Selection and Enhancement of CAS Tools for NBS Policy Formulation

D1.6

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Abstract (for dissemination, 100 words)	Deliverable 1.6 report provides a review and description on Selection and Enhancement of CAS Tools for NBS Policy Formulation. It provides a review of complex adaptive systems, definition and applications. It also describes different methods for coupled sociotechnical systems and natural systems. One such a method is agent-based modelling and this deliverable presents an overview of tools and application of ABMs in the water domain. It also reviews different frameworks to integrate different modelling approaches to aid policy evaluation in regard to nature-based solutions. The report includes the description and application of the CLAIM framework and address the possibilities to enhance the framework to include NBS in the modelling chain and how to address implementation policies.
Keywords	Complex adaptive systems, CHANS, Agent based models, coupled sociotechnical and natural systems.

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Executive Summary

RECONECT will build upon the Complex Adaptive Systems – CAS (*complex system involves adaptation via learning or evolution where adaptation is the improvement of components of the system over time in relation to the environment)* related work developed and tested during the EC-FP7 funded PEARL project and will further enhance its suitability for Nature based solutions (NBS) applications. Going beyond the state-of-the-art, RECONECT will investigate the possibilities for coupling CAS models with other kinds of models (e.g., hydrodynamic, economic, etc.) that may provide advantages when compared with straightforward applications of CAS models. Therefore, this deliverable aims at reviewing different approaches and frameworks that use CAS to assess risk and its integration with other modelling approaches and tools in the scientific literature. It also aims at identifying and selecting a CAS tool that can support NBS policy formulation and testing.

This report summarizes the coupled flood-agent-institution modelling (CLAIM) framework which has been developed in the framework of the PEARL project and RECONECT. The CLAIM framework and its application has been tested in two case studies (Saint Maarten and Hamburg) that are part of RECONECT. The report also presents perspectives on how to enhance the CLAIM framework to include NBS and its assessment to aid decision making, visualization of results to engage stakeholders and ultimately aid decision making and policy changes.

Going beyond the state-of-the-art, RECONECT investigates the possibilities for coupling CAS models with other kinds of models (e.g., hydrodynamic, economic, etc.) that may provide advantages when compared with straightforward applications of CAS models. RECONECT is paying attention to the use of CAS and its integration with other models for NBS assessment. The model integration aims at exploring the formulation of NBS policies and assess their changes and implications in time (evolution).

This report can benefit practitioners, researchers and decision makers interested in the development and application of CAS - complex adaptive systems for NBS policy formulation and analysis. In particular coupled sociotechnical systems and natural systems.

The deliverable report presents and describes different tools for complex adaptative systems (CAS) and how they were used to aid decision making in the water domain (water management, land use change, flood risk, socio-technical systems, etc). The report contains a review of different approaches and frameworks that use CAS to assess risk and its integration with other modelling approaches and tools. The review of the state of art methodologies highlights the need to address the interlinkages between different sub-systems (institutions, physical infrastructure, people's behaviour, etc). The understanding of those interlinkages can help to reveal the influence of policy making and the propagation of effects (i.e. impacts of the policy) in other components or parts of the system. As part of the review process, it was found that there are not many CAS model applications developed for assessing NBS implementation and its effects or impacts in other subsystems (i.e nature, drainage infrastructure, etc). This is also true for the case of frameworks to integrate ABMs (Agent Based Models) with other models to explicitly assess benefits (i.e. added value to properties, air quality, enhancing habitats and biodiversity, etc). Also, in our review we found that there is hardly any large-scale ABM of CHANS (Coupled human and natural systems) developed or applied in the real world and this is an indication of the complexity of the task, data requirements and computational capacity constraints among other issues.

RECONECT would like to look at the resulting consequences of applying policies over decades of interactions between several interdependent systems. Therefore, the report recommends the use the CLAIM framework to include tools for NBS selection and modelling. The integration with other models from different domains could for example reflect the various types of agents present in the CLAIM framework and their respective means of actuation e.g. for institutions it could be different taxes, for urban planning agents, different surfaces of non-permeable pavement allowed in one area, etc. The added value resides mainly in the integration of the multi-disciplinary aspects of the problem i.e. combining together rough estimations of ecosystem diversity, return of investment, flood damages, and socio-economic indicators that just give “order of magnitude” type of results

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1 Introduction

- Deliverable 1.6: Report on the selection and enhancement of Complex Adaptive Systems (CAS) tools to support governance and policy formulation for NBS
- Task 1.6: Selection and enhancement of Complex Adaptive Systems (CAS) tools to support governance and policy formulation. RECONECT will build upon the CAS related work developed and tested in PEARL project and will further enhance its suitability for NBS applications. Going beyond the state-of-the-art, RECONECT will investigate the possibilities for coupling CAS models with other kinds of models (e.g., hydrodynamic, economic, etc.) that may provide advantages when compared with straightforward applications of CAS models.

1.1 Concept underpinning RECONECT

RECONECT adopts the *holistic ecosystem-based concept* which is based on the premise that our ability to adapt to extreme hydro-meteorological events in a sustainable way depends on the co-evolutionary nonlinear interaction between the ever changing social, economic and cultural requirements and technical developments (which combine engineering measures and nature-based solutions) on one side and natural processes on the other. This realisation is crucial to RECONECT. It draws from the understandings brought by *complexity theory* and, as such, it extends the analysis beyond the direct objects or actors of concern (land planning and management practices, social and cultural acceptance, financing mechanisms and engineering solutions or nature-base solutions (NBS) for example), to include the relationships between them. It goes beyond the traditional view which examines input-output relationships to emphasise the importance of interactions and interdependences between different processes and actors. It also fits well with fundamental principles of ecological or ecosystems way of thinking (e.g. Tansley, 1935; Lindeman, 1942; Odum, 1953; Costanza et al., 1997).

The holistic ecosystem-based concept adopted in RECONECT is in response to a very real practical challenge that has long constrained management of extreme hydro-meteorological events, offering opportunities for a meaningful exploration of the contribution of trans-disciplinary approach. It is through the holistic ecosystem-based lens that we can better understand how the relationships between sociotechnical activities and the nature can help transformation towards sustainability where the innovation of NBS may lie.

Based on the holistic ecosystem-based concept described above the holistic ecosystem-based framework will be developed and implemented. The framework will also build upon several closely related concepts including the ecosystems approach, ecosystem-based adaptation and mitigation, green and blue infrastructure, and ecosystem services (EC, 2013; EC, 2015). It takes a *systems* perspective to evaluate potential and impacts of large-scale NBS for enhancement of ecosystems services for different climate conditions, water domains (e.g., river basins, lakes and coastal systems), environmental situations and socio-cultural contexts. Drawing on insights from systems thinking and solution-oriented transdisciplinary research, the framework will focus on those properties of the system where a small shift, which can be potentially intractable, can lead to fundamental changes, which can be potentially highly influential, in the system as a whole. Hence, the following three system properties will be addressed within the RECONECT holistic ecosystem-based framework (Figure 1):

a) interactions in relations to hydro-meteorological events and sociotechnical activities, i.e., system interactions – this will be achieved through systemic assessments of changes in the system's outputs (i.e., ability to achieve multi-benefits from NBS) using coupled complex adaptive system models (e.g., agent-based models) and hydrological/hydrodynamic models. The purpose of this is to analyse the effects of different institutional policies, cultural contexts and land management practices on the effectiveness of NBS under different circumstances and conditions (mainly addressed in WPs 1, 2).

b) interactions in relations to sociotechnical activities (e.g., market demand dynamics, land planning, policy, etc.), i.e., part of the system that relates to "sociotechnical interdependencies" – this will be achieved through the analysis of interactions between drivers for demand and supply for NBS, their replication and upscaling (mainly addressed in WPs 1, 4, 5); and

c) innovative comprehensive evaluation of NBS in relation to three categories of challenges (i.e., water, nature and people) across spatial and temporal dimensions (i.e., part of the system that relates to "Innovative NBS") (mainly addressed in WPs 1,

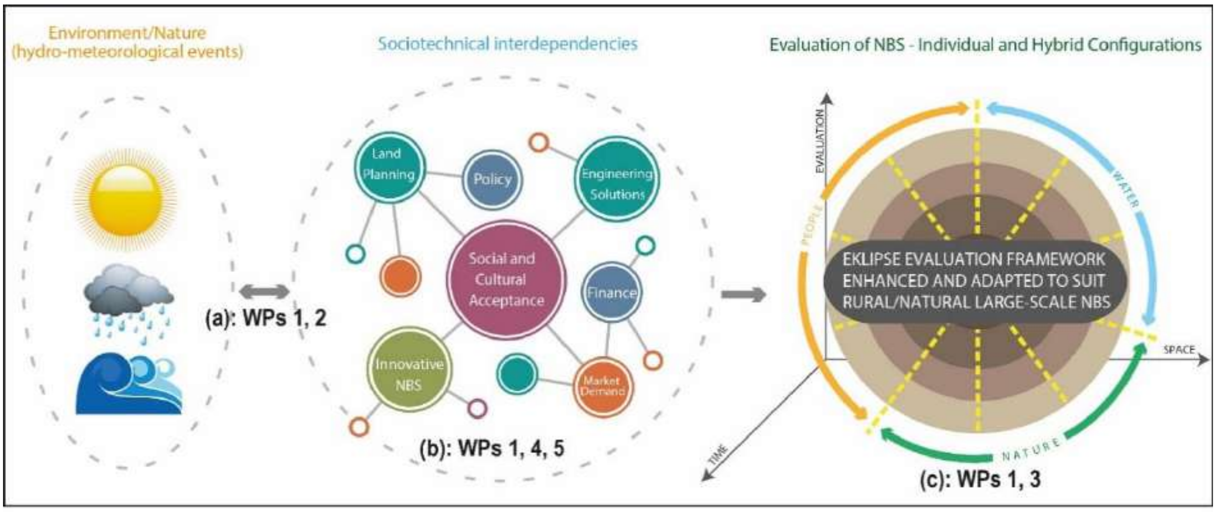

Figure 1. RECONECT holistic ecosystem-based framework – system perspective. Three system properties (a), (b) and (c) will be addressed through WPs1 to 5.

The spatial dimension of RECONECT builds from the "Dutch Room for the River Programme"[1] concept, which aims at providing the river more space to be able to manage higher water levels, and it aims to expand it for application in coastal areas. In addition to the spatial (or space) dimension, the RECONECT holistic ecosystem-based framework also incorporates the temporal (or time) dimension into the analysis which is needed for many considerations (e.g., real-time applications for better management of peak flows during flood events, increasing time for undertaking actions in areas at risk, etc., long-term planning applications, uncertainty analysis and flexibility - allowing mid-term adjustments and modifications of structure (see for example van Buuren et al., 2013; Woodward et al., 2014); keeping investment or implementation options open for future adaptation (see for example Haasnoot et al., 2012; Zhang and Babovic, 2011); and postponing adaptation until the time when the cost of further delay would be more than the benefits (see for example Felgenhauer and Webster, 2013).

[1] https://www.ruimtevoorderivier.nl/english/

RECONECT's holistic ecosystem-based framework will expand the existing EKLIPSE[2] impact evaluation framework for evaluation of large scale NBS in rural and natural areas. This will be done by grouping challenges into three categories (i.e., water, nature and people) and evaluating them in relation to spatial and temporal dimensions for the cases with and without consideration and deployment of NBS. Spatial dimension will concern evaluation in relation to the space required for ecosystem regeneration and hydro-meteorological risk reduction. Similarly, the temporal dimension will concern evaluation in relation to time required for ecosystem regeneration and hydro-meteorological risk reduction.

RECONECT also takes into consideration EU policies and it goes beyond traditional approaches which is one of the innovations in RECONECT (see also Figure 1). The framework will build upon several closely related concepts including the ecosystems approach, ecosystem-based adaptation and mitigation, green and blue infrastructure and ecosystem services (EC, 2013; EC, 2014; EC, 2015; EC, 2016). It takes a systems perspective to evaluate potential and impacts of large-scale NBS for enhancement of ecosystems services for different climate conditions, water domains (e.g., river basins, lakes and coastal systems), environmental situations and socio-cultural contexts. The holistic ecosystem-based framework is at the core of RECONECT, which looks at the system as a whole, overcoming the traditional piecemeal approach. The holistic approach goes even beyond the integrated approach by focusing on interdependences and interrelatedness between different dimensions (social, technical or natural), rather than on their integration into a "whole", which is of the essence of the integrated approach.

1.2 Outline

Given the holistic system perspective endorsed in RECONECT, the rest of the deliverable is structured as follows:

Section 2 introduces the system perspective. It defines complex adaptive systems and lists their characteristics. Coupled complex systems such as socio-technical systems and human-water systems are also introduced. The section characterise policies from the systems perspective. Further, NBS and NBS policies are described from a complex adaptive system perspective.

Section 3 further elaborates on coupled human and natural systems (or socio-ecological systems). It provides applications of the system perspective in such coupled systems. In addition, it provides different methods employed to model coupled human and natural systems.

Section 4 focuses on agent-based modelling paradigm as it is a method that will be used in RECONECT. The section provides agent-based model definition, development, benefits and limitations and applications in coupled human and natural systems.

Section 5 discusses CAS modelling applications, especially how agent-based models are coupled with physically-based models to study the interaction within and between the human and natural subsystems.

Finally, conclusion and outlook is provided in Section 6.

[2] http://www.eklipse-mechanism.eu/de/home

2 Complex adaptive system perspective

2.1 Complex Adaptive Systems

Complexity theory is a relatively new field that began in the mid-1980s at the Santa Fe Institute in New Mexico (Miller and Page, 2007). The definition of complex systems theory must start with the definitions of the component terms. A *system* is a set of “interacting and interrelated elements that act as a whole, where some pattern or order is to be discerned” (Nikolic and Kasmire, 2013). According to Chan (2001), something is *complex* if it “results from the inter-relationship, inter-action and inter-connectivity of elements within a system and between a system and its environment”. Mitchell (2009, p. 13) defined complex system as “a system in which large networks of components with no central control and simple rules of operation give rise to complex collective behaviour that creates patterns and sophisticated information processing”. The complex behaviour that arise from the interaction of individual components is called an *emergent behaviour*. The emergent behaviour of the system cannot be simply inferred from the behaviour of its components.

Hence, to understand the behaviour of a complex system, one must understand not only the behaviour of its components but how those components act together to form the behaviour of the whole (Bar-Yam, 1997). For example, cities are regarded as a complex systems (Bettencourt, 2015). They are composed of people who are diverse in their wealth, race, ethnicity, profession, religion, etc. They are also different in their economic capabilities (e.g., different types of businesses), and spatially (e.g., rich/poor neighbourhoods, residential/commercial neighbourhoods). Cities are interconnected both physically and socially. Policies such as urban planning rules shape how the components behave and how the city evolves (i.e., grow or shrink).

Complex systems can be categorised as *complex physical systems* (CPS) and *complex adaptive systems* (CAS) (Holland, 2014). CPS are systems composed of components that behave according to governing physical laws such as Newton’s laws of gravity. In such systems, the laws of physics are well understood and the components are the same. These systems are mainly described using the partial differential equations, and appear deterministic. However, due to complex interactions or initial conditions, these systems, can be chaotic and nonlinear. For example, the atmospheric system is a CPS. The atmosphere is composed of gases, moisture, temperature and pressure among others, and these entities are governed by mass and momentum laws, gas laws, friction laws, thermodynamic laws and gravity law. Gas molecules interact and influence each other in the atmosphere. Interactions in the atmosphere are so non-linear that tiny perturbation brings large effects. This behaviour is famously known as the *butterfly effect* after the seminal talk of the American meteorologist Edward Lorentz in 1972. The interaction of gas molecules and other elements of the atmosphere leads to macro-level emergent phenomenon such as hurricanes and tornados. Other examples and illustrations of how simple programs produce complex behaviours is given by Wolfram (2002).

