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TOPICAL REVIEW

A systematic mapping review of hydrological hazard management in agent-based systems

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Abstract

Agent-based modelling (ABM) is becoming a widely explored method for investigating human–water systems, given its ability to represent heterogeneous actors and their decisions. ABM can simulate how humans interact and co-adapt with their environment, which is beneficial for understanding the effects of humans' decisions in the face of hazards and climate change. ABMs can serve as tools for examining the effects of current and future hydrological hazard management strategies. However, the implementation of hydrological hazard management in ABMs has not yet been systematically evaluated for floods and droughts. To map the current status of ABMs in hydrological hazard modelling and facilitate a discussion on further potential, we conducted a systematic mapping review based on the ROSES protocol. In this review, we investigate what kinds of hydrological hazards and management strategies that are represented in ABMs. Additionally, we synthesise current practices regarding agent types and their decision-making. A total of 377 articles were screened, and 77 articles were analysed in full text. Our findings indicate that hydrological hazard management strategies in ABMs include both structural and non-structural measures. However, there is an emphasis on the complexity of individual agents' decision-making in implementing these measures, whereas collective agents (e.g. governments) performing non-individual hazard management are implemented more simplistically, often as static scenarios or collective agents with ad-hoc or rational decision-making. Conversely, individual agents are commonly implemented with human-like behaviour. Our study highlights that the simplicity of hazard management in these models could restrict the potential of ABMs as policy and predictive tools, as the implemented hazard management does not capture the full dynamics of human–water systems. Involving stakeholders, adopting interdisciplinary methods, or incorporating bounded-rational decision-making could represent a significant shift to further enhance the explanatory power of ABM for addressing challenges in hydrological hazard management.

1. Background

Climate change, urbanisation, and land-use change are expected to amplify impacts from hydrological hazards (Jongman *et al* 2012, Winsemius *et al* 2016, Tabari *et al* 2021, IPCC 2023). Hydrological hazards encompass a large variety of hazards, such as fluvial floods, agricultural droughts and dam breaks, and their amplification could make hydrological risk management even more complex and challenging. UNDDR's Sendai framework incorporates a system risk perspective for disaster risk reduction measures (UNDRR, 2015, Mitra and Shaw 2023) where the systemic risks perspective aims to create a larger understanding of disaster risk, including that from hydrological hazards, by embracing transboundary effects, dynamics and uncertainty of disasters, especially those deriving from multi-hazards (Sillmann *et al* 2022). This perspective can aid us in finding feedback loops between adaptation and future disaster risk to avoid maladaptation paths (Westra and Zscheischler 2023).

The systemic perspective acknowledges disaster risk reduction as a complex system of which human–water interaction is part. Hydrologists have been focusing for the last decade on contextualising hydrology into this complex system (Sivapalan *et al* 2012, Di Baldassarre *et al* 2013). To investigate the mutual interaction between hydrology and society, new methodological approaches have been introduced (Di Baldassarre *et al* 2019). Typically, bottom–up agent-based modelling (ABM) and top–down system dynamics modelling have been implemented (Blair and Buytaert 2016). The benefit of ABMs is to see emergent patterns from non-aggregated behaviours, in comparison to system dynamic modelling (Zhuo and Han 2020).

ABMs (also called multi-agent systems) consist of multiple autonomous decision-makers, called agents (Wooldridge 2009), see figure 1. It originates from the work by Von Neumann (1966) on cellular automata, where autonomous computer agents were introduced. Agents in ABMs can be heterogeneous, take actions based on specific decision rules and interact with each other or the virtual environment in which they are implemented (Tonn and Guikema 2018). The heterogeneity of agents is a significant capability compared to other modelling frameworks, such as system dynamics, as it is possible to explore processes that cannot be aggregated. This can, for example, be differences in the flood adaptation between households due to a difference in the intrinsic risk perception within a community (Haer *et al* 2016). ABMs can range from simplistic ones that explore qualitative questions, so-called toy or stylised models, to empirically based models that study complex emergent phenomena in human-nature systems (Janssen and Ostrom 2006, Sun *et al* 2016). Thus, the agents can represent humans and their response to imminent disaster risks. ABMs have therefore been coupled with hydrological models to explore the interplays between society and hydrological extremes: for example, riverine floods (Michaelis *et al* 2020), urban pluvial floods (Dubbelboer *et al* 2017) and droughts (van Oel *et al* 2010).

In ABM of water-human systems, the implementation of agents' decision-making is crucial to capture the processes of these complex systems. The decision rules link the agent's observation of its surrounding environment, other agents, and its attributes with a choice of actions (Tesfatsion 2006). For human-like agents, these decision rules can be based on behavioural theories, but it is also common that they are simplistic rules of if-then statements, so-called ad-hoc or heuristic decision-making agents (Sun *et al* 2016, Groeneveld *et al* 2017, Anshuka *et al* 2022). Ad-hoc decision making could, for example, be a farmer agent choosing a different crop type if it has rained more than a predetermined threshold (van Oel *et al* 2010). The behavioural theories that are commonly used are rational, based on, for example, cost-benefit analysis (CBA) or expected utility (Neumann and Morgenstern 1944), and social diffusion theories that explore interaction and learning between agents, such as consumer theory (Jager 2000) or bounded rationality (Simon 1990). Bounded rational agents are assumed to have cognitive limitations, which can be a lack of information or limited skill in interpreting available information. Notable frameworks for this are prospect theory (PT) (Kahneman and Tversky 1979) and protection motivation theory (PMT) (Rogers 1975). An emerging practice in ABMs is to integrate machine learning (ML) methods for the agents' decision-making, such as reinforcement learning (Zhang *et al* 2023). This approach can account for bounded rationality, as the ML can be supervised with human behavioural data. Previous ABM reviews have emphasised the limitations of modelling individuals with ad-hoc or rational decision-making, as bounded rationality shows larger similarities with empirical data on human actions (Zhuo and Han 2020, Schrieks *et al* 2021). To broaden the perspective, in this review we also include decisions for non-individuals, as organisations, authorities and firms.

The complexity of human–water systems does not only arise from the boundary between humans and water but also within society itself. In other words, the interaction between humans and institutions (e.g. organisations, governments, firms) impacts flood and drought risk as well (Richert *et al* 2019, Papathoma-Köhle *et al* 2021). An example of this is the so-called *safe-development paradox*, where large-scale structural mitigation measures, such as levees, dams or dikes, can cause individual complacency regarding individual adaptation and thus, preparedness decreases and risk increases (Di Baldassarre *et al* 2018, Fusinato *et al* 2024). Another factor that influences individual mitigation is that individuals believe that the government is responsible for adaptation, and thus wait to take action (Bubeck *et al* 2012), or that insurance schemes do not always motivate adaptation (Surminski 2014). The institutions' vulnerability to cope with natural hazards also has an impact on the disaster risk, for example, the hazard vulnerability has increased in Greece after the financial crisis has impacted social security, building quality and reduced funds for public measures (Kassaras and Sotirhos 2015, Papathoma-Köhle *et al* 2021). Researchers have therefore drawn attention to the necessity to incorporate political and social processes over multiple scales of actors in hazard management and complex system modelling (Eakin *et al* 2017, Yu *et al* 2017, Elsawah *et al* 2020).

Nonetheless, organisations are not perfect at making decisions to reduce disaster risk. For instance,

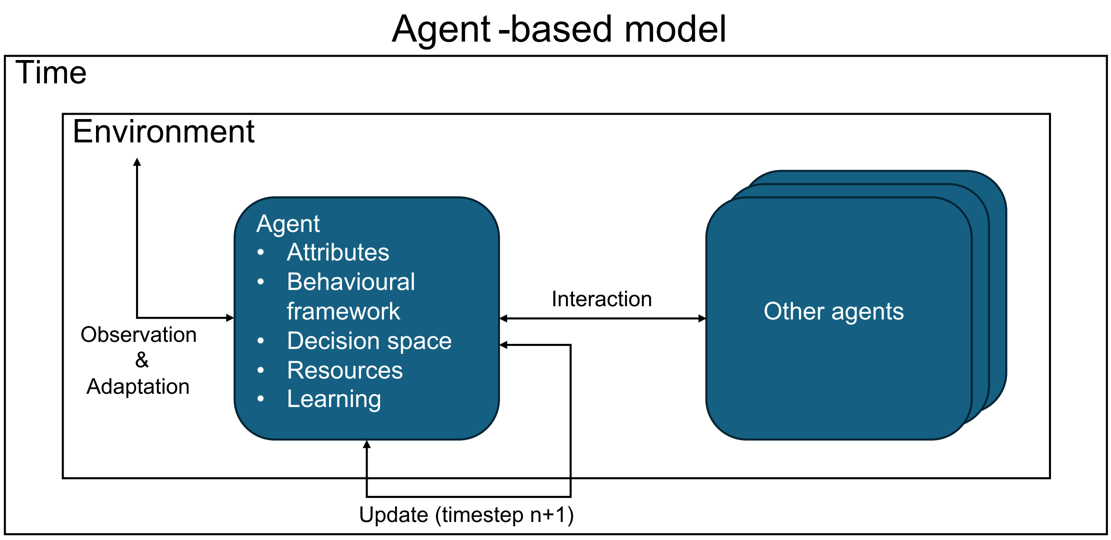

Figure 1. Schematic representation of an agent-based modelling framework.

