the MAS is practical for these areas due to the representation they offer to the environment with their great complexity of detail and that they allow the possibility to integrate human actors, to find solutions, and to contribute to improvements in the assessment of methodologies.

Multi-agent system architectures and agent types

Knowing that we have previously discussed what is an agent, in constructing MASs it is important to define the agent's internal organization and processes that detail how agents pursue and gain their preferred intentions. According to Wooldridge (2009), an agent design can be abstract or concrete. The structure of an abstract concept is defined by the components and its engine structure (e.g., roles, permissions, responsibilities, activities, protocols, etc.). On the other hand, the concrete concept is determined by the assignation of types to each component and executing each function instruction of the engine. In summary, architectures define how an agent perceives data by external sensors, and its internal state determines the actions it will perform and its future behavior (Maes 1991; Russell & Norvig 2010).

There are three main widely used architectures that classify agents with respect to their functions and decision-making attributes: (i) reactive, (ii) belief-desire-intention (BDI), and (iii) hybrid or layered architecture. Reactive agents function by always adapting their internal conditions and responding straightforwardly to changes in the environment. Regardless of the order in which changes occur in the environment and translating this to perform an action is also known as the agent role (Davidsson 2000). The BDI architecture is known for its behavioral capabilities and typical interaction model that can display a rational behavior and realistic reasoning (Franklin & Graesser 1997). The BDI architecture was proposed originally by Rao & Georgeff (1995) and its main components are described in Weiss (1999). Besides these, another two classes, hybrid and layered agent architectures (Figure 4) combine multiple agent mechanisms for a particular benefit and operate by abstracting over different levels of the surrounding environment (Wooldridge 2002).

APPLICATIONS OF ABMS AND MAS IN HYDROLOGIC RELATED PROBLEMS

Tables 2 and 3 provide several articles dealing with various hydrological problems based on ABM and MAS approaches. These articles are classified on ABM (Table 2) and MAS (Table 3). Both tables also give a brief description