On the other hand, if the complex system involves adaptation via learning or evolution (Mitchell, 2009), then it is called complex adaptive system (CAS). Adaptation is the improvement of components of a system over time in relation to the environment which can be physical, social, technical and cultural environment (Nikolic and Kasmire, 2013). CAS have the following common properties (Bar-Yam, 1997; Behdani, 2012; Boccara, 2004; Holland, 2014; Mitchell, 2009; Nikolic and Kasmire, 2013; Rand, 2015):

- Simple and heterogeneous components or agents that interact simultaneously – the components are considered as simple relative to the whole system. The interactions occurred across time, space and scale
- Nonlinear interaction among components – there is no proportionality and no simple causality between the magnitudes of stimuli and responses, and system behaviour is not additive. Small changes in the system components can have a profound effect.
- Information processing – perceive, communicate, process, use and produce information
- Self-similarity or fractal-like behaviour both in structure and behaviour – as CAS are nested, higher system levels are comprised of smaller ones.
- No central control – the system organises itself in a decentralised way. With no imposition of structure from a central or outside authority, the system develops its own structure.
- Emergent behaviour – collective outcome of interactions or networks of agents which is understood at system level and not in individual basis. As interactions in CAS are non-linear, the aggregate properties are not attained by summation of the properties of components. As a result, the whole is more than the sum of the parts.
- Adaptation – the capacity to evolve over time based on interactions, feedbacks and selection pressures, and agents learn to survive or excel in their environment. Adaptation is not a simple random variation.

The main advantage of complex systems thinking is that its ability to dynamically link one part of a system, for example, biophysical part to another part of the same system, for example human part. 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). Complex systems thinking also help to fertilize cross-disciplinary integration (Bar-Yam, 1997). This can be achieved by developing tools for addressing the complexity of subsystem domains which can finally be adopted for more general use by recognizing their universal applicability.

Examples of CAS include ant colonies (Gordon, 2002); immune system (Ahmed and Hashish, 2006); the brain, economies, the World Wide Web (Mitchell, 2009); cities (Bettencourt, 2015); traffic, crowed movement, the spread and control of crime (Ball, 2012); ecosystems and the biosphere (Levin, 1998). Integrated or coupled systems are also categorised as CAS, and recent researches examined such systems using CAS concepts and methods. Below, we briefly describe two types of coupled CAS: socio-technical systems and human-water systems. Another broader coupled CAS, coupled human and natural systems, will be discussed in Section 3.

Socio-technical systems

In broader systems such as coupled human and natural systems, technological processes are considered as exogenous factors (Smith and Stirling, 2010). However, a class of integrated systems called socio-technical systems (STS) consider technical artefacts as an integral part of the system. STS are systems composed of two interconnected subsystems: a social system of actors and a physical system of technical artefacts (Dijkema et al., 2013; Kroes et al., 2006).

The social subsystem is composed of human agents such as managers and users of the technology or technical artefacts, and social institutions including the structure and “rules” of interaction. The technical subsystem encompasses technology, technical artefacts, and processes, which are set of activities. The institutions which define agents interactions among themselves and with the technical subsystem are embedded within complex social structures such as norms, rules, culture, organisational goals, policies and economic, legal, political and environmental elements (Ghorbani, 2013; Qureshi, 2007). The components of the social and technical subsystem interact in all directions as shown in Figure 2. Examples of STS include supply chain (Behdani, 2012), civil aviation such as aircraft maintenance (Pettersen et al., 2010), wastewater treatment plant (Panebianco and Pahl-Wostl, 2006), energy systems (Bolton and Foxon, 2015; Markard et al., 2016), transport system (Watson, 2012), and mobile phone production, consumption and recycling (Bollinger et al., 2013).

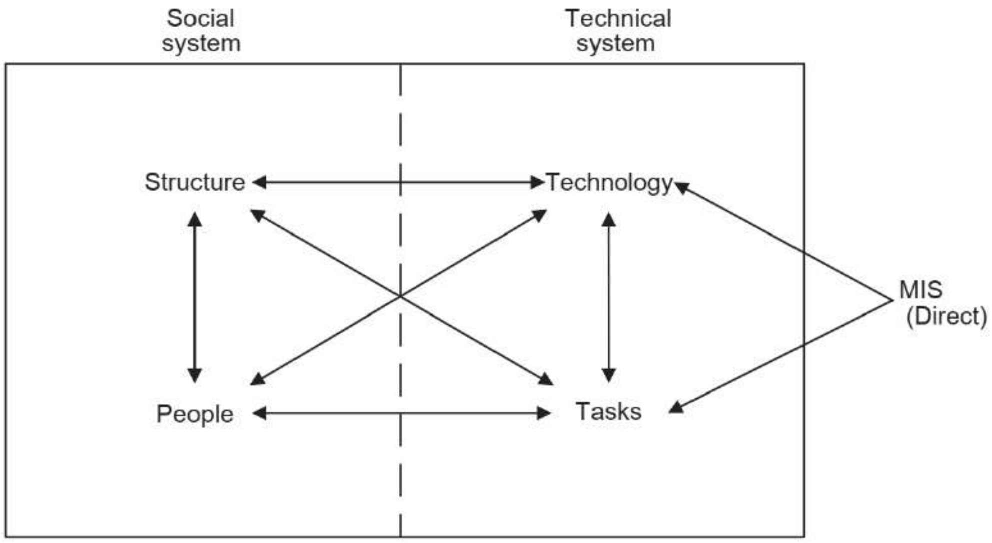

Figure 2. Social and technical subsystem components and their interactions (from Bostrom and Heinen 1977).

Human-water systems

CAS and STS are broader systems that cover wider aspects of natural resources and technical artefacts, respectively. For water managers and hydrologists, a narrower system definition that studies human-water interaction is relevant, and such system is called coupled human-water system. As in the other coupled systems, the human (or social) subsystem is composed of human actors, and aspects such as individual and collective decision-making mechanisms and organisational structures (Blair and Buytaert, 2016). The water subsystem includes processes in the water cycle including the physical rules and water’s cultural and religious significance (ibid). For example, Figure 3 illustrates interactions between surface water, groundwater and residents, and the effect on human health and regional economy. Studies of human-water interaction include irrigation systems (Wescoat et al., 2018), water resources management (Essenfelder et al., 2018), domestic water demand and use (Jepson and Brown, 2014; Koutiva and Makropoulos, 2016), flood risk management (Di Baldassarre et al., 2013; Viero et al., 2019), and water stress conditions (Kuil et al., 2016).

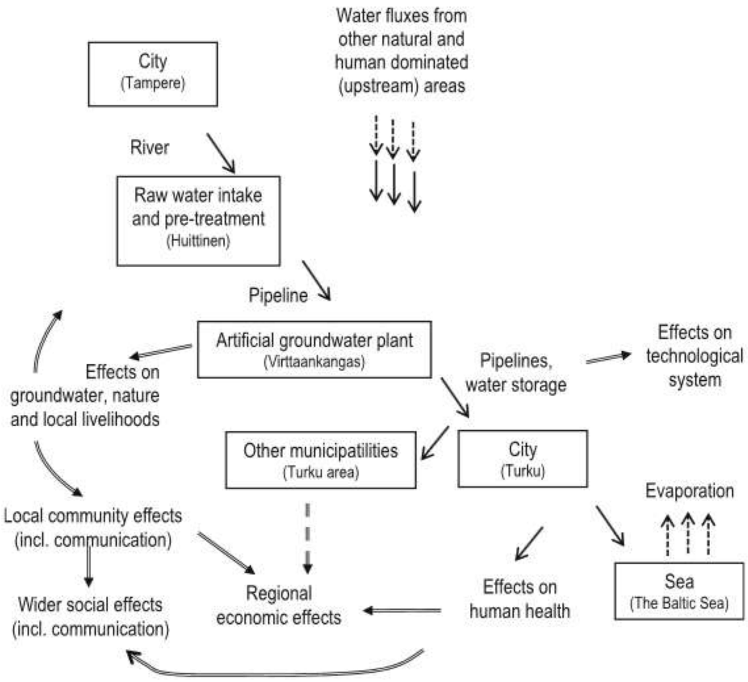

Figure 3. Hydrosocial cycle showing surface water and groundwater interactions with human health and the economy in the cities of Turku and Tampere in Finland (from Lyytimäki and Assmuth, 2015).

2.2 Policies as CAS

The term *policy* can be defined in multiple ways as there is no unified definition given by experts of different background. For example, a policy can be defined as "a statement by government of what it intends to do, such as a law, regulation, ruling, decision, order, or a combination of these. The lack of such statements may also be an implicit statement of policy" (Birkland, 2016, p. 9). This definition clearly stated that the government is the policy determiner. It classified policies as *explicit*, when the statement is clearly written in a document, and *implicit*, when there is lack of definitive statement showing the government chooses not to do. Another definition given by Schneider and Ingram is that "policies are revealed through texts, practices, symbols, and discourses that define and deliver values including goods and services as well as regulations, income, status, and other positively or negatively valued attributes" (Schneider and Ingram, 1997, p. 2). On the other hand, this definition does not specify who determines the policy and expands notions such as values.

Some of the attributes of policies are (Birkland, 2016; Schneider and Ingram, 1997):

- Policies are public, i.e., they are formulated considering the public interest. Hence, policies are also interpreted and implemented by the public.
- Though they are formulated in response to public needs and desires, policies are made by governments.
- Policies have consequences on several levels as they serve several different purposes and interests at the same time.
- Policies evolve, through the addition of new statements, amendments to old ones and through the change in interpretations by the public

Policymaking process includes a number of activities such as problem identification, agenda setting, policy formulation, policy legitimation, policy implementation and policy evaluation

(Dye, 2013). The process is not a linear one, but activities may occurred simultaneously and iteratively. These activities involve the participation of heterogeneous actors that can be individuals or entities, such as legislators, bureaucrats, think thanks, interest groups and members of the public (ibid). There is an interaction between the actors during the policy process across scale, time and space. Further, policies do not work with clear and linear cause and effects. Due to the interaction among the heterogeneous agents, policies should take into account multiple causalities and indirect effects (Furtado et al., 2015). A policy designed to solve one problem may have undesirable or other desirable effects on other issues (Reuter, 2009). The unexpected outcome of a policy have an emergent behaviour. Policies are also shaped by previous policies and environmental factors (Kay, 2006).

Hence, a policy system is regarded as a complex adaptive system with multiple, interconnected and interacting actors, non-linear behaviour both during formulation and its outcome, nested policy subsystems and evolving nature (see Kay, 2006; Furtado et al., 2015). As a result, analysing policies, for example, their formulation, implementation and evaluation, using complex system methods provide a valuable understanding of the underlying complexities of the system.

2.3 NBS Policies as CAS

The International Union for the Conservation of Nature (IUCN) defines nature-based solutions (NBS) as "actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al., 2016, p. 5). As shown in Figure 4, societal challenges addressed by the implementation of NBS include disaster risk, climate change, water security, human health, and social and economic developments. Implementing NBS involves multiple actors. For example, actors such as citizens, engineers, planners and consultants were involved during the revitalisation of the river bank and river valley Slepiotka in Katowice, Poland (Frantzeskaki, 2019).

Figure 4. NBS as an umbrella term for ecosystem-related approaches (from Cohen-Shacham et al., 2016, p. 11).

In most cases, NBS are designed considering multiple benefits. In the previous example, the river bank and valley restoration contribute to ecosystem restoration, flood protection (disaster mitigation) and recreation. Considering the above characteristics, NBS implementations can be seen as CAS. In addition, as NBS are multipurpose and they require multiple disciplinary expertise for their design. Therefore, systems thinking is a useful tool to understand NBS related challenges and their solutions (Keesstra et al., 2018). Nesshöver et al. (2017) also highlighted that framing NBS problems in relation to socio-ecological systems is essential to understand the multiple links within and between human and natural systems. CAS can also be used to explore and advance our understanding in terms of limiting factors or barriers and also opportunities for the implementation and upscaling of NBS. Which is important in order to facilitate favourable market conditions for policy implementation such as the European green deal.

3 Coupled Human and Natural System

3.1 Definition

Coupled human and natural systems (CHANS)[3] are "integrated systems in which people interact with natural components" (Liu et al., 2007a, p. 1513). In CHANS, the human subsystem is also called social subsystem while the natural subsystem can be identified as the environment, ecology, ecosystem or landscapes. Therefore, CHANS are also known as social-ecological systems (Ostrom, 2009; Schlüter et al., 2012), socio-ecological systems (Filatova et al., 2013), human-environmental systems (Harden, 2012) and human-landscape systems (Werner and McNamara, 2007).

Human actions affect biophysical systems and biophysical factors affect human well-being, which signifies the interconnected nature of the social (i.e., human) and ecological (i.e., biophysical) subsystems (Berkes 2011). For example, human activities such as construction of dams for hydropower generation are exerting increasing impacts on the environment by changing the land cover. That, in turn, may change the climate, which changes the frequency of extreme precipitation and extreme draught. The human-natural interactions occur at multiple scales. For example, spatially, it can be in a local, regional, continental and global scales through trades, environmental degradations and disasters (Liu et al., 2007b).

In addition, the component systems are composed of subsystems such as resource systems, resource units, users and governance systems that interact to produce outcomes at system level (Ostrom, 2009). As the subsystem interactions are strong, it is significant to study them as a coupled system (Werner and McNamara, 2007) through multidisciplinary efforts that address the multilevel whole system (Ostrom, 2009). Integrating human and natural systems through the CHANS perspective emphasizes on the complexity of the coupled system, including feedback, nonlinearity, heterogeneity, and time lags in the systems (Liu et al., 2007a).

Figure 5 shows the conceptualization of the development of global climate change as a CHANS, including system components, actions and interactions. Other areas of focus under these systems include bio-gas infrastructures (Verhoog et al., 2016), sustainable agriculture (Teschner et al., 2017), land degradation (Detsis et al., 2017), land use and land cover change (Drummond et al., 2012), recreational fisheries (Ziegler et al., 2017), coastal and marine systems (Glaser et al., 2012), rangeland management (Li and Li, 2012), and wildlife conservation (Carter, 2014). Flood risk management has also been studied under the CHANS paradigm, which will be elaborated in the next section.

[3] CHANS are also addressed as CHNS (coupled human-natural systems)

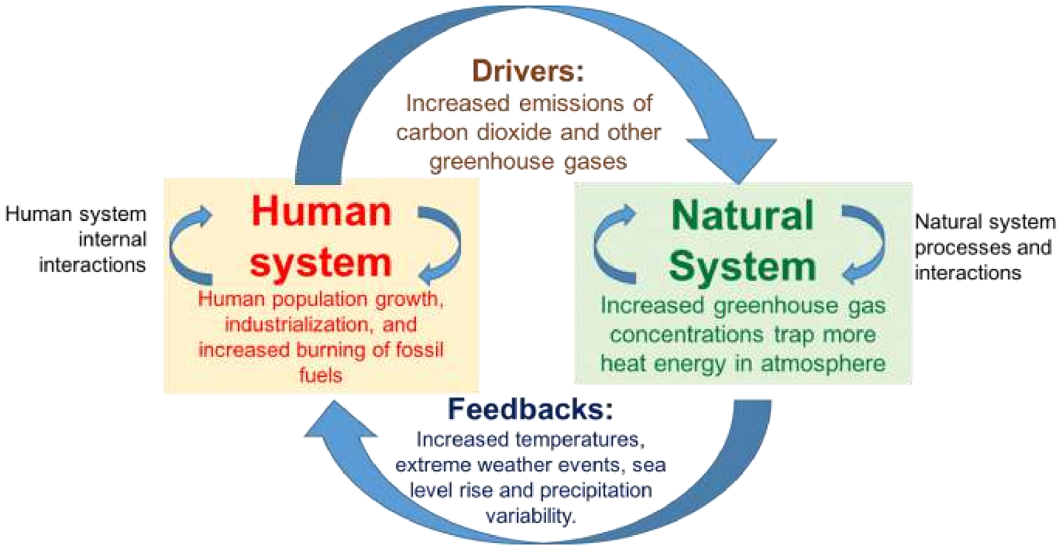

Figure 5. Components, actions and interactions of the development of global climate change as a CHANS (from Karsten et al., 2018).

