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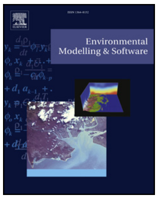

A coupled flood-agent-institution modelling (CLAIM) framework for urban flood risk management

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ABSTRACT

In this paper, we describe a modelling framework that allows the integration of human and physical components of flood risk. Within this framework, flood risk management is conceptualized as a coupled human-flood system. The human subsystem includes individuals and their behaviour and institutions that shape human-flood interaction. The framework presents a dynamic integration between agent-based models of individuals and institutions and numerical flood models. We demonstrate the framework's modelling application by examining the effects of three institutions in the Caribbean island of Sint Maarten. The case study shows the capabilities of the framework by exploring impacts of existing policies on flood risk reduction. Coupled agent-based-flood models built using the framework are useful to analyse policy options that address flood hazard and communities' vulnerability and exposure to support policy decision making. These models also show how flood risk changes over time in relation to the human dynamics on the urban environment.

1. Introduction

Of all weather-related disasters in the last two decades, floods are by far the most common (47%) affecting 2.3 billion people (CRED and UNISDR, 2015). The CRED and UNISDR report emphasizes that after storms and geophysical disasters, floods have been causing the third highest amount of economic damage (662 billion USD) over the past 20 years. The number of flood events has significantly increased, in which urban areas have been hit particularly hard (Jha et al., 2012). The risk associated with floods can be defined as the probability of negative impacts due to floods (Schanze, 2006). Flood impacts are mainly attributed to the extent and magnitude of a flood hazard which can be caused by one or a combination of fluvial, flash, pluvial, groundwater and coastal floods (Vojinovic and Huang, 2014). However, the negative impacts are also due to the vulnerability and exposure of natural and human elements such as individuals, livelihoods, economic and cultural assets, infrastructure, ecosystems and environmental resources (Vojinovic et al., 2016).

Hence, floods are not just nature-related disasters; rather they are the result of meteorological and hydrological factors aggravated by human actions (APFM, 2012). Changes in the climate system and economic, social, cultural, institutional and governance factors are drivers of flood hazard, vulnerability and exposure (IPCC, 2014, 2012). For example, in the context of urban flood risk, population growth and the associated urban expansion result in changes to land use and land cover. That leads to an increase in impermeable surfaces and more flooding, and hence affects flood hazard. When accompanied by inadequate planning and policies, urban expansion may happen in flood-prone areas increasing exposure, or happen in dense, low-quality informal settlements that contribute to a higher number of vulnerable people (Jha et al., 2012). For example, in UK, the government acknowledged that the increasing demand for housing leads to more building in high flood risk zones (Department for Communities and Local Government, 2007), in which the proportion of new residential properties located in flood zones grow from 7% in 2013-14 to 9% in 2015-16 (Department for Communities and Local Government, 2016).

Moreover, the behaviour of individuals plays an important role in flood risk. Based on their economic situation and risk perception, which is a function of values, feelings, experiences and cultural perspectives (Schanze, 2006), heterogeneous individuals living in flood-prone areas may implement their own local measures to reduce hazard (e.g. green roofs or rainwater tanks (Vojinovic and Huang, 2014)) or vulnerability

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Software and data availability

Program title Coupled_ABM-Flood_Model
Developer Yared Abayneh Abebe
Contact address y.abebe@un-ihe.org
Software Access https://github.com/yaredo77/Coupled_ABM-Flood_Model
Software required Repast Simphony 2.4 (https://repast.github.io/) and MIKE FLOOD 2016 (https://www.mikepoweredbydhi.com/products/mike-flood)
Program language Java
Availability The full agent-based model is available for free. The flood model and input data used in the ABM are not available due to data confidentiality

(e.g. dwellings with a non-habitable ground floor (Gersonius et al., 2008)). Further, individuals may insure their properties to avoid huge financial losses or to recover better, in the case of flooding. Currently, governments are reorganizing flood insurance policies changing individual behaviour (Dubbelboer et al., 2017). Individuals may also reduce exposure to flood hazard by relocating assets to less flood-prone areas and through evacuations (UNISDR, 2015).

In flood risk management (FRM), the likelihood of adopting and implementing measures that reduce flood hazard, vulnerability and exposure depends on changes in individual and institutional behaviour in response to the potential of flooding and the accompanying impact (Loucks, 2015). Therefore, on the one hand, FRM is dependent on the rules, regulations, policies and implementations that aim to reduce flood risk, but on the other hand, it relies on how individuals react towards those aspects and adapt their behaviour. The factors, which shape the flood hazard and a community's exposure and vulnerability to flooding, can be understood as *institutions*. Institutions are sets of “humanly devised constraints that shape human interaction” (North, 1990). They are key elements in the social, economic and political makeup of human beings that define our interaction with the physical system. The importance of institutions as social structures that influence the society as a whole, and in turn, are influenced by the society has been repeatedly emphasized by prominent scholars in economics, political science and sociology among others (e.g., Hodgson, 1988; North, 1990; Ostrom, 1990).

To strengthen FRM and to reduce flood risk, a more holistic, interdisciplinary approach that integrates all components of risk is essential (Aerts et al., 2018). This approach should consider the interaction between human and physical subsystems (Schanze, 2006; Vojinovic, 2015). The “human subsystem” consists of decision-making individuals, whose collective behaviour creates and is constrained by institutions such as norms, habits and laws. The human subsystem is embedded in and interacts with the “physical subsystem”. The physical subsystem includes drainage systems and dykes that might be affected by flood events. With interactions across multiple spatial, temporal and organizational scales, and behaviour driven by imperfect information and bounded rationality, the coupled human-flood system is a *complex system* (see also Pahl-Wostl, 2015). Further, as individuals and organizations learn (Mitchell, 2009) from previous flood impacts, the human-flood system is a *complex adaptive system* (CAS).

A systems approach which explicitly takes into account institutions as factors that shape the flood hazard and community's exposure and vulnerability to flooding has not yet been sufficiently addressed in the literature. One notable related work is presented by Yu et al. (2017), which examines collective actions in polder flooding. As a contribution to the major advances in *socio-hydrology* (Sivapalan et al., 2012) in recent years, we aim to add these key social aspects to the domain.

The aim of this paper is to develop a modelling framework and a methodology to build models for holistic FRM. The framework called Coupled fLood-Agent-Institution Modelling framework (CLAIM) integrates actors, institutions, the urban environment, hydrologic and hydrodynamic processes and external factors which affect local FRM activities. The framework defines the system as a CAS and conceptualizes the complex interaction of floods, humans and their environment as drivers of flood hazard, vulnerability and exposure.

