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# Agent-based modelling and flood risk management: a compendious literature review

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## Abstract

The use of agent-based modelling (ABM) to tackle flood-related risk challenges is becoming increasingly popular in recent years. This paper reviews the literature at the interface of ABM and flood-related studies in view of understanding the technique's advantages and limitations to flood risk management, based on a set of 61 representative articles. In particular, to understand how this process-based technique can help to link human (also institutional) decisions and behaviour with flood risks through the whole human-flood systems. Overall, the temporal and spatial distributions demonstrate a growing interest in this research area around the world, especially since 2017. Three topic areas are identified, addressing different research challenges in the field: real-time flood emergency management, long-term flood adaptation planning, and flood hydrological modelling. The review has shown that the potential contribution of ABM to future flood risk management lays in its practical application to decision-making in adaptation policy and strategy planning. The review also critically reveals the limitation of ad hoc implementations of decision-making and behaviour in the ABM models that could make the application less realistic in the field. It is recommended that the future development should be guided/influenced by the continuing development and refinement of ABM modelling framework and theoretical foundations, and enhancement of model testing and documenting capabilities. More importantly, active collaborations between disciplines and sectors such as to involve more social and psychological sciences in ABM decision-making

modelling should be encouraged; and knowledge sharing will encourage more effective uses of ABM by wider audiences.

**Keywords:** Agent-based modelling (ABM); flood risk management; review; coupled human and natural systems (CHANS); adaptation planning; emergency management

## 1. Introduction

Among all weather-related natural hazards in the past two decades, floods are by far the most common (47%) that have affected 2.3 billion people around the world (CRED-UNISDR, 2015). Due to climate change and urban development, it is estimated the global cost from flood disaster will rise from about 46 trillion USD to 158 trillion in 2050 (Jongman et al., 2012;Poelmans et al., 2010). The damages caused by the recent catastrophic flood disaster in Southern China (Everington, 2020), and the projections of even more extreme events around the world, again demonstrate the urgent need for resilient flood disaster risk reduction strategies globally (e.g., to provide effective flood risk assessment and management with resilient and sustainable adaptation and mitigation policies), as also emphasized by the international agreement on losses and damages (UNFCCC, 2013) and the Sendai Framework for disaster-risk-reduction (UNDRR, 2015).

The formation of flood disasters is driven by multiple factors, for example, urbanization can significantly increase flood damages due to population growth and assets exposures (e.g., infrastructures and buildings) within flood-prone zones (Jongman et al., 2012; Aerts et al., 2014; Hallegatte et al., 2013); the land use change of natural surfaces into artificial impermeable surfaces can result in an increase of flooding frequency due to poor infiltration (Huong and Pathirana, 2013); and inadequate planning, risk dissemination and policies can lead to an elevated number of exposures and vulnerabilities (Jha et al., 2012). Therefore, only focusing on understanding the extent and magnitude of the hazard itself is clearly not sufficient for flood risk management, while other interconnected elements such as urbanisation, socio-economy, culture, community, institution and governance should also be taken into consideration (IPCC, 2014, 2012;O'Connell and O'Donnell, 2013). Since flood disaster is becoming more people-centred (e.g., adaptation, mitigation, and rescue planning can all have impacts to the consequence of a flood event) (O'Connell and O'Donnell, 2013), and due to the interactions between hazard and people that span across multiple spatial, temporal and organisational scales, as well as the influence of imperfect information, bounded rationality and continual adapting feature on human decision-making, flood disaster should be seen as a Complex Human And Natural System (CHANS) (Liu et al., 2007;Pahl-Wostl, 2015;Mitchell, 2009). In particular, in order to understand from multiple dimensions or scales of how human decision-making and behaviour lead to certain consequences of flood events, there is a clear need of a more process-based approach to enable in-depth coupling of the two sub-systems (i.e., human and flood) (An, 2012).

Agent-based modelling (ABM) has become a major bottom-up tool to simulate CHANS, which is process-based and capable of mimicking the real-world systems as open-ended dynamic systems of interacting 'agents' (Tesfatsion, 2017; Tesfatsion et al., 2017). In particular, it is very useful in simulating situations where individual behaviour can lead to collective outcomes in ways that cannot be dealt with by aggregate models (Tonn and Guikema, 2018). With the substantial development from computer science and social science, ABM has the advantage in simulating the human decision-making process and behaviour and integrating these with the contextual socio-environmental conditions (Bousquet and Le Page, 2004). Therefore, it can be an efficient tool for understanding the human-flood systems, hence, useful for flood risk management related studies.