In the work of An (2012), a review of decision models used in ABMs for modelling human decisions in CHANS was performed. Nine types of decision models were categorized including microeconomic models, space theory based models, psychosocial and cognitive models, institution-based models, experience- or preference-based decision models (rules of thumb), participatory agent-based modelling, empirical- or heuristic rules, evolutionary programming, and assumption and/or calibration-based rules. These models range from empirically based models to process-based modes and each type of models has its own strengths and weaknesses. The review suggested that more efforts should be invested in process-based models or mechanisms to better understand CHANS and the selection of decision models is better to follow the KISS rule ("keep it simple, stupid") and based on the suitability for the corresponding contexts. This work also advocates for the development of protocols for CHANS-oriented ABMs for better modelling of human decisions in CHANS.

3.2 NBS as CHANS

The benefits that humans gain from the natural environment and from properly-functioning ecosystems are called *ecosystem services* (Wang et al., 2018). One of these services are regulating services including flood and natural hazard regulation (Millennium Ecosystem Assessment, 2005). As floodplains are CHANS, they exhibit interactions among social, ecological and hydrological systems (Moritz et al., 2016), studying the flood regulation services of ecosystems through the CHANS lens is vital to understand the complex interactions of humans and floodplains. To that end, NBS offers the human-ecological connections (Randrup et al., 2020) by providing the necessary regulating ecosystem services and benefits to the environment itself and to the human system too. However, the implementation of NBS as a complex socio-ecological system for flood risk management, including other benefits, is less studied and understood compared to their technical significance (Venkataramanan et al., 2020). Below, we will see some examples of studies that applied NBS as a means of flood risk management, and implemented as CHANS.

Brent et al. (2017) studied households' willingness to pay for distributed green infrastructures that could improve environmental services such as water security, stream health, recreational and amenity values in addition to flood risk reduction and urban heat island effect. Their research, which was based on household surveys, was conducted in Melbourne and Sydney, Australia. The results of the study showed that respondents valued the environmental benefits of local storm waters as significant and positive, especially towards reductions in flash flooding, reductions in water restrictions, improvements in stream health, and cooler summer temperatures. The results also showed that residents of the two cities value the environmental services associated with local flood management. Such studies are useful to inform decision-makers by providing quantitative arguments concerning the societal benefits of stormwater infrastructure investments.

Mayer et al. (2012) studied an approach that encourages landowners to mitigate impervious surfaces, such as roofs, on their properties by implementing green infrastructures. The study applied an economic incentive to place rain gardens and rain barrels onto private properties near Cincinnati, Ohio, USA. These main ecosystem services gained from the stormwater installations are flood protection and improving water quality problem posed by a combined sewer overflow infrastructure. Other benefits to the local residents include reduced nutrient loading due to water infiltration and increased biological productivity within stream networks. Mayer et al. argued that “given the complex social and economic dynamics that occur at this scale, implementation of green infrastructure requires just such a multi-disciplinary approach.” Hence, they monitored hydrological and ecological variables such as discharge, water quality, aquatic biota and ecosystem respiration. Regarding the social system, the measures were distributed to landowners via a reverse auction events. Two rounds of auctions in consecutive years resulted in an increase in implementation of the measures on private properties as residents were encouraged by free rain gardens and rain barrels. However, the measures had a small but statistically significant effect of decreasing stormwater quantity at neighbourhood scale.

Turner et al. (2016) examined NBSs, rain gardens, bioretention cells and rain barrels, installed on private properties for a regional stormwater management program in Parma, Ohio, USA. The study analysed “the socio-cultural factors that influence participation including resident’s self-reported landscaping behaviours, environmental knowledge and values, and attitudes and perceptions toward green infrastructure and stormwater management.” One of the findings of the result is that residents in the study area generally vary in environmental attitudes and perceptions toward stormwater management and green infrastructure. Only a quarter of the residents have a positive perception to the effectiveness of the measures at reducing runoff. Some even perceived the measures created problems such as collecting litter and attracting mosquitoes, and many would not install them in their properties. The study concludes that socio-cognitive factors such as attitudes are more important to residents’ adoption behaviour than environmental values. Further, in addition to providing incentives such as low cost or free installation of the NBSs, higher adoption rates of the measures can be achieved by increasing understanding of the subjective perceptions and attitudes of individuals towards the measures.

3.3 Modelling CHANS

Human-nature systems had been studied as one of the systems constrains or disturbs the other exogenously. “Social scientists have often focused on human interactions, minimizing the role of environmental context or perceiving environmental influences to be constant, whereas ecologists have traditionally focused on pristine environments in which humans are external and rarely dominant agents” (Liu et al., 2007b). However, the CHANS approach provides a means to integrate the two systems as one complex unit in which their interaction is characterised by feedbacks and co-evolutions.

The main advantage of studying NBS using the CAS perspective is its ability to dynamically link two different subsystems, i.e., the human subsystem and the natural subsystem[4], 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).

In the nested human-natural system, the human subsystem is a CAS by itself. Hence, it requires a careful selection of modelling methods to simulate heterogeneity and adaptation. One view of modelling complex systems is the reductionist hypothesis. The hypothesis is explained that with the right simplification, one will understand everything based on particle physics (Miller and Page, 2007). That means, knowledge is an applied physics. However, the fallacy of the hypothesis is that knowledge of the fundamentals of a particle physics may not be useful to reconstruct higher-level systems (ibid).

For example, the classical reductionist modelling methods such as 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, stationarity (Bankes, 2002) and tractability so that they can be solved mathematically (Gilbert and Terna, 2000; Railsback and Grimm, 2012). In addition, Holland argues that differential equations are more powerful to describe systems which can easily be approximated by linear techniques and systems that tend to reach equilibrium. It is also not easy to approximate an agent's behaviour using differential equations as the agent may have conditional actions that are governed by the rules of interaction. Further, Heckbert et al. (2010, p. 42), discussed that "statistical models are at a disadvantage when the subject of the model is not a homogenous population or when that population has coordinated or coherent interactions."

Hence, methods which capture a more "realistic" view of CAS shall be used, such as *exploratory computer-based models* (Holland, 2006). These are computer programs that are used to model processes including those with non-linear relationships (Gilbert and Terna, 2000). The emergent behaviour of the model that is described by computer programs is assessed by running the program multiple times and evaluate the effect of different input parameters. Such modelling process is called *computational modelling* or *computer simulation* (ibid). Computer-based models provide a mental laboratory in which thought experiments can be explored to define system-level possibilities (Holland, 2006). The unique insights gained regarding complex systems is that simulation models provide an improved understanding of the complexity as an emergent phenomenon (Cioffi-Revilla, 2014). The main purposes of simulation model are prediction, forecasting, management and decision-making, social learning and system understanding (Kelly et al, 2013).

According to Gilbert and Troitzsch (2005), developing a simulation model passes through certain steps. The first step is identifying a question or problem in a system, which will be the aim of the research under study. Then the system should be defined, including the model boundaries. Model parameters and initial conditions are set by carefully observing the system. While designing the model, assumptions should be made. As every model is a simplification of the actual system that is modelled, deciding what is included and what is left out is an

[4] The natural subsystem can also be referred to as the physical subsystem or ecological subsystem or environmental subsystem.

important consideration. Finally, the designed model is written into a computer program and the simulation is carried out by executing the programs. To make sure that the simulation output is useful, performing steps such as verification, validation, sensitivity analysis and uncertainty analysis are essential. Balci (1989) presented a more elaborated life cycle of a simulation study, which is composed of ten phases, as illustrated in Figure 6.

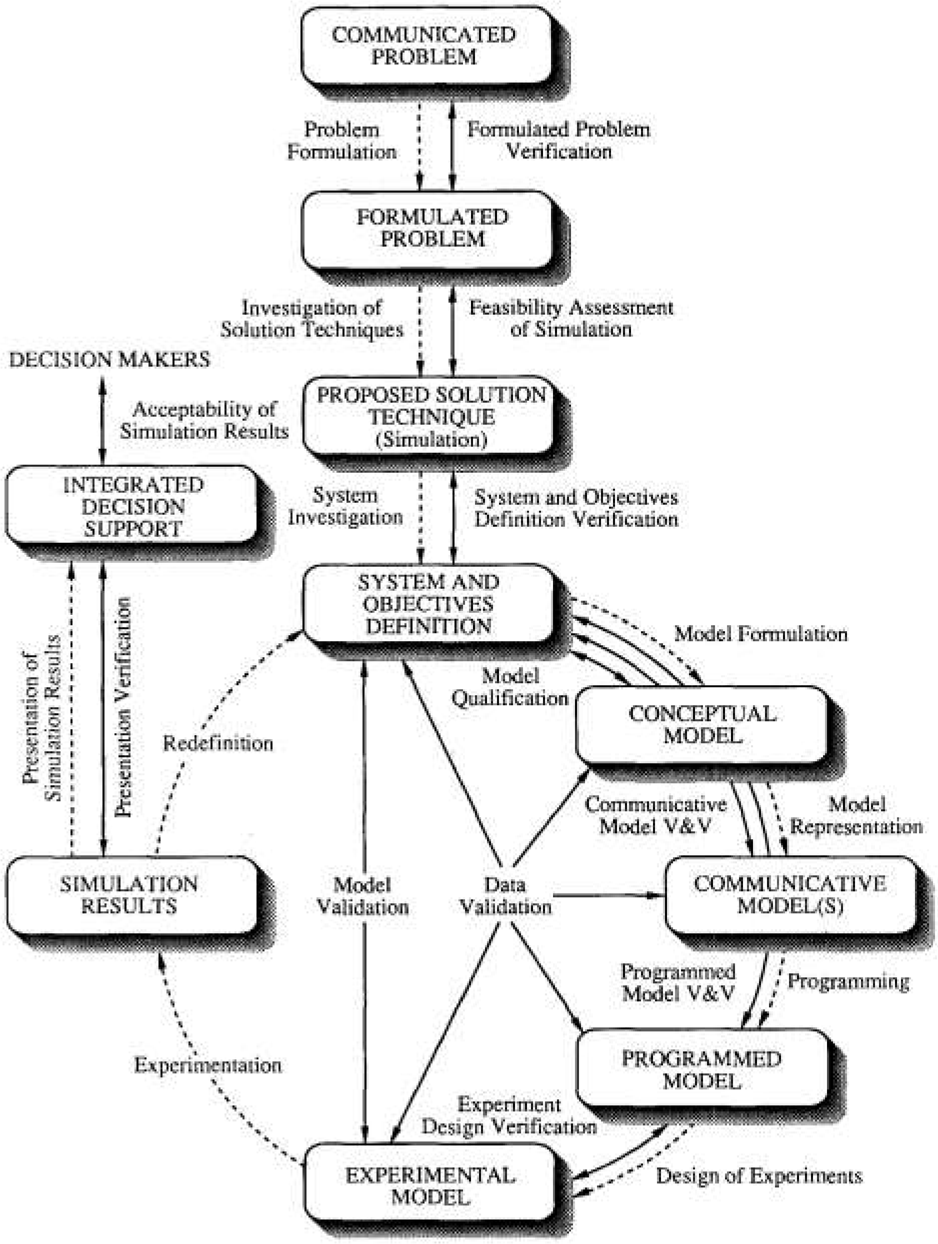

Figure 6. The life cycle of a simulation study (from Balci, 1989).

The main techniques available for building simulation models include system dynamics, microsimulation, queuing models, multilevel simulation, cellular automata and agent-based models (Gilbert and Troitzsch, 2005). However, considering the use of simulation models in CHANS or socio-/social-ecological systems (SES) or human-environmental systems (HES), the most common simulation models are system dynamics, cellular automata and agent-based models[5]. Below, we describe the techniques.

System dynamics (SD) is developed by Jay Forrester in the 1950s and 1960s (Forrester 2007). An SD simulation is “a variable-based computational model for analysing complex systems containing feedback and feedforward dependencies among variables and rates of change, often with high-dimensionality” (Cioffi-Revilla, 2014, p. 251). The philosophy of SD is formalising systems based on difference and differential equations, which is formulated when dynamic hypothesis of a system are converted into a “stocks and flows” representation (Kelly et al, 2013). The stocks and flows are the system state variables and the processes that influence change in the stock levels, respectively. Whereas, a dynamic hypothesis is “a conceptualisation of the causal relationships, feedback loops, delays, and decision rules that are thought to generate system behaviour” (Kelly et al, 2013, p. 164). SD model development uses a Causal Loop Diagram, which is a graphic representation of positive and negative feedbacks of a given variable (Cioffi-Revilla, 2014). The diagram is easy to learn and allow participation of experts in the modelling process.

SD simulations are suitable for policy modelling as it visualises causal relationships and providing the policy maker the access to policy levers (Gentile et al., 2015). They provide the capacity to model feedbacks, delays and non-linear effects as well as improving system understanding and fostering knowledge integration for modellers (Kelly et al, 2013). Some of the limitations of SD models include: limited treatment of space such as spatial aggregation (ibid), lack of exposing underlying micro-level (such as individuals) behaviours (Gentile et al., 2015), and lack of being adaptive as equations and feedbacks are structural (Heckbert et al., 2010).

An example of an SD model is the water and environmental management model presented in (Qin et al., 2011). The study employed SD as a platform to integrate socio-economic system, water infrastructure system and receiving water system in a rapidly urbanised catchment. Aspects considered in the socio-economic system are population growth, gross regional production and water demand and pollutants generated by residents and industries. Elements considered in the water infrastructure system are water supply in the catchment and the total effluent load from sewer and waste water treatment plants. The receiving water system considers rivers including transport, transformation and fate of pollutants in the rivers. The stock-flow diagram showing how the systems and their component are integrated is depicted in Figure 7. The study simulates the interaction between the three systems with the aim of evaluating different water management models and providing a better means of communication between decision makers.

[5] The search was done in Web of Science Core Collection for the years 1900-2020, for document types of “Article” OR “Book” OR “Book Chapter” OR “Proceedings Paper” OR “Review”, and documents written in English. No systematic filter was conducted. A search for “CHANS” OR “CHNS” OR “SES” OR “HES” AND “queuing model”, “multilevel simulation” and “microsimulation” resulted in 0, 3 and 3 documents.

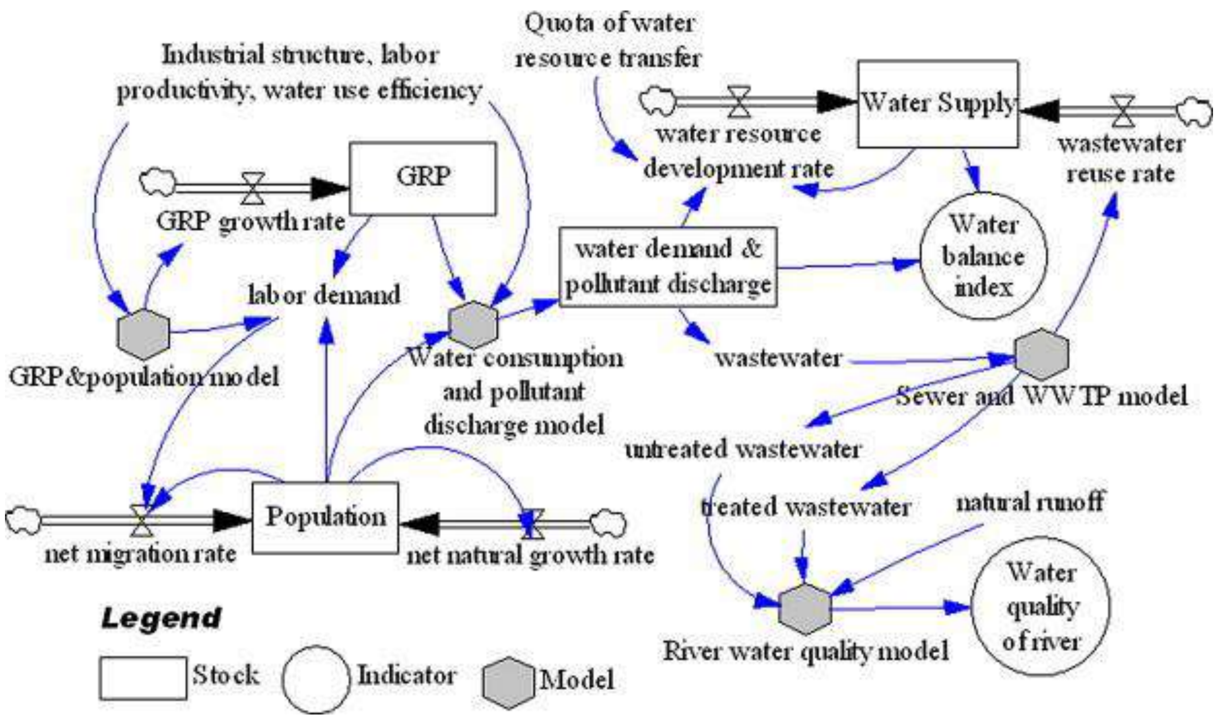

Figure 7. Stock-flow diagram of the system dynamic water and environmental management model (from Qin et al., 2011).