Nohrstedt *et al* (2021) unveiled that hazard occurrence, fatalities, economic damages and impacted people did not cause disaster risk policy change. Institutional actions can also increase hazard vulnerability due to the unintended consequences of policies (Schipper 2020). On Spain's east coast, urban planning has caused an increase in flood exposure with more than 250% (López-Martínez *et al* 2017). Contrary to previous reviews on individual decision-making, there has been limited emphasis on the irrationality of institutional decision-making in ABMs. Taberna *et al* (2020) noted that most governmental and corporate agents acting against urban flooding in ABMs follow either ad-hoc or rational decision-making processes. Our review aims to further evaluate how institutional decision-making is implemented in ABMs of hydrological hazards and discuss the consequences of representing irrational and complex decision-making with simplified behavioural theories.

Hydrological hazard management is a complex phenomenon where individuals, institutions and water dynamically interact with each other in unpredictable or irrational ways. ABMs can be a useful tool to investigate the effects of bounded rational hazard management and how multiple scales of actors contribute to or limit disaster risk reduction. Due to the flexibility of ABMs, it is also possible to explore the effectiveness of hazard management for multi-hazards. Yet, to our knowledge, previous reviews have only studied either floods or agricultural drought (Simmonds *et al* 2020, Taberna *et al* 2020, Zhuo and Han 2020, Schrieks *et al* 2021, Alam *et al* 2022, Anshuka *et al* 2022). Moreover, earlier reviews, except Taberna *et al* (2020), have mainly focused on individual agents and have not assessed how institutions and non-individual entities have been implemented. Hence, there is a knowledge gap on how organisations are implemented in hazard modelling utilising ABMs, and no prior review has compared how the hazard management differs between different hydrological hazards, including hydrological multi-hazards. Yet, the implementation of organisations is of great interest as it plays a crucial role in hazard management and, as mentioned, impacts individual decisions and disaster risk.

To embrace the systemic perspective, we aimed to study how hydrological hazard management is represented in ABMs, with a focus on collective agents, i.e. non-individual entities such as firms, authorities or non-governmental organisations (NGOs). We define hydrological hazard management as decisions made to mitigate the impact of floods and droughts. The measures implemented can be structural and non-structural, and taken by individuals or organisations, such as governments or firms. The study aims to synthesise which types of hydrological hazard management measures are incorporated into the models and how the agents make decisions regarding these measures. To achieve this, a systematic mapping review, based on the ROSES protocol (see section 2), is undertaken to explore the following questions that can contribute to further improve how water-human systems are represented in ABMs:

1. What types of hazard management are represented, and are they linked to the types of hydrological hazards that are studied?
2. Which behavioural frameworks are utilised to implement the decision-making processes for individual and collective agents?
3. Are stakeholders, both individual and organisations, included in the ABM model setup?
4. What are the current practices and limitations in hydrological hazard management studies that utilise agent-based-hydrology models?

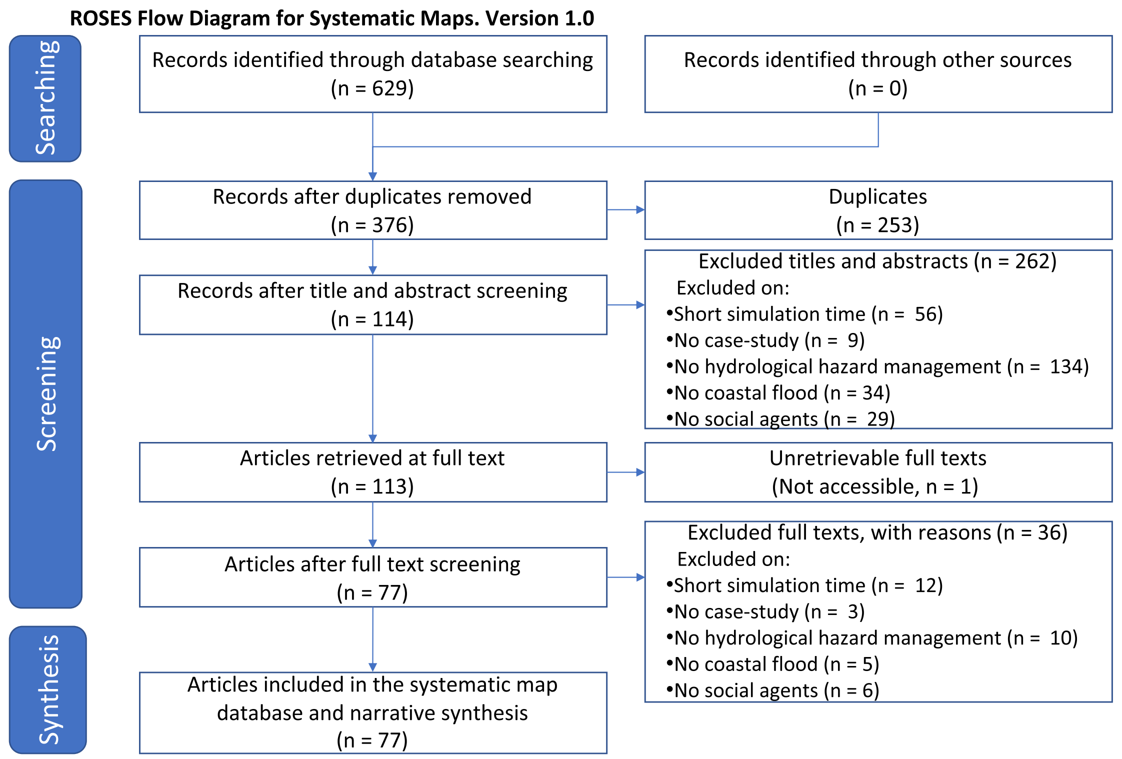

Figure 2. The ROSES flow chart illustrates the searching and screening process for the systematic mapping review, with n indicating the number of articles.

Table 1. The search string used for retrieving articles from scopus and web of science. The asterisk * represents any character(s), and the quotation marks '' represent that that specific phrase is searched.

Agent-based systems		Hydrological hazard		Hydrological hazard management institutions
Agent-based OR 'agent based' OR multi-agent OR 'multi agent'	AND	Flood* OR drought* OR 'water scarcity' OR 'dam break*' OR 'water deficit' OR 'water short*'	AND	'management' OR organisation* OR government* OR ngo OR compan* OR institution* OR polic* OR law* OR guidelin* OR countr* OR authorit* OR admin* OR regulation OR municipalit* OR business* OR industr* OR communit* OR corporation* OR organization*

To answer the first question, we present in sections 3.1 and 3.2 a distributive analysis of the state of the art related to hazard modelling in ABMs. In section 3.3, we answer the second and third questions based on our assessment of the reviewed literature. The last question is answered in section 4, where we present a discussion on the main trends that emerged from our analysis and reflect on the future directions to overcome current limitations.

2. Methods

We conducted the systematic mapping review following the ROSES protocol (Haddaway *et al* 2018) and Siddaway *et al* guidelines (2019). The ROSES protocol (figure 2) was developed to provide a transparent, reproducible and objective method for synthesising environmental knowledge. The ROSES protocol is formed by three different phases: searching, screening, and synthesis, as shown in figure 2. We chose to perform a narrative synthesis to find current practices and knowledge gaps in agent-based systems for hydrological hazard management. A quality assessment and weighing of the validity of the articles was not conducted, as this review aims to describe current practice, both more and less valid, and, hence, all the articles were considered equally important. However, to counteract the lack of qualitative assessment, we have highlighted studies with good examples of model implementation in the results and discussion sections.

Table 1 displays the search query used to find articles to answer the aim of this study. The query is divided into three parts: agent-based systems,

Table 2. Criteria used for the inclusion and exclusion of obtained articles.

Criteria	Description
No hydrological hazard management	Only studies that focused on hydrological hazards and their management were included. Studies modelling, for instance, water quality or water resources under normal conditions were excluded.
Coastal flood	Studies with coastal floods caused by oceanic forces, such as tsunamis, sea-level rise and storm surge, were excluded. However, papers addressing coastal floods caused by a compound effect of oceanic forces and hydrological processes, such as runoff or streamflow, were included.
Modelling	Studies have to include an ABM to be eligible. For example, if the study is a review or an opinion piece, it is excluded.
No human agents	Studies' models had to consist of agents that represent humans or collectives of humans, such as households, countries or companies. Articles with digital agents or smart agents were excluded.
Long-term hydrological hazard management	Studies with a short simulation period (less than a year) were excluded. This could, for example, be models over evacuations or agents' displacement, disaster relief or placement of flood barriers. These studies were excluded since this review focuses on long-term management, e.g. policy processes.

hydrological hazards, and institutions and types of regulations that are involved in hydrological hazard management. We conducted the search on the 13th of May 2024 in two scientific databases, Scopus and Web of Science, on keywords, titles, abstracts and authors. The search was filtered for only English-language peer-reviewed articles and with no date filter. In total, 629 articles were obtained; from Scopus, 303 articles were retrieved, and from Web of Science, 326 articles were retrieved. After obtaining the articles, 253 duplicates were removed, and 376 unique articles were processed in the screening. We benchmarked the comprehensiveness of our search as prescribed by the ROSES protocol by evaluating how many articles that were included in previous reviews on flood and drought management in ABMs were also in our set of retrieved articles. In the review on floods in ABMs (Zhuo and Han 2020), 87% of their included articles were also in our search, while for the drought review (Schrieks *et al* 2021) 73% of the articles in their analysis were included in our search.