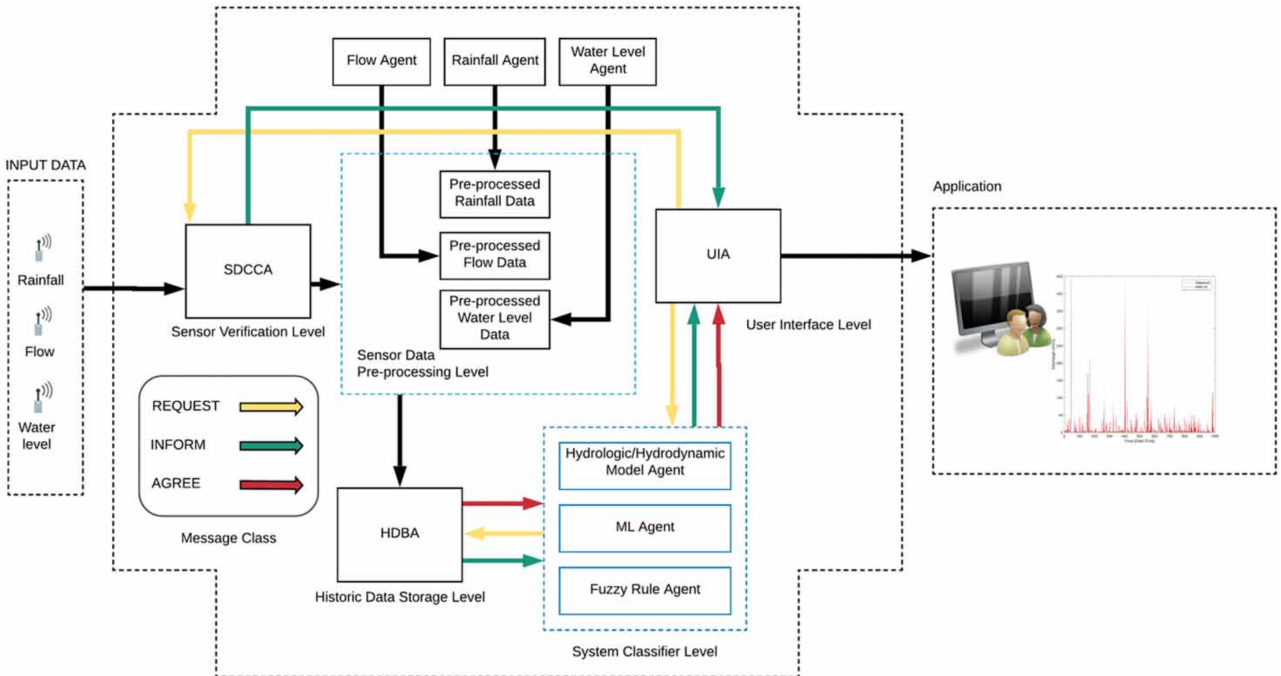

Figure 4 | An example of a MAS architecture.

Table 2 | Flood-based hydrological problems' management and forecasting based on the ABM approach

Method	Reference	Description	Hydrological solution type
ABM	Brouwers & Boman (2011)	An ABM that combines geo-spatial, hydrologic, landscape development, economic, and societal features	Flood management strategies
ABM	Anantsuksomsri & Tontisirin (2013)	A review article on agent-based modeling and disaster management	Disaster management
ABM and Virtual Geographic Environment (VGE)	Coates *et al.* (2014)	An ABM approach coupled with a Virtual Geographic Environment (VGE) for flood estimation to evaluate companies damaged by flooding	Flood recovery and response
ABM and Geospatial Services	Tan *et al.* (2015)	Coupling ABM and web-based geographical system for the creation of mapping scenarios to aid in flood response	Flood response
ABM	Berglund (2015)	Demonstration of the applicability of ABM in water resources as a means for understanding the complexities related to water studies	Water resources planning and management
ABM coupled to hydrological model	Sunde *et al.* (2016)	Investigated the impacts of changes in the imperviousness in urbanized watersheds with ABM coupled to a hydrologic model (e.g., SWAT)	Flood safety and planning
ABM complex adaptive sytsem CAS	Medina *et al.* (2016)	Used CAS theory and ABMs to assume the challenge of testing huge population withdrawal plans in coastline cities prone to flooding events	Flood evacuation strategies
ABM	Du *et al.* (2017)	An ABM configuration to evaluate the effects of the different characters in individual handlings of flood warnings	Flood warning
ABM	Jenkins *et al.* (2017)	ABM applied to future effects of climate change-induced flood risk	Flood safety and planning
ABM	Emlyn Yang *et al.* (2018)	Proposed an ABM for simulating different responses to inundation acceptance with regards to the decision made by every house-owner to ease damages due to floods	Flood recovery and response

of the approaches employed by the researchers and the flood-based hydrological problem/solution type addressed.

Applications of ABMS in hydrologic-related problems

As shown in the previous section, ABM focuses on whether agents (though, not necessarily 'intelligent') are obeying designated rules that formed their behaviors. Given the novelty and ongoing research in the ABMS area, briefly, Table 2 shows the areas in which ABM is under active research.

Some ten years ago, in an attempt to elucidate the progress in the agent-based modeling field, a survey of some 279 manuscripts from 92 research papers was carried out by Heath *et al.* (2009), in a search for authors who had implemented and evaluated an agent-based model, with the need to constantly assess the up-to-date knowledge of the current advances in ABMs and detect cases in which the systems need improvement. The authors identified 'six improvements needed to advance ABM as an analysis tool': (i) the implementation of ABM toolkits specific to the problem domain and are software independent; (ii) ABM development as a unique specialty with a language shared and extended to other domains; (iii) an ABM system that is equivalent to the intended purposes; (iv) an ABM system that is simulation descriptive and provides results that are reproducible; (v) they should be totally adequate for validation; and (vi) that ABM model validation statistic metrics be specific to ABM. Other interesting findings by the researchers showed that ABM is a young method and that standard experiments endorsing ABM as an effective modeling method are not clearly established or accepted. They also noted that the absence of development and typical practices in the ABM arena is reflected by the absence of models that had been completely validated, the absence of reference material for the complete model, and what results are accepted as concluding findings.