Cellular automata (CA) models are object oriented simulation models that use *cells* as elementary units to understand emergent complexity (Cioffi-Revilla, 2014). The cells interact in a two-dimensional grid-like landscape using some rules and change their states. CA are discrete spatio-temporal models which are capable of demonstrating complex behaviour and emergence in a system (Clarke, 2014). CA has the following elements: cells, neighbourhood surrounding a cell, a set of initial conditions and rules (ibid). Conventional CA models are characterised by discreteness (i.e., the model space is divided into cells and the time step has an integer unit), locality (i.e., cells interact only with immediate neighbouring cells), interaction topology (i.e., cell interactions are either with 4-cell von Neumann neighbourhood or 8-cell Moore neighbourhood) and scheduled updating (i.e., the states of cells are updated after each time step) (Cioffi-Revilla, 2014).

Although CA models had been commonly used to investigate complex behaviours in general (see Wolfram, 2002), their capability in representing more realistic geographical systems is well acknowledged recently. CA models are best applied in cases of spatially distributed process simulations (Clarke, 2014) such as urban growth and land use-land cover change models (Santé et al., 2010). By easily integrating with GIS, one can develop high resolution CA models that have high computational efficiency (ibid). CA models are simple and flexible, hence can easily be implemented. However, as CA cells are static, modelling moving agents is not possible (Clarke, 2014). Additionally, Clarke discussed that as CA models use square grids, they are subject to errors in relation to map projection issues. Their simplicity can also be criticised as oversimplification.

An example of a CA model is the MOLAND (Monitoring Land Use/Cover Dynamics) urban and regional growth model presented in (Lavalle et al., 2004). The MOLAND models has been used at European scale to assess scenarios or urban growth in strategic European corridors.

The model takes five inputs (as digital maps): actual land use type, accessibility to transport network, suitability of the area for different land uses, zoning status and socio-economic data such as population, income, production and employment. The MOLAND model is designed for larger urbanised regions (for example, large cities). It can simulate processes at three geographical levels (i.e., global, reginal and local levels) that change the spatial configuration of an area (see for example Figure 8). The model is employed to predict the likely future land use development based on spatial planning and policy scenarios. The predicted land use maps can be used to investigate the contribution of urbanization to flooding. This will allow decision-makers to plan in advance and identify suitable mitigation measures.

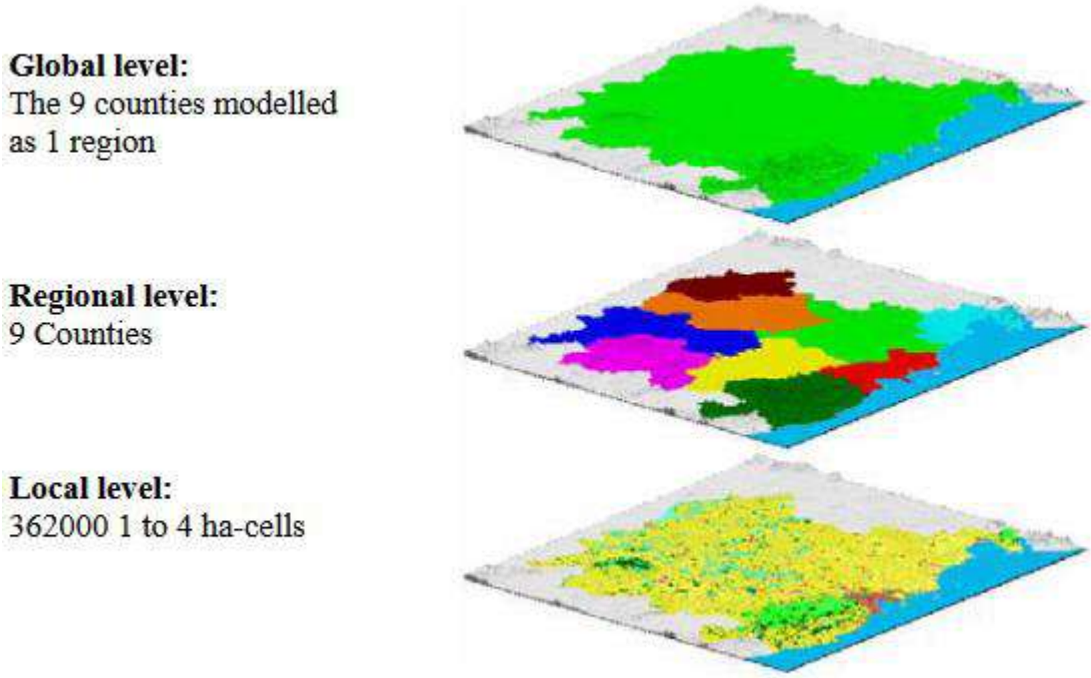

Figure 8. An example of a MOLAND model representing processes at global, regional and local spatial levels for the Greater Dublin Area (from Lavalle et al., 2004).

Of the three simulation techniques, **agent-based models** (ABMs)[6] provide the “most natural” description and simulation of a CAS (Bonabeau, 2002). ABMs are better technique as they compensate the drawbacks of SD and CA. For example, unlike the CA that model cell interactions only between neighbouring cells that are fixed, ABMs allow interactions over space using mobile agents or over other space that is not grid such as social networks (Heckbert et al., 2010). Compared to SD, ABMs represent individual-level dynamics and aggregate features as well as the macro level behaviour. As a result, ABMs are the preferred technique to model NBSs as CHANS in RECONECT, and we shall describe them in detail in the next section.

[6] In the following sections, we use ABM to refer to either an agent-based model or an agent-based modelling paradigm. It should also be noted that, in some literatures, agent-based models are called agent-based simulations, agent-based modelling and simulations, and agent-based computational models.

4 Agent-based modelling

4.1 Agent-based model – Definition

An agent-based model is “a computational method for simulating the actions and interactions of autonomous decision-making entities in a network or system, with the aim of assessing their effects on the system as a whole” (Dawson et al., 2011, p. 172). 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, p. 151). However, agent interaction is not only with each other, but also with their environment (Railsback and Grimm, 2012). ABM is used to discover the global behaviour or the emergent properties of a system based on individual agents' behaviours and interactions, providing a bottom-up modelling perspective (Nikolic and Kasmire, 2013). An ABM is also used to study individual agents' reaction to the emergent system state (Railsback and Grimm, 2012). The emergent patterns, structures and behaviours arise through the agent interactions, but not by explicitly programmed into the models (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; Nikolic and Kasmire, 2013) as shown in Figure 9. An agent can be defined as “a computer system situated in some environment, and that is capable of autonomous action in this environment in order to meet its design objectives” (Jennings and Wooldridge, 1998, p. 4). The autonomy is related to agent's capability to process information and act on its own without the influence of a centralised control, make an independent decision and pursue its own objective (Crooks and Heppenstall, 2012; Macal and North, 2010; Railsback and Grimm, 2012). The authors extend some other characteristics of agents as: agents can be heterogeneous that they different from each other in characteristics; agents can learn from their experience and adapt their behaviours based on the current events and in reference to past events in order to better suit to their environment; agents are social interacting with each other and their environment, which influences their behaviour; and agents have goals to achieve based on their behaviour.

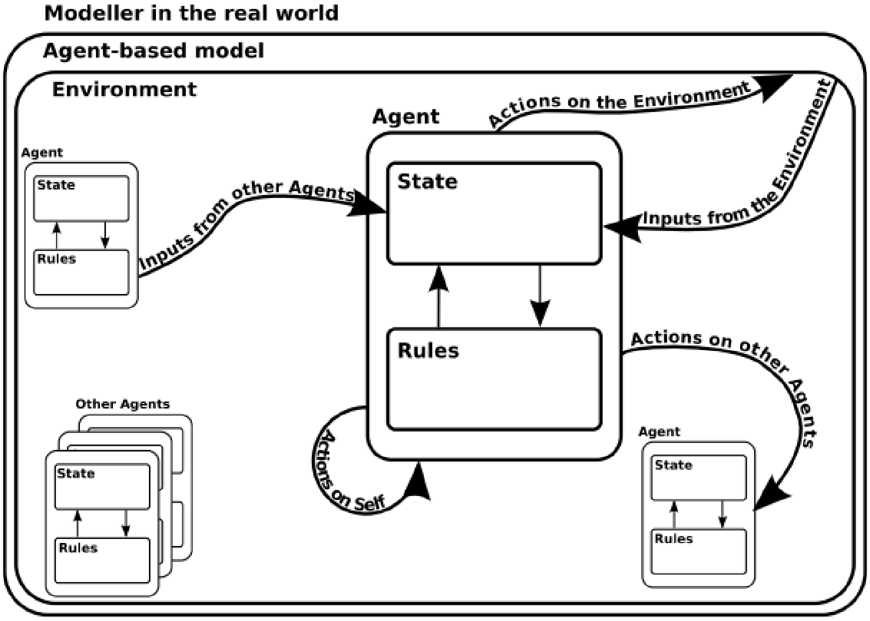

Figure 9. Agent-based model structure depicting Agents, agent interactions and environment (from Nikolic and Kasmire, 2013).

Agents have state and behaviour (Jennings and Wooldridge, 1998; Nikolic and Kasmire, 2013; North and Macal, 2007). The state provides relevant information about an agent's current situation through a set of variables/attributes, and it defines what the agent is. These are information such as age, location, income and type. The state may change over time due to the agent's actions and interactions in the system dynamics. The behaviour includes the actions and interactions of the agent, and it defines what the agent does. It is influenced by agent's states, its decision making and the rules of interaction. The behaviour of agents is represented by rule-based and analytical decision-making functions (Heckbert et al., 2010).

Agents may have relationship and interaction with other agents and their environment. Agents may interact reactively when they are triggered by an external stimulus or they initiate the interaction while pursuing an objective (Crooks and Heppenstall, 2012). At the same time, agents do not interact with all agents, but they interact locally. Interactions constitute feedbacks between an individual agent and the external elements it interacts with (Heckbert et al., 2010) that leads to change in the agent's state or behaviour by taking actions (Wilensky and Rand, 2015). These interactions happen with respect to the rules or methods of interaction and agents' states and behaviours. The most common types of rules are the nested if-then-else types of decision rules (Nikolic and Kasmire, 2013). The "if" part specifies conditions and the "then-else" part specifies the actions or decisions made by agents when the conditions are met.

The environment is the space where agents are situated in and operate (Crooks and Heppenstall, 2012; Nikolic and Kasmire, 2013). It provides the external information that an agent needs to know in addition to the structure it provides in which the agents could situate. The environment can be a continuous space, a grid cell or a social network (Crooks and Heppenstall, 2012). The environment may represent a geographical space such as the physical features of a city using GIS maps (Abdou et al., 2012). In cases of such spatially explicit environment representations, agents have coordinates to show their locations, which can be static or dynamic (i.e., if agents move or not). A detailed discussion on the explicit integration and representation of space in ABMs is given in (Stanilov, 2012).

4.2 Agent-based model – Development

As in any model development, certain steps must be followed to develop an ABM. Railsback and Grimm (2012) suggested an iterative modelling cycle with six tasks: formulate the research question; assemble hypotheses for essential processes and structures that are addressed in the question; choose the model processes and structures such as scales, entities, variables and parameters, and formulate the model; implement the model by converting the verbal model descriptions to computer programs; analyse, test and revise the model; and communicate the model (see Figure 10). Nikolic et al. (2013) also provide ten practical steps for developing and using an ABM, which are a more detailed version of the steps given by Railsback and Grimm, 2012.

Regarding communicating the model, Grimm et al. (2006) develop a standard protocol for describing ABMs. The aim of the protocol is to describe all ABMs in the same sequence so that it is easy to read and understand them. The protocol is called the *ODD protocol* based on the initials of its three blocks: Overview, Design concepts, and Details. The *overview* describes the purpose of the model, its state variables and scales, and conceptual description of processes and the scheduling of these processes including ow time is modelled in the model. The *design concepts* provide key CAS concepts for designing, describing and understanding ABMs. These include emergence, adaptation, fitness, prediction, interaction, sensing, stochasticity, collectives and observation. Finally, the *details* include the initialization of agent attributes and the environment, model inputs that are imposed dynamics of state variables and submodels representing the process including the model parametrization. An updated version of the ODD protocol can be found in (Grimm et al., 2010).

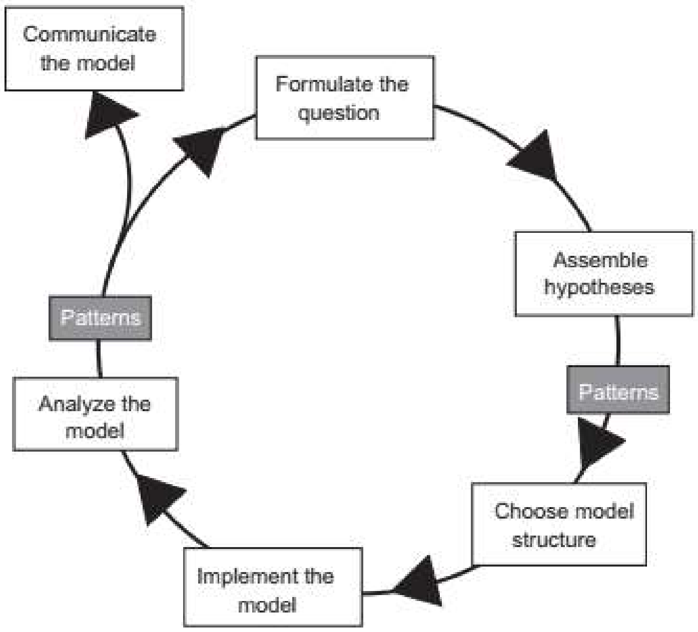

Figure 10. ABM modelling cycle consisting six tasks. Modelling is an iterative process and the tasks may be redone. The iteration is not necessarily follow the full cycle but also going through smaller loops between any of the tasks (from Railsback and Grimm 2012).

The software implementation of ABMs can be done in two ways: using all-purpose software and programming language, or using specially designed software and toolkits (Macal and North, 2010). Implementing ABMs using *general programming languages* such as R, Python, Java, C++ and C provides flexibility as a combination of tools and libraries can be employed. However, writing programs from scratch using these languages are time-consuming as modellers may invest time programming non-content-specific parts such as graphical user interface, data import-export and visualisation (Crooks and Castle, 2012), it requires advanced programming skills and there are less help and support (Nikolic et al., 2013).