During the combined title and abstract screening process, the retrieved articles were divided into equally large sets. For each set, two different contributing authors separately analysed the eligibility of the articles' title and abstract on five criteria, see table 2. These criteria were developed to extract articles that can answer the aim of this study. Studies with a short simulation period were excluded, as this review focuses on the long-term co-evolution of humans, water, and hazard management. Accordingly, evacuation and response studies were not included, while they offer valuable insights into human behaviour during hazards the time scales are generally too short to capture policy development, and thus, they were considered outside the scope of this review. One of the retrieved articles was written by two of the screening authors and was thus assessed by the other two screening authors. When screening authors disagreed on the inclusion of certain articles, a third author did a second screening and made a final decision. If it was unfeasible to determine if the article would be excluded or included after reading the title and abstract, then the paper was included for the full-text analysis, where a second screening on full-text was carried on with the same selection criteria.

After the first screening, 114 articles were included, and 262 articles were excluded. Figure 2 shows that most articles were excluded because they did not include hydrological hazard management. This is because articles from other research fields were excluded based on this category, such as ecology or computer science studies that used ABMs and mentioned floods or droughts. All of the articles except one (Grosskopf *et al* 2015) were available through KTH and SMHI institutional subscriptions to journals. The reason for exclusion for every study is presented in the supplementary material.

A narrative synthesis was performed where information obtained from the reading was compiled into a spreadsheet (see supplementary material). This information includes, for example, simulation time, number of human agents, and type of hydrological hazard. The aims of the articles were also categorised into four groups: 'Test ABM', 'Test agent behaviour', 'Test agent interaction', and 'Test hazard management strategies'. The 'Test ABM' category was assigned to papers that explored the use of ABMs for hydrological issues, such as novel applications of, for example, ice jams. 'Test agent behaviour' and 'Test agent interaction' aimed to study agent decision-making and interaction with other agents, respectively. 'Test hazard

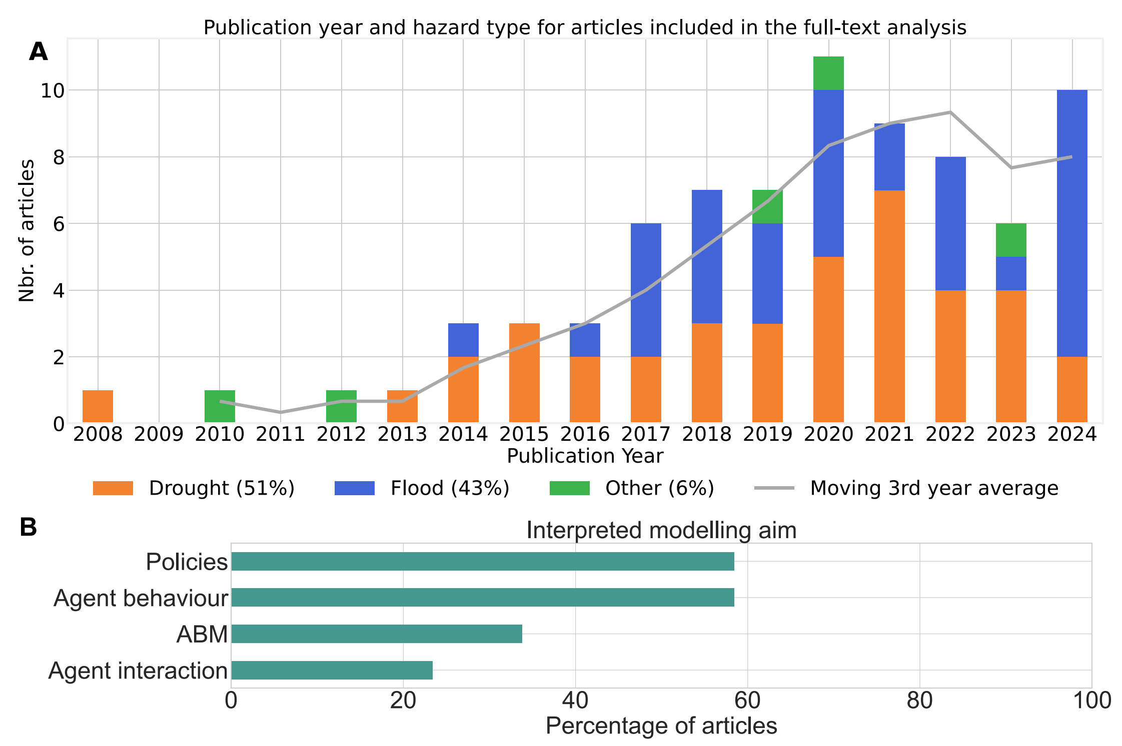

Figure 3. (A) illustrates the years of publication of the included articles and types of hazards that are studied. (B) describes the different aims of the articles. Note: an article can have several aims, therefore, the total percentage is over 100.

management strategies' refers to studies that investigate how different policy and management strategies influence the system. Studies could fall into one or more of the described categories. This classification was based on the studies' descriptions of their aims and objectives, but it represents a subjective judgement by the authors of this paper.

In this review, only agents representing humans are included (see table 2), either as individual humans (individual agents) or as communities of humans (collective agents), such as organisations or firms. The individual categories can also consist of aggregated individuals, as some studies model groups individuals, such as neighbourhoods, as a single agent. They are included in the individual category because the modellers assigned them the same agency and decision-making capabilities as if they were one person. Many studies also model households as a single agent, and consequently, these are also categorised as individuals.

3. Results

3.1. Distributive analysis of included literature

In total, 77 articles were included in the full-text analysis. The first article addressing the topic of our review was published in 2008, but 56% of them were published in the last five years, and the number of articles has increased significantly during the last ten years, as shown in figure 3(A). Only articles published before the 13th of May were included from the year 2024, though ten articles were published that year alone. The studies are categorised after modelled hazard type, droughts (51% of the studies), floods (43%) and other (6%), see figure 3(A). The studies in the Other category either have a multi-hazard approach, where it is a combination of floods and drought events, or, for one study, events are described only as extreme (Egger *et al* 2023). The effect of climate change on the human–water system is simulated in 36% of the studies, either with increasing severity of hydrological hazard events, such as a decrease in rainfall over the simulation period (Berglund *et al* 2023) or as future scenarios where climate-induced events are used to test the effect of climate change on the system (Jenkins *et al* 2017). In the drought studies, 38% of the papers include climate change, compared with 33% for floods and 40% for the Other category. Thus, there is no notable difference in the inclusion of climate change between different types of hydrological extremes.

Most studies were identified with the aim of exploring policy change (58%) and agent behaviour (58%); testing ABMs (33%) and agent interaction (23%) were less explored topics, as visualised in figure 3(B). Commonly, studies have several of these aims; for example, Ghoreishi *et al* (2024) expanded ABM use to ice-jam-induced floods (testing ABMs) and how human adaptation impacted

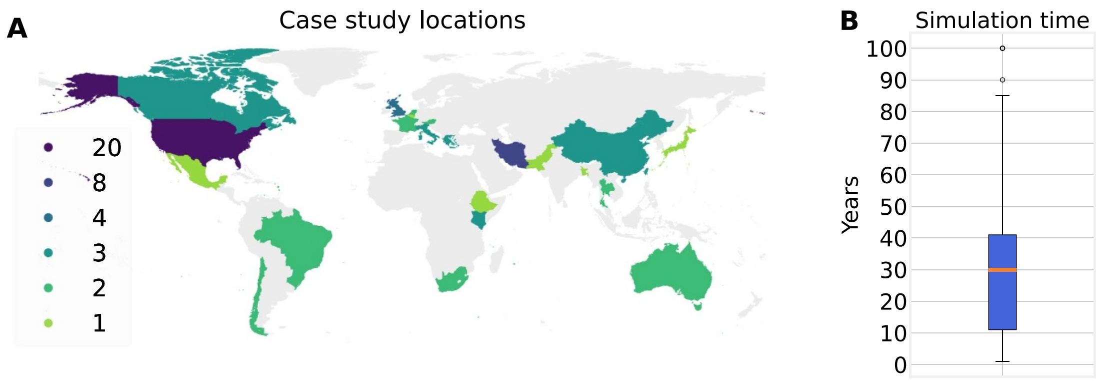

Figure 4. (A) shows the location of case studies, and (B) shows the simulation time in the models.

the flood risk (agent behaviour). Another example is Baeza *et al* (2019) that studied how the government prioritises drainage and drinking water infrastructure development (policies) due to neighbourhood complaints (agent interaction) and other factors by using multi-decision criteria analysis (agent behaviour). An emerging trend is to study the indirect effects of hydrological hazards. These studies also introduce more types of impacted groups than other papers (Taberna *et al* 2023, Bachner *et al* 2024, She *et al* 2024). For example, Taberna *et al* (2023) evaluated the indirect impact of floods due to unemployment that occurs when firm agents lose revenue due to economic turbulence caused by a flood.

We mapped the spatial distribution of the selected papers, based on the case study location, see figure 4(A). The map shows that 26% of the studies are situated in the USA. Iran, China and the United Kingdom are also common case study locations and in total, around 40% of the studies are located in the Global South. The type of hazard is also dependent on location; for example, in the Sub-Saharan region, there are only studies on drought (4 articles), while in Europe, articles mainly study floods, specifically 4 on droughts and 12 on floods. Two studies are also on pan-European scale modelling of governments and households' adaptation to fluvial floods (Haer *et al* 2019, 2020). The other articles' model domains are either on a regional scale (40%), city or river reach scale (49%), or country scale (6%), and 1% do not specify a domain scale (Sapienza and Falcone 2024). The median simulation time, i.e. total timeframe evaluated in the model, for the studies is 30 years, whereas most studies have a simulation time between 10 and 40 years, see figure 4(B). Baeza and Janssen's study (2018) on the decrease of collaborative farming due to drought in Chile has the longest simulation time of 100 years. The temporal resolution, i.e. what period each model time step represents, for decision-making in the studies varies: 60% have a resolution of a year or longer, 19% have a resolution of a month up to a year, 13% have a resolution between 1 and 31 d and 6% have an unknown temporal resolution. Concluding, the median number of decision cycles (total time steps) is 40.