Table 3 | Flood-based hydrologic problems' management and forecasting based on MAS approach

Method	Reference	Description	Hydrologic solution type
MAS	George *et al.* (2003)	A flood forecasting MAS composed of two steps. The first step computes the variation in the water level for an hour and in the second step the sum of the weights of agents is computed	Real-time simulation for flood forecasting
MAS and GIS Grid-Based Flood Model	De Roure *et al.* (2005)	A ubiquitous computing system of static and mobile agents with expert-system to manage available sensors on the network and use their information to monitor the river water level, and feed data into a grid-based flood predictor model, for issuing an alert	Sensor data management and river water level monitoring
MAS	Matei (2011)	Uses distributed systems	Monitoring and analysis of hydrographical basin
MAS and ANN	López *et al.* (2012)	Uses neural networks of counter-propagation type and intelligent agents with mobile devices	Early warning against floods
MAS and DM	El Mabrouk *et al.* (2013)	Combines multi-agent systems and data-mining for flood forecasting and warning	Decision support for flood forecasting and warning system
MAS	Marouane *et al.* (2014)	A MAS for aggregating data from wireless sensors, search for flaws in the data and categorize the data, making them trustworthy for further flood prediction in real-time	Flood forecasting
MAS and VSAT Communications	Iqbal *et al.* (2014)	Applies mobile agent-based algorithm for agent with mobile communication using VSAT technology	Prediction of inundation area
MAS and case-based reasoning	Linghu & Chen (2014)	An ABM approach with CBR for flood disaster forecasting	Flood disaster forecasting
MAS, GIS, and DM	Al-azzam *et al.* (2014)	A MAS architecture for supporting inundation estimation and hazard evaluation coupled with geographic systems and data-mining methods	Flood prediction and risk assessment
MAS	Bao *et al.* (2015)	An application of multi-agent model instead of mathematical runoff equations	Urban water-log simulation and prediction
MAS, ontology and fuzzy logic	TehNoranis *et al.* (2015)	A MAS integrated with ontology concepts and uncertainty modeling	Flood warning prediction
MAS and Expert Systems	El Mabrouk *et al.* (2015)	Uses MAS and domain expert for short-, medium- and long-term real-time flood prediction and alert	Flood forecasting and warning
MAS	El Mabrouk & Gaou (2017)	A smart system that processess data for instantaneous flood nowcasting and awareness with data sorting and gathering	Flood forecasting and warning

Finally, the authors recommended a solution that the ideas, methods, and techniques used for ABM must be adopted from other simulation prototypes or developed toward ABM. A complete study on the potential of ABMS is also referenced by Macal & North (2006), in which a comprehensive insight into the rationale of ABMS is introduced with the idea to address its present settings. The authors re-examine several issues of ABMS, characterize this paradigm as a novel methodology, consider the limits of over-employing and under-employing this AI sub-discipline, and envision its potential as a prospective research tool in complex systems' modeling. Additionally, the study identifies key aspects of agent-based modeling and simulation properties, research, and groups. The study suggests, as well, some corresponding meanings for ABMS, grounded on experience, proposed for determining a unique lexicon to be employed. The authors conclude by recommending research and challenges in this area to advance its growth and potential in the coming years.

In spite of the active research of ABM in domains like economics, social science, biology, military, public policy, ecology, and traffic, and with growing interest in engineering applications, the literature review shows however that ABM applied to stream-flow or flood forecasting problems is relatively limited and is shown not to be thoroughly enriched in that field. Notwithstanding, we observed examples given by some researchers (Table 2) who have used such systems for addressing other related hydrological problems as a problem-solving approach in flood safety and planning, recovery, response, evacuation policies, control, and management.

Brouwers & Boman (2011) designed and implemented a single ABM to discover the preferences of individuals toward assessment on inundation administration plans, for a geographically explicit flood simulation model under situations in communities with spatial accretion. However, the researchers commented that for this model to function, it is important that the results be available and practically outreaching to the entire community.