The concept of ABM was first proposed in the late 1940s (e.g., (Von Neumann, 1951)). It is a computational modelling method which can simulate the actions and interactions of individual, heterogeneous, autonomous agents, or decision-making entities in a network or system (Bonabeau, 2002). ABMs offer “a way to model social systems that are composed of agents who interact with and influence each other, learn from their experiences, and adapt their behaviours so they are better suited to their environment” (Macal and North, 2010). A typical ABM is comprised with three components: a set of agents (as representations of the real-world decision-makers); a set of agent relationships and methods of interactions (how and with whom agents interact), and agents' environment (interactions with the environment) (Macal and North, 2010). Each agent (e.g., individuals, organisations) is encoded with behaviour rules to assess its situation and make decisions. Even a simple ABM can generate complex behaviour patterns due to a series of simple interactions between agents, and lead to rather complex system-scale outcomes that cannot be predicted by simply aggregating the behaviours of individual agents (e.g., due to interactions, feedback loops, nonlinearity and thresholds, heterogeneity) (Dawson et al., 2011). Since ABM is able to analyse the effects of interactions on the system as a whole, it has been widely used to provide decision-making guidance through many ‘what if …’ scenario simulations (Bankes, 2002;Dawson et al., 2011;Wilensky and Rand, 2015). With the emergence of high-performance computing, and the off-the-shelf modelling programs such as NetLogo (Tisue and Wilensky, 2004) and Multi-Agent Simulation of Neighborhoods (MASON) (Luke et al., 2003), ABM has been increasingly recognised and applied in a number of fields to tackle complex system problems, from civil violence (Epstein, 2002), land-use change modelling (Evans and Kelley, 2004; Magliocca et al., 2011), shared autonomous vehicle (SAV) operations (Fagnant and Kockelman, 2014), marketing and organisational behaviour (Gómez-Cruz et al., 2017), to evacuation routes plan to fire and terrorist events, and warning effectiveness test (Still, 1993; Owen et al., 1996; Wong and Luo, 2005), and business resilience assessment (Sauser et al., 2018), and the trend is still rising. Among these fields, research on artificial intelligence is noteworthy, for instance, in which multiple heterogeneous agents are coordinated to solve planning problems (Bousquet and Le Page, 2004), also largely contributing to ABM development is electrical electronic engineering, for instance modelling the multi-carrier energy systems to understanding the interactions of production, delivery and consumption (Krause et al., 2010). With the increasing focus on the human part of the human-flood systems, it seems ABM has also started to attract more interests for flood risk management studies (O'Connell and O'Donnell, 2013; O'Shea et al., 2020), albeit it is still considered to be in its infancy. Therefore, there is an important need to explore this field to encourage its research and application in flood-related studies. This paper aims to review the literature at the interface of ABM and flood-related studies in view of understanding the technique's advantages and limitations to flood risk management for both long-term planning and real-time management applications. Although both research disciplines have gained traction over many years, a current literature review at the interface is absent from the publications. It is hoped that this review will benefit the flood research community by shedding light upon the following points:

1) How has ABM made contributions to flood risk management development?
2) What are the strengths and weaknesses of the methodology based on past contributions?
3) What are the possible improvements that can be made for its future contributions in the field?

The focus of this review paper is from that of flood risk management perspective and how the ABM approach helps link human (also institutional) decisions and behaviour to flood risks based on the whole human-flood systems. Section 2 presents the method to identify and analyse literature at the interface of flood risk management and ABM. Section 3 describes how ABM has contributed to flood risk management studies, from real-time flood emergency management to long-term flood adaptation planning and flood hydrological modelling. This is not intended to be comprehensive in the detailed individual methods for the selected studies, but to touch on a variety of ways that ABM has been applied in the field. Section 4 discusses ABM's benefits, limitations and potential areas for improvements in the field. Section 5 provides the conclusion of this study.

## 2. Methods

To achieve the paper's aim and objectives, the Web of Science was mainly used for the literature selection. The first step was to construct a Boolean expression (search string) by searching the Web of Science using the following combination of keywords: Topic = "agent-based model" or "agent-based simulation" AND Topic = "flood". The first topic defined the methodology of interest, while the second topic restrained further to only show papers within the area of flood research. The second step was complementary to the first, which added journal articles via author's personal archive (i.e., on ABM flood-related research) that has been established since 2017. The third step was to search in Google Scholar (with the searching keywords of 'agent-based' and 'flood', up to 2019 and articles only available online from 2020 were not included in this study due to incompleteness) to pick up any important publications (research areas that were not covered by the papers selected from the first two steps) that were missed from the first two steps. As the quality of the selected literature was important to draw the conclusions of this review paper, any result that was not a journal article (e.g., conference proceeding, book chapter, lecture notes) was not selected.

The main information extracted for each search included the title, author, institution, date of publication, abstract, keywords and URL. In the above online search, 301 pieces of published literature were found (up to 2019) from the first step. Out of these 301 papers, 200 were journal articles. After checking each article manually, 145 were further excluded (i.e., off-topic, unavailable to download due to paywall or similar, not written in English). The second step resulted in another 23 articles, four of which were selected for the review after eliminating those that were found to be duplicated (already chosen in the first step). From the third step, a further two articles were added to the list. As a result, there was a total of 61 publications included in this review, which makes up an important and representative part of the reference list. The selected papers are listed in a table in the attached supplementary document. To the best of the authors' knowledge, no particular ABM flood applications were categorically excluded by the searching.

# 3. Results

## 3.1 Temporal distribution of studies

Figure 1 presents the temporal distribution of the selected 61 papers. The graph shows a clear upward trend over the past 15 years (2005-2019). Only around two papers containing the keywords agent-based model or simulation and flood in the topic were published each year before 2014. The number of publications grew significantly to 14 in 2017 which was a 180% increment from 2016 (5). This demonstrates a growing interest in applying ABM in the field of flood risk management. The number then remain relatively stable between 2017 and 2019 (i.e., 14, 16, and 16 papers for 2017, 2018, and 2019, respectively). A similar trend pattern has been observed in other research fields (for example, ABM in ecology (An, 2012)). An exploration of the possible drivers of the sudden growth in 2017 and then stabilisation should be further investigated, but is beyond the scope of this review.

## 3.2 Spatial distribution of studies

The global distribution of the 61 papers has been plotted in Figure 2. It is based on the case study areas presented in the papers. It can be seen studies are distributed over all continents, with the highest number from Europe (26 papers), Asia (16 papers) and North America (9 papers), covering both highly developed and developing countries. In Europe, the majority of the studies were implemented by the UK (9 papers) and the Netherlands (8 papers). In Asia, most researches were carried out by China and Australia (9 papers). Four papers used synthetic cases and one paper was based on exploring the ABM application to the whole European Union.

### 3.3 Using ABM to understand human-flood systems and increase flood resilience

The techniques applied to modelling the coupled human-flood systems are mainly divided into two types, that is the ABM which is the main focus of this review paper, as well as the system dynamic models which are predominant in the flood risk domain (Barendrecht et al., 2017;Di Baldassarre et al., 2013;Viglione et al., 2014). System dynamic models are based on systems of a few coupled ordinary differential equations (Di Baldassarre et al., 2013; Viglione et al., 2014), in a way that the change of one variable with time would depend on other variables. Most differential equations are conceptual representations of the lumped system behaviour, e.g., through aggregation or using a representative value for the whole domain. In contrast, ABM is built based on the behaviour of individuals and the interactions are described using decision rules. These interactions alter the agents' state (Blair and Buytaert, 2016). However, for ABM, the outputs of the interacted behaviours are sometimes difficult to understand because the connection between the variables is less clear at the macro-scale than the ones for the system dynamic models (Barendrecht et al., 2017). In order to understand how ABM has been applied in flood risk management, the 61 identified publications have been categorised into three main areas: real-time flood emergency management, long-term flood adaptation planning, and flood hydrological modelling. This section briefly describes the existing contribution of ABM in the field.