In the methodology that accompanies CLAIM framework, the human subsystem is modelled using the agent-based modelling approach (ABM). Consequently, CLAIM incorporates heterogeneous actors and their actions and interactions with the environment and flooding. It also provides the possibility to analyse the underlying institutions that govern the actions and interactions in managing flood risk by incorporating MAIA (Modelling Agent systems using Institutional Analysis) meta-model (Ghorbani et al., 2013). The flood subsystem is modelled using physically-based, numerical model. The ABM is dynamically coupled to the flood model in order to understand how humans interact with the environment and to investigate the effect of different institutions and FRM policy options. We apply the framework to the FRM case of the Caribbean island of Sint Maarten to show the functionality of CLAIM and the policy insights gained from coupled ABM-flood model outputs.

2. Relationship to existing human-flood interaction studies

In this section, we summarize the state of the literature regarding modelling approaches that have been used to study coupled human-flood interactions.

The use of numerical flood models has been invaluable in FRM as they are used to simulate the physics of floods in relation to any state of the system. However, careful attention to data collection and processing as well as model instantiation is needed in order to gain full benefits from numerical models (e.g., Vojinovic et al., 2013, 2011, 2006). Recently, modelling of the coupled human-flood system is getting more attention in socio-hydrology, which mainly studies the co-evolution of humans and water explicitly by considering the possibility of generating emergent behaviours (Sivapalan et al., 2012). In socio-hydrology, the human subsystem is considered as an endogenous part of the water subsystem, and there is a two-way interaction between the two subsystems. Sivapalan and Blöschl (2015) identify two possible approaches to model coupled human-flood interactions. The first ones are called stylized models, and they formalize the human and flood subsystems processes using a single differential equation. The second type of models are called comprehensive system-of-systems models, and they represent the subsystems by individual models that are based on well-established methodologies from the relevant disciplines.

Examples of stylized models that conceptualize the dynamics of settled floodplains as a complex human-flood system include those discussed by Di Baldassarre et al. (2013, 2015) and Viglione et al. (2014). In the conceptual models, they consider hydrological, economic, political, technological and social processes that co-evolve over time but can be altered by a sudden occurrence of flooding. They formalize the feedbacks and interactions deriving the behaviour of the system using a set of differential equations. These models are easy to use and flexible. But, as also pointed out by the authors, the main drawback of the stylized models is that they neglect the heterogeneity that exists within the human subsystem. In addition, their conceptualization is based on societal memory or experience of prior flood events as a link between the human and flood subsystems, and it does not incorporate the institutions that shape the behaviour of humans in their interaction with their environment and flood.

Yu et al. (2017) study the human-flood interaction in polders of coastal Bangladesh by including institutions for collective actions. They model informal institutions, mainly, the norm that local people cooperate on the collective maintenance of embankments that enclose the polders because of fear of losing a good name or reputation in the community, which leads to social ostracism that outcasts defectors and refuses help in times of need. Yet again, Yu et al. use stylized models that do not consider heterogeneity, and focus only on institutions for collective actions.

Conversely, studies such as (Dawson et al., 2011; Tesfatsion et al., 2017; Valkering et al., 2005) conceptualize the human and flood subsystems separately and model the human subsystem using ABM considering heterogeneous actors decision making. However, the main gap in these studies is that either they use simplified flood models and a set of behavioural rules or they do not methodically analyze institutions to study drivers of flood risk.

Votsis (2017) utilized cellular automaton model to study the relationship between urbanization trends and FRM strategies. The study shows the effects of bottom-up, flood risk information-based housing market responses and top-down floodplain development restriction scenarios on urbanization. However, the study does not show if the flood extent and depth changes with the development pattern. It also focuses only on the exposure component of the flood risk.

In general, there are important initiatives to model the human-flood interactions using systems perspective. However, these efforts do not address either analysing institutions or heterogeneity of actors or all components of the flood risk (i.e., hazard, vulnerability and exposure) in their modelling exercise. In this paper, we develop a framework that helps to explicitly conceptualize heterogeneous agents and institutions, and propose a modelling methodology that couples ABM and flood model.

3. Theoretical background

In order to build a holistic modelling framework for FRM, a comprehensive systems view needs to be taken into account to cover the human and physical aspects of the system. In this section, we explain our modelling approach by introducing the methods and language used for building holistic models.

3.1. Agent-based modelling approach for FRM

The main advantage of the CAS perspective, introduced earlier, is its ability to dynamically link two different subsystems, i.e., the human subsystem and the flood subsystem, and to model their interaction. Models which incorporate the systems thinking may consider structural change, learning and innovation and hence provide a new basis for policy exploration (Allen et al., 2008).

Since the human subsystem is a CAS by itself, it requires careful selection of modelling methods to simulate heterogeneity and adaptation. For example, the classical reductionist modelling methods such as partial differential equations or statistical techniques such as regression and Bayesian nets have limitations in modelling CAS (Holland, 2006). These methods are characterized by restrictive or unrealistic assumptions such as linearity, homogeneity, normality, and stationarity (Bankes, 2002). Hence, methods which capture a more "realistic" view of CAS shall be used. Of these methodologies, ABMs provide the most natural description and simulation of a CAS (Bonabeau, 2002), and relax the assumptions that characterize differential equations and statistical models (Bankes, 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). An ABM consists of three elements: a set of agents (*actor* is the real "thing" and *agent* is actor's representation in a model); set of agent relationships and methods of interaction, and agents' *environment* (Macal and North, 2010).

As highlighted by Filatova et al. (2013), since ABMs primarily focus on human behaviour, integrating them with other domain modelling methods better inform policy challenges in coupled human-natural systems. Hence, in FRM studies, ABMs can be integrated with physically based flood models to analyse the institutions that affect flood hazard, vulnerability and exposure.

3.2. Institutional analysis

As mentioned previously, human behaviour is governed by a set of rules known as institutions. Institutions can be expressed and modelled through institutional statements described by the *ADICO grammatical syntax* (Crawford and Ostrom, 1995; Ghorbani et al., 2013). According to Crawford and Ostrom, "institutional statement refers to the shared linguistic constraint or opportunity that prescribes, permits, or advises actions or outcomes for actors. Institutional statements are spoken, written, or tacitly understood in a form intelligible to actors in an empirical setting." In a way, institutions have conceptual or abstract nature while institutional statements are linguistic statements (Basurto et al., 2010). In ADICO grammatical syntax "A" refers to *attributes*, "D" refers to *deontic*, "I" refers to *aim*, "C" refers to *condition* and "O" refers to "*or else*" (Crawford and Ostrom, 1995). The attribute is the actor to whom the institutional statement applies. The deontic is the modal operator which can be permitted, obliged or forbidden. The aim describes the actions or outcomes to which the institutional statement refers. It defines what action is conducted and how the action is conducted (Basurto et al., 2010). The condition defines when and where the aim is permitted, obliged or forbidden. Finally, the "or else" describes the sanction for failing to comply with a rule.