In a recent summary of agent-based modeling approaches for solving problems in the area of disaster management, a study was presented by Anantsuksomsri & Tontisirin (2013). In this study, the authors conducted a review on ABM applied to disaster management. From their review, they explained the development of such systems and defined ABM and gave insights into some software toolkits used for building ABM systems. The study also contributed to the present modeling of issues in law models as theoretical testing, whereas robbery and driving behavior models are chosen as the implications of ABM in urban planning. The article also discusses the use of ABM on natural disaster policies and management, flood evacuation simulation, and risk-based flood incident management. Of particular note is the references of the authors to two works related to agent-based modeling coupled to a hydrodynamic simulation model; in either of these cases, the ABM uses the ready to hand information on the hydrodynamic model water levels to address the issues of evacuating the population rather than the ABM system to forecast the water surges.

Interestingly, Coates *et al.* (2014) introduced a study in which they implemented the use of geospatial systems and ABM coupled with flood forecasting estimates to model a system that could identify commercial properties prone to suffering from flood damage. The rationale behind the geospatial system consisted of the development of layers (e.g., topography, integrated transport network, and address) from the Ordnance Survey's Master Map to be used by the ABM system. The study showed that integrating the geospatial system with flood estimate layers enhanced the reliability in modeling flooding occurrences. Finally, the authors proposed the idea that in order to improve operational response and business continuity, it is necessary to build prototypes that can replicate companies throughout and after flood events.

An example of the application of integrating GIS data and ABM in water resources engineering is given by Tan *et al.* (2015). To deal with the huge amount of geospatial data generated, they studied how effective the integration of GIS and ABM could be. The integration approach they presented is based on an agent-based model integrated with a GIS installed on the web, whose function is to gather and handle huge amounts of generated geospatial data and in this manner gain more reliable geospatial service information that could respond more effectively to floods. This integration demonstrated that the proposed method is ideal to avoid the transfer of a massive amount of geospatial information.

Berglund (2015) provided a complete and comprehensive presentation on ABM to the water resources community, with the aim of exploring the use of ABM in the hydrosector given the complexities common to this domain. The author presented and explained two descriptive overviews implemented with ABM. From the analysis, he demonstrated the applicability of the agent paradigm for simulating scenarios like water resources planning problems. Additionally, in the study, the author also pointed out the restraints in employing agent-based modeling to this simulation domain. To comprehend stream-flow on impervious surfaces, with a hydrological simulation coupled to an ABM technology, Sunde *et al.* (2016) employed a 'Pixel-based increased impervious surface' dataset projected from 2011 to 2031. This dataset was linked to a hydrologic model, SWAT (Soil and Water Assessment Tool), in which simulation runs on the potential of hydrologic effects on upcoming urban development were studied. The study offers a structure that permits managers to combine a representative impervious surface estimates' dataset with hydrological simulations.

Medina *et al.* (2016) used 'complex adaptive system' theories and ABMs to undertake the challenges of testing massive withdrawal policies in coastline communities prone to flooding events. The authors showed the viability of agent-based modeling approach in this scenario to test evacuation policies for coastline communities' withdrawals due to severe hydrometeorological incidents. They also stressed its perspective as a toolkit for effective hazard managing.

Du *et al.* (2017) developed an ABM architecture to evaluate the effects of the diversity in human reactions to inundation threats, domestic concentration, and the benefits of inundation alerts. The modeling scheme consisted of the implementation of an ABM coupled to a transportation simulation to model mass departures in a highway grid with different flooding alert cases. Simulation outcomes indicated that if the population behaved subject to the stressing effects of threats, particularly areas with a high-density population, the marginal benefit related to efficient flooding warnings becomes significantly constrained. Results also showed the profits of inundation alerts to notably impact human behavioral heterogeneity and from thence the meaning of seeing human reactions to inundation alert simulation routines. Finally, the authors recommended the development of more accurate models on social reactions and conduct, to inundation alerts, and to increase the number of domestic spaces and elements for better assessing and improving the advantages of inundation alert systems.

In view of the concerns about the future effects of climate change, Jenkins *et al.* (2017) presented a novel ABM, which they fed with information from an inundation hazard scenario analysis. The agent-based model was proposed to evaluate the relationship amid distinct modification alternatives; it could propose that a decline in risk may be achieved by proprietors and authorities.