#### 3.3.1 Real-time flood emergency management

ABMs have been applied to model the movement of people, largely because of their flexibility in incorporating the various components that influence an individual's movement through space. By simulating an individual's dynamic environment and internal state (e.g., behaviours, risk perception), ABMs are capable of simulating the two vital decisions that an individual must continually make: when to move, and where to move (An, 2012). The individual's response (state) to potential flood events can be influenced by multiple factors such as individual's previous experience of flood incidents, warnings (e.g., 'false alarms'), government's dissemination (e.g., flood warning, providing information on flood risk and escaping plans to increase the awareness of flood risks), as well as the adaptation processes (Parker et al., 2007); and accordingly, ABM can simulate these multi-interactional factors. Specifically, individual's decision-making processes to flood response are often represented by a spectrum of predefined simple to complex behaviour rules within the models, which are mainly based on a combination of probabilistic and logical rules to take into considering the uncertainties of the environment and perception capabilities (An, 2012). Through reviewing the selected papers, a number of studies have been identified in the flood emergency management area that mainly focused on modelling the movements of people under flood threats. For example, Dawson et al. (2011) presented a quantified modelling approach to estimate the likely exposures of people to flooding under different storm surge conditions. A wide consideration of defence breach scenarios, flood warning times and evacuation strategies were also tested. For the proposed ABM framework, the interactions and feedbacks between floods and human responses were enabled through the simulation as the event evolved. In particular, a probabilistic finite state machine was used to identify agents' behaviours, including their possible states, the actions they could take and the transitions between states. A similar concept was also adopted in Zhu et al. (2019) and Dai et al. (2020) for dynamic flood exposures and vulnerabilities assessments. In the proposed HazardCM (hazard-human coupled model) model, the probability of death or serious injury as a result of exposure to floods were mainly controlled by the defined water depth and velocity thresholds, as well as individual's characteristics including age, gender, employment status, education level, fitness level and travel model. As discussed in Dawson et al. (2011), although the uncertainties surrounding flood exposures might be large, by simulating a wide spectrum of events and parameterisations, more robust options connected with the uncertainties would be identified. Similar to the above studies but with a focus more on examining the effectiveness of emergency management measures is the Lumbroso and Davison (2018) paper. The study proposed an ABM model called Life Safety Model to particularly test a flood buddy system to potentially reduce loss of life during low-probability flood events. It described detailed human evacuation behaviours that were likely to occur within buildings (e.g., considering different floors, different building types etc.), which provided more detailed building-scale simulations than the studies described above. Moreover, a generic water depth versus velocity curve was adopted to assess the status of agents at each time step. To reduce the associated uncertainties of the model, Monte Carlo analysis was applied to run the model many times. Another interesting study was conducted by Li et al. (2019), which combined a cellular automata model and a ABM system to simulate crowd evacuations in flood disasters, and the model was evaluated by real-participant experiments based on virtual reality (VR) environments. Similar studies on ABM applications in flood evacuation are also found in Higo et al. (2017); Liu and Lim (2016, 2018); Yamamoto and Takizawa (2019); Nakanishi et al. (2019); and Eivazy and Malek (2019).

Another challenging issue in flood risk management is the effectiveness of flood warning systems. Although flood warning systems have been recognised as efficient tools for damage mitigation and crisis management (Parker et al., 2007;Parker, 2017;Cloke and Pappenberger, 2009;Pappenberger et al., 2015), their effectiveness can be influenced by various socioeconomic factors. ABMs have been used to explore this particular area. For example, Du et al. (2017b) adopted an ABM modelling framework to investigate how individuals' evacuation behaviours could be affected by their behavioural heterogeneity to flood warning,

warning accuracy and lead time. In this study, the agents' representations were simplified with three types of physical attributes (agent's geographical location, maximum evacuation speed and evacuation status) that were relevant to the evacuation process, and a psychological attribute (a risk tolerance threshold based on agents' behavioural parameters) that was related to the flood warning response. Being Carried out by the same lead author (Du et al., 2017a), the framework was further developed by including opinion dynamics through ABM to explore social media's influences on individuals' flood risk awareness, and the consequent effectiveness of a flood warning system. However, it was noted both studies were implemented based on a hypothetical residential area due to the lack of empirical data.

Another application of ABM has been found in the exploration of transportation-flood systems. A common approach adopted in this area is by utilising existing ABM based traffic models and applying different behaviour rules to better understand the interactions between the two systems. For example, Suh et al. (2019) used the MATSim (Multi-Agent Transport Simulation) software (Waraich et al., 2015) to assess the benefit of 'transportation infrastructure protection plans' against sea level rise. Specifically, for each sea level rise and protection (levee) scenario, the corresponding inundated links from the original traffic network were removed and the resultant vehicle travel hour was then calculated. Similarly, Pyatkova et al. (2019) examined how flood events could affect road transportation by integrating flood (InfoWorks; (Innovyze, 2020)) and traffic models (a microscopic ABM traffic model called SUMO (Simulation of Urban MObility), (Krajzewicz et al., 2012)). And the interactions were based on described behaviour rules (i.e., rerouting, reduced speed) and predefined threshold from water depth information. A further two studies by Zhu et al. (2018) and Saadi et al. (2018) were found in this research area, which adopted the similar research concept as described above (i.e., couple flood hazard map/model with existing ABM based traffic models).