If an institutional statement consists of "AIC", it is regarded as a *shared strategy*; if the statement consists of "ADIC", it is a *norm*; and if the statement contains all the five components, it is called a *rule* (Crawford and Ostrom, 1995).

To structure and conceptualize social systems by emphasizing on institutions and to build ABMs, we use the MAIA (Modelling Agent systems using Institutional Analysis) meta-model (Ghorbani et al., 2013) as it provides a comprehensive modelling language. MAIA is a formalized representation of the Institutional Analysis and Development framework (Ostrom et al., 1994), and it is the only agent-based modelling language that systematically and explicitly incorporates institutions into models. MAIA makes use of the ADICO grammar to conceptualize and model different types of institutions.

The MAIA meta-model is organized into five structures: social structure defines agents and their attributes such as properties, behaviour and decision making; institutional structure defines the social context such as role of agents and institutions that govern agents' behaviour; physical structure defines the physical aspects of the system such as infrastructure; operational structure defines the dynamics of the system; and finally, the evaluative structure defines the concepts that are used to validate and measure the outcomes of the system (see also (Verhoog et al., 2016) for details of MAIA).

4. CLAIM: the coupled fLood-Agent-Institution Modelling framework

To capture the main components of the coupled human-flood system that is to be studied and modelled, we develop the CLAIM framework. CLAIM is composed of five elements: agents, institutions, urban environment, physical processes and external factors. Using CLAIM, a system can be socially and physically conceptualized and modelled as a coupled human-flood system. Such a holistic model provides the possibility to test various policy scenarios for FRM. Because of the explicit modelling and integration of such policies in the model, it is possible to explore how different scenarios affect actors and the physical environment, and vice versa. The framework also defines the system boundary and identifies the type and level of interaction within the system.

CLAIM is specifically designed for the context of urban FRM. It is based on the CAS perspective, takes ABM and physically-based flood models as the modelling approach and uses MAIA to structure the institutions and build the ABM. Fig. 1 illustrates the concepts of the framework and their relations. In the following subsections, we will describe each element by providing generic examples.

4.1. *Agents*

Agents represent individuals or composite actors that are a collection of actors such as an organizational entity or a household. An agent has an internal state that represents the essential variables associated with its current situation, and behaviours that relate information sensed by the agent to its decisions and actions (Macal and North, 2010). Agents' state may have intrinsic nature such as age, gender and household size. The environment may also define agents' state as agents perceive the urban environment and set their state. For example, the location and elevation of a house which can be extracted from the topographic map define the internal state of an agent. If there is a flood event, agents also perceive whether they are flooded and update their state.

The behaviour of the agent consists of its decision-making process and the action that takes place as a result. Examples of these actions include building a house, constructing FRM measures or purchasing flood insurance. Agents' behaviour can be influenced by their internal state and vice versa. For example, if there is a flood event and a house is flooded (i.e., agent's state updates), the agent may decide to protect the house by flood-proofing (i.e., the new state resulting in a change in behaviour). Alternatively, if an agent decides to build an elevated house (i.e., agent's behaviour), the house will not be flooded (i.e., no update in agent's state) unless the flood level is higher than the floor height. As agents are social, their interaction with other agents may also change their behaviour. Extending the above example, an agent's decision to build an elevated house may be incentivized by an insurance firm agent through lower premiums.

4.2. *Institutions*

Humans devise institutions whose goal is to shape human behaviour. Therefore, institutions have a two-way relationship with agents in CLAIM. On the one hand, institutions may influence agents' behaviour, depending on their heterogeneity in making decisions and complying (or not) with the institutions. For example, the EU Floods Directive (European Commission, 2007) demands member states to assess the potential risk of flooding and to prepare flood hazard and risk maps. Based on these rules, member states engage in activities (i.e., influence on the government agents' behaviour) to comply with an agreed deadline.

On the other hand, agents may create, change or abolish institutions. For example, after Hurricane Sandy, the U.S. Federal Emergency Management Agency improved the high-risk areas map for coastal flooding in New York (Dixon et al., 2013). Consequently, the flood insurance rate maps are also changed, which, in effect, changed the flood insurance premiums of businesses and residents.

The institutions defined here are internal (i.e., set within the system boundary) rules, norms and shared strategies that can influence agents' behaviours, and they can also be changed by the agents. In models, they can be defined exogenously as fixed parameters that the agents only follow or endogenously as dependent variables that are updated over time as a response to agents' behaviour. The latter may show the evolution of institutions through feedbacks.

In CLAIM, institutions are not directly linked with the urban environment as their impact is only through the influence they have on agents. Agents perceive and follow (or not) institutions prescribed by them and act on the urban environment. Conversely, agents perceive the urban environment (mainly when there is a change in the urban environment such as flooding) and may update institutions (for example, to designate floodplains as no building zones).

4.3. *Urban environment*

Agents are situated in an environment which contains all the information external to the agent and provides space for agents' interaction (Nikolic and Kasmire, 2013). In CLAIM agents live and build their livelihood and physical artefacts in the urban physical environment. At the same time, floods also happen in the same environment. As a result, in Fig. 1, we illustrate the urban environment as a link between the human and flood subsystems. For example, if agents want to reduce flood hazard, they do not try to directly influence rainfall magnitude and patterns. They rather implement measures such as detention basins in the urban environment to retain excess rainfall.

The urban environment consists of the built and natural environments. The built environment includes buildings, roads, drainage networks and flood reduction measures whereas the natural environment includes natural watercourses and floodplains. Changes in the urban environment are driven by the institutions and states of the agents. For example, with an increase in income level, individuals may decide to build more houses; based on a new economic policy, governments may build more roads; or to reduce a recurrent riverine flooding, municipalities may invest on the construction of dykes along a river bank. As geographic information is crucial in FRM, the urban environment is a physically defined space based on GIS maps such as topography map and building and road layers. The urban environment sets the spatial boundary, and its size depends on the objective of the study.

