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Research article

Flood risk management in Sint Maarten – A coupled agent-based and flood modelling method

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ABSTRACT

Disaster risk reduction is a major concern of small island developing states. Measures to reduce risk should not only be based on the magnitude of physical hazard, but also on the exposure and vulnerability of communities. In this article, we examine flood risk management policies in the Caribbean island of Sint Maarten using coupled agent-based and flood models. The agent-based model is used to model actors' behaviour in relation to urban building development and policies that are designed to reduce flood hazard and communities' vulnerability and exposure. The policies considered in the model are a Beach Policy, a Building and Housing Ordinance, a Flood Zoning policy and hazard mitigation structural measures. The flood model is used to simulate coastal and pluvial floods on the island. Agent behaviour such as building new houses and implementing hazard reduction measures affect the flood model as these actions affect the rainfall-runoff process. The flood maps generated from the updated flood model simulations are then used to assess the impact and update agents' attributes and behaviour. The simulations results show that low-lying areas are populated, which increases the exposure, and the number of vulnerable houses is also high. Hence, out of the four policies, implementing hazard reduction measures is the most important. Reducing the flood hazard by widening existing drainage channels, constructing new ones and building dykes as coastal flood defence would reduce the hazard, hence reducing the number of flooded houses. As it affects all households on the island, the Building and Housing Ordinance is an important policy to reduce vulnerability. In general, the coupled model outputs can be used to inform policy decision making and provide insights to policymakers on the island.

1. Introduction

Hydro-meteorological and climatological disasters caused by floods, hurricanes/tropical cyclones and droughts have had damaging effects on the economies and livelihoods of populations living in small island development states (SIDS) (Mycoo and Donovan, 2017). In particular, disasters due to coastal flooding, storm surges and sea level rise pose a risk of death, injury and disruption to livelihoods (IPCC, 2014a). The main reasons for the disaster impacts on small islands is that they are characterised by small land area, rapid rate of urbanization, low elevation coastal zones, concentration of human communities and infrastructure in coastal zones, and high levels of informal urbanisation (IPCC, 2014b; Mycoo and Donovan, 2017, UN General Assembly, 1994).

Recognizing the hazards, exposure and vulnerability of communities in SIDS, national and international initiatives were designed and implemented to reduce disaster risk. For example, in the Barbados Programme of Action, participating SIDS recognised the impacts of disasters and affirmed their commitment to implement national actions and policies that establish/strengthen building codes and regulatory system, promote early warning systems, establish a national disaster emergency fund, integrate disaster policies into national development plans and improve resilience of local communities to disaster events (UN General Assembly, 1994). In addition, SIDS implement regional Comprehensive Disaster Management strategies and the Hyogo Framework for Action to address mitigation, prevention and recovery of disaster risk (DRRC, 2011). These include land use planning regulations, zoning laws, insurance funds and government contingency funds for recovery.

The challenges of implementing the policies, strategies and plans

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include financial constraints, lack of political commitment and lack of enforcement resulting in unregulated developments in exposed areas (DRRC, 2011). Individuals may also refuse to follow the policies as their behaviours depend on their level of risk, economic situation and awareness. This shows disaster risk reduction is the responsibility of all actors involved, from higher level decision makers to individuals (see also Vojinovic, 2015). Thus, in addition to quantifying the hazard, it is vital to include human behaviour and risk perception in disaster risk assessment to design relevant policies (Aerts et al., 2018). One way of including the social elements in disaster risk reduction studies is using agent-based models (ABM). An ABM is a computational model where autonomous and heterogeneous agents interact with each other and their environment (Railsback and Grimm, 2012), exploring the behaviour of agents in a system. For example, Dubbelboer et al. (2017) develop an ABM to simulate the vulnerability of homeowners to flood risk and to investigate the effect of adaptation and insurance measures in reducing the risk. Tonn and Guikema (2017) use an ABM to analyse how flood protection measures, individual behaviour, policies and near-miss flood events affect community flood risk.

The limitations of recent efforts to incorporate the human behaviour in flood risk management include models focus more on the human element while simplifying the flood hazard, and not systematically analysing the policies that shape the risk. Addressing the limitations, Abebe et al. (2019) develop a coupled flood-agent-institution modelling framework (CLAIM) to capture and conceptualize coupled human-flood systems. CLAIM has five components: (i) *Agents* are a representation of an individual or composite actors/stakeholders in a model; (ii) *Institutions* are rules, norms and strategies (Crawford and Ostrom, 1995) that shape agents' actions, interactions and decision makings; (iii) *urban environment* is where agents live and floods occur, and is the component that connects the human and flood subsystems; (iv) *physical processes* are hydrologic and hydrodynamic components which include rainfall-runoff processes, storm surge and floods; (v) *external factors* are elements that affect the "local" agent-flood interactions but are not affected by the direct actions and interactions of agents in the local settings. Using CLAIM, the human subsystem is modelled with ABMs and the flood subsystem is modelled with numerical hydrodynamic models. The framework employs the MAIA (Modelling Agent systems using Institutional Analysis) meta-model (Ghorbani et al., 2013) to structure the human subsystem.

Models, including those developed using the CLAIM framework, are abstractions of the reality, make use of assumptions, have parameters and have initial and boundary conditions that cannot be measured/known of full certainty. It is important to perform uncertainty analysis (UA) and sensitivity analysis (SA) to better understand and communicate the outputs that inform policy decision making. Concerning ABMs, although computationally intensive, recent studies analyse uncertainty and sensitivity using Monte Carlo simulations that are based on samples of the full range of model input factors (Fonoberova et al., 2013; Ligmann-Zielinska et al., 2014). Those studies employ the global SA approach based on variance decomposition (Saltelli et al., 2008). In another study, ten Broeke et al. (2016) conclude that global SA does not adequately address issues such as nonlinear interactions and feedbacks, and emergent properties in ABMs. They recommend using one-factor-at-a-time (OFAT) SA, by varying one parameter at a time while keeping all other parameters fixed, to address the above-mentioned issues. Then, they recommend performing global SA methods to address interaction effects of parameters.

Focusing on flood disasters, for the purposes of the present work, we apply an ABM coupled with a numerical flood model to examine existing and proposed flood risk management (FRM) policies in the Caribbean island of Sint Maarten. The island is selected as a case because it is frequently affected by flash, pluvial and coastal floods due to isolated rainfall events and hurricanes. Further, the Government of Sint Maarten has adopted some of the policies implemented in other SIDS and it is planning to put in place new ones. Hence, we aim to model the FRM of Sint Maarten using coupled ABM-flood model to inform decision making and provide insights to policymakers.

ABM is used to model actors' behaviour, including their decisions, actions and interactions, with respect to the FRM policies that shape the behaviour. The emphasis within the ABM is to evaluate long-term, strategic level FRM policies (or policy implementations) such as flood zoning, building codes and improving drainage systems. Operational level policies such as early warning systems and evacuation policies are not included in this study. In the flood model, we consider coastal and pluvial flood sources, which are modelled using one- and two-dimensional (1D-2D) hydrodynamic model. The tightly coupled ABM-flood model is conceptualized using the CLAIM framework.

Abebe et al. (2019) describe the CLAIM modelling framework and the step-by-step methods to build coupled ABM-flood models. To show the functionality of CLAIM and to illustrate how models are developed, a preliminary coupled model was developed for the FRM case of Sint Maarten. In the current paper, we fully develop the previous preliminary model, particularly the ABM. One of the improvements is that we have used better datasets. For example, the model decomposition is enhanced by using a risk root cause analysis, the initial number of houses is based on a buildings shapefile that we further refined, and the future development locations are improved based on discussions with local experts and field observations of the island. We also improve the FRM module that captures the government agent's decision making on where and when to implement structural flood hazard reduction measures. The module now reflects the decision-making process to improve drainage systems and the plan to implement coastal defences. In addition, in this paper, we focus on the model evaluations, outputs analysis emphasising on implications of institutions and agents' responses, and the resulting insights into the FRM of Sint Maarten. In the following sections, we will describe the study area, the ABM and flood models setup and input data used, model verification and validation, sensitivity and uncertainty analysis, model experimentation and results, and finally, discussions and conclusions.

2. Study area

The Caribbean island of Saint Martin is divided into two parts: the northern part called Saint-Martin and the southern part called Sint Maarten (see Fig. 1). The study area of the present work is the island state of Sint Maarten (hereafter, *the island* refers to only Sint Maarten). Below, we describe the geography, climate, hydrology, as well as the organisations and institutions in the island in relation to FRM.

2.1. Geography and climate

The total area of Sint Maarten is approximately 34 km^2 and its total population is more than 40,000 people (STAT, 2017). The island has hilly terrains where elevation ranges from near sea level to about 420 m above mean sea level (see Fig. 1). The lowlands are highly urbanized with predominantly residential buildings, and businesses are located mainly along the coast. Sint Maarten is located within the Atlantic hurricane belt, and hence, subject to frequent hurricanes. Major hurricanes that affected the island include Hurricane Luis in 1995 (Lawrence et al., 1998), Hurricanes Jose and Lenny in 1999 (Lawrence et al., 2001) and, more recently, Hurricane Irma in 2017. Those hurricanes brought an enormous amount of damage to the people of Sint Maarten both economically and socially, including loss of life (see more in MDC, 2015). The damages due to hurricanes are associated with one or a combination of strong wind, storm surge, pluvial flooding and mudslides.

2.2. Hydrology

The stormwater catchments and streams in Sint Maarten have several unique characteristics that contribute to the severity of flood-