### 3.3.2 Long-term flood adaptation planning

Flood resilience in practice relies on an understanding of socioeconomic and environmental systems and importantly their interactions (Chandra-Putra and Andrews, 2020), and is maintained/improved by applying sustainable adaptation plans against flood risks. However, because the adaptation measures often take a very long time (e.g., 30 years and more) to verify and involve large investments (Löwe et al., 2017), there is a desire of a modelling framework that could assess the effectiveness of different measures in advance for improved decision-making. The assessment would focus on understanding how adaptation measures reduce risk and how much risk remains after adaptation. In particular, there is a need to test the effectiveness of rules, regulations, policies and implementations that aim to reduce flood risks, as well as considering individuals react towards these aspects and adaptations (Tonn and Guikema, 2018). ABM has the capabilities to realise these testing requirements, and assess the robustness of a wide range of potential future developments/policies/strategies. Studies by Dawson et al. (2011); Zhu et al. (2019); Du et al. (2017b); Lumbroso and Davison (2018) and similar have conceptualized both human and flood subsystems within ABM frameworks and considered the heterogeneous features within the decision making processes. But when it comes to long-term flood adaptation planning, the main issue of these studies is that they do not methodically consider the influence of socioeconomic factors (e.g., institutions, risk perceptions, development plans, policies, societal preferences) to understand the drivers of flood risks (Abebe et al., 2019b).

A number of ABM papers have been published specifically focusing on the socioeconomic interactions for long-term flood adaptation and planning studies. For example, Jenkins et al. (2017); Crick et al. (2018); and Dubbelboer et al. (2017) presented an ABM framework to assess how Sustainable Drainage Systems, property level protection measures and flood insurance scheme could affect local surface water flood risk in the context of various climate change projections. With a similar research direction, a ABM approach has also been applied to explore individual's adaptive decision making behaviours against coastal flood risks and considered households' risk perception, insurance policies, and local flood mitigation measures (Han and Peng, 2019).

To support the identification of adaptation measures that were economically efficient and robust to changes of climate and urban layout, Löwe et al. (2017) proposed a framework based on the 1D-2D MIKE FLOOD hydrodynamic simulation and the DAnCE4Water agent-based urban development model to systematically understand the effectiveness of adaptations based on the changes of water drainage system and urban planning policies. The DAnCE4Water model simulated the urban evolution from a parcel level detail and directly provided information on the shape and location of urban features such as buildings and streets, and allowed the dynamic interactions among hazard, exposure and vulnerabilities. In a similar research area, Becu et al. (2017) integrated a coastal flooding model with a spatially explicit agent-based land planning model (LittoSIM) to simulate a coastal development area and its management of flood prevention measures. Similarly, studies by Haer et al. (2019) presented a multi-disciplinary approach integrating different types of adaptive behaviours of governments (proactive and reactive) and households (rational and boundedly rational) in a continental-scale risk-assessment framework for river flooding in the European Union. In particular, the adaptive behaviour of households was built based on an economic decision-making model called discounted expected utility, and at each time step these agents decided to either flood-proof existing buildings or to elevate newly developed buildings. Similar micro- (household) and macro (government) integrated ABM approaches have also been observed in a number of papers that were reviewed, e.g., Abebe et al. (2019b); Mustafa et al. (2018); and Abebe et al. (2019a).

For community flood risks, individual agents can mitigate risks by household mitigation or by moving based on risk and coping perceptions and are influenced by other agents' mitigation behaviours, whilst the community can mitigate or disseminate information to reduce risks. Both can have a significant influence on each other, therefore, community flood risks are the outcomes of an evolving process. To capture information on how community policies and individual decisions can affect on the evolution of flood risks under different future climate scenarios, Tonn and Guikema (2018) and Tonn et al. (2020) developed an ABM based approach to understand the temporal aspects of flood risk by integrating behaviour, policy, flood hazards and engineering interventions within a whole dynamic system. The ABM model focused on simulating a number of adaptation and mitigation methods from the dissemination of flood management information, installation of community flood protection, elevation of household mechanical equipment, to elevation of homes.

To reduce the adverse impacts from flood events, risk communications play a vital role in the aspect of increasing people's flood risk awareness. Risk communication is commonly done through a top-down manner from the governments and organisations (e.g., brochures, media campaigns, and internet websites). However, such an approach has been found less efficient, because of the lack of considering of cultural differences and local circumstances (INTERREG, 2013;Burningham et al., 2008;Martens et al., 2009). ABM has been applied to assess the effectiveness of flood communication strategies and influences of social networks in the Netherlands (Haer et al., 2016). Its highlight was that the social-psychological simulation of individual's flood-risk preparedness decision was firmly based on the Protection Motivation Theory (Rogers, 1983). By the same first author (Haer et al., 2017), three economic decision models were employed for simulating human behaviours (i.e., household investments in flood loss-reducing measures) in flood risk analysis, based on an Expected Utility Theory which is a traditional economic model of rational agents (Von Neumann and Morgenstern, 2007), a Prospect Theory which takes account of bounded rationality (Wakker, 2010) and a Prospect

Theory model that accounts for changing risk perceptions and social interactions through a process of Bayesian updating (Viscusi, 1989).

Hazard migration could also be modelled by ABM, which might be triggered by environmental threats like flood events as well as temporal changes in resource availabilities (e.g., population growth, employability, house price) along with a number of other factors. Hassani-Mahmooei and Parris (2012) reported the development of an ABM tool on investigating the migration dynamics that might arise in Bangladesh as a result of extreme hazards (include flood) that were likely to occur due to climate change. This study was based on district-level, with each district represented in the model by one main agent only who managed the interactions within the district and made decisions on movement depending on the results of three factors (the push factors that are associated with climate change scenarios and socio-economic conditions such as poverty level and unemployment rate; the pull factors which are the socio-economic conditions in the potential destinations; and intervening factors such as house ownership and employment conditions). The districts were connected as a network with nodes representing the centroids of the districts and links representing possible migration paths between districts. Past stay/migration decision outcomes were used as inputs through feedback loops for their future decisions. Similarly, Husby and Koks (2017) applied the ABM approach for post-hazard household migration and coupled that with input-output and computable general equilibrium models to estimate economy-wide flood disaster losses.