4.4. *Physical processes*

Although the physical processes occur on the urban environment, we separate the two elements (i.e., the processes and the environment) to emphasize that our focus is only on flooding and not on other types of hazard (e.g., earthquake or landslide) that may occur in the same environment. Aspects of the urban environment that are directly linked to floods, such as drainage networks, rivers and hydraulic structures, are represented in the hydrologic and hydrodynamic processes. Depending on the magnitude of the source of flood and presence and capacity of FRM measures, flood may occur. Flood is represented by flood maps showing its extent, depth and velocity, and the map is overlaid over the urban environment to assess the impacts on people and properties.

Agents affect the hydrologic and hydrodynamic processes through their actions on the urban environment. For example, land cover change such as the construction of more houses and paved parking lots may increase the imperviousness of the surface and hence contribute to

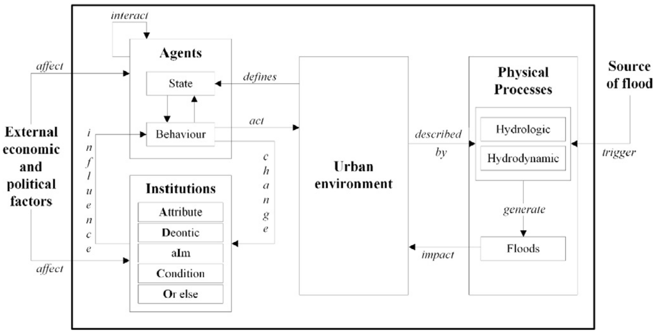

Fig. 1. CLAIM framework showing interactions among humans (agents and institutions), their urban environment (i.e., in the context of urban flooding), the physical processes including flood, and external factors. The drawing shows the system boundary in which elements within the outer rectangle (thick line) are related directly to local conditions and can influence each other whereas elements outside the outer rectangle affect but are not directly affected by those inside the rectangle.

higher runoff. Whereas, if agents implement adaptation and mitigation measures such as green roofs, water harvesting barrels or levees, that reduces runoff generation. Similarly, the processes have an effect on the agents through the urban environment. Flood maps overlaid on the urban environment may define agents' internal states, for example, by changing their states from "not flooded" to "flooded".

4.5. External factors

There are two sets of external factors which are important in influencing the flood-human-urban environment interaction: source of flood and external economic and political factors. A flood occurs when there is a hydro-meteorological event that causes it. For example, in flash floods, the source can be intense rainfall; or in the case of coastal floods, the source can be a hurricane-induced surge. Although the hydro-meteorological events are necessary conditions for the occurrence of floods, they are classified as external factors given agents do not have the power to regulate them. Agents can only reduce the flood hazard associated with the events by implementing FRM measures (i.e., drivers of hazard).

The external economic and political factors can be institutions though these factors are beyond the direct influence of the actions and interactions of agents and internal institutions in the defined urban system. Thus, in models, they can only be defined exogenously. For example, a global financial crisis may affect budgets a government agent may allocate for FRM measures. An example of external political factors can be the requirements of EU Floods Directive (European Commission, 2007) demanding member states to map and assess their flood risk.

5. Building a coupled model using CLAIM

To model the complex human-flood system, we use a coupled component model approach (Kelly et al., 2013) that integrates a physically-based model to model the flood subsystem and an ABM to model the human subsystem. Model integration may follow multiple phases such as pre-integration assessment, preparation of models, model orchestration, data interoperability and testing (Belete et al., 2017). To build a coupled ABM-flood model, we have summarized the modelling process into four main steps:

1. Conceptualizing the system using the CLAIM framework
2. Building an ABM of the human subsystem
3. Building a flood model of the flood subsystem
4. Coupling the ABM and the flood model

Step 1 is related to the pre-integration assessment; Steps 2 and 3 are related to the preparation of component models and Step 4 incorporates orchestration and data operability.

To demonstrate the application of the CLAIM approach, we use the Sint Maarten FRM, which is one of the FP7 PEARL project (www.pearl-fp7.eu) case study areas, as a case study for a complex human-flood system. We would like to emphasize that this case study is used to help explain the functionality and applicability of the framework. Therefore, we have not gone into the details of the model output and lessons learned from it to keep the focus. After describing the case, we discuss the above four steps in more detail.

Case description: Sint Maarten is a Caribbean island state located in the North Atlantic Ocean and subject to frequent hurricanes (Vojinovic and Teeffelen, 2007). The potential impact due to hurricanes and isolated heavy rainfalls has increased considerably over the recent years due to economic and population growth on the island. Reflecting on previous disasters, it is apparent that the disaster prevention, preparedness and mitigations on the island have not been sufficiently developed to be able to cope with potential disasters. For Sint Maarten authorities, the ability to address and minimize the risk of flood-related disasters represents a major challenge. Hence, a policy plan was drafted to improve disaster management on the island. The Government of Sint Maarten is also drafting a national development plan (NDP). With the plan, the government will introduce building codes and suggest floor height elevations for flood-prone areas to reduce flood risk. Therefore, our aim is to conceptualize the FRM in Sint Maarten using CLAIM and to build a coupled ABM-flood model. We perform scenario-based simulations to analyse the implications of policies (i.e., institutions) and evaluate how different agents' responses to existing and future policies influence the overall flood risk.

5.1. Conceptualizing the system using CLAIM

The first step towards building a coupled ABM-flood model is to formulate the human-flood interaction problem that needs to be investigated and to decompose and structure the concepts related to the two subsystems. Besides guiding the collection of primary and secondary data, depending on the level of detail we want to represent in the models, this step provides the different knowledge domains or expertise required to build the agent-based and flood models. Basically, this step is about deciding the model boundary and identifying the five components of the CLAIM framework in the coupled system.

For the Sint Maarten FRM case, we have identified two key agents: household agents and government agent. The household agents are individual agents that represent the population living in Sint Maarten. These agents make decisions on whether to implement policies that are devised by the Government of Sint Maarten to reduce flood risk. The government agent in our conceptualization is a composite agent that comprises the Permits, the Inspection and the New Projects and Management Departments of the Ministry of Public Housing, Spatial Planning, Environment and Infrastructure of the Government of Sint Maarten (VROMI). The three departments play a major role in designing, regulating and inspecting urban planning policies that shape the hazard and household agents' exposure and vulnerability.