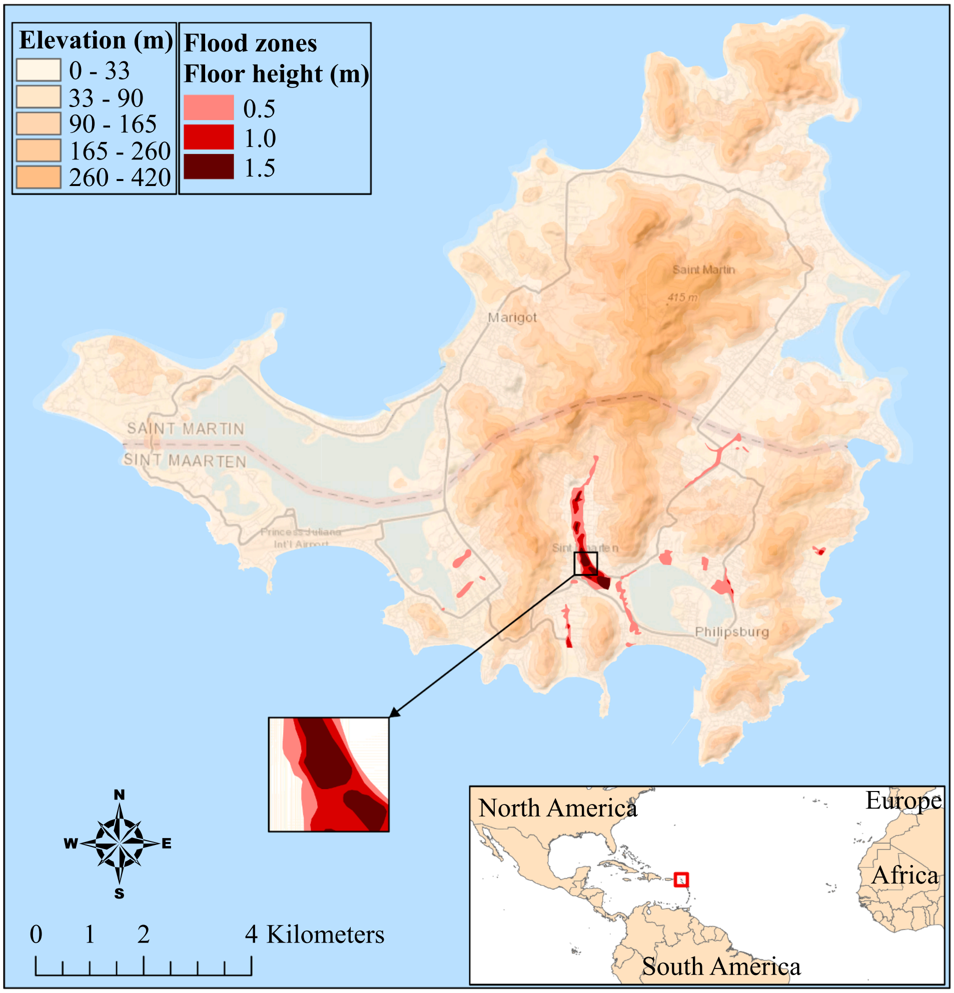

Fig. 1. A map of Saint Martin showing the northern, Saint-Martin and the southern, Sint Maarten. The map also shows the elevation ranges in the whole island. The areas in shades of red are flood zones delineated by Sint Maarten's Ministry of Public Housing, Spatial Planning, Environment and Infrastructure as part of a draft National Development Plan. New buildings constructed in the light, medium and dark red zones must have elevated floors of 0.5 m, 1.0 m and 1.5 m, respectively. (Source: the base map is an ESRI Topographic Map).

related impacts. As urban environments are usually situated in low-lying areas with little consideration for stormwater drainage, they are subject to flash flooding from surrounding hills or extreme rainfall events such as thunderstorms (Vojinovic and van Teeffelen, 2007). The stormwater channels or streams are often short, entering the ocean as low or mid-order streams. They are typically inadequate to convey runoff due to their limited capacity and obstructions. In addition, hurricane-induced storm surges may also cause coastal flooding. The potential impact due to hurricanes and isolated heavy rainfalls has increased considerably over the recent years with the economic and population growth on the island.

2.3. Organisations and institutions

Flood prevention, preparedness and mitigations on the island have not been sufficiently developed to cope with potential disasters. Addressing and minimizing the risk of flood-related disasters is a major challenge for the island government. For a long time, the effort of the government to manage flood risk has been concentrated on the reduction of flood hazard by canalizing and widening natural gutters and controlling stormwater levels using gates. The reasons those efforts may not always work include: the government has financial limitations to construct drainage channels in all neighbourhoods of the island; there might be a lower probability flood event beyond the channels design criteria, which can be intensified by the effects of climate change and urbanization; and gates might fail to regulate water levels during flood events.

Recently, the government acknowledges that FRM should include not only reducing the flood hazard but also reducing the exposure and vulnerability of elements-at-risk. Hence, a policy plan was drafted to improve disaster management on the island. A National Ordinance on Disaster Management is put into action to lay out the “rules and regulations” about preparation for and management of disasters, referring to immediately before and after the onset of an event. The government is also drafting a national development plan (NDP) to manage the spatial development of Sint Maarten. This plan with zoning regulations is prepared and undertaken by the Ministry of Public Housing, Spatial Planning, Environment and Infrastructure (as commonly known as VROMI, a Dutch acronym) of the Government of Sint Maarten. The flood hazard management techniques covered in the plan are maintaining green areas, preserving and enhancing natural gutters and reserving spaces for retention ponds. The aspects specified in the plan to manage the exposure and vulnerability to flooding are the location of buildings from the sea, building codes and floor-height elevations.

3. Models setup

3.1. CLAIM decomposition

Before building the coupled model, we first decompose the coupled human-flood system of the Sint Maarten FRM into the five elements of CLAIM, i.e., agents, institutions, urban environment, physical processes and external factors. The decomposition is based on the case study description given in the previous section, the risk root cause analysis for Sint Maarten that investigates the root causes and drivers of flood risk (Fraser, 2016; Fraser et al., 2016) and consultation with experts of VROMI and Disaster Management Department.

a) Agents: The two main agent types considered in this case are household agents and a government agent. The household agents represent the people living in residential houses in Sint Maarten. Due to lack of data, our conceptualization does not explicitly consider businesses and public entities. However, we include the buildings these actors own by assigning them to household agents to ensure that they are considered in flood impact computation. The government agent is a composite agent that represents the VROMI. There are three relevant departments of VROMI that the government agent represents: the Permits, the Inspection and the New Projects Departments. The first two departments are responsible for designing, regulating, inspecting and enforcing policies related to buildings, spatial planning, and development. The latter is responsible for the design and implementation of public/government buildings and drainage works. Hence, through the three departments, the government agent's actions shape the hazard and household agents' exposure and vulnerability.

b) Institutions: The institutions considered are the Sint Maarten Beach Policy (BP), the Sint Maarten Building and Housing Ordinance (BO), the Flood Zoning (FZ) under the NDP and hazard mitigation structural measures. As beaches are an integral part of the tourism-based economy, the main objective of the BP is to protect the recreational value of the beaches on the island. The Government ensures that there is no construction of dwellings, hotels and businesses on the beach as that may restrict their normal uses. Although the policy is not formulated in relations with flood risk reduction, its implementation can have a direct effect on the exposure of household agents. Hence, it is included in the conceptualization. In the presence of natural sea sand, the policy covers up to 50 m of the strip from the coastline.

   BO and FZ are drivers of the vulnerability of household agents to flood because agents are obliged to elevate the floor of new houses. The BO states that the minimum floor height of a house must be at least 0.2 m above the crown of a road whereas the FZ requires households to raise the floor of their house by 0.5 m, 1.0 m or 1.5 m as illustrated in Fig. 1. The other difference between the two institutions is that BO is applicable to the whole island while the FZ is relevant only to delineated flood zones. It should be noted that vulnerability is a multifaceted concept (Sorg et al., 2018). But, in this case, we focus only on the physical vulnerability, which is measured by the number of elevated houses.

   After major flood events, the Sint Maarten Government may implement structural measures to reduce the flood hazard. The commonly implemented measures are widening channel cross-sections and constructing new ones if there is no drainage channel in the flooded area. Although it has never been implemented on the island, we also included building dykes along the coast in the conceptualization as a measure to reduce coastal flood risk.

c) Urban environment: The agents mentioned above live and interact on the island. Hence, the island is part of the urban environment. Both inland and coastal floods also occur on the same environment. However, since the coastal floods are generated in a water body, we include part of the Atlantic Ocean in our conceptualization. In addition to agents, physical artefacts such as houses/buildings and drainage channels are constructed on the environment. Most houses are located in the valleys of the island though there are settlements on the hills. In some neighbourhoods where there are no drainage channels, streets drain runoff. The environment is represented by a digital terrain model as shown in Fig. 1.

d) Hydrologic and hydrodynamic processes: The hydrologic and hydrodynamic processes included in the conceptualization are related to the inland and coastal floods. The processes include rainfall-runoff processes, 1D channel flows, 2D surface flows and hurricane-induced storm surges. Agents' dynamics such as an expansion of built-up areas and construction or widening of drainage channels on the island may affect the flood hazard by altering the imperviousness of catchments.

e) External factors: The sources of flooding are rainfall for inland flooding and hurricane-induced surge for coastal flooding. We do not include external political and economic factors in the conceptualization.

3.2. Agent-based model inputs and setup

As mentioned before, MAIA is used to conceptualize and structure the human subsystem, and provides the language to develop ABMs. The MAIA meta-model is organised into five structures: social, institutional, physical, operational and evaluative structures. Description of the first four structures of MAIA is given below.

Agents in CLAIM, their states and behaviours, are defined in the *social structure* of MAIA. The two agents defined are the household and the government agents.

- Households: Household agents make house plans and they build houses. In the ABM environment, these agents are spatially represented by their houses. Household agents know about the three institutions, which are BP, BO and FZ, and have compliance rate attributes that reflect their behaviour to the institutions. These attributes state the level of compliance and shape agents' exposure and vulnerability. Since agents may comply with one institution but not with another, each household agent has three compliance rates corresponding to the BP, BO and FZ. These compliance rates are drawn from a uniform random distribution for every new agent at every time step.
- Government: The government agent is characterized by a level of policy enforcement. The enforcements correspond to the three institutions and are expressed using compliance threshold attributes. For BP and BO, the threshold values are set based on the percentage of houses that followed the institutions whereas for FZ, it is based on assumptions as the policy is in a draft stage. Compliance thresholds set at the beginning of a simulation are kept constant throughout that same simulation. In the model setup, the threshold values are expressed in percentages (or fractions) setting the percentage of household agents that comply with the institution. For example, if the BP compliance threshold is 100% (or 1), then all households will comply with the BP as agents' BP compliance rates generated from a uniform random distribution is less than or equal to 1. The government agent also constructs new drainage channels and improves existing ones to reduce flood hazard. This agent does not have a geographic representation in the ABM environment.

Agents' physical artefacts, which are the plans and the houses, and the urban environment in CLAIM are defined in the *physical structure* of MAIA.

- Plans: Before building houses, household agents develop plans to set the location, elevation and floor height of houses that will be constructed.
- Houses: The houses are also characterized by location, elevation and

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
Flood hazard reduction	Government		implements flood hazard reduction measure	e.g., if number of flooded houses > a threshold		Shared strategy

floor height. Houses are geographically represented by point vector data (i.e., shapefiles). Further, houses can be flooded and record their flood depth to assess the impact.
- Urban environment: The main attribute of the environment is its imperviousness, which is directly related to the number of new houses. The environment is geographically represented by a raster data of 30 m resolution.

Institutions in CLAIM are coded using the ADICO grammar within the *institutional structure* of MAIA. ADICO refers to the five elements institutional statements might contain: Attributes, Deontic, aIm, Condition and "Or else" (Crawford and Ostrom, 1995). We code the four institutions using the ADICO grammar as shown in Table 1. The BP, BO and FZ are written formal policies (although the FZ is still in draft stage) and therefore, their type is set to "rule". However, since there is no strict enforcement of the policies on the island, there are no proper sanctions for violating these rules. Hence, the "or else" component of the ADICO is left blank. The flood hazard reduction, on the other hand, is of a type "shared strategy" that is implemented by the government agent to reduce flood risk. As there is a budget constraint to implement flood reduction measures in every flooded neighbourhood in Sint Maarten, the government gives priorities based on the number of flood houses in a hydrologic catchment (i.e., based on flood model outputs).

The dynamics of the human subsystem, which include agents' actions and their interactions with other agents and the environment, are defined in the *operational structure* of MAIA. Fig. 2 (a) shows all the actions and interactions conceptualized in the coupled model. In the Sint Maarten ABM, we define two agents' dynamics: urban building development and FRM (flood hazard reduction).