Therefore, modellers opt to use *tools/toolkits* or *development environments* to implement large-scale ABMs (Macal and North, 2010). Toolkits are "simulation/modelling systems that provide a conceptual framework for organising and designing agent-based models" (Crooks and Castle, 2012, p.229). They consist of a library of pre-defined routines that modellers call to define the model. They also provide the functionality to extend their capability by integrating external libraries such as GIS libraries that provide spatial analysis and better data management. A development/modelling environment is a "programming language or modelling suite that provides the software infrastructure for programming the agents, their states and behaviour, their interactions and the environment … [including] support code, such as a scheduler, graph plotting, statistics collection, experiment setups, etc" (Nikolic et al., 2013, p.94). It also provides built-in functionalities to compile and execute models (Macal and North, 2010). There are also hybrid services that provide a stand-alone library and a development environment (ibid).

There are numerous ABM toolkits and development environments. A comprehensive survey can be found in Abar et al., (2017), Kravari and Bassiliades (2015), Nikolai and Madey (2009) who reviewed 85, 24 and 53 ABM software, respectively, using multiple evaluation criteria. Focusing only on the use of ABMs for disaster risk management (DRM) and in particular hydro meteorological hazard events such as floods, tsunamis and hurricanes. As described in section 2.3 one of the main societal challenges addressed by the implementation of NBS is disaster risk mitigation and climate change among others.

Medina et al. (2020) systematically search for particular combinations of keywords in the main academic databases such as Scopus and Web of Science. The study reviewed 115 peer-reviewed articles and their findings, see Figure 11. ABM tools for disaster management of Hydro meteorological events show that NetLogo is the most used ABM development environment (23.5%) followed by Repast Simphony (8.7%).

The preference for using Netlogo can be explained as it incorporates easy to use interface and have a fast learning curve. Netlogo is the right choice for novice users or non-specialist. It has been extensively reported that it provides several libraries and examples that can be re-used and adjusted to the modeller needs

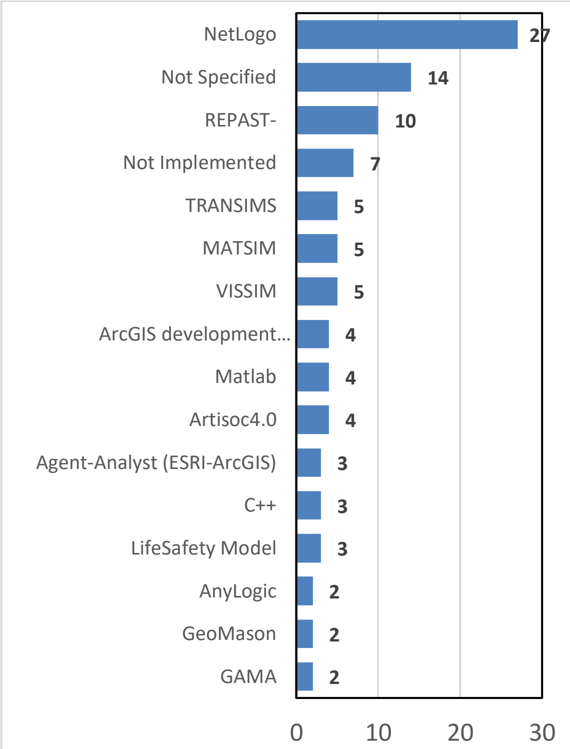

Figure 11. ABM tools for disaster management of Hydro meteorological events

Table 1 presents a summary of the main characteristics of selected ABM tools that have the most potential to be used in NBS implementation for hydro meteorological risk reduction in particular floods, tsunamis and hurricanes. Adopted from Medina et al, 2020.

Table 1. Comparison of the most suitable ABM tools for DRM and its recommended use. Listed in alphabetical order.

ABM Software Tool	**License / Availability**	**Coding Language --------- IDE**	**Model development effort**	**Modelling Strength --------- Scalability Level**	**Remarks**
General-purpose ABM software					
Anylogic	Proprietary, Commercial	Java --------- IDE: Own platform	Moderate	High --------- Large Scale	If access to the software is not a limitation. When the model is already built in this software For large applications When user-friendly IDE is preferred Can be applied in several sectors such as simulations in transportation, healthcare, social sciences, economics, urban dynamics, supply chains, computer/telecom networks, logistics, and complex adaptive dynamic/discrete-event systems.
GAMA	Open source, GNU GPLv2, Free	GAML modelling language	Moderate	Medium --------- Large scale	To prototype models

ABM Software Tool	License / Availability	Coding Language --------- IDE	Model development effort	Modelling Strength --------- Scalability Level	Remarks
		--------- IDE: Eclipse platform + Plotting and graphical editors			To be used in medium to large scale case studies When advance and sophisticated and built-in GIS capabilities are required When programming skills are intermediate or not a limitation Modelling & development platform for building spatially explicit agent-based simulations such as Land-use and land-planning, social, institutional, economical, ecological or biophysical systems.
NetLogo	Open source, GPL, Free	Netlogo language --------- IDE: Own interface	Simple /Easy	Medium --------- Large scale	To prototype models To be used in small or medium-scale case studies To be used in academic settings When GIS and graphical representation is secondary When programming skills are not strong Modelling and development environment for different types of simulations in social and natural sciences, and education (teaching/research)
Repast-HPC	Open source, BSD, Free	C++ --------- IDE: Eclipse platform	Complex / Hard	High --------- Large Scale	When the system to model is very large or complex scale When GIS integration is a must. To be used in large scale parallel or distributed computing clusters When programming skills is not a limitation Simulations in computational social sciences, cellular automata, complex adaptive systems
Repast Simphony	Open source, BSD, Free	Java --------- IDE: Eclipse platform	Complex	High --------- Large Scale	When the system to model is very large or complex scale When GIS integration is a must. When programming skills is not a limitation Platform for simulations in social sciences, supply chains, geographical Information Systems (GIS), cellular automata, complex adaptive systems.

Based on the benefits and limitations of ABM software given in the above mentioned review papers and other literature such as: Crooks and Castle, 2012; North and Macal, 2007; Railsback et al., 2006. The *Repast Simphony* development environment (North et al., 2013) is one of the modelling environments with the highest computational capability and scalability. Repast Simphony is a free, open source, integrated, interactive, hybrid and cross-platform Java-based ABM environment. It uses the multilingual and integrated Eclipse development environment. The most recent version is 2.6 and was released in 2018. Repast Simphony has a high computational modelling capacity and large model scalability level. It provides time scheduling, space management, behaviour activation, random number generation, interactive two- and three-dimensional model visualizations, GIS modelling and visualization, third-party application sets, batch runs and data collection while it is running. It also has a high degree of support through tutorials, example models, a reference manual, frequently asked questions, Application Programming Interface (API), an active mailing list including archives and a Stack Overflow page. Some disadvantages of the Repast Simphony environment is that it is hard to learn and requires higher development effort. However, based on its capabilities the Repast Simphony environment is the preferred choice in RECONECT's complex systems studies.

4.3 Agent-based model – Benefits and limitations

The benefits of ABM as a simulation technique include: it captures emergent phenomena that result from the interaction of agents; it provides a natural description of a system in which the model seems closer to reality; it is flexible in such a way that the modeller can tune the complexity or change levels of description and aggregation of agents (Bonabeau, 2002); it is useful to get deeper understanding of drivers and their influence on the system characteristics, and to explore various institutional arrangements and potential paths of development to assist decision and policymakers (Pyka and Grebel, 2006). ABM also provides feedback with a visualization that allows modellers to understand and examine the system at an overall, aggregate level or at an individual agent level (Wilensky and Rand, 2015). Furthermore, Axelrod (2006) stressed that ABM is a wonderful technique to study problems that bridge disciplinary boundaries by addressing fundamental problems and by facilitating interdisciplinary collaboration.

The major limitation of ABMs is the difficulty of modelling human agents decision (An, 2012) due to their potentially irrational behaviour and subjective choices (Bonabeau, 2002). Modelling individual agents' behaviour and their interaction requires a description of many agent attributes and behaviour and relationships, hence, detailed data is required to parametrise the model and ABMs tend to have high numbers of parameters (Kelly et al., 2013). Other limitations of ABMs are the difficulty in model calibration and validation (Crooks and Heppenstall, 2012; Heckbert et al., 2010), the high computational requirements associated mainly with modelling large systems (Bonabeau, 2002; Wilensky and Rand, 2015) and the low predictive power of ABMs because of their sensitivity to factors such as small variations in interaction rules (Crooks and Heppenstall, 2012).

4.4 Agent-based model – Applications

A good practice for ABM modellers should be the definition of whether or not this is the appropriate modelling technique followed by the proper definition of the purpose of the model (Manson et al., 2020; Schulze et al., 2017). A standard categorization of the model purpose in ABMs is whether it is intended as a *descriptive* or as a *predictive* model. Predictive models have a general purpose of demonstrating and exploring ideas or for testing hypotheses whereas descriptive models are built to provide decision making and management support.

Findings of an extended literature review of 115 relevant peer-reviewed articles that applied ABM in water-related disasters studies by Medina et al. (2020) showed that 82.6% of ABMs are of a predictive nature (see Figure 12). These models were designed as a model of a specific real system using observations or data. ABMs in the world of DRM have been used as predictive model in different backgrounds and purposes such as exploring the effects of policy and management strategies implementation, exploring the role of spatial planning in risk management, evacuation simulation, loss and damage assessment, risk insurance and risk communication during a disaster. Despite the use of ABMs in DRM studies is a relatively recent approach, the high number of direct applications the study found shows the acceptance of ABMs as a prominent and feasible tool to model CAS such as NBS for disaster risk reduction.

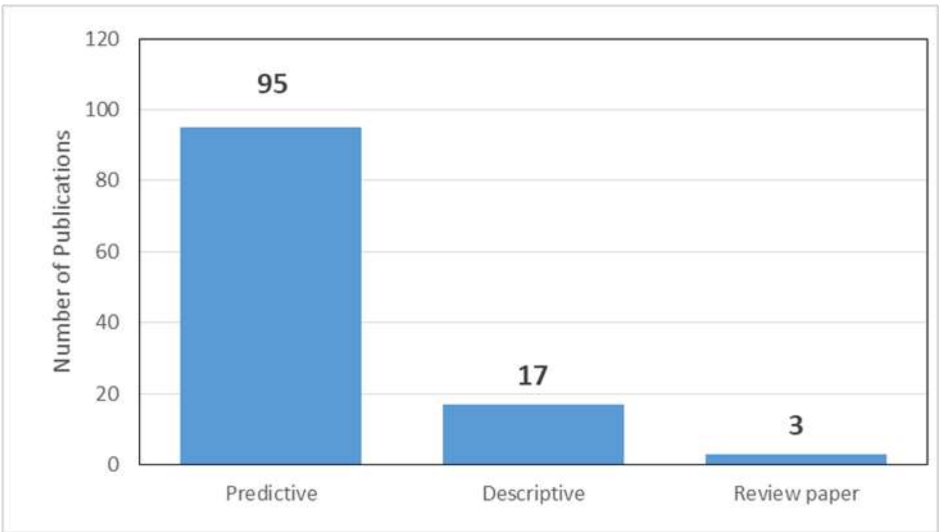

Figure 12. Number of publication listed based on model purpose.

Findings of Medina et al. (2020) show that more than half of the ABM articles reviewed applied ABMs to model the evacuation behaviour of agents (Figure 13). Evacuation models were used mainly by practitioners and engineers who look for a numeric answer in a complex system such as evacuations processes of cities where multiple actors are involved, interacting among themselves and with both the city and the potential hazard. Accounting about 26%, the second use of ABM models is in policy related disaster management studies.

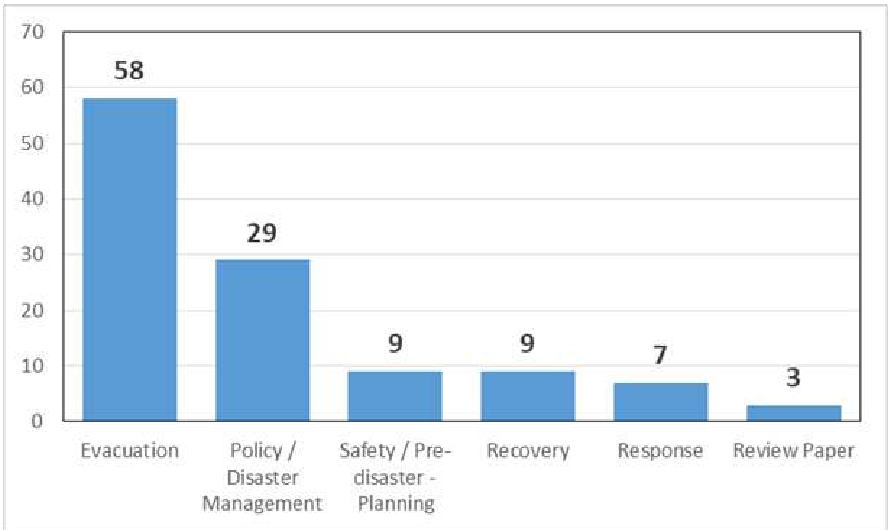

Figure 13. Distribution of articles based on the use of ABM in different disaster phases.

Zooming specifically to FRM (Flood Risk Management), the use of ABMs in FRM studies has been limited though it is gaining more attention in this decade. Researchers have been developing ABMs to investigate both operational level and strategic level flood risk reduction strategies. For example, Mustafa et al. (2018) used a spatial ABM and a 2D hydraulic model to investigate the impacts of spatial planning policies on future flood risk for a case study of Wallonia, Belgium. The ABM simulates urban expansion and densification in flood zones for multiple urbanization scenarios and for flow discharges corresponding to 25-year, 50-year and 100-year recurrence intervals. Their study focuses only on the elements-at-risk, especially the exposure of buildings, and do not address the vulnerability of agents. In contrast, Sobiech (2012) developed an ABM to explore vulnerability dynamics, risk behaviour and self-protection preferences of household agents against fluvial and coastal flooding in the German North Sea Coast. Individual, relational and spatial aspects influence the agent's decisions to apply self-protection measures. Though the social vulnerability dynamics is based on empirical evidence the model conceptualization does not explicitly capture the flood hazard and the spatial environment.

Brouwers and Boman (2010) applied an ABM to test FRM strategies in the Upper Tisza River catchment, Hungary. The agents conceptualised in the ABM are property owners, insurer and the government. Floods occur due to dyke failure or seepage. The FRM strategies investigated include different government compensation rates for property owners and market-based insurance compensations in case of flood damages. Haer et al. (2016) evaluate flood risk communication strategies in relations to individuals' social network and their decisions to implement measures using ABMs. Their conceptualization includes household agents and the attitudes and decisions agents make to purchase flood insurance, use flood barriers or implement adaptation measures to reduce flood risk. The communication strategies evaluated are people-centred and a more limited top-down approach in the Rotterdam-Rijnmond region, the Netherlands. Tonn and Guikema (2017) also used an ABM to analyze how flood protection measures, individual behaviour, and the occurrence of floods and near-miss flood events influence community flood risk. The agents in the ABM are households that also implicitly represent the community. The model conceptualisation includes FRM measures such as building a dyke, elevating homes and elevating equipment; and moving out of the area based on agents risk perception and neighbours influence. The model was developed for a case study area in Fargo, North Dakota, USA.

Löwe et al. (2017) coupled an agent-based urban development model with a hydrodynamic flood model to assess city development, climate change impacts and flood adaptation measures. The adaptation options include a master plan controlling future urban development, reducing exposure through property buybacks, rainwater harvesting facility and increasing drainage pipe capacity. The model is tested for a pluvial flooding case in Melbourne, Australia. Dubbelboer et al. (2017) developed an ABM to simulate the vulnerability of homeowners, and to facilitate an investigation of insurance mechanisms. The ABM focuses on the role of flood insurance, especially public-private partnership between the government and insurers in the UK and the re-insurance scheme Flood Re. The agents conceptualised in the ABM are homeowners, sellers and buyers, an insurer, a local government and a developer. Jenkins et al. (2017) utilised the ABM developed by Dubbelboer et al. (2017) to assess the interplay between different adaptation options; how risk reduction could be achieved by homeowners and government; and the role of flood insurance in the context of climate change. Both studies applied the ABM for a surface water flood risk case of London, UK.