We have also identified three formal institutions to shape the human-flood interaction. These institutions are the Sint Maarten Beach Policy (BP), the Sint Maarten Building Ordinance (BO) and the Flood Zoning (FZ) under the NDP. The BP forbids construction works within 50 m from the coastline. It is ratified mainly for the purpose of protecting beaches' recreational value. However, the policy implementation can have a direct effect on the exposure of household agents. The BO and FZ are drivers of the vulnerability of household agents because agents are obliged to elevate the floor of new houses. The difference between the two is that the BO requires a minimum floor height of 0.2 m irrespective of the location of a house while the FZ requires floor height of 0.5 m, 1.0 m or 1.5 m depending on the delineated flood zones as shown in Fig. 2. The BP and BO are existing institutions while the FZ is in the draft phase.

In our conceptualization, we considered the whole island including part of the Atlantic Ocean as the urban environment. The ocean is included to study impacts of coastal floods. The urban environment is represented by a digital terrain model. The hydrologic and hydrodynamic processes included in this study are rainfall-runoff processes, one-dimensional channel flows, two-dimensional floodplain flows and hurricane-induced storm surges. As a result, the flood impacts on the island are attributed to inland and coastal floods. Agents' dynamics such as an expansion of built-up areas on the island may affect the inland flood hazard. The institutions mentioned above directly affect the exposure and vulnerability of agents, rather than the flood hazards. The only external factors considered here are the sources of flood. Rainfall and hurricane-induced surge are the sources of inland and coastal floods, respectively.

5.2. Building the agent-based model

Once the CLAIM elements are identified, the MAIA meta-model is

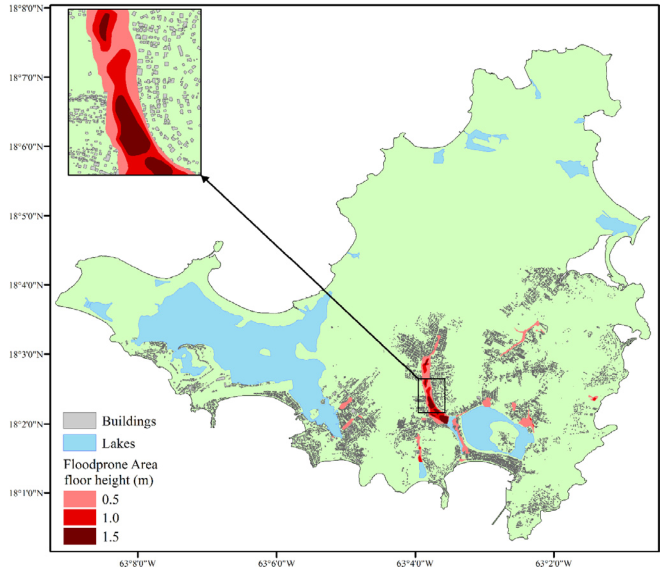

Fig. 2. Map of Sint Maarten. The three shades of red areas show the flood-prone zones delineated by Sint Maarten's Ministry of Public Housing, Spatial Planning, Environment and Infrastructure. If the draft NDP is put in work, new houses/building constructed in the light, medium and dark red zones must elevate the buildings' floors by 0.5 m, 1.0 m and 1.5 m, respectively.

used to conceptualize and structure the human subsystem and to formally describe it as a model. Agents in CLAIM, their states and behaviours, are defined in the social structure of MAIA. Agents' physical artefacts and the urban environment in CLAIM are defined in the physical structure. Institutions and the external political and economic policies in CLAIM are coded using the ADICO grammar within the institutional structure. The dynamics of the subsystem, which include agents' actions and their interactions with other agents and the environment are defined in the operational structure.

Then, the MAIA-structured descriptions of the human subsystem is converted to pseudo-codes that can be implemented in programming languages (the ODD protocol (Grimm et al., 2006) describing the ABM is provided in the GitHub repository mentioned in the Software and data availability section). For the actual software implementation, one of the main criteria for choosing an ABM modelling environment is that the environment should have GIS capabilities as spatial considerations are important in CLAIM (e.g., households are identified by their unique locations, and flood extents also have spatial attribute). The second criterion would be ease of use in processing results of the coupled flood model or in manipulating flood model input files. For the Sint Maarten case, we develop an ABM using the Repast Simphony modelling environment (North et al., 2013).

For our case study, we implement two agent types in the social structure: household agents and government agent. Household agents are characterized by location and elevation, and they have houses. Corresponding to the policies, agents have attributes that reflect their behaviour. We assume that there are only residential houses; a household owns only one house; and the agents have a static location. The government agent is characterized by a level of policy enforcement.

In the institutional structure, we describe the three institutions: BP, BO and FZ. We code the institutions using the ADICO grammar as shown in Table 1. Since there is no strict enforcement of the policies in Sint Maarten, the "or else" component of ADICO is left blank. However, the institutions are still classified as rules and not norms as they are formal policies. We assume that all household agents know about all the institutions.

As agents may not behave in the same way for all institutions (e.g., an agent may build an elevated house but 20 m from the coastline), each household agent has three parameters that correspond to the compliance of the three institutions (i.e., BP, BO and FZ compliances). These behaviour parameters are assigned randomly. For the institutions, we specify threshold compliance values in which agents comply with the institutions if their behaviour parameter is less than or equal to the compliance threshold. The thresholds implicitly reflect the level of policy enforcement by the government agent. For example, household agents have an attribute, a number between 0 and 1, that reflect their compliance to BO. If the BO compliance threshold is 1, all household agents will comply with the BO since their attribute is less than the compliance threshold. That can be interpreted as there is a strict enforcement of BO. On the other hand, if the compliance threshold is 0, household agents will not follow the BO because their compliance attribute has a value greater than the compliance threshold.

The physical structure is composed of houses and the urban environment. The houses are characterized by location, elevation and floor height. The most important attribute of the urban environment is its imperviousness.

In the operational structure, we define agents' actions and interactions. Agent related actions are making a plan to build a house, implementing the policies depending on the location of the plan and building the new house. For example, if the location of a house in the plan is 20 m from the coastline and if there is strict enforcement of the policy, the government agent will not give building permit and there will not be new house. Whereas, if there is low enforcement of the policy, there will be a new house with potential exposure to coastal flooding. Flood-related actions described in the operational structure are updating catchments' imperviousness, running the flood model executable, processing result file, uploading flood map and assessing impact.

5.3. Building the flood model

The flood subsystem can be modelled using a coupled hydrologic and hydrodynamic models. The preferred way of hydrodynamic modelling is simulating rivers and urban drainage networks (open channels or pipes) using one-dimensional models coupled with two-dimensional models for urban floodplains. The flood model may simulate any one or combination of fluvial, flash, pluvial, groundwater or coastal floods.