- Urban building development: In our conceptualization, a new house is built (or planned) when there are new household agents as all households are represented spatially by a house they live in. 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, new agents choose from a predefined set of potential future house locations randomly. Every time step, household agents make house plans by deciding where to build new houses and if they elevate the floor height of the houses. For example, if an agent develops a plan to build a new house, the first institution the agent checks is the BP (see Fig. 2 (b)). If the planned house's location is within 50 m from the coastline and the agent's BP compliance rate is less than the BP compliance threshold, the agent complies with BP; hence, the plan will be cancelled and the planned house will not be built. But, if the agent's BP compliance rate is greater than the threshold, the agent will build the house within 50 m of the coastline. If the plan is not cancelled, the next institution the agent checks is the FZ (see Fig. 2 (c)). If the planned house is located in the flood zones and the agent's FZ compliance rate is less than the FZ compliance threshold, the agent complies with the FZ and the house plan will be improved to change the floor elevation to the height stated in the policy. In that case, since the minimum floor elevation in FZ (i.e., 0.5 m) is higher than the floor elevation stated in BO (i.e., 0.2 m), there is no need to check the compliance to the BO. But, if the agent does not comply with the FZ, the agent will check if it complies with the BO (see Fig. 2 (d)). Similarly, if the agent's BO compliance rate is less than the BO compliance threshold, the agent complies with the ordinance and the house plan will be improved to change the floor elevation to 0.2 m. If the BO compliance rate is greater than the threshold, the house will not be elevated. The newly built house will have the same location, elevation and floor height as the plan.
- FRM (flood hazard reduction): in Sint Maarten, most flood hazard reduction measures are implemented in a reactive, ad hoc manner. There is no systematic way of prioritizing neighbourhoods that are frequently flooded. When the budget for the construction of measures comes from the government, neighbourhoods may be selected based on their political alliance (for example, campaign promises during elections). In case budget comes from donor funds, priority may be given to economically poor areas (for example, to improve sanitation and drainage). As a result, the dynamics run only if there is a flood event. In the model, the government agent selects a maximum of one catchment at a given time step where a measure is implemented based on certain conditions (Fig. 2 (e)). The first set of conditions checked are: (i) if there is a rainfall event with a recurrence interval of 50yr or above as these magnitudes of rainfall causes major flood or (ii) if a previous measure was implemented at least three years before the "current" time step, assuming it takes an average of three years to implement a measure and all relevant budget is directed to that measure. When those criteria are met, the next set of conditions are if the number of flooded houses in a catchment is greater than a threshold, and if that number is the highest.

After structuring the system using the MAIA meta-model, the descriptions and flowcharts are converted to pseudo-codes that can be coded in object-oriented programming languages. The ABM is implemented using the Java-based Repast Simphony modelling environment (North et al., 2013). The environment is selected as it provides capabilities for spatial data analysis, and the Java programing language it uses provides ease of integration of the ABM and flood model (for example, in terms of input-output data processing). The full ABM software can be accessed at https://github.com/yaredo77/Coupled_ABM-Flood_Model. Model assumptions that have been made during the conceptualization are listed in Appendix A.

3.3. Flood model inputs and setup

In the flood model, we consider both pluvial and coastal floods. The inflow for the pluvial flood simulations comes from design rainfall events of 5yr, 10yr, 20yr, 50yr and 100yr recurrence intervals. The maximum intensities of these rainfalls are 52 mm/h, 62 mm/h, 76 mm/h, 90 mm/h and 100 mm/h, respectively. The island is divided into sub-catchments and the rainfall-runoff process of each sub-catchment is analysed with the unit hydrograph method (DHI, 2016a). In this method, the excess rainfall is calculated by the runoff curve number (CN) method. The factors that determine the CN values of a catchment include the soil type, land cover, treatment, hydrologic condition, size of impervious areas and the antecedent moisture condition at the start of the storm. In this study, the CN values are updated depending only on the increase in impervious surfaces due to the urban developments

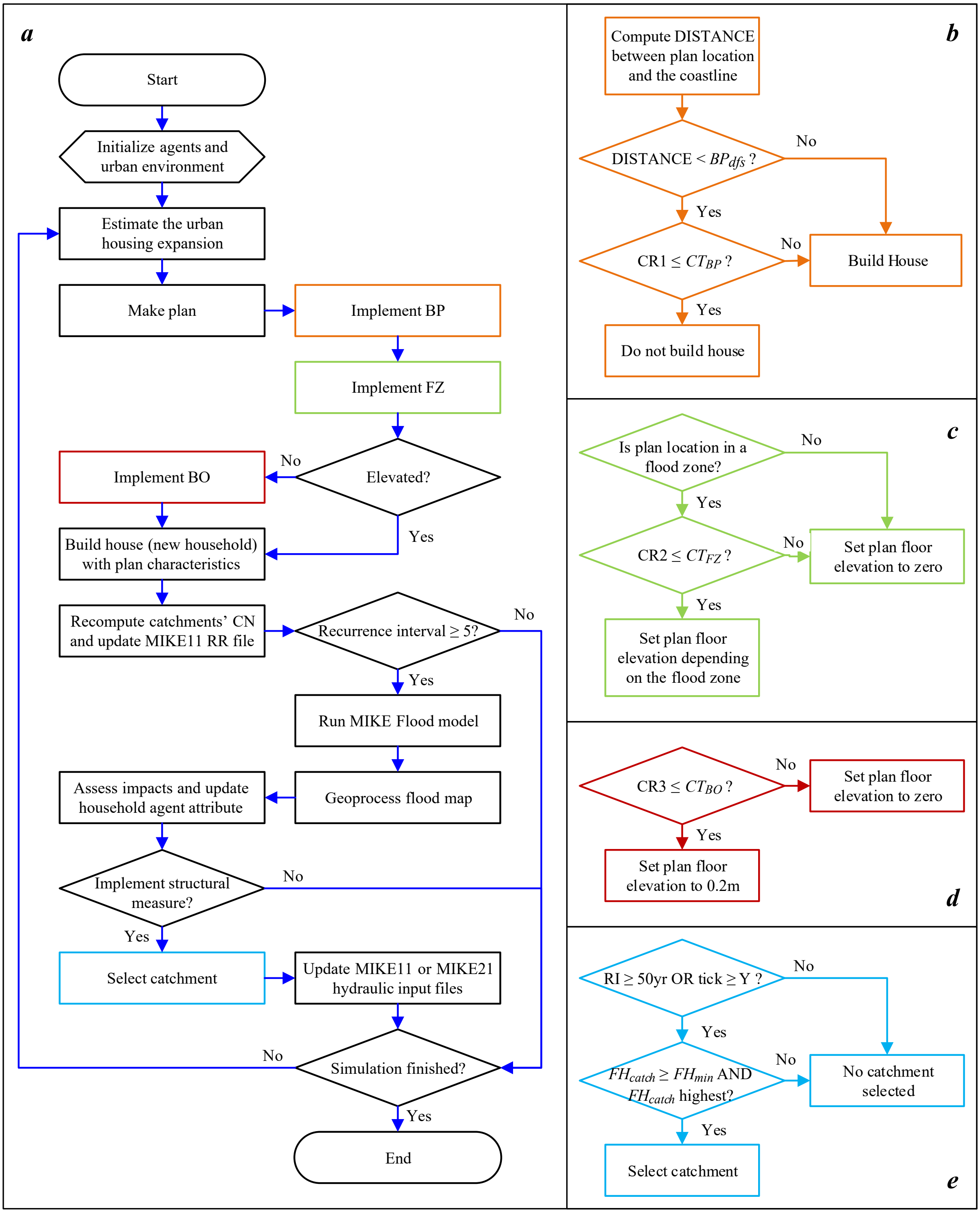

Fig. 2. CLAIM implementation flowchart for the Sint Maarten FRM. The flowchart also shows the coupling process (i.e., ABM-flood model coupling) as the coupling is done from the ABM modelling environment. (a) shows the general flow chart while (b), (c) and (d) show how the BP, FZ and BO policies are implemented, respectively. (e) shows the criteria to select catchments where structural measures are implemented. In the figure, CN is curve number; RR is rainfall-runoff; CR is compliance rate, RI is recurrence interval, tick is the ABM time step, Y is the years between the implementation of consecutive measures, BP_{dfs} is the BP distance from the sea, CT_{BP}, CT_{FZ}, and CT_{BO} are the compliance thresholds for BP, FZ and BO, respectively, and FH_{catch} and FH_{min} are the catchment and minimum (threshold) number of flooded houses, respectively.

defined in the operational structure of MAIA.

The inflow for the coastal flood simulations comes from open boundaries in which a boundary condition of 0.5 m water level is used. The value is derived from a hurricane storm surge simulation and it is the same in all flood simulations. In contrast, the inflow for the pluvial flood comes from a 1D runoff routing. The model bathymetry used in the 2D, for the pluvial and coastal simulations, has a spatial resolution of 30 m (shown in Fig. 3). The flood subsystem is modelled using the MIKE FLOOD hydrodynamic modelling package, which couples MIKE11 and MIKE21 (DHI, 2016b). MIKE11 is used to model the rainfall-runoff processes and 1D flows in the drainage channels while MIKE21 is used to model the 2D coastal and pluvial flooding in the

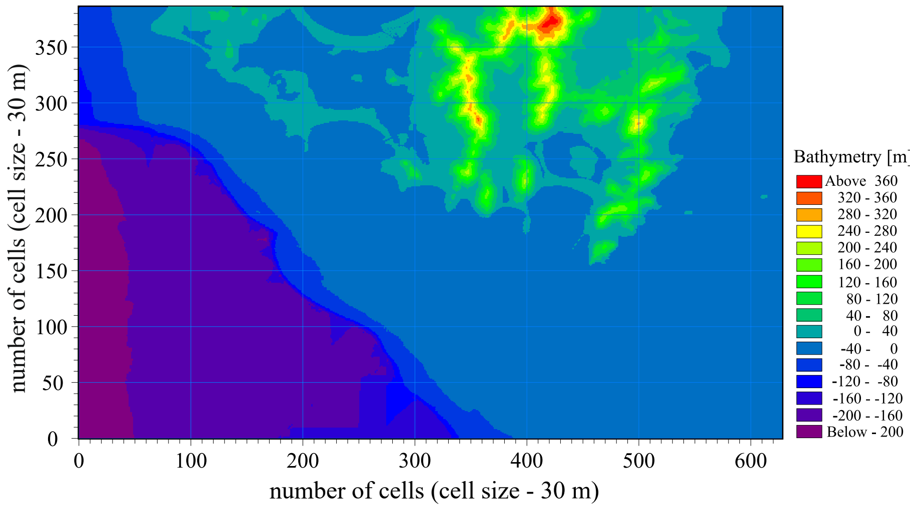

Fig. 3. Bathymetry used in MIKE21 coastal and pluvial flooding simulations (based on Vojinovic et al., 2013). The model domain is 18.8 km by 11.6 km with a grid resolution of 30 m. This is also the same urban environment used in the ABM.

urban floodplains. The output of the MIKE FLOOD model is a map showing the flood extent and depth.