3.2. Implementation of hydrological hazard management

3.2.1. Agents and hazard management

Studies often contain both individual and collective agents (52% of the studies), usually, several individual agents and one collective agent, see figure 5(A). Some studies contain only individual agents (43%), and a few contain only collective agents (5%). It is more common for flood articles to include both types of agents. The individual agents are often described as households (57% of studies contain household agents) or farmers (34%), while the collective agents are either a business (25% of the studies) or part of the government, such as a municipality (47%). No NGOs are simulated in our set of included articles. The number of agent types is typically one (44%) or two (34%). The study by Bakhtiari *et al* (2020) implemented the highest number of agent types, 9, to represent different sectors dependent on drinking water in a city, such as construction companies. Only 69% of the articles reported the number of agents implemented per type for all agents. Of these articles, the median of the number of individual agents simulated per study is 2500, and for the collective agents, it is 1.

Of the 77 included studies, 84% implement individual hazard management, while 77% have introduced non-individual hazard management, as visualised in figures 5(C) and (D). However, only 56% of the studies that include non-individual hazard management are governed by collective agents, see figure 5(B). The remaining 21% (77%–56%) of studies are models where the non-individual hazard management either is static throughout the simulation; e.g. Wens *et al* (2020) where a random set of farmers receive drought management practice education, or there are hazard management scenarios that are changed between model runs, e.g. Naqvi and Rehm (2014) where either aid in food or cash is given

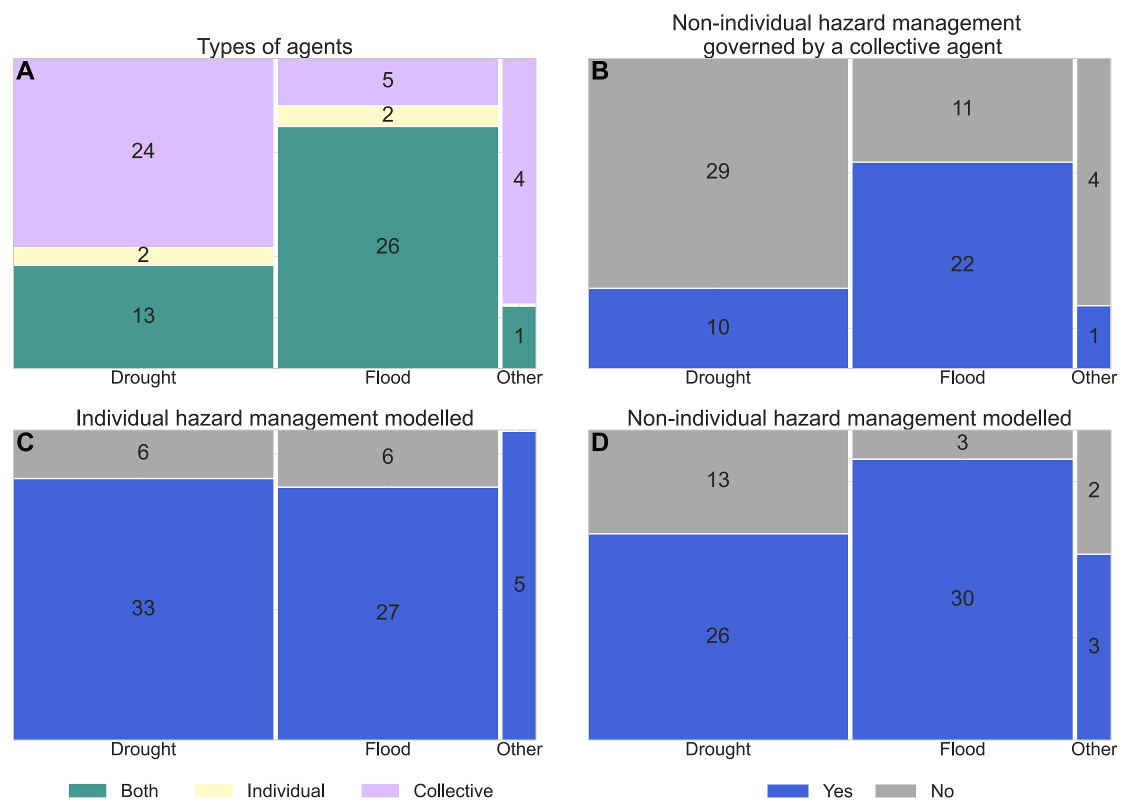

Figure 5. (A) shows the implementation of individual and collective agents for each type of hydrological hazard. (B) describes whether the non-individual water management is governed by an agent. (C) and (D) show which type of management is included for different hydrological hazards. The numbers indicate the number of agent types within each category.

during a flood, or there are collective agents, but they have no influence on the non-individual hazard management, often a collective agent representing a firm, as in Taberna *et al* (2023). The implementation of hazard management scenarios is a common approach to test policies and is sometimes combined with a collective agent. For instance, Haer *et al* (2016) tested various governmental flood communication strategies (e.g. target households' flood risk perception) to increase individual flood measure adaptation, and Giacomoni *et al* (2013) combined a water utility manager overseeing drought-saving stages in a city with static scenarios of different development restrictions to address increased demand and drought.

3.2.2. Floods

The most common single cause of floods in the studies is fluvial (39% of the flood articles), visualised in figure 6. These studies are simulated on an urban scale (Tonn and Guikema 2018, Tonn *et al* 2020, Hemmati *et al* 2021), rural (Tesfatsion *et al* 2017, Mustafa *et al* 2018, Dziubanski *et al* 2020, Michaelis *et al* 2020, Nortes Martínez *et al* 2021, Sung *et al* 2022, Moradzadeh and Ahmadi 2024), national (Bachner *et al* 2024) or continental scale (Haer *et al* 2019, 2020). For fluvial studies, most ABMs are coupled with a hydrological or hydrodynamic model that creates a flood based on a predetermined set of return periods. For example, Dziubanski *et al* (2020) coupled the rainfall–runoff model Hydrologic engineering centre—Hydrologic modelling system with an ABM that simulates farmers and a city manager to find when flood-land renting would be beneficial. In their study, the rainfall–runoff model is used to obtain the annual maximum flow to estimate urban flood damages. Two studies (6% of the flood articles) simulate fluvial floods due to ice jams instead of peak flows, where the non-individual hazard management is to artificially break-up the ice jam (Ghoreishi *et al* 2024, Ghoreishi and Lindenschmidt 2024).

The second most common (21% of the flood articles) type of floods are events that are described simply as 'floods'. The cause of the flood is not described, and there is no coupled hydrological model, rather, the hydrological input is implemented as an external shock that impacts the agent. For example, to study how individual adaptation changes after floods and communication about flood risk (Haer *et al* 2016, Erdlenbruch and Bonté 2018). Five studies (15% of the flood articles) modelled pluvial floods in urban areas. Three studies use static inundation maps (Dubbelboer *et al* 2017, Jenkins *et al* 2017, Crick *et al* 2018). Löwe *et al* (2017) coupled the ABM with a hydrodynamic model to see how house development is impacted by floods under different development policies. Nazemi *et al* (2024) used Storm Water Management Model to simulate the flood volume from a design rainfall to evaluate

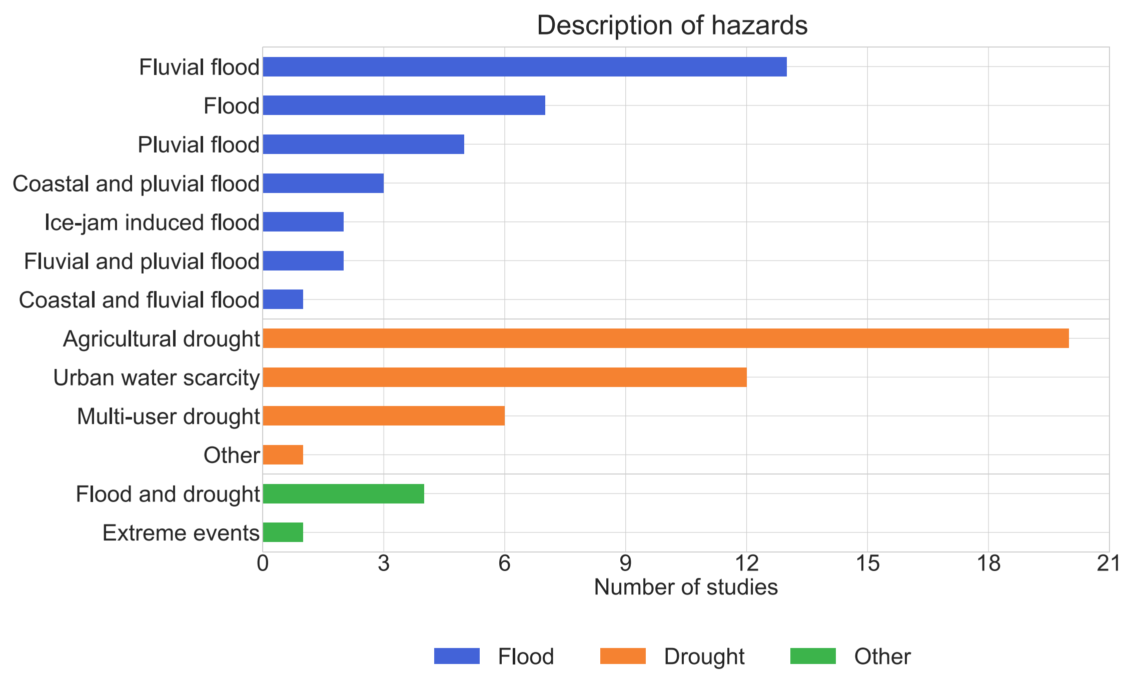

Figure 6. Types of hydrological hazards that are modelled in the included articles.

economically optimal urban flood management and management motivation for authorities.