For the Sint Maarten FRM case, we build the flood model using the MIKE FLOOD environment which couples MIKE11 and MIKE21 (DHI, 2016a). In the flood model developed (earlier version in (Vojinovic and Tutulic, 2009)), MIKE11 is used to model the rainfall-runoff processes and flows in the drainage channels. We use design rainfall events of 5yr, 10yr, 20yr, 50yr and 100yr recurrence intervals. We assume that any rainfall magnitude below the 5yr recurrence interval does not cause flooding. For rainfall-runoff analysis, we use the unit hydrograph method with SCS runoff curve number (DHI, 2016b). MIKE21 is used to model coastal flood and inland flood flows in the urban floodplains.

Table 1
ADICO table for the institutions identified in the Sint Maarten FRM case.

Name	Attributes	Deontic	aIm	Conditions	Or else	Type
Beach Policy	Households	must not	build house	within 50 m of the coastline		Rule
Building Ordinance	Households	must	elevate house	regardless of location		Rule
Flood Zone Policy	Households	must	elevate house	if located in a flood zone		Rule

5.4. Coupling ABM and flood models

In the coupled model, we consider the ABM as a "principal" model, and when we mention time steps, we are referring to the time steps of the ABM. The reason is that the agent dynamics defined in the operational structure occur continuously, and hence, the ABM runs in all the time steps. The MIKE FLOOD model, to the contrary, is executed only if there is a flood generating rainfall in a given time step. For example, based on a design rainfall event series given in Fig. 3, in the first time step, since there is no flood generating rainfall, only agent-related actions are executed. When the time step is 2, there is a rainfall with a recurrence interval of 100yr, and hence, all agent and flood-related actions defined in the operational structure are executed. In addition, for practical reasons (i.e., to be able to run the flood model automatically), the link between the ABM and flood model is embedded within the ABM; and hence, the flood model is called and run from the ABM environment.

The coupled ABM-flood model method starts by initializing the agents and the urban environment. The initialization includes setting the social and physical structures and geographic boundaries. Then, in each time step, agent-related actions run first. Agents' actions and interactions that drive their exposure (e.g., following the BP) and vulnerability (e.g., following BO or FZ) do not affect the flood model input files. In that case, only agents' state is updated and its effect is evaluated later in the modelling process. On the other hand, if their actions and interactions lead to a change in the urban environment that affects the hazard component, the hydrologic or hydrodynamic states and parameters are updated. For example, as agents continue to build new houses, catchments imperviousness may increase. Therefore, the rainfall-runoff parameters should be updated accordingly.

Next, the flood-related actions run. As the link between the ABM and flood model is embedded within the ABM, the flood dynamics are also coded in the operational structure of MAIA. Before running the flood model for the first time, it must be calibrated in advance. The calibration is based on the initial urban environment setting and after that, the flood model runs based on the continuously updated urban environment. The urban environment is updated in two cases. The first is when new houses are built every time step. We simplified the housing expansion mechanism in which the number and locations of new houses are based on the building permits issued by VROMI and on the NDP land use map. That is, agents choose from a predefined set of potential future house locations. The second case is when there is a decision to build flood hazard reduction measures, which are improving drainage networks and building dykes.

An important remark here is that the coupled model building is designed considering long-term FRM plans, in which institutions are created/updated or measures are implemented in a longer time scale (i.e., ABM has time steps in years), whereas flood events may happen for hours or days (i.e., flood models usually have time steps in seconds or minutes). Thus, we couple the two models by considering one flood event of a given duration happening within one ABM time step in which the ABM is suspended while the flood model runs. The ABM resumes once the flood model completes the run and produces the result.

Finally, flood impacts are assessed by overlaying the flood map over the urban environment. Agents' attributes that reflect their state of exposure (i.e., location and BP compliance) and vulnerability (i.e., floor height, BO compliance and BP compliance) may affect the outcome of the impact assessment. For example, if the flood depth where a house is located is below the house floor height, the flood impact on that household will be zero. Since not all flood cases result in the implementation of FRM measures, the need for measures is an important decision-making process in FRM. In the Sint Maarten FRM case, the government agent implements two structural measures: widening channel cross-sections and building dykes. Catchments, where measures are implemented, are selected based on the highest number of flooded houses. If a measure is implemented, the hydrologic and hydrodynamic states must again be updated.

After setting up the coupled model, it is necessary to perform model verification and validation. ABMs developed in the CLAIM framework are verified using the evaluative structure of MAIA (Ghorbani et al., 2013), which indicates the relationship between expected outcomes and agent actions. In the Sint Maarten FRM model, if the BO and FZ compliance thresholds increase, a higher number of elevated houses are expected. However, changing the BP threshold should not affect the number of elevated houses. Regarding the model validation, due to lack of empirical data regarding the flood and human dynamics at the same time, validating the ABM and coupled model is a challenge. Thus, we performed expert validation using domain experts from the Sint Maarten Disaster Management and the VROMI who were engaged during the model development.

6. Simulation result and discussion

6.1. Simulation execution

We design an ABM experimentation to test the effect of the three institutions in reducing flood risk. For that purpose, we design a full factorial experiment setup by varying the institutions threshold values as follows:

- the BO compliance threshold value is varied between 0.5 and 1 with a space of 0.25
- the FZ compliance threshold value is varied between 0 and 1 with a space of 0.25
- the BP compliance threshold value is varied between 0 and 1 with a space of 0.25

In case of the FZ and BP compliance threshold values, the lower and higher limits of the ranges are set to 0 and 1 to test the extreme conditions of no compliance and total compliance, respectively. The lower end of the BO compliance threshold range is set to 0.5 because many people in Sint Maarten comply with this institution. In addition to varying the threshold values, we tested three other scenarios of the BP. As indicated in Table 1, the BP forbids the building of houses within 50 m of the coastline. However, considering the tradeoff between the economic benefits of building close to the coastline and reducing flood impacts from coastal floods, we also tested if the policy forbids the building of houses within 0 m (i.e., no policy) and within 100 m of the coastline.