3.4. Coupled model inputs and setup

The ABM and flood model are coupled within the Repast Simphony ABM environment so that we use one programming language, and it is suitable to manage the input-output data of the two models. Hence, we conceptualize the coupling within the operational structure of MAIA. Fig. 2 (a) shows the coupling process. The computation time step of the ABM is 1 year as it takes years to build houses and flood hazard reduction measures. As the urban development agent dynamics happen at every time step, the ABM runs during the whole simulation period. However, since flooding does not happen every year, the flood model does not run every time step. The coupled model computation time step is the same as the ABM time step. When there is a rainfall event in a given time step, the flood model runs on a different timescale. In all the simulation runs, we use the synthetic design rainfall event series shown in Fig. 4. The input parameters and variables used in the coupled model and the ABM together with their default values are presented in Table 2. In the table, the input parameters and the policy-related fixed variables are *control variables* whereas the other policy related scenarios that are used to set up experiments are *independent variables* (see Lorscheid et al., 2012, pp. 29–30 for definitions of dependent, independent and control variables).

3.5. Model evaluation

3.5.1. Model verification and validation

The flood model is developed using the commercial off-the-shelf software MIKE FLOOD, MIKE21 and MIKE11. Hence, we rather focus on verifying the ABM and the coupled model computer programs we developed. To verify the ABM, we use the *evaluative structure* of MAIA, which indicates the relationship between expected outcomes and agent actions. We record, debug and assess selected evaluation variables and check whether their values match agents' actions. For example, there is a direct relationship between the number of elevated houses and the compliance thresholds of FZ and BO. If CT_{FZ} and CT_{BO} increase, we expect to record a higher number of elevated houses. However, there is no relationship between the number of elevated houses and the BP. As another example, the number of flooded houses is directly related to the implementation of all the institutions – BP, BO, FZ and structural

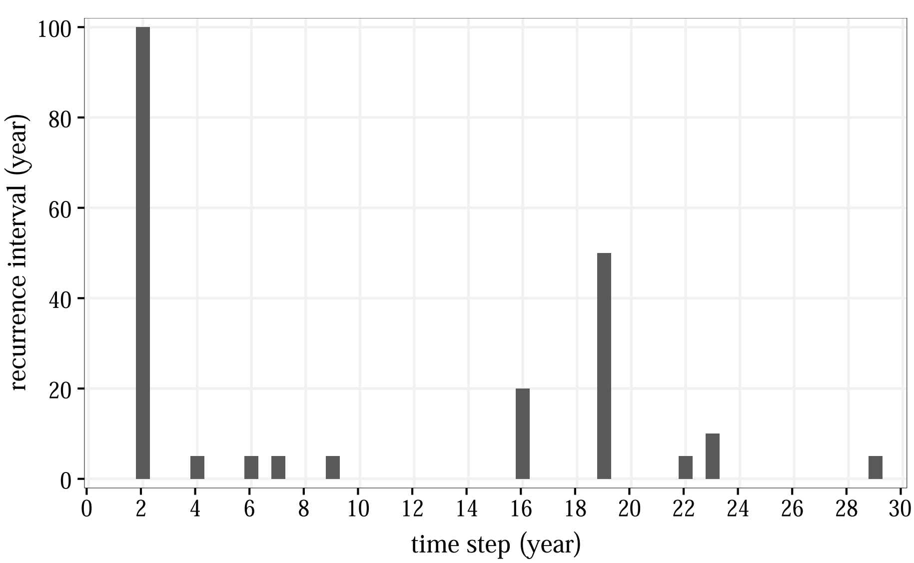

Fig. 4. Input design rainfall events series. It shows discrete recurrence intervals in years assuming that there is a maximum of one major flood event per time step. The coupled model runs for 30 years of simulation period in which the flood model runs ten times.

Table 2
Default values for input parameters and variables used in the coupled model. The fixed policy-related variables are well-defined values used in all simulations, whereas the rest of policy-related variables are used for scenario experimentation purpose.

	Input parameter or variable	Symbol	Default Values	Remark
Input parameters	Initial number of households/houses	HH_{ini}	12000	Based on a buildings shapefile (ca. 2010) obtained from VROMI
	Minimum number of flooded houses in a catchment that triggers structural measure	FH_{min}	20	Authors estimation[a]
	Number of years between the implementation of consecutive structural measure	Y	3	Authors estimation[a]. This is only when a flood event is caused by a rainfall of recurrence interval less than 50yr.
	Increase in CN of catchments per house	CN_h	0.1	Authors estimation based on 0.02 ha average lot size per house
	Initial number of houses with elevated floor (BO)	$HElev_{ini}$	$0.8HH_{ini}$	Authors estimation[a]
Policy-related variables (fixed)	Floor height elevation (BO)	FH_{BO}	0.2 m	Building and Housing Ordinance, February 2013
	Floor height elevation (FZ)	FH_{FZ}	0.5 m, 1.0 m and 1.5 m (depending on the zone)	Draft Sint Maarten National Development Plan, 2014
Policy-related variables (used to set up experiments)	BP compliance threshold	CT_{BP}	75%	Authors estimation[a]
	FZ compliance threshold	CT_{FZ}	75%	Authors estimation[a]
	BO compliance threshold	CT_{BO}	80%	Authors estimation[a]
	Structural measures	SM	No	Authors estimation[a]
	Beach policy distance from the sea	BP_{dfs}	50 m	Sint Maarten Beach Policy, August 1994

[a] These estimations are based on discussions with Sint Maarten Disaster Management and VROMI experts.

measures.

In the case of the coupled model verification, we monitor whether catchments CN values are updated properly reflecting the urban development in the catchments. We also monitor if the right flood map is used to compute the number of flooded houses. If there is no structural measure implementation, we expect a higher number of flooded houses when the rainfall recurrence interval at a given time step is higher. In addition, if a structural measure is implemented in a catchment, we expect to record a lower number of flooded houses in that catchment, not in any other catchment.

The flood model is validated using a historic flood event in Sint Maarten. The hydrodynamic model results, flood depth and extent, were validated against eye-witness accounts. However, it should be noted that in this study, we use design rainfall event series rather than historical flood events. Due to the lack of empirical data regarding the flood and human dynamics at the same time, validating the ABM and coupled model is a challenge. As a result, we opted to validate the models using domain experts/problem owners from the Sint Maarten Disaster Management and the VROMI. We consulted with these experts throughout the model development process to validate the conceptualization, the modeller's estimation of input data and the model outputs. For example, earlier versions of the coupled model resulted in an overestimated number of flooded houses. The result is improved to a "reasonable" value after the experts suggested to adjust the default initial values of model inputs (for example, the initial number of elevated houses) and policy compliance thresholds. Given the aim of developing the coupled model is to provide insights into the long-term FRM dynamics of Sint Maarten, we do not strive to reproduce an empirically observed behaviour and system states.

3.5.2. Model uncertainty and sensitivity

Considering the computational cost of performing both OFAT and global SA, in this study we only perform the OFAT SA analysis. To further reduce the computational cost associated with this analysis, we first performed an initial UA of the coupled ABM-flood model output with respect to the uncertainty of the 2D flood model computational grid. High-resolution topography data may provide a better representation of urban features in urban flood modelling. However, using high-resolution computational grids in 2D flood modelling is computationally demanding. This implies that performing SA and UA for the coupled ABM-flood model that uses high-resolution topography data significantly increases the computational cost.

The initial UA evaluates the effect of 10 m, 30 m and 60 m computational 2D grids on the total number of flooded houses. The simulations are carried out using the default input parameters and variables set in Table 2. Each simulation is replicated 20 times considering the stochasticity of the ABM that is caused by the randomization of household agents' compliance rates. All simulations in this study are performed using the SURFsara high performance computing cloud facility (https://userinfo.surfsara.nl/systems/hpc-cloud) with Windows 64x operating system and 9 CPUs.

To perform the SA, not all the model input parameters and variables are selected. The fixed policy-related variables (see Table 2), FH_{BO} and FH_{FZ}, are formally defined values recorded in ordinance/policy documents. The other policy-related variables are the independent variables used to set up experiments that test the effect of agents' behaviours on institutions and how that affect the overall flood risk in Sint Maarten. Hence, all the policy-related variables are set to their default values in the SA. The input factors selected for the SA are the five control variables listed in Table 3.

We perform the OFAT SA for the input factors specified in Table 3. In each simulation, we run the model for the extreme values of the input factor range and four equidistant points in between; hence, six runs per factor. We run 20 replications per factor setting to show the uncertainty of the coupled model output. The first three simulations are executed in a case where no hazard reduction structural measure is

Table 3
Selected input factors for the sensitivity analysis and their uniform distribution bounds.

Simulation	Input factor	Distribution	Range
1	HH_{ini}	Uniform	[10000, 12500]
2	$HElev_{ini}$	Uniform	[0.5, 1]
3	CN_h	Uniform	[0, 0.5]
4	FH_{min}	Uniform	[10, 50]
5	Y	Uniform	[1, 6]

implemented whereas for Simulations 4 and 5 (in Table 3), measures are implemented.

3.6. Experimental setup

To assess the effect of institutions on the hazard, vulnerability and exposure, we run simulations by varying the values of the policy-related variables (see Table 2). The BP-related variables, CT_{BP} and BP_{dfs}, affects the exposure, whereas the FZ- and BO-related variables, CT_{FZ} and CT_{BO}, influences the vulnerability of agents. Whether there is a structural measure or not, i.e., the value of SM, affects the level of hazard.

As shown in Table 4, the compliance threshold values for the FZ and BP ranges between 0 and 1 to test the extreme conditions of no compliance/no enforcement and total compliance/full enforcement, respectively. Whereas, in the case of the BO compliance threshold, the lower value is set to 0.5 because many houses in Sint Maarten are already elevated. We also tested the effect of the BP buffer zone that prohibits the construction of buildings. In addition to the default value of 50 m, we test no-building zone of 0 m, and 100 m from the coastline. Finally, the scenarios for the implementation of structural measures are based on the Boolean values of “Yes” and “No”. For the other input factors, we used their default values as stated in Table 2. The rainfall event series used for all the scenarios is the one shown in Fig. 4.

4. Results

4.1. Uncertainty and sensitivity analysis

The approximate computation time a single simulation of coupled ABM-flood model takes to run using 10 m, 30 m and 60 m 2D grid sizes is 120 h, 6 h and 1.5 h, respectively. A single simulation has 30 time steps in which the 2D flood model runs in 10 of the time steps as shown in Fig. 4. Although using the 60 m 2D grid reduces the computational time, Fig. 5 shows that the total number of flooded houses are lower compared to the results when using the 10 m and 30 m 2D grids, especially during rainfall events with higher recurrence intervals. This can be due to the shallower flood depths associated with the low-resolution grid (see Vojinovic et al., 2011), and the floor elevations as a result of complying with BO and FZ are greater than the flood depth.

On the other hand, in most cases, the differences in the total number of flooded houses when using the 10 m and 30 m 2D grids are within the simulation output distributions as illustrated by the boxplot in Fig. 5. However, running simulations using the 10 m grid requires 20 times the computational time required to run simulations using the 30 m grid. Hence, in the subsequent uncertainty and sensitivity analysis and the scenario experiments, we use the 30 m 2D computational grid.