Emlyn Yang *et al.* (2018) proposed an agent-based model that could perform flood response simulations in regards to the choices and actions taken by every house owner to ease flood damage. The model implements a framework for individual response in which agents evaluate different flooding situations concurring with inundation alert systems, collect and select if and what amount they would spend in reaction procedures to ease latent flood losses. The researchers observed that estate worth, forewarning communication, and heavy rainfall situations together influence housing damage, and those located in lowland areas of the watershed and highly populated zones are most likely to be susceptible. The ABM also demonstrated being useful for analyzing housing damage in large-scale flooding and reactions in storm-water flooding episodes.

Applications of MAS in hydrological related problems

In the previous section, we briefly examined how various agent-based models were implemented to simulate human behavior in response to complex phenomena such as disasters that could be climatic in nature or otherwise, as part of disaster management. On the other hand, it could be seen that most of the modeling approaches with ABM are not carried out directly for either stream-flow or flood forecasting, but rather for simulations on population dynamics responses to risk and hazardous conditions, as well as for the design, implementation, and evaluation of risk policies, flood warning, safety, and planning. However, as the numbers of risk and hazards worldwide continue to escalate and become more frequent and severe due to weather-related events (Figure 5), especially in regions where the precipitation regime can be even higher than the annual global rainfall, there is a continuous need for the development of more sophisticated agent-related technologies that can be applied to hydrologic-related problems and water-dynamics forecasters are the order of the day. Hydrologic-related problems, where in this case we give special attention to events such as floods, are triggered by severe weather conditions like heavy rainfall. At urban and catchment levels, floods are of importance given the damage they cause to the impacted domain (human settlements, animals, environment, agriculture, infrastructure, and economy). In order to monitor these weather or climatic variables that are responsible for flooding, it is necessary to have at hand and to deploy a network of hydrometric sensors (Figure 6) for data collection to allow us to study and forecast flooding events. In response to the latter, a MAS is an option that is best suited for addressing a network of distributed sensors (Rogers 2011). This is owing precisely to the fact that a multi-agent system comprises a network of agents displaying intelligence, a framework that involves collective features and individual thinking for

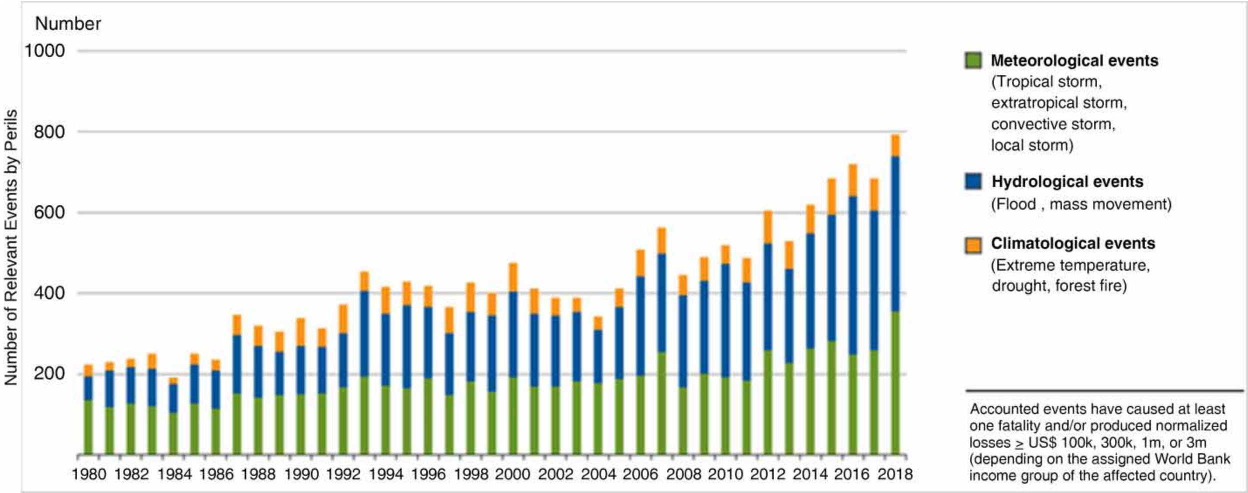

Figure 5 | World weather-related natural phenomenon 1980–2017 (*source*: 2018 Munich Re, Geo Risks Research, NatCatSERVICE, as of January 2018).