In addition to the aforementioned studies, ABM model has also been used in a wider range of flood adaptation and planning cases, for example, assessed the effectiveness of a range of physical/structural and social preparedness adaptation measures for manufacturing small and medium-sized enterprises to reduce the impacts of and expedite recovery from major flood events (Coates et al., 2019); determined when and where in a region flood investments should take place through coupling with a regional annual maximum floods model and cost–benefit analysis (O'Connell and O'Donnell, 2013); coupled with a property value estimation model to simulate coastal real estate market performance after different storm-event scenarios (Chandra-Putra and Andrews, 2020); used as a flood risk management teaching tool to allow participants to play the role of decision makers in a developed ABM based gaming platform and found an appropriate balance between flood associated socioeconomic and environmental challenges (Taillandier and Adam, 2018;Shelton et al., 2018;Daré et al., 2018); as well as assessed various management and adaptation plans on flood risks in a general way (Valkering et al., 2005;Erdlenbruch and Bonté, 2018;Dressler et al., 2016;Baeza et al., 2019).

### 3.3.3 Hydrological modelling

Another area that ABM has been lightly explored in the field is on hydrological modelling which is related to flood risk management. One specific application was on mapping the connectivity of potential runoff source areas and flow paths to reduce flood risks, in particular, to improve our understanding of the hydrological dynamics of low-frequency, high-intensity rainfall events in semi-arid catchments (Reaney, 2008). The challenges of modelling such events are due to the infrequent nature of the storms, as well as the complex interactions among runoff generation, transmission and re-infiltration over short temporal scales (Cerda, 1995;Reaney et al., 2007). Most of the distributed hydrological models do not provide sufficiently accurate information on the origin of runoff within a catchment. To tackle this challenge, an ABM approach was applied in Reaney (2008) to trace the path taken by water through a semi-arid catchment. Specifically, autonomous software agents were given information on their local environment generated by the hydrological model and decided on their next spatial locations based on probability theory (i.e., stay in the current cell, infiltrate into the soil, or flow into a neighbouring cell). Another interesting area was explored by Sanchez et al. (2014) on adopting ABM for evaluating flow path in urban drainage networks, specifically to simulate raindrops movements over topography under the gravity rule. Each agent has an elevation as a property and several agents can be stacked together until they reach a positive gradient from the location to the nearest minimum neighbouring cell, hence indicating the direction of flow in the pipes. Unlike most of the reviewed studies described in this paper, the agents in this study were manually generated by clicking the computer's mouse at particular points of interest,

## 4. Discussions

### 4.1 ABM platforms/tools

The availability of the off-the-shelf software has made the ABM developing procedures much easier for flood risk management applications. A variety of studies have been carried on evaluating different ABM tools in a general way (Abar et al., 2017;Allan, 2010;Arunachalam et al., 2008;Kravari and Bassiliades, 2015;Nikolai and Madey, 2009;Railsback et al., 2006). In particular, Abar et al. (2017) has compared over 80 ABM tools in the aspects of their technical features and specifications including model development effort and modelling strength; and Kravari and Bassiliades (2015) evaluated 24 ABMs platforms based on their operating ability and pragmatics. Although a number of ABM tools/platforms are available as either open-sourced or close-sourced, based on the reviewed papers, the most commonly used are found to be Netlogo, Repast (Recursive Porous Agent Simulation Toolkit) (Collier, 2003), and MASON. The comparison of the three tools is summarised in Table 1. They all have limitations and benefits in relation to specific requirements, evaluation criteria and individual's programming preference. Overall, Netlogo is the quickest to learn and the easiest to use which is particularly suitable for beginners, but might not be the best option for building large and complex models. Although Repast is slower than MASON, it has a significantly larger user base, meaning getting support and advice from the community is easier. A comprehensive comparison of the three tools is out of the scope of this study and interested readers are referred to Railsback et al. (2006) and the above review papers for more details.

## 4.2 Advantages

ABM is an ideal tool for dynamically modelling the heterogeneity of individuals for flood-related studies (Dawson et al., 2011), and in principle, agents can be simulated to almost any level of details. Each agent can have state variables to represent their behaviour rules, as well as interactional history with its surrounding environments and other agents (DeAngelis and Grimm, 2014). Integrating each agent's decision makings will result in an overall consequence of the whole community/population (Vincenot, 2018). Even the simplest decision-making rule based on logical "if-then" structure can result in rather complex interactions. Not to mention that the decision-making rules can become a lot more complicated such as probabilistic where an array of possible actions response to some stimulus is defined for each agent and also adopt complex theoretical models from economical, psychological and sociological fields as rule representations (Haer et al., 2017). ABM allows a model to be designed in a way that is more representative to the real-world systems rather than forcing the researchers to simplify system representations purely for analytical tractability (Tesfatsion et al., 2017). In particular, the key elements (e.g., physical, biological, institutional, individual, and communal) of the flood system can be simulated interactively under one modelling framework, and accordingly, important questions could be answered: under certain environmental conditions, what would the agents do? What could they do? And what should they do? (Tesfatsion et al., 2017)

Although ABM models are only an approximation of the full complexity of the real-world entity' behaviour, it is very effective for disentangling specific behavioural processes (Haer et al., 2016). Moreover, by adjusting certain ABM parameters, it can be very useful in investigating the key drivers, scope, and limitations for future flood adaptation and mitigation plans, as well as visualize different planning scenarios for improved understanding among relevant stakeholders. As such ABM has the advantage as being a bottom-up supporting tool for flood-related policy-making (Van Dam et al., 2012). Besides, it can simulate real-time agent behaviours when facing flood threats (Yang et al., 2018), making the model suitable for delivering insights into emergent features such as evacuation, traffic plan, and exposure assessment which are difficult to be extracted from other approaches (e.g., Event and Fault trees, Bayesian Networks, Microsimulation, Cellular Automata, System dynamics as described in Gilbert and Troitzsch (2005)) (Dawson et al., 2011). Another benefit of the ABM framework is that it has the flexibility of quick revision and add/change modules (Crick et al., 2018). For example, when new policy or literature on improved decision-making methods become available, prompt updates could be made to the framework.