Table 4
Policy-related variables and their value range used in the experimental setup.

Scenario variable	Value range	Step
CT_{BP}	[0, 1]	0.25
CT_{FZ}	[0, 1]	0.25
CT_{BO}	[0.5, 1]	0.25
SM	No or Yes	–
BP_{dfs}	[0, 100] in m	50 m

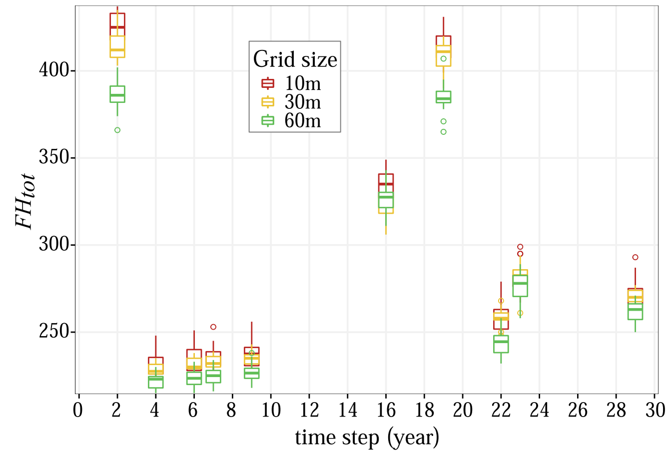

Fig. 5. Coupled ABM-flood model simulation outputs - total number of flooded houses (FH_{tot}) - when using 10 m, 30 m and 60 m computational grids in the 2D flood model. Each boxplot corresponds to 20 replicated simulations. The distributions are the result of the stochasticity of the ABM as heterogeneous agent behaviours are generated randomly.

The SA results in Fig. 6 show that all factors but $HElev_{ini}$ have a direct relationship with the number of flooded houses. Increasing the initial number of household agents increases the number of exposed and vulnerable houses, which in turn increases the number of flooded houses. Higher CN_h intensifies the flood hazard while higher FH_{min} and Y reduce the chance of structural measures implementation, increasing the flood impact. Increasing $HElev_{ini}$, in contrast, reduces the vulnerability of household agents, resulting in lower flood impact. Based on Fig. 6, the important factors are HH_{ini}, $HElev_{ini}$and CN_h. The first two factors show a uniform relationship between the range of the factors and the range of the median number of flooded houses. Hence, these factors exhibit a linear relationship with the total number of flooded houses. But, the change in the value of CN_h is more important towards the end of the simulation time when more houses are built. Of the three factors, $HElev_{ini}$ is the most crucial factor.

FH_{min} and Y have a marginal effect on the total number of flooded houses. The latter has more effect in the first half of the simulation time, but its effect diminishes in the last half. After $time\ step = 9$, the next flood happens seven years later. Therefore, there is an implementation of a measure as the maximum Y in the SA is six. The other reason is that structural measure implementation is not only dependent on Y (see the illustration in Fig. 2 (e)). As there is a 50yr event at $time\ step = 19$, a measure is implemented irrespective of the value of Y.

In summary, the UA shows the underlying uncertainty embedded in the bathymetry input data. The analysis justifies why a 30 m grid bathymetry is used in the flood model. The SA analysis highlights that the total number of flooded houses is sensitive to HH_{ini}, $HElev_{ini}$and CN_h. Model result interpretations, discussions and conclusions presented in the following sections are subject to the uncertainty and sensitivity of input factors discussed above.

4.2. Experimentation results

4.2.1. The effect of the Beach Policy on the exposure of houses

As the BP prohibits the construction of buildings within a certain distance from the coastline, it directly affects the exposure component of the flood risk. That means, if households do not follow the BP or if there is no strict enforcement of the policy, more buildings will be constructed on coasts exposed to potential coastal flooding. Fig. 7 (a) shows the worst case scenario when BP_{dfs} is zero, which effectively means there is no policy. In that case, there is no violation of or no need of enforcing a policy. Hence, despite the value of the CT_{BP}, the

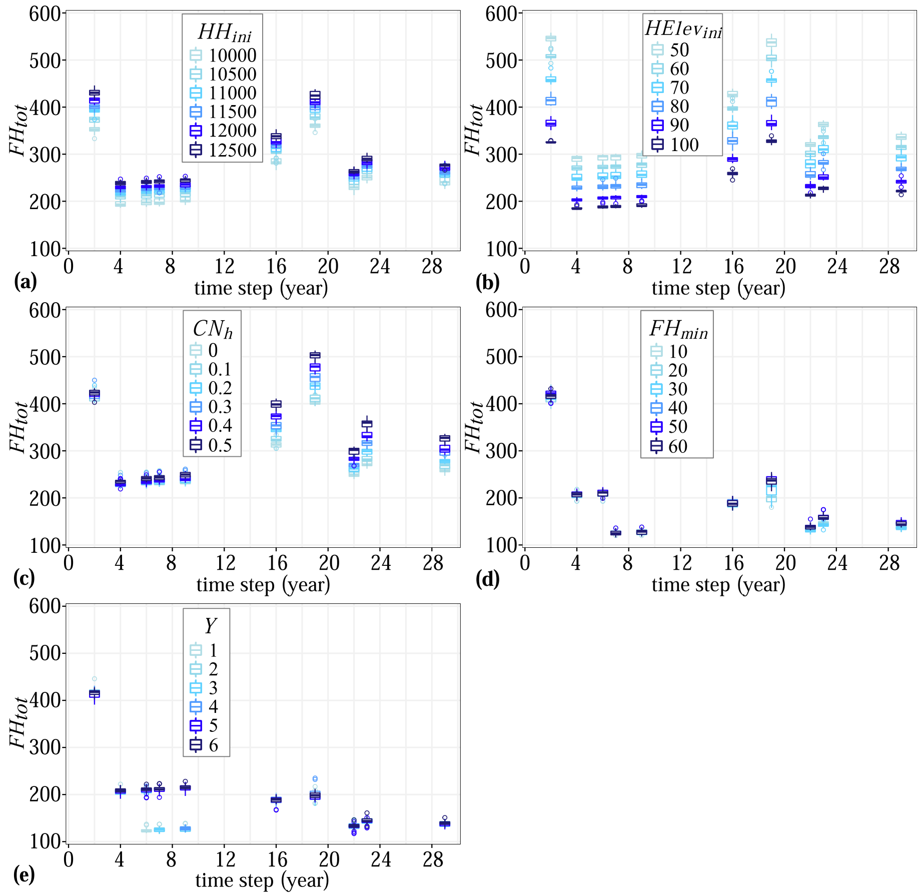

Fig. 6. OFAT sensitivity result for (a) initial number of households (HH_{ini}), (b) initial number of houses with elevated floor ($HElev_{ini}$), (c) increase in CN of catchments per house (CN_h), (d) minimum number of flooded houses in a catchment that triggers structural measure (FH_{min}) and (e) number of years between consecutive structural measures (Y). FH_{tot} is the total number of flooded houses.

cumulative number of households (HH_{cum}) that do not follow the BP is also zero. Fig. 7 (c) and (e) show HH_{cum} that do not follow the BP when BP_{dfs} is 50 m (i.e., as mentioned in the policy) and 100 m, respectively. In these cases, since there is a policy, there can be violations based on the value of the CT_{BP}. The figures show that HH_{cum} that do not follow the BP decreases when the CT_{BP} increases. However, the number of exposed houses shows major reduction between the CT_{BP} values of 0.5 and 1 than between 0 and 0.5. For example, HH_{cum} that do not follow the BP reduces by about 36% when the compliance threshold increases from 0.5 to 0.75 compared to only about 5% reduction when the compliance threshold increases from 0 to 0.25. This shows that starting from zero, it seems little effort of complying or enforcement does not payoff but through time and with more effort of complying or enforcement, the payoff increases as more households follow the BP.

Regarding widening the no-building zone, increasing the BP_{dfs} value from 0 m to 100 m results in an increase in the number of potentially exposed people. This is because more households can be affected by widening the no-building zone. For example, the maximum number of affected households increases from about 120 to 350 units with an increase in BP_{dfs} from 50 m to 100 m. That means, with more compliance or enforcement (i.e., higher CT_{BP} values), the number of exposed households will show a major reduction when the no-building zone widens.

The effect of the BP, in terms of increasing the values of CT_{BP} and BP_{dfs}, on the total number of flooded houses (FH_{tot}) is very little. Fig. 7 (b), (d) and (f) show that when the compliance threshold increases, there is a marginal reduction in the median FH_{tot}, especially towards the end of the simulation period. That is more visible when the no-building zone widens. For example, at *time step* = 29, the increase in CT_{BP} from 0 to 1 has almost no contribution in reducing the total number of flooded houses when BP_{dfs} is zero while it contributed about 10% reduction when BP_{dfs} is 100 m. The reason is that the BP affects a small group of agents along the coast and some part of the Sint Maarten coast is a cliff that is higher than the storm surge level simulated in the flood model.

4.2.2. The effect of the flood zones and building ordinance on the vulnerability of houses

The results in Fig. 8 (a) and (b) show the effect of the FZ and BO on the vulnerability of household agents, which is measured in terms of the number of (not-) elevated houses. The figures show a linear relationship between HH_{cum} that do not follow FZ and BO and the increase in the values of CT_{FZ} and CT_{BO}, respectively. The figures also illustrate that BO influences a larger number of agents than the FZ (for example, by more than 25 times at the end of the simulation for compliance threshold values of 0.5). It should be noted that Fig. 8 (b) does not include the initial number of houses that do not follow the BO, and it only shows the result after the simulation starts as in the case of non-compliance of the FZ in Fig. 8 (a). Further, for the same CT_{FZ} and CT_{BO} values, not complying with the BO results in a higher number of flooded houses compared to not complying with the FZ. For example, Fig. 8 (c) and (d) show that for CT_{FZ} and CT_{BO} values of 0.5 (i.e., about 50% compliance/enforcement), the median number of flooded houses that do not follow BO is about 30 times the number that do not follow FZ at *time step* = 29.