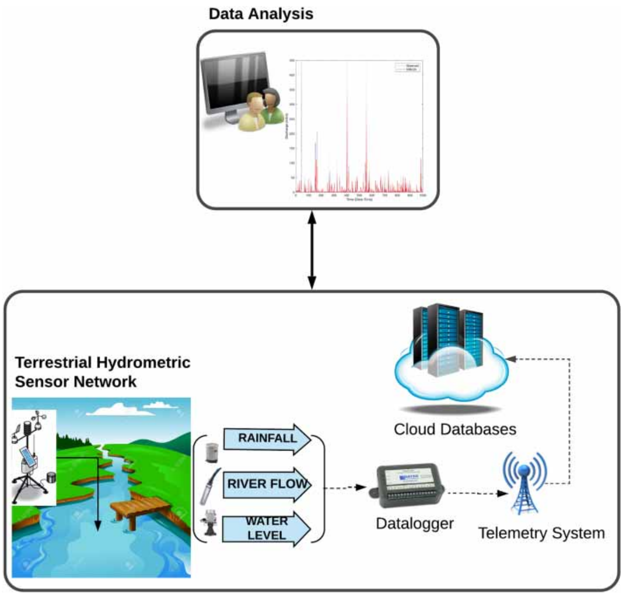

Figure 6 | Deployment of a hydrometric sensor network.

the solution of complex issues. The MAS approach to investigating and assessing stream-flow, flood, or high-water level forecasting and its association with management in civil society is a recent effort.

From a careful review of the related literature, the applications of MASs have been successfully applied to several problem domains, including energy market forecasting, monitoring, system analysis, and corrective actions (Pinto *et al.* 2009; Bearzotti *et al.* 2012; Skarvelis-Kazakos *et al.* 2016; Villarrubia *et al.* 2017).

Within the field of hydrology, the community of MAS researchers has also made some progress; therefore, to get some understanding into the performance of MAS methods, a comprehensive comparison was necessary to explore MAS methods. Table 3 shows a summary of the major MAS methods, i.e., single MAS methods in real-time simulation for flood forecasting, monitoring and warning, ANNs, GIS, DM, fuzzy logic, case base reasoning (CBR), mobile communications systems (using VSAT), and expert systems. A review and discussion of these methods ensure identifying the most appropriate methods that exist in the literature.

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George *et al.* (2003) built a platform for the actual simulation that is coupled to a model for estimation of floods, with a two-level self-adapting MAS implemented. In this system, the objective of each level is well defined, such that, at the top, the variation in water level is measured for an hourly period and in order to achieve this, it adjusts the weights in the lower stage. The adaptiveness of this model is really acquired by adjusting the weights, carried by the agents that cooperate among themselves. This adjusting of the weights renders the model generic and allows it to improve its performance. The authors analyzed several cases (e.g., noisy and missing data, number of upstream stations) where the use of hydrologic simulation is inappropriate. Lastly, they studied the features of the knowledge system, taking into account classical measures and related works.

De Roure *et al.* (2005) implemented a ubiquitous computing system of static and mobile agents, in which the static agents are designed to have complex functionalities; for example, using an expert system to manage available sensors on the network and use the information to monitor river level and determine if the network is storing data that differ significantly from the standard, feed the data into a grid-based flood predictor model, and issue an alert. The main functionality for mobile agents is to ensure they are lightweight with actual specific functions to perform, like data discovery routes across the network and to deliver sensor data. The authors concluded in this study that the use of intelligent static agents employing simple mobile agents in combination to perform assignments on their behalf results in an effective, self-organizing ubiquitous computer for a simulated network of nodes.

Matei (2011) developed and evaluated a multi-agent system for inundation forecast and water level observation. The MAS is fed by an automatic hydrometric data collection module. The author concluded by identifying some advantages and disadvantages of the system. As the MAS is implemented on independent units, the modular arrangement of such and the collaboration among these units permits the assessment in hydrological problems in an easy manner.