Liu and Lim (2018) developed an ABM to simulate a range of evacuation scenarios in flood emergencies in Brisbane, Australia. The flooding considered in the study is a fluvial one, from the Brisbane River. The agents conceptualized in the model are vehicle-based evacuees in which the evacuation is affected by departure times and communications between informed and regular evacuees. Similarly, Dawson et al. (2011) estimate the likely exposure of individuals to flooding under different storm surge conditions, defence breach scenarios, flood warning times and evacuation strategies using an ABM. Their model conceptualization includes traffic simulation, risk to life in terms of exposure to certain depth and velocity of floodwater, and economic damage assessment. They model the coastal flooding due to storm surge using a simplified raster-based inundation model.

Table 2 presents a summary of applications of ABMs for environmental management and nature based solutions.

Table 2 Application of ABMs for environmental management and NBS

Application	Description	Remarks
Water Management		
SHADOC: Viability of Irrigated Systems in the Senegal River Valley	SHADOC was develop for simulating scenarios of collective rules and individual behaviours. It focuses on water and credit distribution in irrigation systems issues. Farmers are the main agents. It was applied in a case study of the Senegal River Valley.	• Barreteau and Bousquet (2000); Barreteau et al. (2004)
MANGA: Collective Rules of Water Allocation in a Watershed	MANGA was developed to improve the collective management of water resources by testing consequences of particular water rules. The model takes into account farmers and water supplier agents who negotiate with each other to get the water they want.	• Le Bars et al. (2005)
SINUSE: Viability of Irrigated Systems in the Senegal River Valley	SINUSE was developed to simulate water table level and it's interactions with the decisions of farmers (agents). It was applied for farmers in Tunisia.	• Organization at Watershed level • Cormas platform is used. • Feuillette et al. (2003)
Water Management and Water Temple Networks in Bali	The model was re-implemented in Bali to investigate the system of temple level for coordination. Water management and water temple networks of 172 villages were simulated.	• Organization at Watershed level • Lansing and Kremer (1993); Janssen (2007)
Limbukha: Viability of Irrigated Systems in the Senegal River Valley	Limbukha was developed to facilitate water management negotiations in Bhutan. It was applied for the Lingmuteychu Watershed, Bhutan. The communications between Farmer agents and the sharing irrigation water were simulated.	• Organization Village level • Cormas platform is used • Gurung et al. (2006)
Forestry		
LUCIM: Deforestation and Afforestation in South-Central Indiana	The LUCIM is developed to improve the knowledge of the interaction between human activities and forest patterns. Farmers are the agents and actions are deforestation and afforestation. Simulations are analysed considering the impact of ecological, social or	• Organization at state level • Hoffmann et al. (2002)

Application	Description	Remarks
	economic factors. The model was applied to a case study of artificial landscape in Indiana, USA, during the last 200 years.	
Forest Plantation Co-management	The model was developed to facilitate negotiations between stakeholders for growing trees. It simulates scenarios of collaboration between stakeholders (developer, smallholder, broker, government) as agents and both biophysical and economic indicators to provide the impact on forest landscape and smallholders incomes. The model was applied to a case study of forest plantation co-management in Indonesia.	• Organization at forest massif level • Purnomo and Guizol (2006); Purnomo et al. (2005)
Nature Based Solutions		
Water runoff and catchment improvement by NBS promotion in private household gardens	A Netlogo model was developed to simulate the water runoff and retention capacity in private gardens with and without NBS to improve water management at the household level and in urban level. Agents considered in the model are resident garden owners who might change their gardens based on three factors: motivations, abilities, and willingness. There are three types of private gardens and the type of NBS is not specified. The model has two key outputs: changes in the number of gardens and the runoff across the city at a cumulative level. The model was applied to four case studies of Nature4Cities project.	• NBS at household level
Urban heat mortality impacts reduction through NBS	A model was developed in Netlogo to simulate the impact of heatwave in the city in local mortality. The focused agents are elderly citizens. The simulation would investigate the effectiveness of NBS on lowing indoor temperature and its impact on reducing mortality rates. The model was applied to four case studies of Nature4Cities project.	• NBS at urban level
Socio-economic and commercial development resulting from NBS changes	A model was developed in Netlogo to assess the change of commercial activities due to the development of large NBS. Two types of agents are considered: residents (customers) and shop owners. NBS has the potential effect of visiting and shopping intentions and the change due to NBS is simulated. The indirect economic benefit of NBS on a neighbourhood's economic structure is an added value of the modelling. The model was applied to four case studies of Nature4Cities project.	• NBS at urban level

The NBS models described in table 2 were developed in the framework of the EU project Nature4Cities. The three ABMs targeting the effect of NBS on water runoff, heat mortality and commercial development were also tested in four European cities. Since, there are not many applications of ABMs developed specifically for NBS a brief summary of their finding is presented next.

The water runoff ABM model considered the influence of the transformations of private gardens own by different private garden owners (proud gardener and backyard barbeque segments) to urban water runoff control. The gardens are categories into three types: paved gardens, partially green gardens, and green NBS based gardens. The urban heatwave model considers green roofs as NBS in simulations. It was used to investigate the influence of reduced indoor temperature due to green roofs on heatwave mortality of elderly citizens. The commercial development model assesses the change of commercial activities of small retail shops due to the development of large NBS.

The case of **Szeged, Hungary**, where the green waterfront NBS is used as a green space. Results from the water runoff model show substantial difference from two garden owners. The majority of transformed gardens become green NBS based gardens and partially green gardens for proud gardeners and backyard barbeques, respectively. Three measures (gardening knowledge workshops, gardening network group organisers, and subsidies) have no effect to backyard barbeques while the measure of subsidies has large effect for proud gardeners. The result also shows the combination of measures can have different effects for different segments. There is a non-measurable impact on total water runoff for backyard barbeque segments while, for proud gardeners, private garden based NBS promotion can reduce water runoff by 5% to 10%. The urban heatwave model shows that if the green roofs implementation reduces the indoor temperature by 3˚C for 2016, it will generate a reduction of 80% heatwave mortality for elderly people. The simulations also show an increase in the mortality rate for future years as the urban temperature rise due to climate change. The commercial development model indicates no substantial difference for different initial number of retail shops in model runs. The location of the shops was related to green spaces: the majority were in green spaces.

In the case study area in **Alcalá de Henares, Spain**, where the edible forest NBS is used as a green space in the project. The water runoff model results show the majority of transformed gardens become partially green gardens for backyard barbeques. In case of proud gardeners, 50% of transformed gardens become green NBS based gardens. There is no effect of measures to backyard barbeques while the measure of subsidies has large effect for proud gardeners. There is a non-measurable impact on total water runoff for backyard barbeque segments while, for proud gardeners, private garden based NBS promotion can reduce water runoff by 10% to 20%. The urban heatwave model shows a reduction of 76% heatwave mortality for elderly people as long as the green roofs can reduce 3˚C of the indoor temperature for 2016. The reduction of mortality rate due to the heat stress remains significant for future years. The commercial development model indicates no substantial difference for different initial number of retail shops in model runs. In this case, most of the shops are located at residential centres further away from larger greenspaces.

In the area of **Città Metropolitana di Milano, Italy.** The simulation of water runoff model shows few transformed gardens for backyard barbeques compared to proud gardeners. The influence of measures is negligible for backyard barbeques while the measure of subsidies increases largely the motivational and ability factors for proud gardeners. Also, combining measures can lead to better results. There is a non-measurable impact on total water runoff for backyard barbeque segments while, for proud gardeners, private garden based NBS promotion can reduce water runoff by of up to 5%. The simulation of urban heatwave model indicates no reduction of the heatwave mortality in all runs. This can be explained due to no substantial mortality impact from heatwave in the area. The commercial development model shows similar results from previous cases while most of the shops are located mostly in residential centres at reasonable distance from larger greenspaces.

In the study area of **Çankaya Municipality**, at the south-east portion of Ankara, **Turkey.** The METU forest NBS is identified as a green space in the simulation. Results from the water runoff model also show substantial difference from two garden owners. The case study area already has mostly green gardens. All of the transformed gardens become green NBS bases gardens for proud gardeners. The measures of subsidies have large influence for proud gardeners. The combination of measures also has medium effect on backyard barbeques indicating the combination of measures can have different effects for different segments. There is no measurable impact on total water runoff for backyard barbeque segments while, for proud gardeners, private garden based NBS promotion can reduce water runoff by the order of magnitude of 5% to 10%. The Results from the urban heatwave model indicate that green roofs do not have substantial effect on the heatwave mortality reduction due to the limited heatwave impact in 2016. However, the reduction impact becomes increasingly prominent in the area for future years. The commercial development model indicates no substantial difference for different initial number of retail shops in model runs. In this case, most of the shops are located at residential centres further away from larger greenspaces.

5 CAS modelling applications

5.1 Model integration

Studying CAS requires understanding the social, economic, governance and physical processes, their interactions and the feedbacks. As a result, an integrated assessment of the processes in which knowledge from diverse scientific disciplines are combined, analysed, interpreted and communicated to better understand the complex phenomena is essential (Rotmans and Van Asselt, 1996). One prominent method of performing an integrated assessment for both scientific and policy analysis is by integrating expert models (ibid). *Integrated environmental modelling* (Laniak et al., 2013) and *multimodel ecologies* (Bollinger et al., 2015) are two examples showing the relevance and applications of model integration in complex environmental and sustainability problems.

Integrated modelling is a "method that bring[s] together diverse types information, theories and data originating from scientific areas that are different not just because they study different objects and systems, but because they are doing that in very different ways, using different languages, assumptions, scales and techniques" (Voinov and Shugart, 2013, p. 149). In general, "the term integrated … convey[s] a message of holistic or systems thinking … while modeling indicates the development and/or application of computer based models" (Laniak et al., 2013, p.5). There are two ways of model integration (Voinov and Shugart, 2013):

a) *Integral models*: data from various scientific fields are collected, processed, translated into one formalism and modelled as a whole. Such models are developed commonly based on the same modelling approach.

b) *Integrated models*: already built domain models are assembled for more complex system representations. Such models are made out of two or more relatively independent components that can operate on their own and are based on different modelling approaches.

In RECONECT, the focus is on the second approach as we develop integrated models to study human-nature interactions. One of the most commonly used modelling type to develop integrated models is using a *coupled component model* approach (Kelly et al., 2013). These models loosely or tightly couple a process-based biophysical model (for example, a hydrodynamic flood model) with a social and economic model (for example, an ABM). The advantages of coupled component models include they explore dynamic feedbacks and they may incorporate detailed representations of the studied system. The challenges of developing the models include the difficulty in conceptually and technically linking legacy models as they are developed in advance, and balancing between the complexity of component models and time and resources limitations to develop and run the models.

Although done iteratively, model integration follows five phases (Belete et al., 2017):

1. Pre-integration assessment: in this phase, experts set problem statements for a study area, conceptualize the system and its components, define scenarios, define the methods of analysis, and set constraints and solution criteria.

2. Preparation of models for integration: this phase is mainly related to software engineering considerations such as selecting the programming language, model

development, model modification in case of existing models, and developing wrappers for language interoperability.

3. Model orchestration: this phase is about identifying the component models that will be coupled, establishing the links between the components, defining and executing workflows, and defining the sequential or iterative exchange of data between components.
4. Data interoperability: in this phase, the main issue to address is if data exchange between component models is unambiguous, correctly mapped and translated, and the dataset is formatted in the required format.
5. Testing: this phase includes integrated model verification, model output validation and uncertainty quantification.

As discussed in section 4.4 there are not many ABM model applications developed for assessing NBS implementation and its effects or impacts in other subsystems. This is also true for the case of frameworks to integrate ABMs with other models to explicitly assess benefits. In the case of the project Nature4Cities the proposed ABM models are run or tested independently and there is not description on integration. In such a way that the multi-functionality and multi-benefits of different NBS technologies implementation on the same case study area cannot be assessed. According with Ge and Polhill (2020) in Sang (2020) (Chapter 2 of Modelling of Nature Based Solutions), there is hardly any large scale ABM of CHANS developed or applied in the real world is an indication of the complexity of the task, data requirements and computational capacity among other issues.

One recent work in this regard is the coupled flood-agent-institution modelling (CLAIM) framework by (Abebe et al., 2019), which was developed in the framework of the PEARL project and RECONECT. The CLAIM framework and its application to two case studies (Saint Maarten and Hamburg) is presented in the next section.

5.2 *Coupled flood-agent-institution modelling (CLAIM) framework*

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. For example, to study the effect of NBS in flood risk management, ABMs can be integrated with physically based flood models to analyse the policies (or policy implementations) that affect flood hazard, vulnerability and exposure. One recent work in this regard is the *coupled flood-agent-institution modelling (CLAIM) framework* by (Abebe et al., 2019). CLAIM is a modelling framework that is designed to capture and conceptualize coupled human-flood systems. It helps to decompose and conceptualize human and flood subsystems, and to lay out the levels of interactions between and within the subsystems. In CLAIM, policies, regulations, laws, plans, ordinances, norms and cultures, which are collectively referred to as *institutions* (Crawford and Ostrom, 1995), are conceptualized as drivers of flood hazard and communities vulnerability and exposure. Hence, CLAIM is used to understand the effects of institutions, and model outputs can provide relevant policy evaluations for decision-makers.

CLAIM has five components – agents, institutions, urban environment, physical processes and external factors – as shown in Figure 14.

1. *Agents* are a representation of an individual or composite actors/stakeholders in a model. Agents have internal states, behaviours and an environment. Agents are social, and their actions and interactions are defined by their behaviours.
2. *Institutions* are rules, norms and strategies in which observed patterns of interactions among actors are based on common understandings, shared perceptions or mutual expectations (Crawford and Ostrom, 1995). Agents and institutions have a two-way relationship - agents formulate institutions and institutions shape agents' behaviour.
3. The *environment* is the component that connects the human and flood subsystems. Agents live and build their livelihood and physical artefacts in the environment. Floods also occur in the same environment. Based on their behaviour and the institutions in place, agents implement measures on the environment to reduce flooding impacts.
4. The *physical processes* are hydrologic and hydrodynamic components which include rainfall-runoff processes, runoff routing, storm surge and floods.
5. The *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.

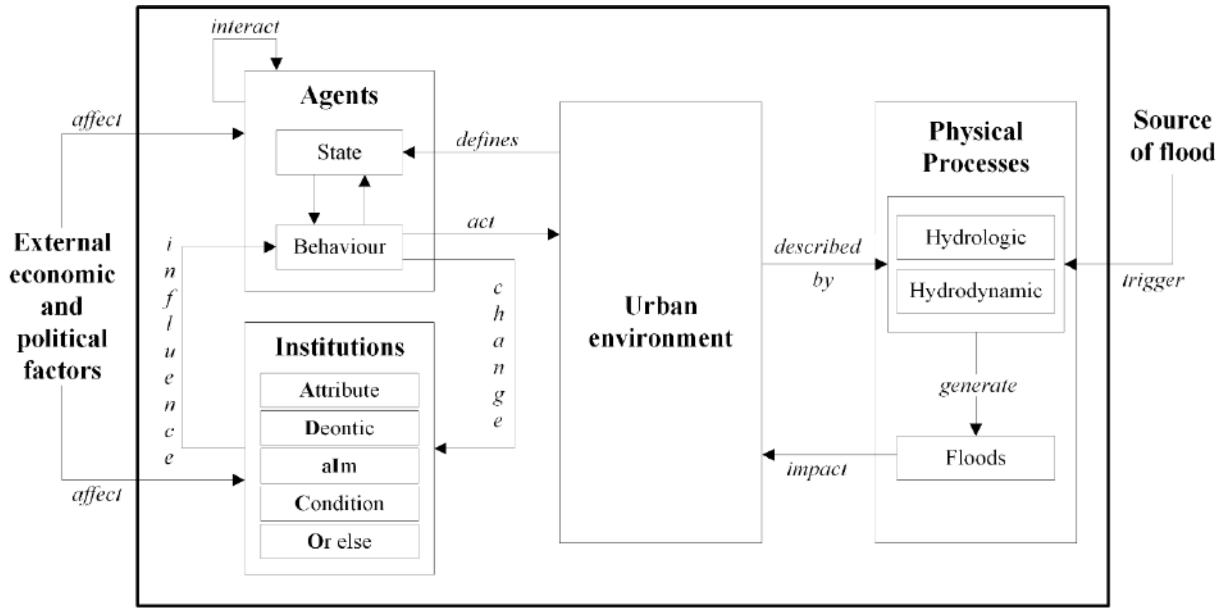

Figure 14. CLAIM framework showing interactions among humans (agents and institutions), their urban environment, the physical processes that generate flood, and external factors.