18% of the flood articles have a compound hazard approach. These studies combine two out of three causes of floods, coastal, pluvial and fluvial. All of them, except one, have combined flood hazard maps from the different hazard types. For example Abebe *et al* (2019a, 2019b) combined storm surge and pluvial flood hazard maps over Sint Maarten. The one exception is Koutiva *et al* (2020) which instead only includes coastal and pluvial as a trigger to evaluate flood management strategies in a city on Crete.

The type of implemented non-individual hazard management depends mainly on the type of flood hazard compared to individual hazard management (figures 7(A)–(C)), where the difference is small between different types of floods. The most common measure implemented is structural measures to cope with floods, both regarding individual and collective agents' actions, see figures 7(A)–(C). The collective agent, for example, improves drainage systems regarding pluvial floods and constructs levees for fluvial floods, while individuals dry- or wet-proof their homes regardless of the cause of the flood. Limitation of development in flood zones is also a common measure implemented by non-individual hazard management for all types of floods. An individual measure that is closely linked to the development in flood zones is migration; several studies investigate how individuals move after being repeatedly flooded (Naqvi and Rehm 2014, Dubbelboer *et al* 2017, Jenkins *et al* 2017, Crick *et al* 2018, Tonn and Guikema 2018, Tonn *et al* 2020, Tanaka *et al* 2022, Ku 2024). Insurance is also a common individual measure, especially for pluvial floods (Dubbelboer *et al* 2017, Jenkins *et al* 2017, Crick *et al* 2018). Insurance is one of the few measures business agents provide for individual agents in the included studies.

In a few studies, farmers are present to study flood impacts on agriculture (Nortes Martínez *et al* 2021) or study how farmland can be used to cope with floods (Dziubanski *et al* 2020, Zagaria *et al* 2021). In the latter category, rural and urban land use conflicts are studied by examining how a city can rent or buy parts of the floodplain to change land use and, thus, decrease the peak discharge. Some studies find or explore unintended effects of non-individual hazard management. This is, for example, the increase in housing prices due to floodplain zoning (Tanaka *et al* 2022), how government funding can cause less collaboration for a community flood protection (Sung *et al* 2022) or how governmental flood protection can lead to higher flood risk due to the safe-development paradox (Haer *et al* 2020, Michaelis *et al* 2020). However, this is rather uncommon and most often governmental hazard management is seen as a benefactor, e.g. sending aid, or necessary control, e.g. irrigation restrictions without unintended side effects.

3.2.3. Droughts

Drought studies mainly explore two types of impacts: agriculture (51% of the studies) and drinking water in urban areas (31%), illustrated in figure 6. Drought impacts on multi-user systems (15%), where, for example, both farmers and drinking water are

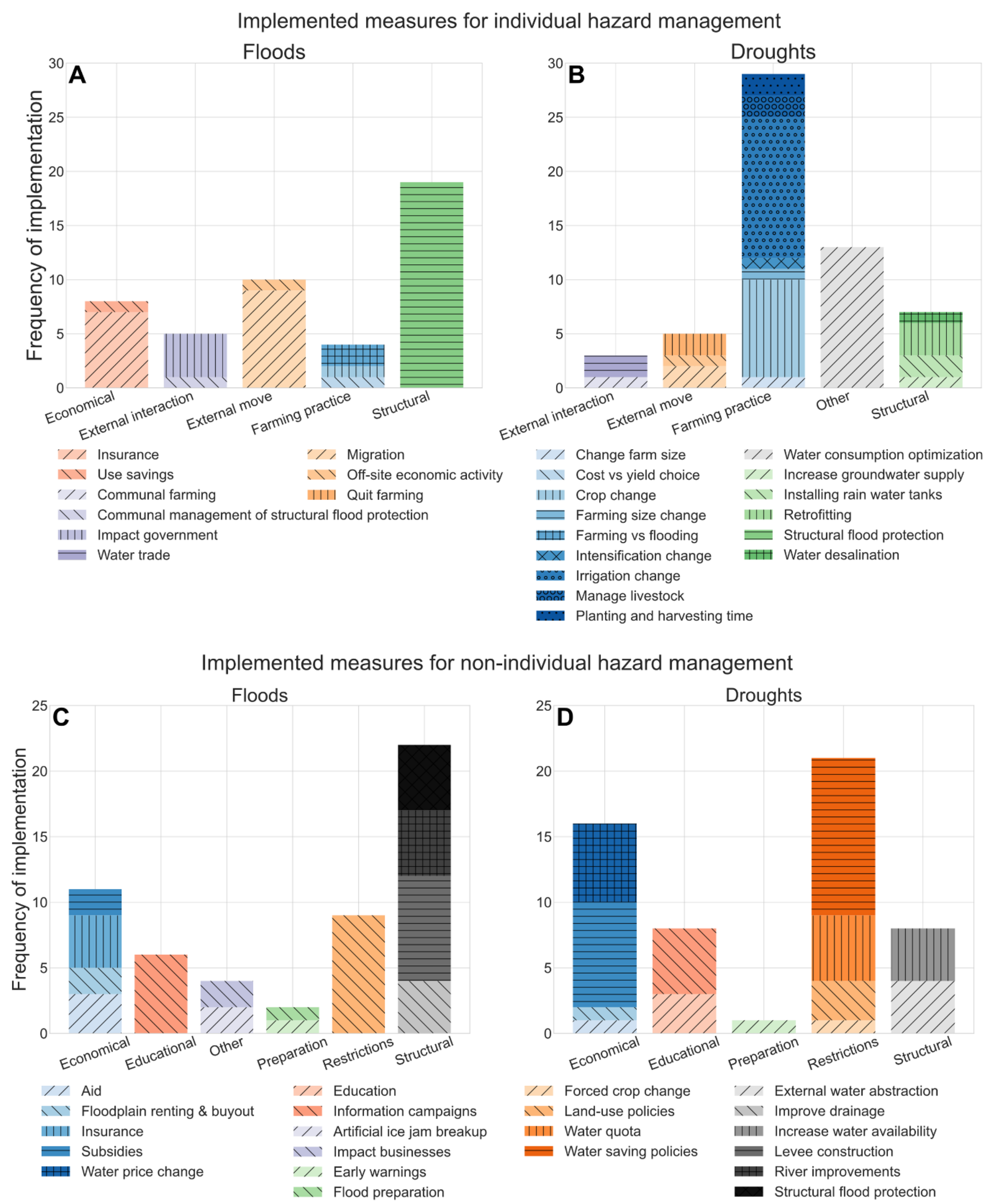

Figure 7. Types of hazard management implemented in the studies for floods (A) and (C) and droughts (B) and (D). Note that several different management strategies can be implemented for the same study.

affected, are less studied. Unlike the flood studies, the drought studies usually do not incorporate distinct hazard events. Commonly, the drought is described as dry spells for agricultural droughts, while urban water scarcity is triggered by an increase in demand and/or a decrease in supply. Only 13% of the drought studies use a measure of drought severity, either standardized precipitation evapotranspiration index (Wens *et al* 2020, Streefkerk *et al* 2023), standardised runoff index (Bahrami *et al* 2022) or return period (Arnold *et al* 2015, Wens *et al* 2022).

The implementation of the hydrological environment in agricultural studies varies from simple input to full hydrological models. For example, Zagaria *et al* (2021) use a crop yield model, Hung and Yang (2021) implement a river system model over the Colorado River basin, Streefkerk *et al* (2023) uses a distributed hydrological model together with a crop yield model, while Baeza and Janssen (2018) does not incorporate hydrological processes and instead classifies years (time step) as wet or dry years. Studies on agricultural drought often only include one agent type, such as farmers, either as individuals, part of a household, or as an agent representing an aggregate of several farmers in the area. The aggregated farmers are represented by agents that share similar decision rules as individual farmers. Collective agents are only represented in one agricultural study (Wang *et al* 2024), as irrigation managers that respond only to previous years' water availability.

Urban water scarcity studies focus on how to cope with growing demand and decreasing supply, typically due to urbanisation and climate change. Half of the urban water scarcity studies couple a reservoir storage model to the ABM, while the other half does not implement a hydrological model. All the urban water scarcity models implement household agents, and 75% of them also incorporate a collective agent representing a governmental water manager, see Supplementary material. The multi-user droughts must consist of several agents with competing interests over a limited water source during droughts (Becu *et al* 2008, Bakhtiari *et al* 2020, Ding *et al* 2021, Huber *et al* 2021, Bahrami *et al* 2022, She *et al* 2024). In one instance only farmer agents are included, but with scenarios for the water demands from other sectors, such as the industrial sector (Bahrami *et al* 2022). An example of the competing interests in the multi-user drought studies is in Huber *et al* (2021) where agriculture, households' drinking water, hydropower and tourism use water from the same mountain stream.