The multi-agent system proposed by López *et al.* (2012), uses a technique based on counter-propagation neural networks and intelligent agents to analyze and assess flood risk caused by rainfall. Additionally, they implemented agents, on mobile devices, for the dissemination of early warnings on floods. Other features of the system are that it can display flood forecasts and enable messages in order to administer a hydropower plant basin with the aim of preventing damage to the infrastructure. It offers other smart means for messaging and broadcasting of massive warnings to the population.

A MAS proposed by El Mabrouk *et al.* (2013) coupled with a data-driven approach was developed to improve flood prediction and alerts for a decision support system and management at catchment scale. Their study aimed at providing technical support for the flood control and warning division. The approach involved the applications of decision trees using the C4.5 algorithm to construct a real-time flood prediction and early awareness model. Also, to couple the decision tree to the multi-agent system, an algorithm, which they named the 'ANYtime Multi-Agent System' (ANYMAS) was developed and used to obtain the coupling between the two systems.

In a paper by Marouane *et al.* (2014) an intelligent system is presented that gathers and handles hydrometric data from sensors. The system detects errors in the data and classifies them, so as to render them reliable and acceptable for their storage in a database where they undergo data processing. The data once processed are further used for performing inundation estimation, and the results are distributed in collaboration with the MAS and mobile agents for the dissemination of results to the central station.

Iqbal *et al.* (2014) developed a MAS model implemented with 'Very Small Aperture Terminal' (VSAT) technology that optimized the agents in mobile-phone communication. The team of researchers considered the system to be useful in any type of critical conditions of floods, of course, because the signal strength is enhanced by the technology. Nevertheless, although the cellular signal could be optimized, a setback is that for the implemented agents on the server to be proficient in taking the decision about flooded zones, it depends on the available river historical flow data.

Linghu & Chen (2014) presented an innovative example of MAS coupled with 'Case-based Reasoning' (CBR) for inundation disaster prediction. The authors implemented an algorithm for this particular task and they concluded that the algorithm implemented could estimate the river stage correctly and realized the prediction offset of the algorithm was smaller than the existing scheme.

Al-azzam *et al.* (2014) presented a MAS architecture linked to a geographic system set up on a virtual environment and data-mining techniques to assist in flood forecasting and risk evaluation. Although the objectives of the implementation were met, the authors pointed out that during the implementation phase they could discover issues that are of concern when building such systems. They emphasized the trials that arise whenever building systems like these and such predicaments need to be considered, especially when classifying and aggregating erroneous hydro-data from wireless sensors.

Bao *et al.* (2015) proposed a MAS to simulate and estimate water level in an urban watershed domain. The system design was configured in such a way for simulating water level saturation using the MAS approach instead of hydrological modeling. This approach was done by using a method that was able to simulate the uncertainties in the flow regime and calculate the flow depth at any point in time, optimizing reservoir storing capacity to allocate water excess. Hydrometric data are used as inputs to the MAS. To validate the system, the authors compared the results of the MAS with outputs from cellular automata modeling. The authors concluded that the improved system, given the methodology applied, is feasible for mitigating the loss of life and infrastructure damage by high water levels.

Aris *et al.* (2015), in their research paper, proposed a flood forecasting theoretical model that was based on agent ontology and fuzzy systems. In this system, the function of agents is to offer reports on flooding situations according to the river stage and precipitation via alert warnings sent to the population. The ontological setup was meant to categorize the inundation awareness to aid in the agent interaction. Fuzzy techniques are used to forecast weather undefined conditions.

An innovative knowledgeable scheme for flood estimation at three chronological terms (e.g., short, medium, and long) and awareness, was implemented by El Mabrouk *et al.* (2015). Given the authors' concerns to work with a system that could integrate many components into one, they realized that the multi-agent systems had the benefits and the advantages in terms of the distributed artificial intelligence, and to allow the system to cope with rule-based features, they made use of expert systems due to the advantage of the concept of logical coding and the theories of proofs and directions.