### 4.3 Limitations and potential ways for improvements

Despite a growing interest in ABMs across various research fields, there is still limited application of this technique for flood-related studies. The main challenges of the ABM modelling have been categorised into three areas: 1) model development, 2) model assessment and testing, and 3) model documentation.

**Model development**

First, the ABM models applied in the field lack a clear conceptual framework and theoretical support. As pointed out by Robinson and Rai (2015), the effectiveness of an ABM over other methodologies, relies on a rigorous combination of theoretical and empirical foundations. Therefore, when implementing ABM models to simulate studies that have an overall high degree of sophistication, the model rigour should also meet the same standard. However, most of the reviewed papers lack a sound theoretical underpinning (Kellens et al., 2013), and often with a plethora of independent ad hoc assumptions of the decision-making process without being grounded on the established behavioural theories. Although there is a few studies focused on the testing of theories (Haer et al., 2016;Haer et al., 2017;Haer et al., 2019), they are based on economic theories only, and ignoring other relevant disciplines, such as psychological (e.g., the theory of planned behaviour) field (Groeneveld et al., 2017). Using decision-making models based on theory has several advantages over ad hoc implementations (Rai and Henry, 2016). For examples, it fosters interdisciplinary communications, makes improvement of models easier, allows to test alternative theories even when data is sparsely available, and leads to more robust and faster scientific progress (Groeneveld et al., 2017;Bell et al., 2015;Klabunde and Willekens, 2016).

Instead of relying on fixed theoretical rules to control the way agents make decisions, we can borrow concepts from other fields such as computing science and ecology to setup decision-making processes and human behaviour based on technologies such as machine learning and artificial life studies (e.g., artificial neural network (ANN), genetic algorithm (GA)) (Hamblin, 2013;Huse et al., 1999;DeAngelis and Diaz, 2019). For example, ANN can train the weights of different inputs by continuously modifying these weights until the resulting decisions and agent behaviours achieve required accuracy. It captures the decision-making processes by learning from how individual's brain functions and once the model is trained, with any new inputs it can determine the decisions that meet the required degree of accuracy and evolve (Huse et al., 1999;Lek and Guégan, 1999). In ecology, when utilising ANN in ABMs, a common way of training is by using the GA, which was also adopted in one of the reviewed papers (Mustafa et al., 2018) for calibrating the ABM-based land-use change model. GA is an optimisation tool that is based on the principles of crossing over and mutation to essentially evolve the decision-making processes of individuals, without the need for probabilistic or logistical rules (DeAngelis and Diaz, 2019).

Alternative approaches to inform model structure can also be learnt from other more established fields such as ecology and land-use change. For instance, a strategy called Pattern Oriented Modelling (POM) could provide a unifying framework for decoding the internal organisation of the complex agent-based systems and might provide insight towards unifying algorithm theories for building up the relationship between adaptive behaviour and system complexity (Grimm et al., 2005), and reduce model uncertainty (Magliocca and Ellis, 2013). Patterns are the defining characteristics of a system, hence important indicators for underlying processes and structures. When modelling agent decisions with the POM, adopting "strong inference" (Platt, 1964) by contrasting alternative decision models or "theories" (Auyang, 1998;Grimm and Railsback, 2005) is recommended as a useful strategy (Grimm et al., 2005;Magliocca and Ellis, 2013).

For the simulation of human behaviours, in the majority of ABM applications, a rational actor model is normally used, which is clearly insufficient to describe the complexity of the human system. Furthermore, various decision-making processes might be applied to different agents, and even by the same agent under various situations because humans are not constrained by one identity or act following the predefined rules (Haer et al., 2017; Kurtz and Snowden, 2003). Although there exist many theories scattered across different fields (Groeneveld et al., 2017) for simulating human behaviours, most of them cover only a certain aspect of decision-making and vary in their degree of formulation. A framework for behavioural theory comparisons and alternative theory communications such as the one proposed by Schlüter et al. (2017) could be useful in tackling those challenges.

Furthermore, different approaches could be adopted to empirically inform ABM development, such as through sample surveys, participant observation, field and laboratory experiments, companion modelling, and GIS and remotely sensed data as reviewed by Robinson et al. (2007). In flood risk domain, for examples, survey data such as those about flood risk perception and behaviour could be collected for model refinement through purposely designed questionnaires (Haer et al., 2019; Dawson et al., 2011; Wang et al., 2018), experiments (e.g., VR experiment used in (Li et al., 2019)) and role-playing games (e.g., Taillandier and Adam, 2018; Shelton et al., 2018; Daré et al., 2018)). Since data collection capabilities are enhanced rapidly by technologies, and global remote sensing data are becoming more available, it is expected the ABM approach would become more popular in the field. Nevertheless, more coordinated efforts are required for data sharing within the whole modelling community.

Given the flexibility of representation by the ABM, and the increment of data availabilities, there is a need to identify the appropriate level of complexity in the models. If a model is too simple, it neglects essential mechanisms of the real system; however, if a model is too complex, it can become cumbersome and get bogged down in unnecessary details (Grimm et al., 2005). In practice, 'a simple model that can be well communicated and explained is more useful than a complex model that has narrow applicability, high costs of data, and more uncertainty' (Voinov and Bousquet, 2010). In order to find an optimal zone of model complexity, systemic methods such as the POM, stepwise approaches (e.g., either building up components starting with simple prototypes/models, or removing components progressively from complicated models), and modular design (e.g., extensive planning phase, the use of unified model language diagrams) can be used to guide modellers in reaching an appropriate level of model complexities (Sun et al., 2016).