Drought management by collective agents is mainly focused on restrictions of water use for individual agents, see figure 7(D). The individual agents only take three actions during urban droughts: retrofit household equipment, install rainwater tanks, and, by far the most common, alter their behaviour to reduce water consumption, see figure 7(B). The reduction of water consumption is linked to non-individual hazard management, that is, for example, water price changes, subsidies, information campaigns or water-saving policies, such as an outdoor watering ban. The agricultural drought studies have more emphasis on individual management, especially changes in farming practices such as irrigation and crop change. Individual agricultural adaptation is also more varied, for example, communal farming (Baeza and Janssen 2018) and water desalination techniques (Mehryar *et al* 2019). In contrast, there are few model implementations of non-individual agricultural drought management, the most common are subsidies and education to farmers. However, few agricultural studies include non-individual hazard management in general. In multi-user drought studies focus is on increasing water availability by the government, and individual adaptation is only implemented in one study (Bahrami *et al* 2022).

3.2.4. Compound flood-drought studies and extreme events

Except for the earlier mentioned studies that studied compound flood events, 6% of the studies incorporate a multi-hazard approach, see figure 6. These studies have implemented a combination of floods and droughts (van Oel *et al* 2010, 2012, Baeza *et al* 2019, Entwisle *et al* 2020) or a study on how extreme events impact farmers (Egger *et al* 2023). van Oel *et al* studies (2010, 2012) are similar to other agricultural studies as they implement farmers that are impacted by droughts, but, in these models, the farmers can also be impacted by yearly floods, which impact their planting time and thus farm yield. Baeza *et al* (2019) and Entwisle *et al* (2020) have a different outlook. The first explores how a government prioritises infrastructure development (drinking water and drainage) and how the prioritisation depends on complaints from neighbourhoods. The latter study evaluates how out- and in-migration is impacted by droughts and floods in rural areas in northern Thailand. That study used long-term panel survey data from all individuals in 51 villages. The hydrological modelling in the studies varies from no model at all (Baeza *et al* 2019, Entwisle *et al* 2020) to hydrological or crop yield models (van Oel *et al* 2010, 2012, Egger *et al* 2023). The hazard management is also varied, all of these studies have implemented individual adaptation, such as farming practice or migration, and three of them have non-individual management.

3.3. Agents' decision-making and stakeholder involvement

3.3.1. Theory of behaviour for agents

In our analysis, the agent's decision-making was clustered into four categories: Ad-hoc, bounded rationality, rational and social diffusion.

The Ad-hoc category is a more common behaviour model for collective agents (54%) than for individual agents (28%), see figure 8. This category includes agents that use heuristics or ad-hoc decision-making as well as static agents. Giacomi and Berglund (2015), for example, implement a governmental policymaker that enforces different levels of water-saving plans based on set water reservoir levels in a city. Abebe *et al* (2019b) implemented a government agent that builds structural flood measures if the rainfall that caused the flood is greater than a 50 year return period and no measure had been built in the previous three years.

Rational agents are agents that assess their situation and take action to maximise utility, for example, through methods such as CBA, expected monetary value, or multi-criteria analysis. For individual agents, 21% use rational decision-making compared to 31% for collective agents. An example of this is in Tanaka *et al* (2022) study on fluvial floods in development areas where household agents maximise the utility of their move to new houses and developers use utility maximisation to find locations for new house projects. Another example is when governmental agents use CBA with levee cost and expected annual damage to assess the levee construction height (Michaelis *et al* 2020, Moradzadeh and Ahmadi 2024).

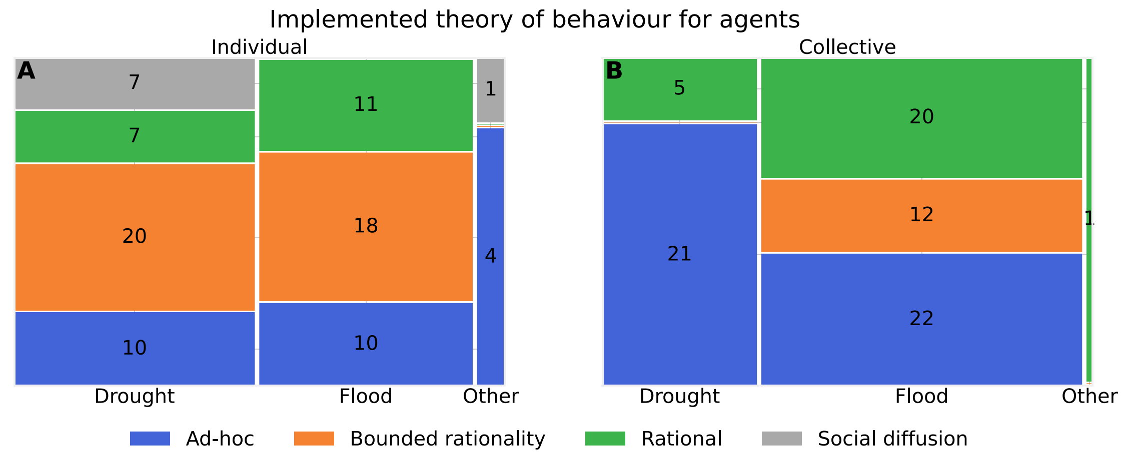

Figure 8. Visualises how many individual agents (A) and collective agents (B) that are implemented with a certain theory of behaviour. Note that several types of agents can be implemented for the same study.

Bounded rationality agents are the most common type for individual agents (42%) but are notably less common for collective agents (15%). Bounded rational agents are not fully rational, instead, they are impaired by, for example, lack of information, limited risk evaluation and/or cognitive biases. Bounded rational agents' decision-making is regarded as a more realistic depiction of how humans act (Zhuo and Han 2020, Schrieks *et al* 2021). Examples of theories are PT (Kahneman and Tversky 1979) and Protection motivation theory (Rogers 1975). Individual agents' decision-making utilises these theories for bounded rational agents, PT (Baeza and Janssen 2018, Bahrami *et al* 2022, Lin *et al* 2022, Geaves *et al* 2024) and Protection motivation theory (Haer *et al* 2016, Erdlenbruch and Bonté 2018, Hailegiorgis *et al* 2018, Michaelis *et al* 2020, Wens *et al* 2020, 2022, Zagaria *et al* 2021, Martin *et al* 2022, Streefkerk *et al* 2023, Taberna *et al* 2023, Ghoreishi and Lindenschmidt 2024, Moradzadeh and Ahmadi 2024). Two of the studies that include bounded rational individual agents instead utilise reinforcement learning, a method that relies on ML rather than behavioural theories (Hung and Yang 2021, Hung *et al* 2022).

Of the 77 studies, 12 collective agents are implemented with bounded rationality as a behavioural theory. However, these 12 agents are only in six studies since two papers contain several collective agents (Taberna *et al* 2023, Bachner *et al* 2024). In three of these six papers, the collective agents do not have a role in the governmental hazard management (Naqvi and Rehm 2014, Taberna *et al* 2023, Bachner *et al* 2024) while in the other three papers, the collective agents do have a mandate over the hazard management (Haer *et al* 2019, 2020, de Ruig *et al* 2022). The latter studies use CBA for the government agents' decision-making regarding levee construction but alter the original rationality of this approach by testing reactive versus proactive rational agents. The reactive agents did a CBA when flooding occurred, while the proactive agents also did it every sixth year (time step). de Ruig *et al* (2022) note that by testing these two different agent behaviours, they could obtain an uncertainty analysis of the governments' decision-making for flood management.

The social diffusion category includes various behavioural theories where information and adaptation spread through a community of individual agents (Kanta and Zechman 2014, Kanta and Berglund 2015, van Duinen *et al* 2016, Entwisle *et al* 2020, Koutiva *et al* 2020, Aghaie *et al* 2021, Moosavi *et al* 2023). Other studies can also include social communication but rely on other theories as well to create the agent's decision-making. For instance, using the theory of planned behaviour together with the social impact theory (Koutiva and Makropoulos 2016, 2019) or PMT, together with adaptation diffusion (Erdlenbruch and Bonté 2018). There is information sharing between agents in several papers; it can be between the same agent types (31% of the studies), different agent types (21%) and by both same and different agent types (6%). Examples of cross-agent communication are Michaelis *et al* (2020) were households send a complaint to the authorities if they get flooded, or Tesfatsion *et al* (2017) where a city flood manager and a farmer share information about the possible conversion of farmland to floodplain to reduce the flood risk for the city.