Using CLAIM, the human subsystem is modelled with ABMs and the flood subsystem is modelled with numerical hydrodynamic models. To structure and conceptualize the human subsystems by emphasizing on institutions, and to build ABMs, the MAIA (Modelling Agent systems using Institutional Analysis) meta-model (Ghorbani et al., 2013) is utilized in CLAIM as it provides a comprehensive modelling language. MAIA is the only agent-based modelling language that systematically and explicitly incorporates institutions into models. 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 (for further discussions and application of MAIA, see Verhoog et al., 2016).

5.3 Coupled ABM-flood model in the case of Sint Maarten

Sint Maarten is a Caribbean island state located in the North Atlantic Ocean (see Figure 15) and subject to frequent hurricanes (Vojinovic and van 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. This cases study conceptualizes the FRM in Sint Maarten using CLAIM and builds a coupled ABM-flood model. We will analyse the implications of policies (i.e., institutions) and evaluate how different agents' responses to existing and future policies influence the overall flood risk.

5.3.1 Decomposing concepts using CLAIM

Before building the coupled model, we first decompose the coupled human-flood system of Sint Maarten FRM into the five elements of CLAIM, i.e., agents, institutions, urban environment, physical processes and external factors. The agents included in this study are household agents and a government agent. The institutions identified are Beach Policy, a Building Ordinance and a Flood Zoning Policy. The urban environment includes the island, houses on the island and the flooding. The physical processes are related to pluvial and coastal floods. The sources of flood are rainfall for inland flooding and hurricane induced surge for coastal flooding. In this case study, we do not consider any external economic and political factors that may affect the human-flood interaction in Sint Maarten.

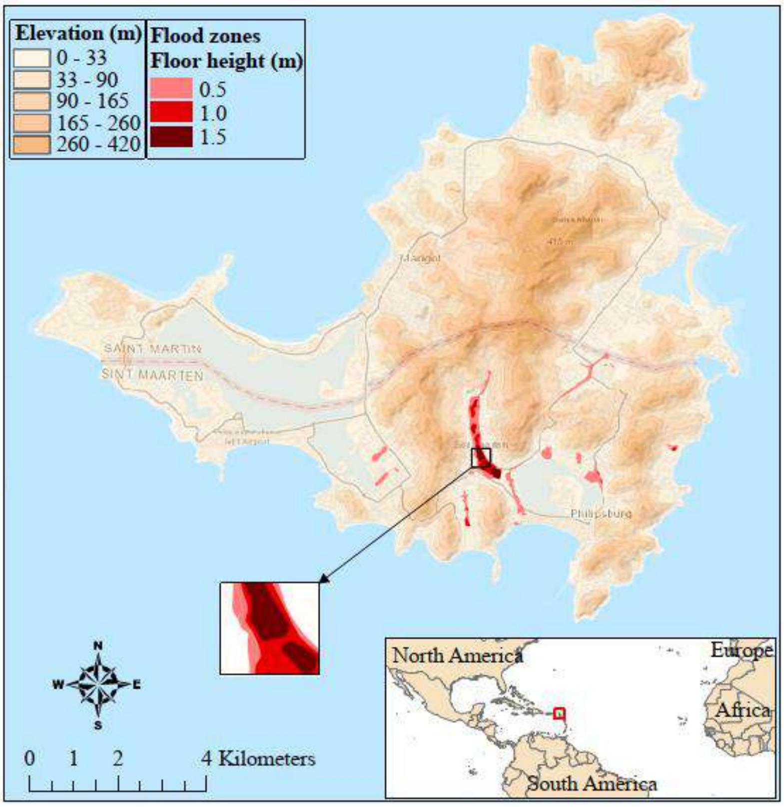

Figure 15. Map of Sint Maarten showing the elevation ranges and flood zones in shades of red. The flood zones are delineated as part of the draft NDP. If the FZ is put into work, household agents must elevate new houses constructed in the light, medium and dark red zones by 0.5m, 1.0m and 1.5m, respectively.

5.3.2 Building the agent-based model

To model the human subsystem, we develop an ABM using the Repast Simphony development environment (North et al., 2013). The ABM is built by describing the concepts related to the agents and institutions, which are mentioned in Section 5.3.1, using the MAIA language.

Social structure: we have identified two key agents: household agents and government agent. The household agents are individual agents that represent the residents of Sint Maarten. These agents make decisions on whether to implement policies that are devised by the Government of Sint Maarten to reduce flood risk. Household agents are characterized by location and elevation, and they have houses. We assume that there are only residential houses; a household owns only one house; and the agents have a static location.

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. 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. The government agent is characterized by level of enforcement.

Institutional structure: 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 50m 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 elevation of 0.2m irrespective of the location of a house while the FZ requires floor elevations of 0.5m, 1.0m or 1.5m depending on the delineated flood zones as shown in Figure 15. The BP and BO are existing institutions while the FZ is in draft phase.

We assume that all household agents know about all the institutions, and corresponding to the policies, agents have attributes that reflect their behaviour. As agents may not behave in the same way for all institutions (e.g., an agent may build an elevated house but 20m from the coastline), each household agent has three parameters that correspond to the compliance of the three institutions. Agents' 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. For example, if the threshold value of the BO is 0.8 (assuming about 80 percent of new agents comply with the BO) and the randomly generated BO compliance of an agent is 0.7, the agent will comply with the policy and raise its house by 0.2m. We assume that all the households who build new houses can afford the extra cost incurred in raising the floor levels.

Physical structure: 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 (see Figure 15). Houses in the island are part of the physical component. The houses are characterized by location, elevation and floor height. Household agents may raise the floor of houses by 0.5m, 1m and 1.5m if they are located in one of the three flood zones and follow the FZ or by 0.2m if they follow the BO.

Operational structure: in this structure, we define agents' actions and interactions. Agent related actions are making 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 20m from the coastline and 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.

5.3.3 Building the flood model

The hydrologic and hydrodynamic processes included in the coupled model 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 does not directly affect the flood hazards, but mainly the exposure and vulnerability of agents.

We build the flood model using the MIKE FLOOD environment which couples MIKE11 and MIKE21 (DHI, 2017a). In the flood model developed, which is an updated version of the model presented in (Vojinovic and Tutulic, 2009), MIKE11 is used to model the rainfall-runoff processes and flows in the drainage channels. We only use design rainfalls of 5yr, 10yr, 20yr, 50yr and 100yr recurrence intervals. We assume that any rainfall magnitude below the 5yr recurrence interval does not result in a flood. For rainfall-runoff analysis, we use the unit hydrograph method with SCS runoff curve number (DHI, 2017b). MIKE21 is used to model coastal flood and inland flood flows in the urban floodplains.

5.3.4 *Coupling ABM and flood model*

The coupling of the ABM and flood model is dictated by the rainfall time series shown in Figure 16. Since the agent dynamics defined in the operational structure occur continuously, 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, in the first time step, since there is no flood generating rainfall, only agent-related actions are executed. When 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. Then, the flood map generated from the MIKE FLOOD model is used to assess the impact. Because of lack of flood depth-damage relationship data for Sint Maarten, we assess impact based on the number of flooded houses.

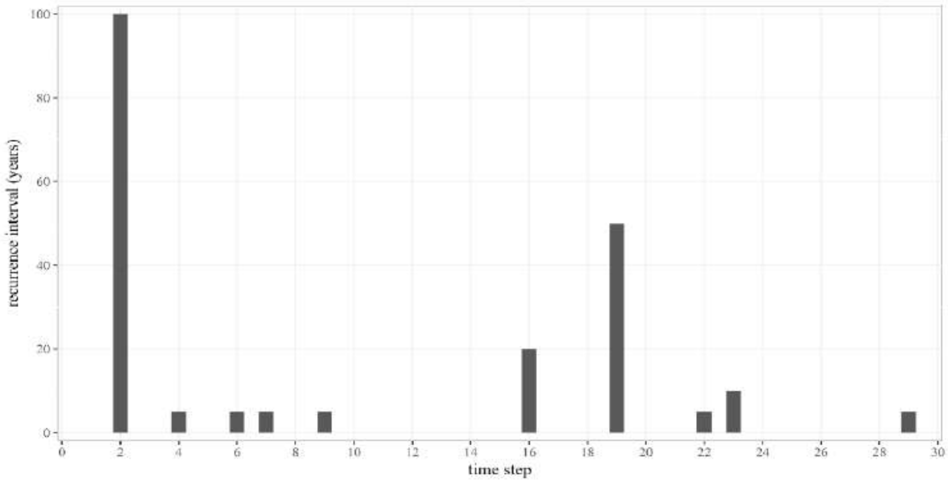

Figure 16. Input rainfall time series. It shows discrete recurrence intervals in years assuming that there is a maximum of one major flood event per time step.

The only agent dynamics that affect the flood hazard is the increase in impervious surfaces due to urban development. We update catchments' curve number based on the number of new houses built in a given catchment to reflect the increase in imperviousness. Since the decisions made by agents related to the three policies only affect their exposure and vulnerability, the flood model characteristics do not change in response to the implementation of these policies.

5.3.5 *Simulation execution and results*

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

We instantiate the simulations with 12000 households and run each experiment for 30 time steps with similar design rainfall time series (shown in Figure 16). We assume that a maximum of one flood event happens in a given time step where a time step represents one year.

The results in Figure 17 show the number of flooded houses in response to agents' compliance rate of the BO and FZ. Figure 17 (a) and (c) correspond to new houses whereas Figure 17 (b) 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 rates, and it increases in time as the number of houses increases.

Figure 17 (a) and (c) show, for the same rate of compliance of both the BO and the FZ, not complying with the BO results in higher number of flooded houses compared to not complying with the FZ. In addition, change in compliance rate values, for example, an increase in compliance rate from 0.5 to 0.75, has 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. The areas delineated as flood zones are already well developed and not a lot of agents are affected by the FZ.

Results shown in Figure 17 (b) and (d) also follow the same reasoning. Increase in the rate of compliance of BO has bigger effect on the total number of flooded houses. That is observed more at the end of the simulations with increase in 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 rate of 0.75 in Figure 17 (d)). This is mainly attributed to the increase in the number of new houses in areas exposed to flooding.

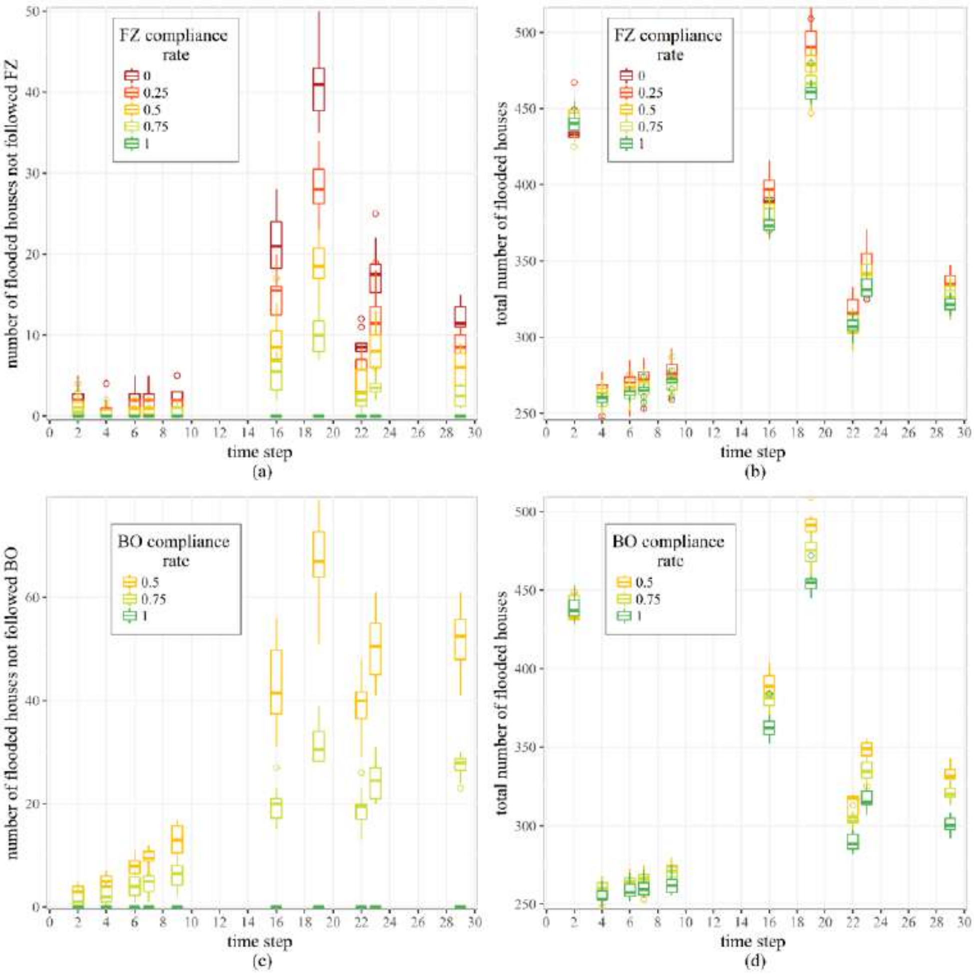

Figure 17. The effects of FZ and BO on the number of flooded houses in time. (a) and (b) show the number of flooded houses that do not comply with the FZ and the total number of flooded houses, respectively, for FZ compliance rates between 0 and 1. Except the FZ compliance rates, all the other parameters were kept the same. (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 rates between 0.5 and 1. Except the BO compliance rates, all the other parameters were kept the same.

Figure 18 shows the effect of the BP on the exposure of agents. In both cases of BPs that forbids construction within 50m and 100m from the coastline, increasing the compliance rate has a minor effect on the total number of flooded houses. Moreover, widening the no-construction zone from 50m to 100m, has a marginal improvement on 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 and most part of the coast is not prone to flooding with the current model setup.