For both institutions, HH_{cum} and the number of flooded houses is higher with lower compliance thresholds (i.e., low policy compliance/enforcement). This is more important with bigger flood events and towards the end of the simulation as more vulnerable household agents

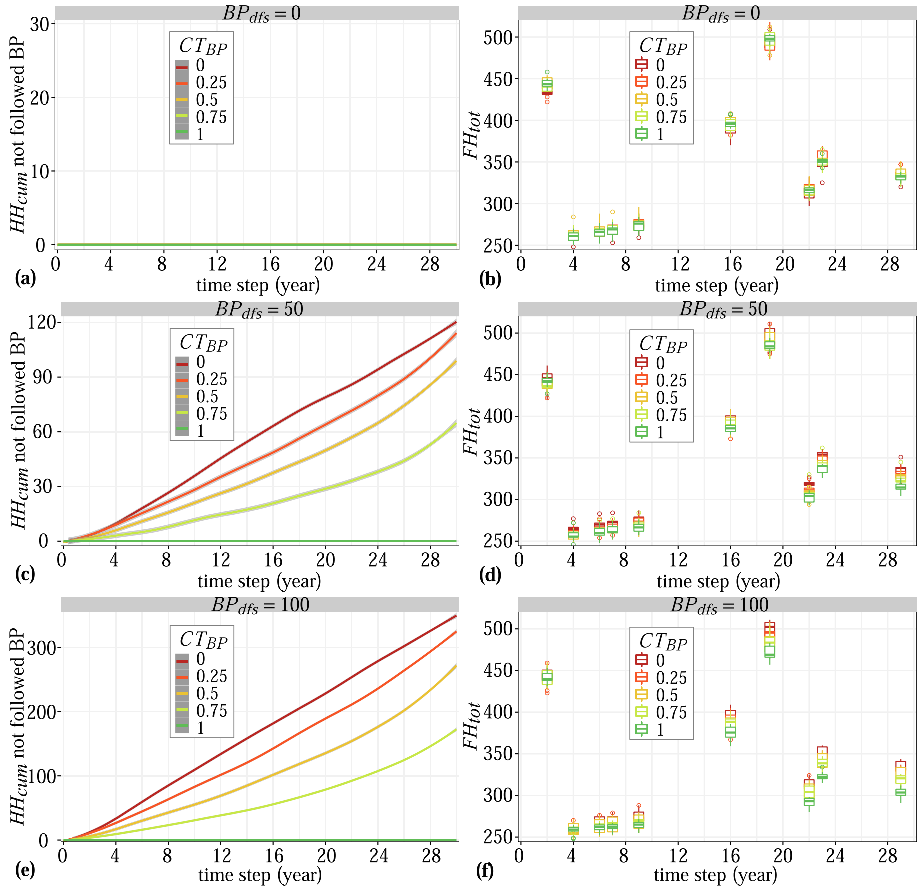

Fig. 7. The effect of BP on the number of exposed and flooded houses over time. All figures show BP compliance thresholds between 0 and 1. (a), (c) and (e) show the number of houses that do not follow the BP for BP_{dfs} values of 0 m, 50 m and 100 m, respectively, whereas (b), (d) and (e) show the total number of flooded houses for the same BP_{dfs} values. For these figures, the CT_{FZ} and CT_{BO} values are 0 and 0.5, respectively, and without structural measures.

are affected by the flood hazard. For example, as illustrated in Fig. 9, with the increase in the CT_{BO} value from 0.5 to 1, the number of potentially vulnerable and flooded houses decreases. Regarding the effect of a change in compliance threshold values, not enforcing/complying with the BO results in more flooded houses than not enforcing/complying with the FZ. The main reason is that the BO applies to the whole island, affecting all agents while the FZ affects small portions of the island (as shown in Figs. 1 and 8 (a) and (b)).

The wider impact of complying with BO is again illustrated in Fig. 8 (e) and (f). Considering exposed houses (i.e., those houses that registered 5 cm or more flood), the median number of houses that are not flooded as they are elevated by 20 cm is about 20 times the number of agents that comply with FZ but not flooded for CT_{FZ} and CT_{BO} values of 0.5. However, Fig. 8 (g) and (h) show that for the same CT_{FZ} and CT_{BO} values, FH_{tot} are similar. This is because the effect of not enforcing/complying with the FZ to FH_{tot} is very small. The figures also show that, regardless of the institution, there is an increase in FH_{tot} even when the compliance thresholds and the rainfall recurrence intervals are the same. For example, in Fig. 8 (f), the median FH_{tot} increases by about 27% between *time step* = 4 and *time step* = 29, when CT_{BO} is 0.5 and the rainfall event in both time steps has a recurrence interval of 5 years. This is mainly attributed to the increase in the number of new houses in areas exposed to flooding. The median FH_{tot} also increases by about 12% even if the rainfall event is lower in intensity, as in the case of *time step* = 2 and *time step* = 19. Though the rainfall recurrence interval is reduced from 100 year to 50 year, FH_{tot} increases as the flood depth is high and the extent is large enough to affect more houses when the number of new houses increases.

4.2.3. *The effect of the structural measures on the hazard*

The fourth institution tested is the implementation of structural measures. As shown in Fig. 10, when flood hazard reduction measures are implemented, FH_{tot} decreases significantly compared to the results shown above. For example, comparing Fig. 7 (d) and Fig. 10 (a) or Fig. 8 (h) and Fig. 10 (b), FH_{tot} reduces by more than a half starting from *time step* = 7. In addition, comparing of *time step* = 2 and *time step* = 19, Fig. 10 (c) shows that with the implementation of structural measures, the number of flooded houses reduces. The reason is that the structural measures reduces the flood hazard (i.e., flood depth and extent), which in turn, also reduces the exposure of houses. However, there are still flooded houses especially along the coast as shown in Fig. 10 (c). This is because the measures are not implemented in all catchments. For example, a coastal flood reduction dyke is implemented only in one catchment (see the difference between *time step* = 4 and *time step* = 29 in Fig. 10 (c)), hence, other coastal areas register flooded houses.

Finally, Fig. 11 shows the total number of houses on the island together with the elevated and the flooded houses over time in the "worst" and "best" case scenarios. The two scenarios are formed by taking the lowest and the highest values of the variable ranges in Table 4, respectively. The total number of houses in 30 years is lower in the best case as more households followed the BP and did not build houses. But, the number of elevated houses, complying with BO and FZ, is larger in the best case. As all household agents follow the BP, FZ and BO, and structural measures are implemented, the exposure, vulnerability and flood hazard are reduced in the best case. Hence, FH_{tot} is lower in that case, especially in the second half of the simulation period.

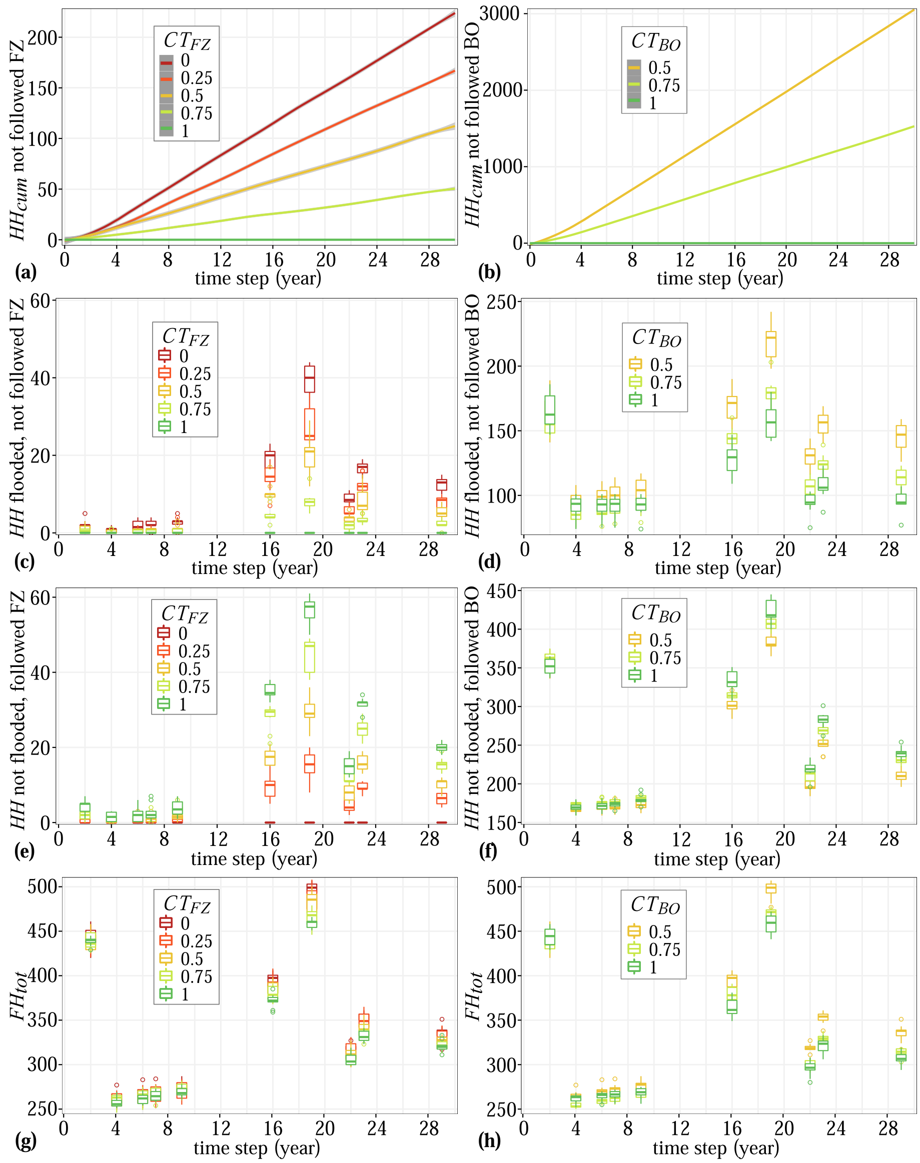

Fig. 8. The effects of FZ and BO on the number of vulnerable and flooded houses over time. (a) and (c) show the cumulative number of houses and number of flooded houses that do not follow FZ, respectively. (b) and (d) show similar results but when household agents do not follow BO. (b) does not include the initial condition. (e) and (f) show number of houses that followed FZ and BO, respectively, exposed in a flood event but not flooded as they are elevated. (g) and (h) show the total number of flooded houses for ranges of compliances of FZ and BO, respectively. For (a), (c), (e) and (g), CT_{BO} is 0 and for (b), (d), (f) and (h), CT_{FZ} is 0. For all the figures, BP_{dfs} is 50 m, CT_{BP} is 0 and no structural measures implemented.

5. Discussion and conclusion

The paper presents an improved and fully developed coupled ABM-flood model, which was preliminarily developed in (Abebe et al., 2019), using the CLAIM framework to comprehensively study flood risk management. The coupled model examines existing and draft flood risk management policies in the Caribbean island of Sint Maarten. It also presents model evaluations in the form of uncertainty and sensitivity analysis, and model experimentations by defining policy enforcement/implementation scenarios. The four institutions considered in the model conceptualization are the Beach Policy, the Building and Housing Ordinance, the Flood Zoning and the hazard mitigation structural measures. In the experimentation and the analysis of the model, emphasis is given to degrees of compliance or enforcement of the institutions by heterogeneous household agents. The contribution of housing development to the flood risk is highlighted as well.

The conducted model evaluation shows that the coupled model output is affected by the flood model grid resolution. Fixing all other coupled model inputs, in general, the coarser the grid size, the lower the number of flooded houses. However, the use of a coarser grid significantly reduces the computation time. This is a relevant aspect especially considering the need to replicate the coupled model due to the stochasticity of the ABM. Therefore, one should be careful when selecting the flood model grid size to balance the accuracy of model output and the total computation time. Furthermore, the sensitivity analysis indicates that the coupled model output is sensitive to the initial number of households, the initial number of elevated houses and the increase in catchment imperviousness. Hence, collecting better quality datasets of existing houses, and acquiring better knowledge on how much a new house contributes to the imperviousness of a catchment will improve the model output analysis.