## Model assessment and testing

ABM assessment and testing is the key to understand if development is appropriate to address the question or problem at hand. While it is the advantage of an ABM that a wide range of flood adaptation plans and risk management strategies could be compared, the method is still limited by the lack of empirical data support for model testing. For instance, it is challenging to firmly identify adaptive behaviours in a specific study area and obtaining these kinds of datasets for model testing is normally challenging. In order to make the model robust, uncertainty analysis to test a large range of parameter settings could be essential (Lumbroso and Davison, 2018;Dawson et al., 2011;Jenkins et al., 2017;Du et al., 2017a). Moreover, there is a continuing need for sensitivity analysis, especially in the forms tailored specifically for ABM (e.g., global sensitivity analysis (Magliocca et al., 2018)), not just standard measures such as Kappa that is more suitable for linear models (O'Sullivan et al., 2016).

While the ability to replicate empirical evidence is often seen as the only truly decisive criterion for the quality of an ABM model, it has been suggested by Bert et al. (2014) that the ABM testing should also rely on the validation of model processes and components during the model development. This is because most ABM models are applied to non-observable scenarios such as the implementation of hypothetical adaptation policies. As a result, there are no observational data available for the testing. The model should show theoretical validity, agent-behavioural validity, validity under extreme conditions and structural validity (Damgaard et al., 2009). A number of approaches may be used for the model process validation, such as the TAPAS (Take A Previous Model and Add Something) (Polhill et al., 2010), "modelling for a purpose" (Takama and Cartwright, 2007), POM (Grimm et al., 2005), and the participatory modelling (Voinov and Bousquet, 2010). Clearly, such approaches are beneficial for both model development and testing. For the empirical testing, it is not only to assess how good the model can reproduce the reality, but also for the simultaneous calibration, tuning and further development of the model (Bert et al., 2014). For the latter, methods such as the "Post-hoc POM" could be used  (Topping et al., 2012). To find the balance between empirical validation and process validation, the "invariant-variant" method proposed by Brown et al. (2005) could be a useful guide which has been applied in the land-use field to help modellers to understand the situations with good model results, and the instances with poor model results due to either path dependence (Arthur, 1988) or stochastic uncertainty.

When dealing with complex models especially these with a large number of different adaptation options and a large group of heterogeneous agents, the computational requirements could explode to infeasible levels that certainly cannot be handled by desktop PCs. With the rapid development of supercomputing facilities, this issue could be addressed through implementation in cluster environments as well as the application of surrogate models and design experiments with a minimal amount of simulations (Löwe et al., 2017), for instance, sequential setups proposed by Kleijnen (2015).

**Model documentation**

Documentation for ABMs is often incomplete, opaque and difficult to understand, which hamper their applications and further developments by the community. Without a standard protocol, it would be difficult to understand, compare and duplicate the ABM models that have been developed. Grimm et al. (2006) has proposed a standard protocol called ODD (Overview, Design concepts, and Details) for describing ABMs, which has been widely received in the scientific community. First, the 'Overview' provides the purpose and main processes of the model with three subcomponents of purpose, state variables and scales, and process overview and scheduling; second, the 'Design concepts' describes the general concepts underlying the model design; and third, the 'Details' shows all the necessary information for the reimplementation of the model with three subcomponents of initialization, input, and submodels. A more recent version of the protocol (ODD + Decision) has been presented in Müller et al. (2013), which is added with a new component for human decision-making. The new version is more useful for documenting ABMs in general when human decisions are included which is more suitable for flood-risk related ABM models. The ODD and its extension have been used widely for documenting ABMs including in flood-related studies (Tesfatsion et al., 2017;Noël and Cai, 2017). It is also expected if developed ABM models/frameworks could be shared and reused such as through open-source software platforms (e.g., http://www.comses.net, and https://github.com/), it might allow more researchers to focus on exploring the choices of appropriate decision models (Bell et al., 2015).

## 5. Conclusions

The utilisation of ABM to tackle flood-related challenges is becoming more popular in recent years. The variety of identified topic areas illustrates that, on one hand, there is a continuing prominence of real-time flood emergency management and planning focused studies; and on the other hand, there is a significant rise of studies interested in the application of ABM to flood adaptation policy and strategy planning support in recent years. A particularly valuable area might be the latter. This is based on two reasons. First, studies in this area have significant potential to contribute to practically driving flood resilience by guiding and improving multi-shareholder decision-making. Second, such a topic could tackle interdisciplinary issues and encourage cross-disciplinary collaborations more directly than other topics. As increasing flood resilience is high on the agenda of policy-makers and academics alike in many countries, it is expected that the importance of this topic in the context of flood risk management studies will remain.

While technical comparisons of the ABM models are not the focus of this paper, the review however reveals the limitation of ad hoc implementations of decision-making and behaviour in the models, and lack of a consistent format of presentation and documentation. This, as a result, makes the model comparison difficult across the studies and is challenging to summarize a common framework for ABM applications in flood risk management. Future ABM development in the field will be influenced by the continuing development and refinement of modelling framework and theoretical foundations, and enhancement of model testing and documenting capabilities. While the review has identified the limitations and potential areas for future improvement of ABM applications in the field, it would be the most efficient to develop across disciplines to include all actors in ABM systems. For instance, it would benefit from the interactive involvement of environmental scientists, social scientists, economists, and psychologists in the development process. Especially, for adaptation and mitigation planning, models that encourage collaboration between disciplines and sectors, will more likely promote knowledge sharing and allow easier acceptance by wider audiences/users naturally (Hansen et al., 2019).

Based on the review, although ABM has shown valuable advancements for flood risk management studies, its application is still in a state of infancy, especially its contribution to the understanding of how human decisions and behaviours affect the whole human-flood systems has yet to be fully exploited.