A few studies compared different types of agent behavioural models, mainly rational and bounded rationality models in individual decision-making (Baeza and Janssen 2018, Haer *et al* 2019, 2020, Wens *et al* 2022, Harik *et al* 2023, Taberna *et al* 2023, Geaves *et al* 2024, Ghoreishi and Lindenschmidt 2024, Sapienza and Falcone 2024,). For example, Wens *et al* (2022) showed that the PMT leads to a more realistic description of farmer agents' adaptation of irrigation measures during droughts than the expected utility theory. Studies that compare collective

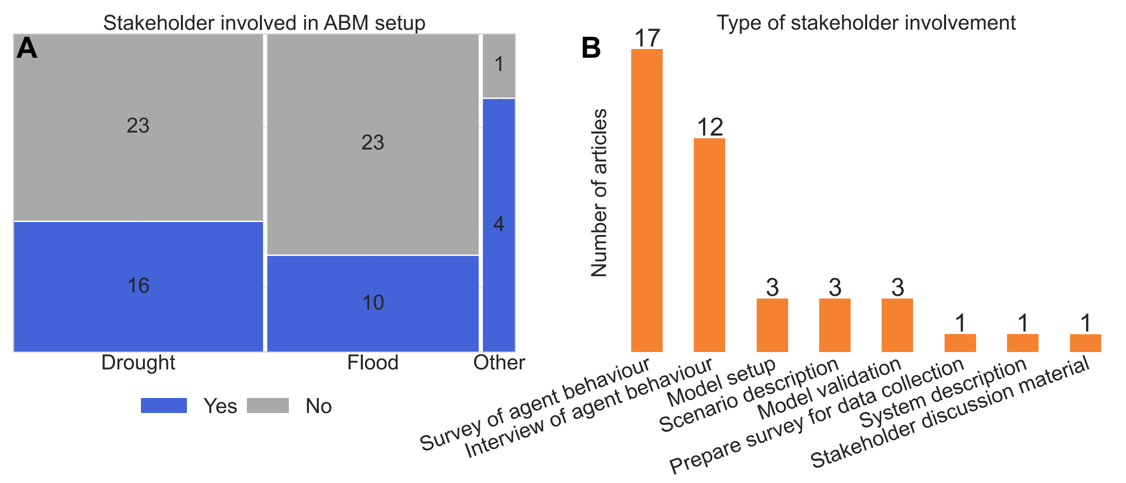

Figure 9. (A) Number of articles that have stakeholder involvement, and (B) types of involvement those articles utilise.

decision-making for hazard management are built by the same modellers who see if reactive or proactive flood management has an effect (Haer *et al* 2019, 2020, de Ruig *et al* 2022). They discovered that the proactive agent could cause the safe-development paradox as they unintentionally lower the individual risk perception.

3.3.2. Stakeholder involvement in ABM system setup

The inclusion of stakeholders in the modelling system setup is described in 39% of the papers, see figure 9. This often involves interviews or surveys of individual agent behaviour; however, only 10% of the collected papers include stakeholder interaction in other stages, such as scenario description or model validation. Koutiva *et al* (2020) incorporated stakeholders as modellers; the authors held workshops for stakeholders where they input their estimations of flood management costs, effectiveness, and likelihood of collaborating with other stakeholders into an ABM. The ABM, with input data from several stakeholders, could then assess the likelihood of implementation of flood management measures in the city.

Implementation of a stakeholder engagement framework was described in 5% of the studies, participatory modelling (Egger *et al* 2023, Harik *et al* 2023), companion modelling (Becu *et al* 2008) and participatory scenario design (Huber *et al* 2021). Companion modelling is a type of participatory modelling that incorporates ABMs and role-playing games with a focus on co-developing the model through a series of workshops, while participatory scenario design incorporates stakeholders for creating input scenarios for the model (Voinov and Bousquet 2010). Huber *et al* (2021) used participatory scenario design to create future storylines of land-use, tourism, etc., to input into the ABM together with inhabitants in an Alp valley and government officials; they reported that the workshops helped with providing plausible scenarios but also created a knowledge transfer between stakeholders and researchers about the complexity of human–water systems. Becu *et al* (2008) studied water use conflicts between two villages in Thailand by inviting the communities to workshops where discussions were aided by an ABM that simulated water scarcity. The authors reported that there were several challenges with companion modelling, for example, describing the ABM simulations for the stakeholders and ambiguity in the researcher's role in the present water conflict.

4. Discussion

It emerged from our synthesis that ABM with hydrological hazard management follows certain practices. These practices include a focus on individual adaptation to hazards, while governmental hazard management is characterised by either static scenarios or one simplistic agent and long simulation times with static assumptions on the hazard management. This often aligns with the study's aim, to investigate policy change. Another practice is the simplification of collective agents and non-individual hazard management; most often, it is assumed that they are rational or only reactive, i.e. if-then decision making, while hazard management strategies are static throughout a 30 year simulation period. Previous reviews (Taberna *et al* 2020, Anshuka *et al* 2022) support the findings regarding simplistic collective agents, which can limit the explanatory power of ABMs of human–water feedbacks, including the conclusions drawn about individual hazard management.

There is also a tendency to study direct tangible impacts on one specific group, especially in drought studies that most often focus on households or agriculture. That simplifies ABM setup, including data collection, which can be valid for stylised models but with the risk of finding policy strategies that are maladaptive or ineffective. However, this tendency is currently expanding with research that explores indirect damages across multiple groups (Taberna *et al* 2023, Bachner *et al* 2024, She *et al* 2024). A few studies deviate from these general practices, for instance, by incorporating authorities as both agents and modellers (Koutiva *et al* 2020) or evaluating the effect of firm-government partnerships to mitigate flood risk (Crick *et al* 2018).

The practices are likely to stem from the capabilities and limitations that ABMs are usually described to have. For example, several studies emphasise that ABM is a bottom-up approach which makes it possible to study heterogeneous decision-making among individuals (Blair and Buytaert 2016, Wens *et al* 2022, Egger *et al* 2023, Streefkerk *et al* 2023, Ghoreishi *et al* 2024, Ghoreishi and Lindenschmidt 2024, Moradzadeh and Ahmadi 2024, Wang *et al* 2024). Another possible reason is that ABMs can become complicated when many agents and parameters are introduced (Sun *et al* 2016). Therefore, to avoid this risk, modellers have excluded multiple agents, impacts and intricate decision-making processes. Modelling should be purpose-specific, but excluding system components, such as non-individual entities, might lead to overlooking dynamics vital to understanding how hazard management strategies impact the long-term flood and drought risk. We believe current practices do not fully utilise the beneficial capabilities of ABMs for hazard management studies. Benefits such as capturing complex dynamics between different hydrological scales and the flexibility of what an agent can represent (Lempert 2002).

In the following sections, we will elaborate on some of these practices, discussing their limitations and exploring potential opportunities to expand the use of ABMs in hazard management.

4.1. Current practices and limitations of the field

Implementing bounded rationality decision-making for individuals that was previously called for has been effective (An 2012, Schrieks *et al* 2021). This is beneficial as, for instance, PMT has been shown to better describe observed human decisions compared to rational theories (Wens *et al* 2020). Yet, 12% of studies have bounded rational or social individual agents but with a rational or ad-hoc collective agent. In 22% of the studies, non-individual management is included but not modelled as an agent, even though there are bounded rational or social individual agents. To the authors' knowledge, no study has studied the effect of combining bounded rational individual agents and ad-hoc collective agents. Thus, there is a need to evaluate the effect of individual agents' decisions in a system where they can be impacted by a simplistic collective agent. This need for vertical scaling of decision-making has previously been identified as an important topic to study (Elsawah *et al* 2020)

A common practice, especially in agricultural drought studies, is the absence of collective agents as well as non-individual hazard management, with a predominant focus on individual adaptation. This emphasis on individual agents in ABMs can present an unfair perspective and an incomplete picture of hydrological hazard management; individuals often believe that governments are responsible for hydrological hazard management and may subsequently act irrationally from a governmental standpoint (Terpstra and Gutteling 2008). At the same time, Terpstra and Gutteling (2008) found that individuals also perform more climate change adaptation than governments (Petzold *et al* 2023). Thus, to evaluate and find effective as well as fair climate adaptation policies, actors' responsibility and perceived responsibility should be considered. ABMs would be a beneficial tool as they can implement both bounded-rational households and governments into the same system. For this reason, our knowledge on how to implement multiple scales of agents should expand, as this can lead to new knowledge on the dependency of actions between different scales and types of actors within the human–water system.

The lack of specific descriptive theories for organisations might explain the simplicity currently used in representing collective agents in ABM, as PMT and PT are focused on individual decision-making. In addition to that, often many of the individual agents are small groups, like households, that are assumed to act as individuals. Fortunately, some new knowledge is emerging in this field, for example, intra-group decision-making for ABMs (Beal Cohen *et al* 2021) and hybrid behavioural theory for bounded-rational decision-making among businesses for flood protection (Hudson *et al* 2022). Another promising approach could be to integrate ML methods into collective agents' behaviour and thus, expand these methods that previously only been used for individual agents (Hung and Yang 2021, Hung *et al* 2022). Nonetheless, Mazzega *et al* (2014) points out that decisions made on an organisational scale are difficult to predict. This shows that there is an opportunity to enhance our knowledge about organisations' decision-making regarding hazards and how to incorporate them into agents in the models.

Generally, there is a focus on single hazards and impacts in the studies. Specific studies on floods or drought in ABMs can share valuable insight on how to manage the hazards, but to obtain knowledge on systemic risks in human–water systems, multi-hazards should be incorporated (McGlade *et al* 2019). The reason for the focus on single events and impacts could be the complexity of these events and the limited knowledge on how society copes and interacts with these complex phenomena. However, recently, more research has focused on multi-hazard events, on their occurrence (AghaKouchak *et al* 2018, 2020, de Ruiter *et al* 2020) as well as on frameworks and data to aid risk and vulnerability assessments of multi-hazards (Simpson *et al* 2021, Claassen *et al* 2023, Stolte *et al* 2024). Even though a multi-hazard approach can increase the complexity of the model, ABMs, including stylised models, can become a useful tool to explore different multi-hazard management strategies in a sandbox environment. ABMs could, for example, study the resilience of a society to different types of multi-hazard events such as consecutive, cascading or compound events.

Another practice is that studies also have a long simulation time, a median of 30 years, with unaltered non-individual hazard management strategies. Wens *et al* (2022) stated that they only model 30 years to avoid black swan effects, i.e. unforeseen, unpredictable events with severe consequences. Longer simulation time can be important to find the emergent patterns of human decision-making and study the long-term effects of a policy. Yet, paradigms flood management strategies can have a shorter cycle than 30 years, and specific political policies can have even shorter cycles, e.g. terms of office can usually be around 5 years (Chan *et al* 2022). Thus, in studies that aim to explore long-term development in a community, it might be worth considering these changes of political will when modelling hazard management. For instance, to introduce stochasticity or do a sensitivity analysis on collective decision-making, such as changing levels of subsidies and aid.