In general, simulation results show that when there is strict enforcement of the policies, which are manifested in higher compliance thresholds, communities' exposure and vulnerability reduces as more people follow the policies. That means, the number of potentially flooded houses decreases. This is observed mainly during bigger flood

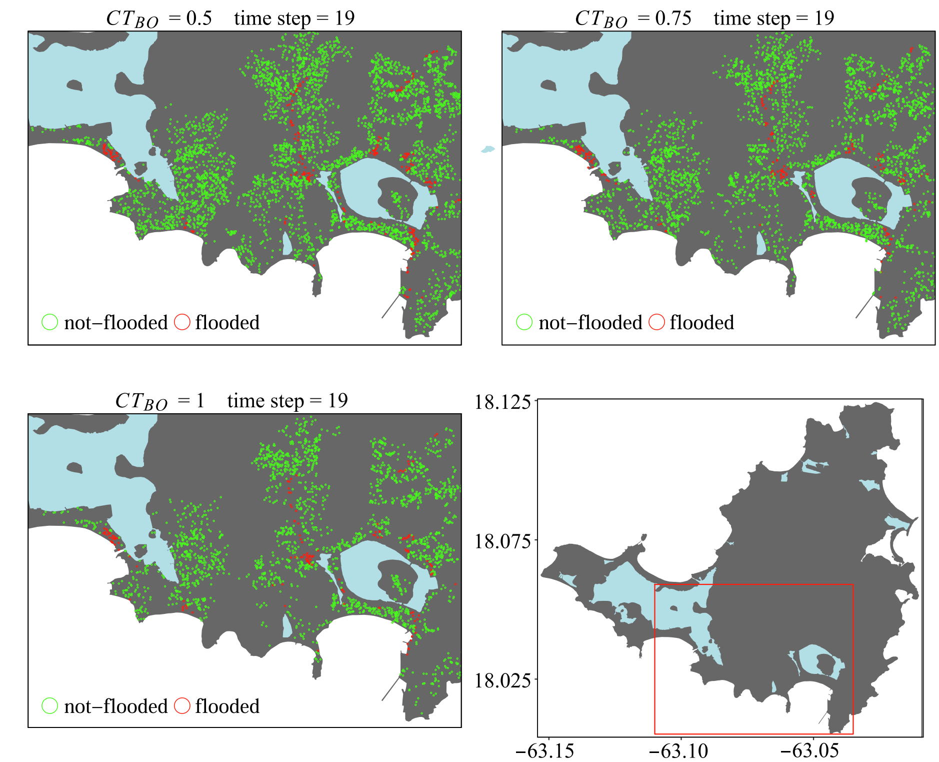

Fig. 9. Maps showing houses that do not follow the BO and (not-) flooded at *time step* = 19. The CT_{BO} values for (a), (b) and (c) are 0.5, 0.75 and 1, respectively. CT_{FZ} and CT_{BP} are 0 in the three cases. (d) shows part of Sint Maarten (red rectangle) plotted in (a), (b) and (c).

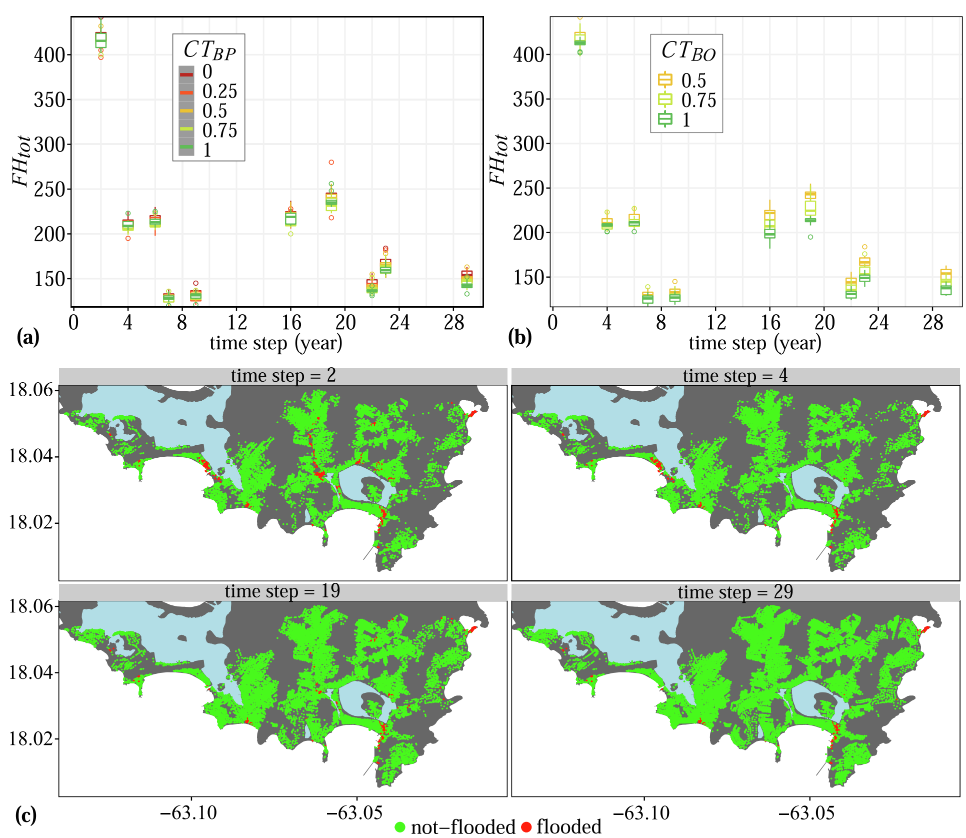

Fig. 10. The effect of structural measures on the number of flooded houses. (a) and (b) show the total number of flooded houses for ranges of compliances of BP and BO, respectively. For (a), CT_{BO} is 0.5 and for (b), CT_{BP} is 0. For all the figures, BP_{dfs} is 50 m, CT_{FZ} is 0 and structural measures are implemented. (c) shows maps of flooded and not-flooded houses at different time steps.

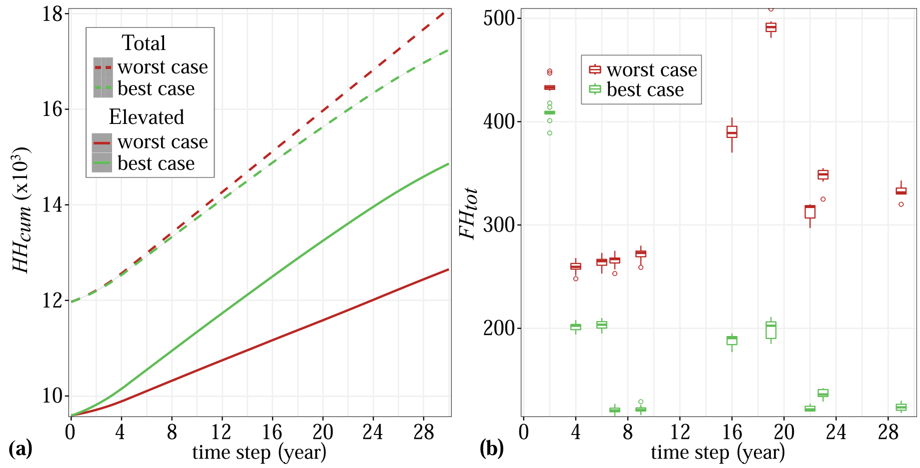

Fig. 11. (a) total and elevated number of houses (cumulative) and (b) total number of flooded houses in the "worst" and "best" simulation cases. In the "worst" case, the variable settings are: CT_{BO} is 0.5, CT_{BP} is 0, BP_{dfs} is 0, CT_{FZ} is 0 and no structural measures; whereas, in the "best" case, the variable settings are: CT_{BO} is 1, CT_{BP} is 1, BP_{dfs} is 100 m, CT_{FZ} is 1 and with structural measures.

events (for example, at *time step* = 19) as their flood extents cover large area affecting a higher number of new household agents. However, in absolute terms, the significance of policy enforcement in reducing the flood risk depends on the aim and conditions of the institutions.

Because of the wider effect of the Building and Housing Ordinance, if household agents fully comply with the ordinance or if there is strict enforcement by VROMI, the ordinance has an important contribution in reducing the vulnerability of residents. Even when houses are exposed to flooding, they are not flooded as they are elevated. The number of exposed but not flooded houses (because they followed the ordinance) is slightly less than the total number of flooded houses. However, there are houses that are elevated but flooded in areas where the flood depth is greater than 0.2 m. This shows that the ordinance is not fully effective although all agents comply with it.

On the other hand, with its localized effect, the Flood Zoning reduces the vulnerability of household agents located only in the delineated flood zones. In addition, the zones are already populated and there is no much housing development in those areas. Hence, the policy's effect on reducing the total flood risk is low. In contrast to the Building and Housing Ordinance, the implementation of the Flood Zoning is very effective within its area of effect as household agents will not likely flooded if they comply with it. That is because it obliges house floors to be elevated as high as 0.5 m–1.5 m. However, it should also be noted that the policy is in draft stage and based on field observation and expert discussions, it would be challenging to convince developers to elevate building floors to such height as it is costly.

Similarly, the Beach Policy also has a localized effect and its contribution to the overall flood reduction is low. Most parts of the Sint Maarten coast, especially where there are sandy beaches, are already occupied. Considering the values of the properties developed in those coastal areas (most are hotels and service providers related to the tourism industry), a flooded property may result in bigger damage and loss. Hence, the policy can be an important institution if impacts are measured based on monetary values.

The simulation results indicate that the structural flood hazard reduction measures are the most important institution to reduce the flood risk. Upgrading channels cross-sections and building coastal flood reduction measures such as a dyke reduce the flood hazard, hence, reducing the number of flooded houses. Coastal measures are not often considered in Sint Maarten as there is a consensus that the measures may reduce the beauty of the beaches, hurting the tourism economy. However, as shown in the modelling scenarios, these measures are important to reduce the flood hazard unless all exposed buildings are demolished and a strict policy that prohibits any construction along the coast is implemented.

Therefore, given the model setup and scenario simulations, implementing hazard reduction measures as well as strict enforcement of the Building and Housing Ordinance have a more important effect to reduce the number of flooded houses. However, the results and analysis of the coupled model outputs are subject to the challenges and limitations of modelling. Models are abstractions of reality and they should not represent every feature of the system. Thus, assumptions are important elements of a model. In the coupled model we developed, we made assumptions to reduce the complexity of the models. We also made some assumptions merely because of lack of data. For example, had reliable data on the use of buildings in Sint Maarten been available, agent types such as businesses and public entities could have been represented in the model. Agents' behaviour such as their decision making is also simplified because of the limited data availability. For example, the influence of agent interactions on the decision to follow a policy can be incorporated in the ABM based on household survey data. Regarding the flood model, it only considers storm surges as sources of coastal flooding. Including wave actions and climate change impacts such as sea level rise scenarios may intensify the coastal flood hazard affecting more houses. In such a case, the significance of the Beach Policy could be higher.