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**Table 1.** Comparisons of Netlogo, Repast and MASON. Source (Salgado and Gilbert, 2013).

| | Netlogo | Repast | MASON |
|---|---|---|---|
| Licence | Free, but not open source | General Public Licence | General Public Licence |
| Documentation | Good | Limited | Improving, but limited |
| User Base | Large | Large | Increasing |
| Modelling Language(s) | NetLogo | Java, Python | Java |
| Speed of Execution | Moderate | Fast | Fastest |
| Support for graphical user interface development | Very easy to create using ‘point and click’ | Good | Good |
| Built-in ability to create movies and animations | Yes | Yes | Yes |
| Support for systematic experimentation | Yes | Yes | Yes |
| Easy of learning and programming | Good | Moderate | Moderate |
| Easy of Installation | Good | Moderate | Moderate |
| Link to geographical information system | Yes | Yes | Yes |

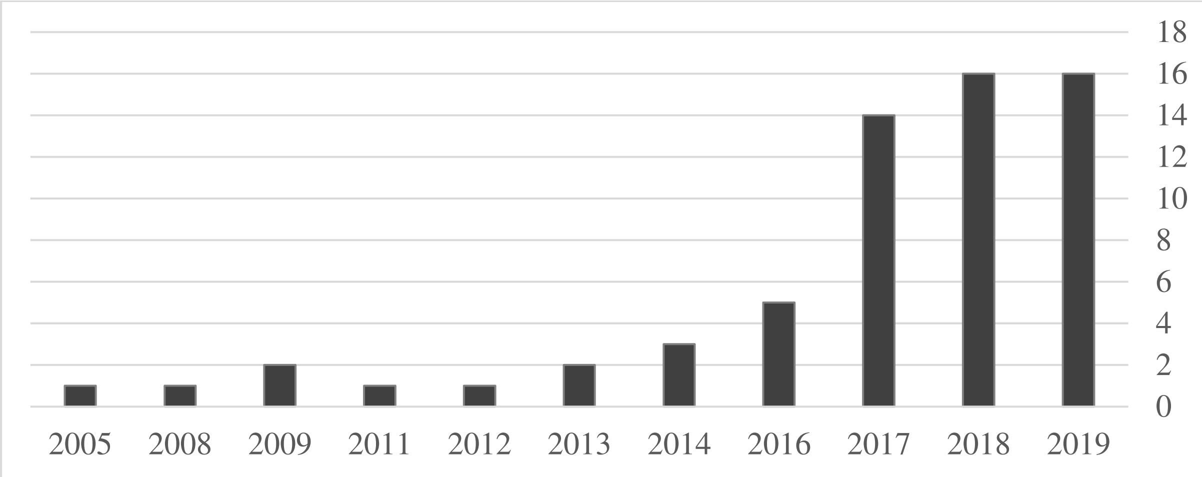


**Figure 1.** Annual distribution of the identified articles.

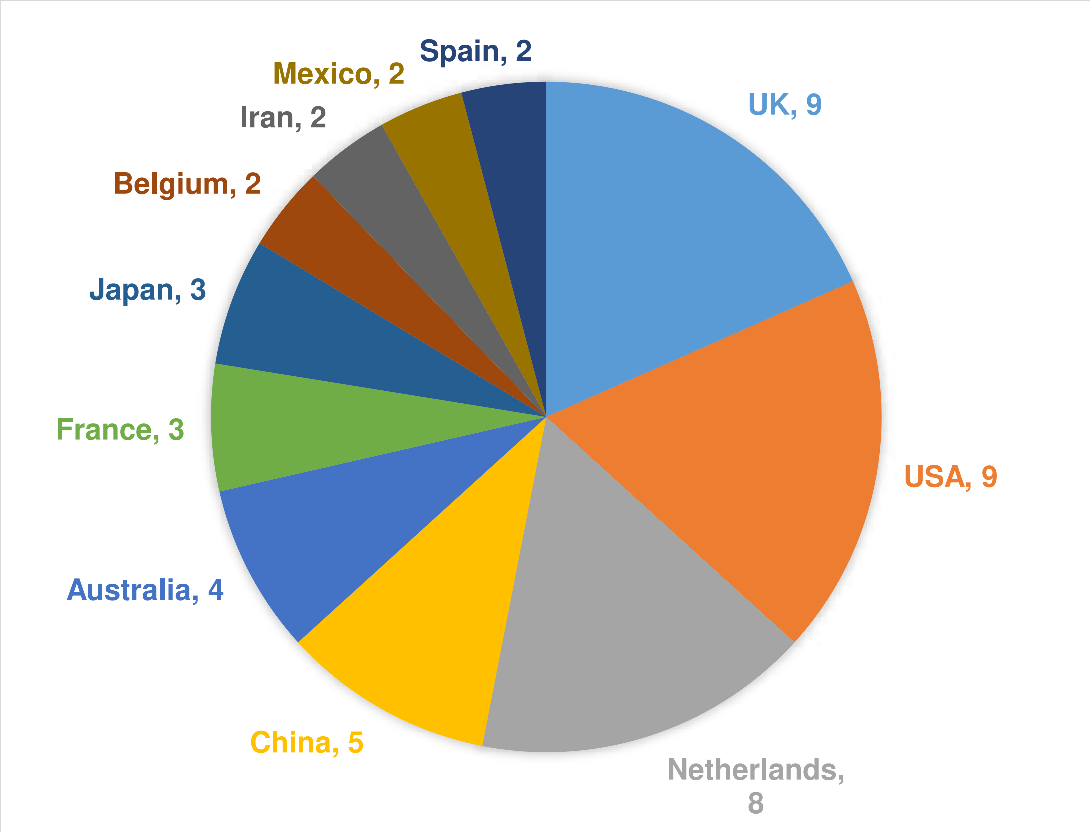


**Figure 2.** The global distribution of ABM applications in flood risk management (by their case study areas). Only countries appeared more than once are listed (49 papers). Additional seven papers have one case study carried out in Bangladesh, Chile, Ethiopia, Germany, Ghana, Italy and Pakistan, respectively. The remaining five papers are based on synthetic scenarios (four) and the whole European Union (one), respectively.