Only a few studies in our systematic mapping utilised stakeholder interaction (10%) for purposes other than collecting data on individuals, and of them, only a handful used established frameworks, such as participatory design (Huber *et al* 2021). This was surprising for us as frameworks such as participatory modelling and general stakeholder involvement could be a way forward in increasing the robustness of the ABMs and decreasing the gap between researchers and policy developers, especially since 77% of the studies include non-individual hazard management.

For some studies, it was challenging to obtain details about the models, such as the number of agents implemented, how the hazard event was integrated and the system boundaries of the models. This limitation affected our study and is a recurring issue, ABMs have previously been criticised as not being sufficiently transparent (Voinov *et al* 2018, Zhuo and Han 2020, Anshuka *et al* 2022). This can be helped by using the Overview, Design concepts and Details (ODD) protocol (Grimm *et al* 2006) or the ODD protocol for human models, the ODD + D (Müller *et al* 2013). Of the 77 articles, 27% employed the ODD protocol, 14% utilised the expanded ODD + D protocol, and 60% did not implement any protocol.

Another aspect of our review concerns the hazard management context that the case studies are exploring. Several of the studies with no non-individual hazard management are investigating rural communities in the Global South where informal decision-making is common, such as pastoral communities (Hailegiorgis *et al* 2018, Streefkerk *et al* 2023) and other farming communities (van Oel *et al* 2010, Baeza and Janssen 2018, Entwisle *et al* 2020). This contributes to the proportion of studies in our review that do not incorporate collective agents, but in these cases, the absence of non-individual hazard management in the ABM may be appropriate. However, most of the studies in the sample are located in data-rich contexts in the Global North, yet they still lack implementation of formal governance. Therefore, our findings primarily highlight the under representation of governance and formal institutions. This insight may not be as transferable to communities with informal decision-making and low institutional capacity, and thus, more research on such communities is needed to understand how informal governance can be represented in ABMs, as our sample is too limited to generalise from. Nonetheless, during ABM development, it is important to evaluate system boundaries and identify the agents necessary for the specific case study to reach a suitable level of complexity (Sun *et al* 2016). We argue that in many contexts, but not all, organisations and authorities play a significant role in hazard management and thus, should not be neglected.

4.2. Opportunities to move forward

We see a need to expand the hydrological implementation of ABMs, and a way forward to enhance our knowledge about ABMs on hydrological hazards would be to incorporate methods and knowledge from social sciences (Xu *et al* 2018). Computational sociology has used ABMs since the 1960s, with multiple methods and purposes (Janssen and Ostrom 2006, Bianchi and Squazzoni 2015). In our sample, the studies by Abebe *et al* (2019a, 2019b) developed the flood-ABM framework CLAIM, which included institutions (defined as '*humanly devised constraints that shape human interaction*', (North 1990)) and was built upon Ghorbani *et al* (2010), (2012), Ghorbani (2022))'s framework MAIA. Both CLAIM and MAIA utilise the ADICO syntax, an institutional analysis method that systematically describes institutions (Crawford and Ostrom 1995). In CLAIM institutions, rules, norms and policies are interpreted as decision rules that agents follow. Abebe *et al* (2019b) studied flood management strategies in Sint Maarten. The framework is mainly focused on static institutions and does not incorporate the bounded rationality of the organisations creating the studied institutions (e.g. policies) that form the system. Yet, using knowledge and methods from sociology regarding institutional analysis is favourable and could be further developed and expanded to hydrological hazard studies, especially for drought studies, where increased understanding of the connections with society is needed (Van Loon *et al* 2016).

Another opportunity is to more thoroughly explore the collective agents' impacts on an ABM system. Many studies perform a sensitivity or uncertainty analysis, but mainly with a focus on the individual agents' decisions, for example, comparing the impact of behavioural theory on individual adaptation (Wens *et al* 2020, Taberna *et al* 2023, Ghoreishi and Lindenschmidt 2024, Sapienza and Falcone 2024). By focusing on individual decision-making risks to underestimate the uncertainty of the hazard management system, especially when non-individual management is governed by a simplistic collective agent. A few studies however show the importance of uncertainty among non-individual hazard management: for example, how changes in governmental flood support can influence flood protection (Sung *et al* 2022) and how protective or reactive behaviour influence flood risk (Haer *et al* 2020, de Ruig *et al* 2022). We encourage future research on ABMs to consider the uncertainty that the human-system, including non-individual management, contributes to. A simple but effective method could be to explore the parameters controlling collective agents' behaviour using a sensitivity analysis, as in, for example, Michaelis *et al* (2020).

A valuable input to many ABMs is surveyed or interviewed data on individual adaptation, see figure 9(B), to improve and validate the individual agents' behaviour (Streefkerk *et al* 2023, Taberna *et al* 2023, Moradzadeh and Ahmadi 2024). However, there is a lack of studies that incorporate surveyed data on other actors, e.g. firms or governments, that influence hydrological hazard management. Such data would enhance the validity of ABMS and, more importantly, empirical data collected on multiple scales (e.g. spatial and political) could deepen our understanding of how hydrological hazard management is carried out. For instance, several empirical studies have explored how individual behaviour regarding floods, like near-miss effects (Bogani *et al* 2023), flood recovery (Bubeck and Thieken 2018) and flood memory (Bandyopadhyay *et al* 2024) while studies on multiple actors remain sparse (Plummer *et al* 2018, Räsänen 2021, Hudson *et al* 2022). A way forward could therefore be a combined effort of empirical and modelling research to understand cross-sectional interactions in human–water feedback systems.

Studies on stakeholder involvement in ABMs and hazard management have been developed in the last 20 years (Barreteau 2003, Hare 2011, Barreteau *et al* 2012, Elsawah *et al* 2015, Basco-Carrera *et al* 2017, Voinov *et al* 2018), creating a plethora of participatory methods with various purposes and frameworks. For instance, it can be used for model validation using role-playing games (Shelton *et al* 2018), creating input scenarios during workshops with multiple stakeholders or as discussion material during conflict mitigation meetings (Becu *et al* 2008). It is not, however, a silver bullet for the implementation of collective agents in ABMs. It is time-consuming (Huber *et al* 2021), challenging to convey the meaning of the processes and output of an ABM (Becu *et al* 2008) and does not guarantee a larger uptake of scientific methods (Landström *et al* 2024). Additionally, scholars have highlighted the implications of using ABMs for policy development; Becu *et al* (2008) stated that researchers must address ambiguous spaces of influencing stakeholders in a public space, and Mazzega *et al* (2014) emphasised that modelling policy development can infer the democratic processes and collective decisions as decision-support tools become decision-making tools.

Nevertheless, there are benefits to involving stakeholders in the modelling process. Benefits of stakeholder involvement can include a larger uptake of research outcomes, increased public trust and an increased understanding of complex phenomena if executed with participation in mind (Reed 2008, An 2012). Huber *et al* (2021) reported that the participatory scenario design workshops led to both realistic scenarios and improved the knowledge creation and dialogue between researchers and stakeholders. We also believe that the inclusion of stakeholders will increase the researchers' knowledge about the system and be a guide to which processes, agents, and decision-making are important, and which parts can be simplified. For instance, obtaining knowledge about possible hazard management strategies in the system and their limitations according to the stakeholders.

5. Conclusions

Our systematic mapping has synthesised current practices of hazard management studies that utilise agent-based models. To our knowledge, this is the first review that has mapped both flood and drought management. This systematic mapping has also expanded the topic by including hydrological multi-hazards and urban drought management in the analysis.

The 77 papers included in this study demonstrate almost an equal share of flood and drought studies. Multi-hazards are less common and utilise rather simplistic models but still show promise for enhancing understanding of the complexity of human–water systems. Overall, most studies focus on a single impact aimed at a specific group, such as farmers for droughts and households for pluvial floods. Recent studies have explored indirect impacts on various scales of society, but this could be expanded further to fully utilise the flexibility of ABMs.

The synthesis also confirms that many types of hazard management are included in the models, but it places an emphasis on structural measures, farming practices, and land-use policies. The decision-making for these management options varies depending on the types of agents; individual agents have a plethora of different behavioural theories, yet bounded rational agents are the most common. This is favourable, as previous research has shown that it describes human decision-making more accurately. Unfortunately, this understanding has not expanded as much to collective agents, where rational or ad-hoc decision-making is more common. We believe that implementing more complex collective agents will enhance the capacity of ABMs to study governmental hazard management and increase the validity of bounded rational individual agents in ABMs.

These practices are often related to the model's purpose in many studies. ABMs possess significant capabilities for modelling individual decision-making and their impact on water systems. Yet, both models and their purposes could be expanded by incorporating more knowledge from the system they aim to represent. This could be achieved by using ABMs in interdisciplinary research with social scientists or by including stakeholders in the modelling process.

ABM has become an effective method for supporting the investigation of human–water system hazards in the last decade. Yet, ABMs remain an emergent tool in the field, and future model development is necessary to understand the systemic risks caused by multi-hazards, multi-scale actors, and the complex behaviours of all human entities.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Supplementary data available at https://doi.org/10.1088/1748-9326/ae0fb2/data1. The supplementary data file includes the ROSES protocol, article inclusion decisions and data extracted from the reviewed papers.

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Conflict of interest

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

Author contributions

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