We instantiate the simulations with 12000 households, in which 80% are elevated, and run each experiment for 30 time steps with similar design rainfall event series (shown in Fig. 3). We assume that a maximum of one flood event happens in a given time step, where a time step represents one year. A one-factor-at-a-time sensitivity analysis (ten Broeke et al., 2016) is performed to assess how changes in some key

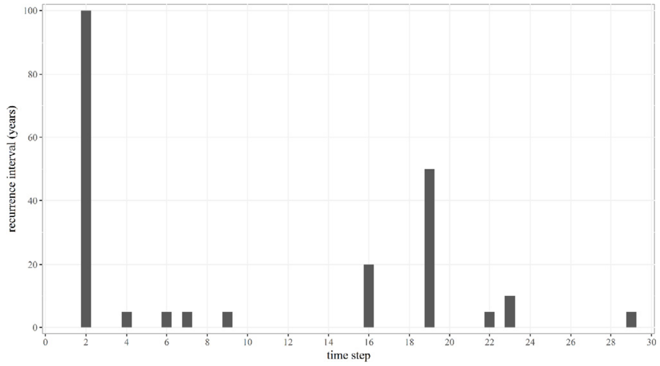

Fig. 3. Input design rainfall events. It shows discrete recurrence intervals in years assuming that there is a maximum of one major flood event per time step.

input factors change the model outcome. For example, the initial number of agents has a direct linear relationship with the total number of flooded houses whereas the initial number of elevated houses has an indirect relationship. Furthermore, to quantify the uncertainty related to the use of random numbers in the ABM, we run each model setup in repetition (10 times). The results in Figs. 4–6 show the uncertainties using box-plots.

6.2. Results and discussion

The results in Fig. 4 show the number of flooded houses in response to agents' compliance rate of the BO and FZ. Fig. 4a and c correspond to new houses whereas Fig. 4b and d correspond to all the houses on the island. In general, irrespective of the institution, the number of flooded houses is higher with lower compliance thresholds (i.e., low policy enforcement), and it increases over time as the number of houses increases. Fig. 4a and c shows the number of vulnerable agents (in this case, vulnerability is measured by the number of not elevated houses) increase during the simulation period. However, for the same compliance threshold of both the BO and the FZ, not complying with the BO results in higher number of vulnerable agents compared to not complying with the FZ.

In addition, change in compliance threshold values, for example, an increase from 0.5 to 0.75, has a bigger effect in case of not complying with BO than not complying with FZ. The reason is that the BO affects the vulnerability of agents in the whole island while the FZ affects small portions of the island as shown in Fig. 2. Furthermore, the areas delineated as flood zones are already well developed and existing agents are not affected by the FZ. Results shown in Fig. 4b and d also follow the same reasoning. Increase in the compliance threshold of BO has a bigger effect on the total number of flooded houses. That is observed more at the end of the simulations with an increase in the number of houses. The figures also show that in 25 years, i.e., from time step 4 to 29, the number of flooded houses because of a rainfall with 5yr recurrence interval rises by more than 20% (in case of BO compliance threshold of 0.75 in Fig. 4d). This is mainly attributed to the increase in the number of new houses in areas exposed to flooding.

In general, because of the wider effect of the BO, if agents fully comply with the ordinance or if there is strict enforcement by the government agent, the vulnerability of residents will reduce, which in turn, will reduce the total impact. On the other hand, with its localized effect, the FZ can have a huge effect on reducing the vulnerability of residents in the delineated flood zones though its effect on reducing the total flood risk is very little.

Fig. 5 shows the effect of the BP on the exposure of agents. In both cases of BPs that forbids construction within 50 m and 100 m from the coastline, increasing the compliance threshold has a minor effect on the total number of flooded houses. Moreover, widening the no-construction zone from 50 m to 100 m has a marginal reduction in the total number of flooded houses only at the end of the simulation period. The reason is that, as in the case of the FZ, the BP also does not impact all agents, and the coastal flooding affects localized areas.

The results in Figs. 4 and 5 show the effect of an increase in the number of houses with varying exposure and vulnerability on the total impact. However, agents may also implement measures that reduce the flood hazard. To demonstrate this feedback, we introduce an institution in which the government agent implements a flood hazard reduction measure in a catchment with the highest number of flooded houses. The conditions for this institution to be executed are (i) when there is a rainfall with a recurrence interval of 50yr or above in a given time step or (ii) the last measure was implemented at least 3 years before the current time step. Fig. 6 shows that, compared to results in Fig. 4a and b, the total number of flooded houses decreases by almost half because of the reduction in the flood hazard.

With the model setup described, analysing the flood risk even when agents have the highest compliance rate for each policy, the total number of flooded houses increase with the increase in urban development. In fact, the total number of flooded houses is high at the beginning of the simulation. However, implementing flood hazard reduction measures in some catchments may reduce the number of flooded houses significantly especially in case of a bigger flood event. At this point, it is important to highlight that our analysis is subject to the uncertainties associated with the ABM, the flood model and the coupled model.

7. Conclusion

Traditional flood risk management and flood modelling practices have been solely focusing on the flood hazard reduction. However, as policymakers are challenged to develop resilient climate change adaptation and mitigation measures, impacts of these policies on the exposure and vulnerability of communities is increasingly important.

In this work, we presented the CLAIM modelling framework, which allows for improved conceptualization and simulation of coupled human-flood systems. The human subsystem consists of heterogeneous agents and institutions which shape agents' decisions, actions and interactions, and are modelled using ABM. The flood subsystem consists of hydrologic and hydrodynamic processes which generate floods, and are modelled using numerical flood models. The dynamic link between the two subsystems happens through the urban environment.

The ABM is coupled with the flood model to study the behaviour (i.e., actions and interactions) of agents in relation to the defined institutions and to evaluate agents' exposure and vulnerability as well as the flood hazard. The methodology presented to build a coupled model is designed considering long-term FRM plans than operational level, during-flood strategies. The output of the coupled model is a level of flood risk in terms of assessed impact, which is used as a proxy to measure the effectiveness of the institutions in the study area.

The main advantage of CLAIM is that it is possible to explicitly

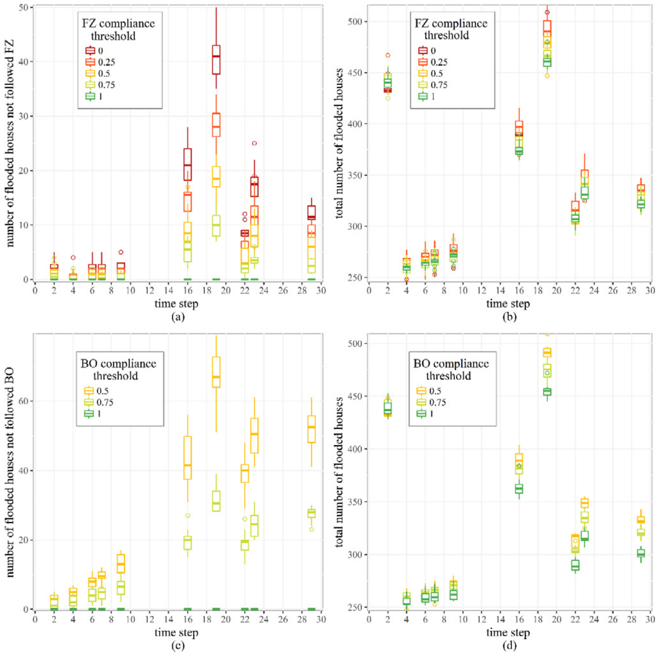

Fig. 4. The effects of FZ and BO on the number of flooded houses over time. (a) and (b) show the number of flooded houses that do not comply with the FZ and the total number of flooded houses, respectively, for FZ compliance thresholds between 0 and 1. For these figures, the BP and BO compliance thresholds are 0 and 0.5, respectively. (c) and (d) show the number of flooded houses that do not comply with the BO and the total number of flooded houses, respectively, for BO compliance thresholds between 0.5 and 1. For these figures, both the BP and FZ compliance thresholds are 0.