Most recently, El Mabrouk & Gaou (2017) proposed a smart system that could pre-process data before performing instantaneous flood prediction and awareness. The system is composed of some levels that supervise the cordless instruments and their accurate performance, to ensure the incoming information from the sensors is of the best quality and to generate a historical database from which data would be used in future flood prediction tasks. Finally, it can be concluded from the study that wireless sensor networks could be used for a distributed and auto-organized method of information management in a dispersed system (Guijarro & Fuentes-Fernández 2011; Hamzi *et al.* 2013) and could be considerably upgraded with the supervision and the application of MAS.

CONCLUSIONS

A brief overview is presented on the literature of some of the methodologies and tools offered by agent technologies such as ABMS and particularly MASs as a tool other than the traditional hydrologic models that can be used for addressing hydrologic-related problems caused mainly by flood-based impacts. The review highlights the areas in the hydrological analysis where these methods have been successfully applied. As far as the authors are concerned, there have been few studies done in hydrological flood prediction and warning using ABMS and MAS. Hence, the review highlights the areas in the hydrologic analysis where these methods have been successfully applied.

Contrary to the traditional hydrological approach, we also observed from the literature review that for recent decades, AI methodologies have been shown to be highly favored by some researchers.

The AI sub-disciplines of ABM and MAS techniques introduced here appear to be extensively useful in the business field and social sciences for dealing with the simulation of population behavioral response to flooding impacts. At this point, we have reached the sole purpose of this review, which is to provide recent feedback and extend the existent flood forecasting capacities precisely of MAS as a methodology that can handle the complexities present in hydrological systems. Despite the extensive use of agent-based modeling in the sociological sciences, the bibliographic review shows that in the context of disaster management induced by flood-based phenomena, the integration of ABM and other analytical based techniques applied to examine the dynamics of social phenomena under flood disaster management was shown to be useful. The combination of hydro-climatic models and an agent-based model reveals insights into the social phenomena and associated policies of flood incident management at local (Liu *et al.* 2009) and global scale (Dawson *et al.* 2011). On the other hand, ABM can examine the heterogeneous conduct of the different information, rules, environment, to the overall behavior of a system (Lempert 2002). We also showed some examples of both agent modeling techniques in addressing flood risk phenomena, flood management strategies, flood recovery and response, flood evacuation, and flood warning, while there are few examples focused on flood forecasting. While the knowledge of ABMS is appealing, there are some drawbacks to be mentioned, including the difficulty for agents to predict on a micro-level, the fact that the relation of agents' behavior to the behavior of the overall model can be a problem, and that computational needs can also be a setback (Klügl 2006; Jennings 2000). On the other hand, we recall the capabilities and strengths offered when taking ABMs and extending them to implement MASs which are capable of dealing with instantaneous prediction of floods and awareness on different levels of complexity, as shown in the section 'Multi-agent systems architecture and agents types'.

Some remarkable advantages offered by agent technologies over standard models is that where standard models consider only the dynamics of the surrounding factors to take decisions on their measures, agents, aside from considering such aspects of standard models, would permit the interactions of the dynamics of the surrounding factors with other features (i.e., non-dynamic features) of a system, to agree on their behaviors.

This feature of agents creates a major drawback for conventional models of not modeling the core representation of the system entirely, whereas agents can. In this sense, regarding agents' qualities and activities, they are logical, diverse, adaptable and perceptive to past judgments, and have the potential to be localized in geo-social arrangements. This creates state models of the real world that are better suited to agent-based models and simulation and the multi-agent systems.

FUTURE PERSPECTIVES

Future perspectives are aimed at potentiating the coupling capabilities offered by MASs and presenting a multi-agent system that integrates and couples physically based models (i.e., hydrologic, catchment, and/or hydraulic models) with the strengths provided by data-driven models, AI methods, and soft computing techniques for monitoring and handling problems emcountered in hydrometric data (weather, hydrologic and hydraulic), analysis, and forecasting of flooding events in data-scarce river basins at lead times from 1 up to 3, 4 hrs. In this manner it will provide a tool for the exchange of electronic information recorded by hydrometric sensors displayed in the basin, acquire data from the various web-based weather forecasts, and expert knowledge in order to provide support to water resources managers in decision-making, issue protection policies and the protection of infrastructure, civilian and wildlife.

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