Another limitation is that housing development is exogenously imposed. The locations of the urban expansion are predefined based on a master plan. Including or coupling an urban growth model that simulates multiple scenarios of urban growth may give a better insight into how human dynamics contributes to flood risk in Sint Maarten. In addition, empirical validation of the model results was a challenge because of the exploration of non-existing scenarios and a lack of data. For example, floods are generated using synthetic rainfall event series in which a rainfall event occurs only once in a given year. Hence, instead of focusing on reproducing a historical event, we emphasize the usefulness of the model by involving experts during the model conceptualization and parameter setting, and by consulting with them whether the results are realistic. We also analysed the model results based 20 replications for each parameter combination. Estimating the experimental error variance using a statistical measure such as the coefficient of variation of the outputs indicates that more than 20 replications are needed to better analyse the output. However, we select the number of replications mainly based on the practical constraints in the computational resources.

Lastly, further analysis such as global sensitivity analysis to look into interaction effects in the input parameters, using various rainfall event series to investigate whether the input data has an effect on the policy analysis, and more uncertainty analysis to see the effect of uncertainty propagation from the individual models to the coupled model results can be performed in the future.

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Appendix A. List of assumptions made to build the coupled ABM-flood model

To structure and conceptualize the Sint Maarten flood risk management case and develop the agent-based model, we have made the following assumptions. The reasons to make these assumptions are model simplification (i.e., to develop a less complicated model) and lack of data.

f) All buildings have the same function, i.e., they are residential houses.
g) Household agents are represented by the houses they live in; hence, they are static.
h) There is a one-to-one relationship between household agents and houses (i.e., a household owns only one house and vice versa).
i) Houses are geographically represented by a single point feature, which is the centroid of the house polygon. Houses are considered flooded if the point features intersect a flood extent map. This is a simplified way to compute impact. See Chen et al. (2016) that uses polygon features.
j) All household agents know about all the institutions.
k) If an agent decides to implement a measure or follow a policy, it implies that it has the financial resource to do so (for example, to elevate house or to upgrade the capacity of drainage channels).
l) One type of structural measure is implemented in a catchment only once.
m) Household agents do not implement hazard reduction measures. They only implement measures that reduce their vulnerability and exposure.
n) If there is a decision to implement a structural measure, it will be implemented at the same time step. Its effect is evaluated in the next flood event.
o) The government agent implements a structural measure only in one catchment per time step.
p) Structural measures are designed for floods of rainfall with 50yr recurrence interval.
q) Structural measures are implemented only after a flood event.
r) The average lot size of a new house is 200 m2. Hence, the average increase in CN value of a catchment for every new house built is 0.1. This does not consider other factors such as slope.
s) The imperviousness of catchments is adjusted based only on the number of new houses built. We do not consider the expansion of roads, sidewalks and parking lots.
t) A rainfall with a recurrence interval of 5yr is the minimum threshold that causes flooding. A rainfall magnitude below the 5yr recurrence interval does not result in flooding.
u) Drainage channels in MIKE11 have the same roughness coefficient at every time step and in all the simulations (i.e., no blockage or special maintenance or cleaning is assumed).
v) A maximum of one flood event occurs per time step.
w) Rainfall is uniformly imposed on the study domain over the specified time period.
x) No climate change impact considered. Design rainfall intensities and sea level are the same throughout the simulation period.
y) MIKE21 is run with a hurricane-induced storm surge level of 0.5 m. This value does not change over time, and wave actions are not included.
z) In the coupled model, flooding occurs after agent dynamics.
aa) A house is considered to be flooded if the flood depth is greater than 5 cm assuming that all houses have floor elevation of at least 5 cm.
bb) Only new houses apply measures such as elevated floors.
cc) Effect of policies and their implementations is evaluated based on the number of houses flooded. We neither considered other assets (e.g., flooded cars, boats and yachts) nor other impact metrics such as damages and business interruption losses in monetary values.

References

Abebe, Y.A., Ghorbani, A., Nikolic, I., Vojinovic, Z., Sanchez, A., 2019. A coupled flood-agent-institution modelling (CLAIM) framework for urban flood risk management. Environ. Model. Softw 111, 483–492. https://doi.org/10.1016/j.envsoft.2018.10.015.

Aerts, J.C.J.H., Botzen, W.J., Clarke, K.C., Cutter, S.L., Hall, J.W., Merz, B., Michel-Kerjan, E., Mysiak, J., Surminski, S., Kunreuther, H., 2018. Integrating human behaviour dynamics into flood disaster risk assessment. Nat. Clim. Chang. 8, 193–199. https://doi.org/10.1038/s41558-018-0085-1.

Chen, A.S., Hammond, M.J., Djordjević, S., Butler, D., Khan, D.M., Veerbeek, W., 2016. From hazard to impact: flood damage assessment tools for mega cities. Nat. Hazards 82, 857–890. https://doi.org/10.1007/s11069-016-2223-2.

Crawford, S.E.S., Ostrom, E., 1995. A grammar of institutions. Am. Pol. Sci. Rev. 89, 582–600. https://doi.org/10.2307/2082975.

DHI, 2016. MIKE11: A Modelling System for Rivers and Channels - Reference Manual. MIKE Powered by DHI, Hørsholm, Denmark.

DHI, 2016. MIKE FLOOD: 1D-2D User Manual. MIKE Powered by DHI, Hørsholm, Denmark.

DRRC, 2011. Caribbean Implementation of the Hyogo Framework for Action: Mid-term Review. Caribbean Risk Management Initiative - UNDP Cuba, Disaster Risk Reduction Centre. University of the West Indies, Kingston, Jamaica.

Dubbelboer, J., Nikolic, I., Jenkins, K., Hall, J., 2017. An agent-based model of flood risk and insurance. J. Artif. Soc. Soc. Simul. 20, 6. https://doi.org/10.18564/jasss.3135.

Fonoberova, M., Fonoberov, V.A., Mezić, I., 2013. Global sensitivity/uncertainty analysis for agent-based models. Reliab. Eng. Syst. Saf. 118, 8–17. https://doi.org/10.1016/j.ress.2013.04.004.

Fraser, A., 2016. Risk root cause analysis paper for PEARL (preparing for extreme and Rare events in coastaL regions project): St Maarten, Dutch caribbean. In: Contested Development Working Paper Series. Department of Geography, King's College London (No. Paper #74).

Fraser, A., Paterson, S., Pelling, M., 2016. Developing frameworks to understand disaster causation: from forensic disaster investigation to risk root cause analysis. J. Extreme Events 03, 1650008. https://doi.org/10.1142/S2345737616500081.

Ghorbani, A., Bots, P., Dignum, V., Dijkema, G., 2013. MAIA: a framework for developing agent-based social simulations. J. Artif. Soc. Soc. Simul. 16, 9. https://doi.org/10.18564/jasss.2166.

IPCC, 2014a. Summary for policymakers. In: Field, C.B., Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1–32.

IPCC, 2014b. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 688.

Lawrence, M.B., Avila, L.A., Beven, J.L., Franklin, J.L., Guiney, J.L., Pasch, R.J., 2001. Atlantic hurricane Season of 1999. Mon. Weather Rev. 129, 3057–3084. https://doi.org/10.1175/1520-0493(2001)129<3057:AHSO>2.0.CO;2.

Lawrence, M.B., Mayfield, B.M., Avila, L.A., Pasch, R.J., Rappaport, E.N., 1998. Atlantic hurricane Season of 1995. Mon. Weather Rev 126, 1124–1151. https://doi.org/10.

1175/1520-0493(1998)126 < 1124:AHSO > 2.0.CO;2.

Ligmann-Zielinska, A., Kramer, D.B., Spence Cheruvelil, K., Soranno, P.A., 2014. Using uncertainty and sensitivity analyses in Socioecological agent-based models to improve their analytical performance and policy relevance. PLoS One 9. https://doi.org/10.1371/journal.pone.0109779.

Lorscheid, I., Heine, B.-O., Meyer, M., 2012. Opening the 'black box' of simulations: increased transparency and effective communication through the systematic design of experiments. Comput. Math. Organ. Theor. 18, 22–62. https://doi.org/10.1007/s10588-011-9097-3.

MDC, 2015. Hurricanes and Tropical Storms in the Dutch Caribbean. Meteorological Department Curaçao, Willemstad, Curaçao.

Mycoo, M., Donovan, M.G., 2017. A Blue Urban Agenda: Adapting to Climate Change in the Coastal Cities of Caribbean and Pacific Small Island Developing States. Inter-American Development Bank, Washington DC, USA.

North, M.J., Collier, N.T., Ozik, J., Tatara, E.R., Macal, C.M., Bragen, M., Sydelko, P., 2013. Complex adaptive systems modeling with Repast Simphony. Complex Adapt. Syst. Model. 1, 3. https://doi.org/10.1186/2194-3206-1-3.

Railsback, S.F., Grimm, V., 2012. Agent-Based and Individual-Based Modeling: A Practical Introduction. Princeton University Press, Princeton, New Jersey, USA.

Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., Tarantola, S., 2008. Global Sensitivity Analysis: the Primer. John Wiley & Sons, Chichester, England.

Sorg, L., Medina, N., Feldmeyer, D., Sanchez, A., Vojinovic, Z., Birkmann, J., Marchese, A., 2018. Capturing the multifaceted phenomena of socioeconomic vulnerability. Nat. Hazards 92, 257–282. https://doi.org/10.1007/s11069-018-3207-1.

STAT, 2017. Statistical Yearbook 2017. Department of Statistics Sint Maarten, Philipsburg, Sint Maarten.

ten Broeke, G., van Voorn, G., Ligtenberg, A., 2016. Which sensitivity analysis method should I use for My agent-based model? J. Artif. Soc. Soc. Simul. 19, 5. https://doi.org/10.18564/jasss.2857.

Tonn, G.L., Guikema, S.D., 2017. An agent-based model of evolving community flood risk. Risk Anal. 38, 1258–1278. https://doi.org/10.1111/risa.12939.

UN General Assembly, 1994. Report of Global Conference on the Sustainable Development of Small Island Developing States (Barbados Programme of Action) (No. A/CONF.167/9. Bridgetown, Barbados.

Vojinovic, Z., 2015. Flood Risk: the Holistic Perspective - from Integrated to Interactive Planning for Flood Resilience. IWA Publishing, London, UK.

Vojinovic, Z., Abebe, Y.A., Ranasinghe, R., Vacher, A., Martens, P., Mandl, D.J., Frye, S.W., van Ettinger, E., de Zeeuw, R., 2013. A machine learning approach for estimation of shallow water depths from optical satellite images and sonar measurements. J. Hydroinf. 15, 1408–1424. https://doi.org/10.2166/hydro.2013.234.

Vojinovic, Z., Seyoum, S.D., Mwalwaka, J.M., Price, R.K., 2011. Effects of model schematisation, geometry and parameter values on urban flood modelling. Water Sci. Technol. J. Int. Assoc. Water Pollut. Res. 63, 462–467. https://doi.org/10.2166/wst.2011.244.

Vojinovic, Z., van Teeffelen, J., 2007. An integrated stormwater management approach for small islands in tropical climates. Urban Water J. 4, 211–231. https://doi.org/10.1080/15730620701464190.