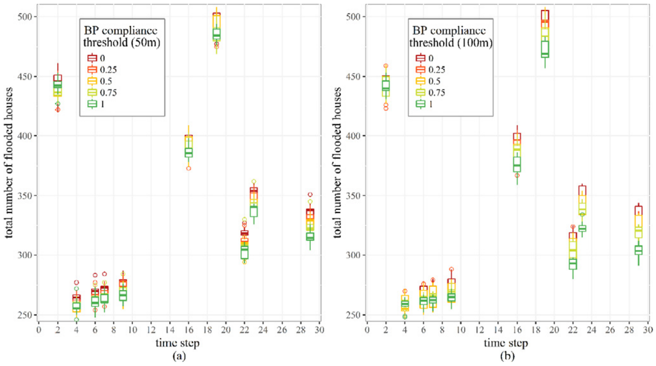

Fig. 5. The effect of BP on the number of flooded houses over time. (a) and (b) show the total number of flooded houses for BP that forbids the building of houses within 50 m and 100 m of the coastline, respectively, and for BP compliance thresholds between 0 and 1 in both cases. For these figures, the FZ and BO compliance thresholds are 0 and 0.5, respectively.

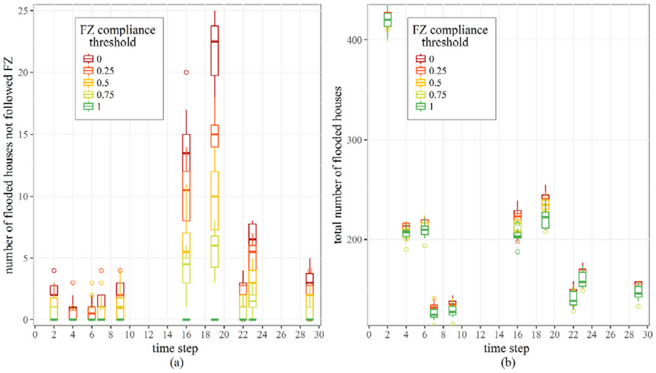

Fig. 6. The combined effects of FZ and a hazard reduction measure on the number of flooded houses over time. (a) and (b) show the number of flooded houses that do not comply with the FZ and the total number of flooded houses, respectively, for FZ compliance thresholds between 0 and 1. For these figures, the BP and BO compliance thresholds are 0 and 0.5, respectively.

model the human and flood subsystems using knowledge from the respective domains, and link the two subsystems dynamically to study their interactions. The framework provides an interdisciplinary approach by allowing knowledge integrations from hydrologists/hydraulic engineers and social scientists. The coupled ABM-flood modelling method also helps to study how levels of exposure (i.e., number of assets-at-risk), flood hazard (i.e., flood magnitude and extent) and vulnerability (i.e., propensity to be affected) change with changes in human behaviour (i.e., policies and their implementations).

As demonstrated in the case of Sint Maarten FRM, models developed using CLAIM can assess the dynamic impacts of proposed policies, taking into account imperfectly rational and heterogeneous responses of individuals to the policies. Model outputs allow policymakers in FRM decision making to adopt an appropriate adaptation measure that will reduce the future flood risk. For example, in Sint Maarten, implementing hazard reduction measures significantly reduce the number of flooded houses. In addition, the government (i.e., VROMI) may need to improve its inspection and enforcement of the Building Ordinance as it has a wider effect over the island to reduce the vulnerability of households.

Further, by incorporating implementations that change flood hazard, exposure and vulnerability, coupled ABM-flood models which utilize the CLAIM framework allow flood risk to be examined as a function of time. This provides a more comprehensive view of a flood risk than if it were calculated based on a single historical and fixed urban environment condition. It is our belief that the CLAIM framework and models built to represent heterogeneous agents together with the institutions that shape their behaviour will extend to socio-hydrological orientated studies.

One of the limitations of CLAIM is that conceptualizing and modelling two complex subsystems which in turn are comprised of further complex subsystems requires large amount of data. The inclusion of additional or nested subsystems requires a balance between better representation of a system (or “needed complexity”) and building a very complicated model (Sivapalan and Blöschl, 2015; Voinov and Shugart, 2013). In addition to the large data sets required to build each model, model runs may require large computational resources. In the current study, this was a consequence of the two-dimensional hydrodynamic model and the number of experiments and repetitions of the ABM setup. Concerning the coupled ABM-flood model paradigm proposed to model the human-flood interaction using CLAIM, the coupled model suffers from the limitations of both the ABM and flood modelling techniques. A substantial issue in modelling human-flood interaction is the parametrization of human behaviour in ABMs (see Crooks and Heppenstall (2012) for detailed limitations of ABM). The uncertainty of the coupled model will also increase as it includes uncertainties of the individual models.

CLAIM is designed to analyse long-term, strategic level institutions that are considered during the flood disaster recovery and prevention stages. To study the implications of operational level institutions that are considered during the preparedness and response stages, the system conceptualization changes as the focus shifts to institutions such as early warning and dissemination plans, and evacuation policies. The agents and their attributes will change considering individual agents and their age, gender or education status become more significant at that scale. The structure of the coupled model also changes because the ABM and flood model run simultaneously to evaluate agents' behaviour as the flood propagates.

The modelling exercise presented in this paper analysed predefined institutions that agents may follow given their individual resources. To extend the applicability of coupled ABM-flood models in socio-hydrologic studies, future studies could include endogenous institutional changes or the evolution of institutions through feedback mechanisms (as described in (Ghorbani and Bravo, 2016; Smajgl et al., 2008)). This may provide insight into how FRM policies emerge bottom-up or evolve in the future. In addition, analysing the uncertainty of the coupled model will help to better communicate the model outputs with stakeholders.

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