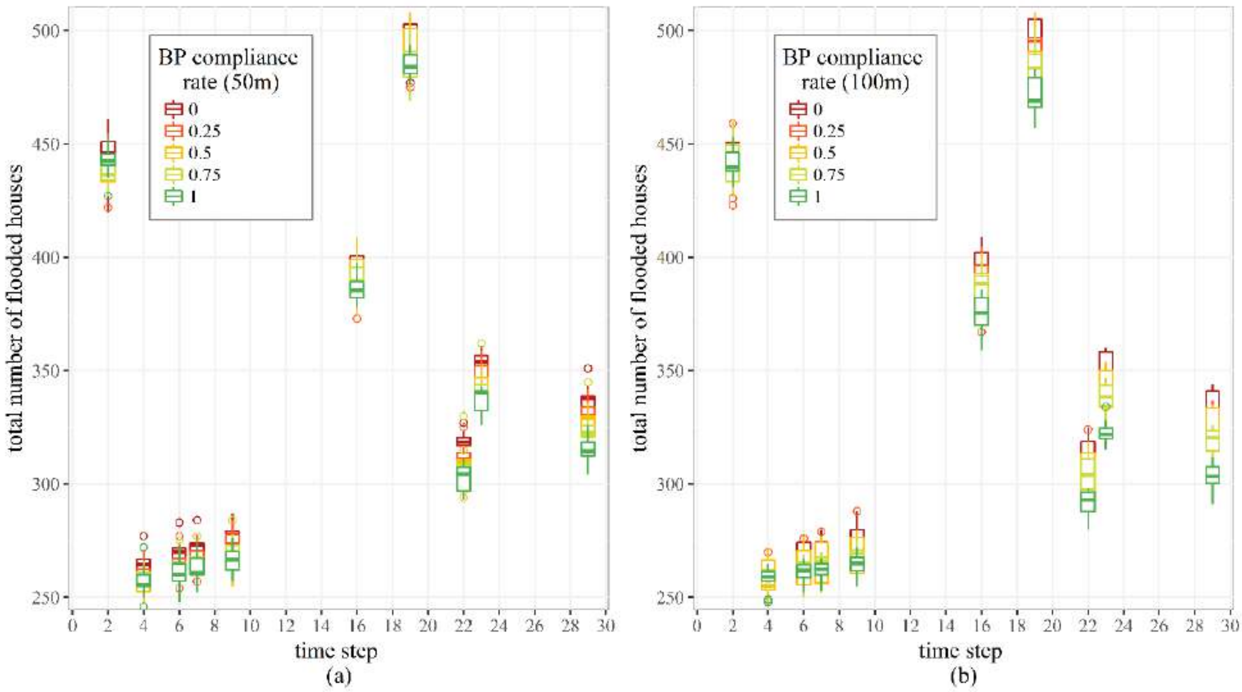

Figure 18.The effect of BP on the number of flooded houses in time. (a) and (b) show the total number of flooded houses for BP that forbids building of houses within 50m and 100m of the coastline, respectively, and for BP compliance rates between 0 and 1 in both cases. Except the BP compliance rates, all the other parameters were kept the same.

5.4 Coupled ABM-flood model in the case of Hamburg, Germany

We develop a coupled ABM-flood model to evaluate households' flood vulnerability reduction behaviour for the FRM case of Wilhelmsburg, a quarter of Hamburg, Germany. The Wilhelmsburg quarter is built on a river island formed by the branching River Elbe, as shown in Figure 19. Most areas in Wilhelmsburg are just above sea level. Thus, flood defence ring of dykes and floodwalls protect the quarter. In 1962, a hurricane-induced storm surge (5.70 m above sea level) overtopped and breached the dykes, and more than 200 people lost their lives and properties were damaged due to coastal flooding in Wilhelmsburg (Munich RE, 2012). As a result, the authorities heightened and reinforced the coastal defence system.

Residents have high reliance on the dyke protection system. The reliance on public protection is promoted by the authorities, who do not encourage the implementation of individual flood risk reduction measures referring to the strength of the dyke system. On the other hand, the authorities disseminate warning and evacuation strategies to the public, acknowledging that there can be a flood in future. There is a probability that a storm surge bigger than the design period of the coastal defence may occur in the future, and climate change and sea level rise may even intensify the event. Hence, protecting houses from flooding should not necessarily be the responsibility of the authorities. Households should also have a protection motivation that leads to implementing measures to reduce flood risk.

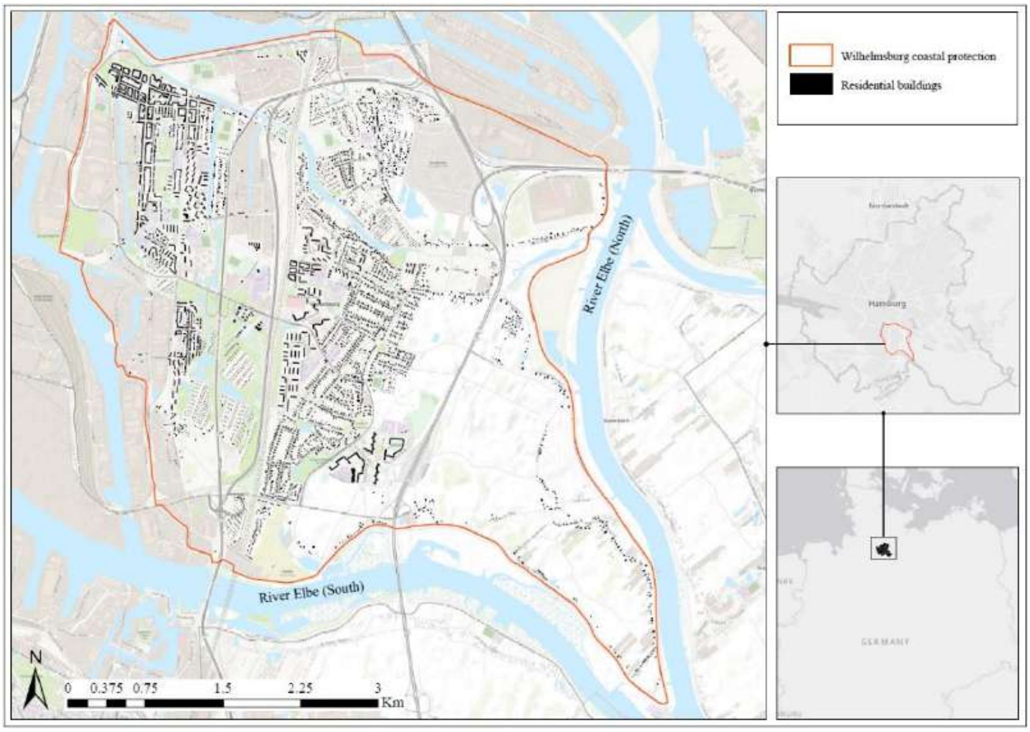

Figure 19. A map of the study area of Wilhelmsburg. The red polygon shows Wilhelmsburg's coastal protection ring of dykes and walls. The study focuses on residential housings within the protected area. The buildings shown in the map are only those that are part of the model conceptualisation. The inset maps in the right show the map of Germany (bottom) and Hamburg (top). (Source: the base map is an ESRI Topographic Map).

5.4.1 CLAIM decomposition and model setups

Here also, we use the CLAIM framework to decompose and structure the FRM case of Wilhelmsburg as CLAIM provides the means to explicitly conceptualise household behaviour and decision making, households interaction among themselves and with floods, and institutions that shape household behaviour. The agents, institutions and urban environment components of the CLAIM framework are part of the ABM. The hydrologic and hydrodynamic processes and some part of the urban environment are included in the flood model. There is no external institution conceptualised in this model. Although there is a European Union Floods Directive that requires member states such as Germany to take measures to reduce flood risk, it does not specify the type of measure implemented. In Wilhelmsburg, the authorities invest primarily on the dyke system; hence the implications of the Floods Directive on individual adaptation measure is not relevant in this study.

5.4.2 Agent-based model setup

Agents: we identified two types of agents – the household and the authority agents.

- The household agents are representations of the residents of Wilhelmsburg. These agents live in residential houses. The actions they pursue include assessing the flood threat, decision on coping alternatives, implementing adaptation measure, and assessing direct damage. The agent attributes related to flood threat assessment are flood experience, reliance on public protection, perception of climate change and source of information about flooding. The attributes related to the coping decision making are direct flood experience, house ownership and household income.

- The authority agent represents the relevant municipal and state authorities that have the mandate to manage flood risk in Wilhelmsburg. This agent does not have a spatial representation in the ABM. The only action of this agent is to provide subsidies to household agents based on the policy lever defined in the experimental setup of the ABM.

Urban environment: The Wilhelmsburg quarter that is surrounded by the ring of dykes and walls defines the urban environment (see Figure 19). The household and authority agents live and interact in this environment. In our conceptualisation, we focus only on household behaviour to protect their houses. Therefore, the only physical artefacts explicitly included in the conceptual model are residential houses, which spatially represent the household agents in the ABM. Houses also have types, which are classified based on “the type of building, occupancy of the ground floor and the type of facing of the building.” (Ujeyl and Rose, 2015, p.1540006–6). If a house is flooded, the potential building and contents damages of the house are computed in monetary terms based on the house type. A raster file represents the urban environment, and if floods occur, agents obtain information about flood depth at their house from the environment.

Institutions: There is no institution, formal or informal, that influence household behaviour to reduce vulnerability. As a result, we will test hypothetical shared strategies that may have some effect on household agents flood risk. The institution related to the authority agent is that the agent may give subsidies, but it is not obliged to do so and faces no sanction if it decides not to provide subsidies. In our conceptualisation, households implement a specific primary measure or a secondary flood mitigation measure based on the category of a house they occupy. For example, as most single-family houses in Wilhelmsburg have two or three floors, household agents that live in such houses install utilities such as heating, energy, gas and water supply installations in higher floors. Household agents that live in bungalows implement flood adapted interior fittings such as walls and floors made of waterproofed building materials. Agents that live in garden houses and apartment/high-rise buildings implement flood barriers. The barriers implemented by garden houses are sandbags and water-tight windows and door sealing while the latter implement flood protection walls. Household agents that have already implemented a primary measure may also implement a secondary measure. This measure is adapted furnishing, which includes moving furniture and electrical appliances to higher floors. As most bungalows and garden houses are single-storey housings, they do not implement adapted furnishing.

5.4.3 *Flood model setup*

Hydrologic and hydrodynamic processes: Located in the Elbe estuary, the main physical hazard that poses a risk on Wilhelmsburg is storm surge from the North Sea. If the surge is high or strong enough to overtop, overflow or breach the dykes, a coastal flood occurs. The study only considers surge induced coastal flooding due to dyke overtopping and overflows.

Urban environment: The dyke system is implicitly included in the hydrodynamic processes to set up the boundary conditions of overflow and overtopping discharge that causes coastal flooding. The conceptualization does not include any other infrastructure.

The flood model in this study is based on extreme storm surge scenarios and two-dimensional (2D) hydrodynamic models explained in (Naulin et al., 2012; Ujeyl and Rose, 2015). The three storm surge events – Event A, Event B and Event C – used in this study has a peak water level of 8.00 m, 7.25 m and 8.64 m, respectively (Naulin et al., 2012). Numerical 2D hydrodynamic models are used to calculate water levels and wave stages around the dyke ring. In turn, these data are used to compute the overflow and wave overtopping discharges for the three scenarios.

To assess the flood hazard from the three scenario events, flood models that simulate coastal flooding are implemented. The model is developed using the MIKE21 unstructured grid modelling software (DHI, 2017c). The output of the hydrodynamic model relevant for the current study is the inundation map showing the maximum flood depth in Wilhelmsburg. This is because the main factor that significantly contributes to building and contents damage is the flood depth (Kreibich and Thieken, 2009).

5.4.4 *Coupled model factors and setup*

The input factors of the coupled ABM-flood model are grouped into two. The first group includes the initial conditions and parameters that are regarded as control variables. These include the initial percentages of households with flood experience, households with climate change perception, households occupying own house, households with high income and source of information. Varying these factors is not of interest for the model experimentation. The second group comprises of factors that are used to set up model experimentation and to evaluate the effect of household adaptation measures in FRM. These include subsidy parameter, shared strategy parameter, secondary measure parameter, social network threshold, mitigation measures adaptation duration and delay parameter. The flood event scenario, which is a randomly generated storm surge events series, is also in this group.

The simulation period of the ABM is 50 time steps in which each time step represents a year. The number of household agents is 7859. Every simulation of parameter combinations is replicated 3000 times.

5.4.5 *Simulation execution and results*

We design an ABM experimentation to test the effect of the institutions on the adaptation behavior of agents and the related risk mitigation. For that purpose, we set up the values of some parameters as follows:

- The subsidy lever is varied between 1 and 3 with a step of 1 in which 1, 2 and 3 represent no subsidy, subsidy only for flooded household agents and subsidy for all agents that consider flood as a threat, respectively.
- A delay parameter is varied between 1 and 10 with a step of 2. The delay parameter represents the average number of years agents take to actually implement a primary measure.
- A secondary measure parameter is varied between 0 and 0.6 with a step of 0.2. The parameter determines a percentage of agents that implement secondary measures.
- We evaluate two flood event scenarios by varying the time steps when the three flood events take place.

Impacts of subsidies: The cumulative number of implemented primary measures plotted in Figure 20 shows that providing subsidies increases the protection motivation behaviour of agents irrespective of the flood event scenarios. For example, in the case of Scenario 1 flood event series, the building damage mitigated increases by about 130% when a subsidy is provided to agents. However, giving subsidies either only to flooded agents or to all agents does not have a difference in the coping responses of agents. That is depicted by the overlapping curves of $SS = 2$ and $SS = 3$ in Figure 20. The result can be justified by the fact that (i) the subsidies only affect agents that implement permanent measures; and (ii) when a big flood event happens, it floods most of the agents, essentially levelling the number of agents impacted by $SS = 2$ and $SS = 3$.

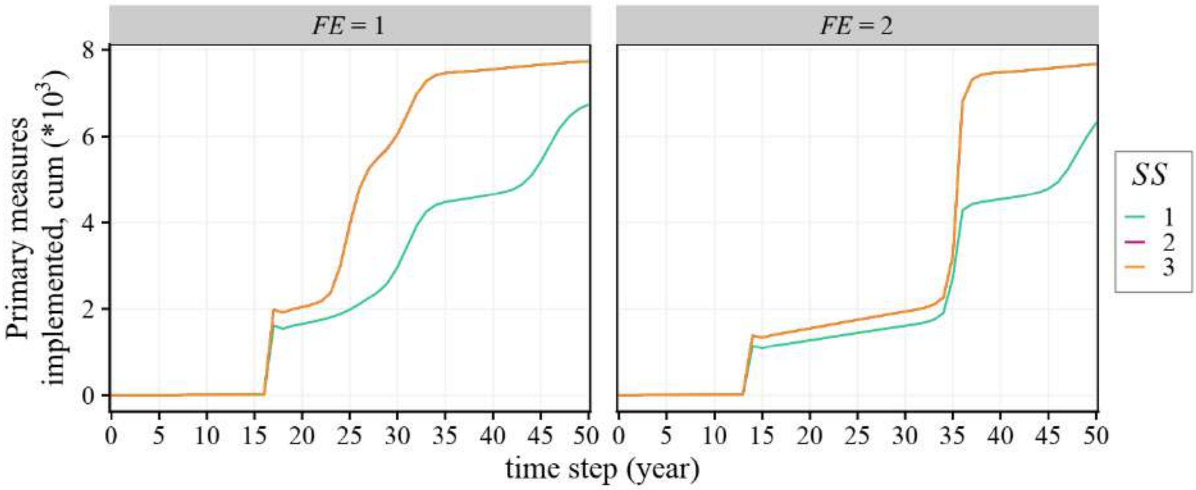

Figure 20. Impacts of subsidy on the adaptation behaviour of agents. The subsidy levers 1, 2 and 3 represent no subsidy, subsidy only for flooded household agents and subsidy for all agents that consider flood as a threat, respectively. The left and right panels show simulation results with flood events scenarios of 1 and 2, respectively.

Impacts of delay parameter: As shown in Figure 21, the percentage of agents that transform the coping behaviour to action decreases as the value of the delay parameter increases. When $DP = 1$, all agents that developed coping behaviour implement adaptation measures at the same time step. However, when $DP = 9$ (i.e., when the probability that a coping agent will implement a measure at a given year is $1/9$), the number of agents that implement measures is 75% of the number that develop a coping behaviour by the end of the simulation period.

Furthermore, both the number of coping agents and agents that implemented measures decreases with increase in DP value. For example, when $FE = 2$ and the value of DP increases from 1 to 9, the numbers of coping agents and agents that implemented a primary measure drop by about 27% and 48%, respectively, at $time\ step = 50$. This also has a knock-on effect on the implementation of a secondary measure, which reduces by about 50%. Based on the outputs of the simulations, the delayed implementation of measures reduces the potential building and contents damage that could have been mitigated by €36.3 million and €8.7 million, respectively.

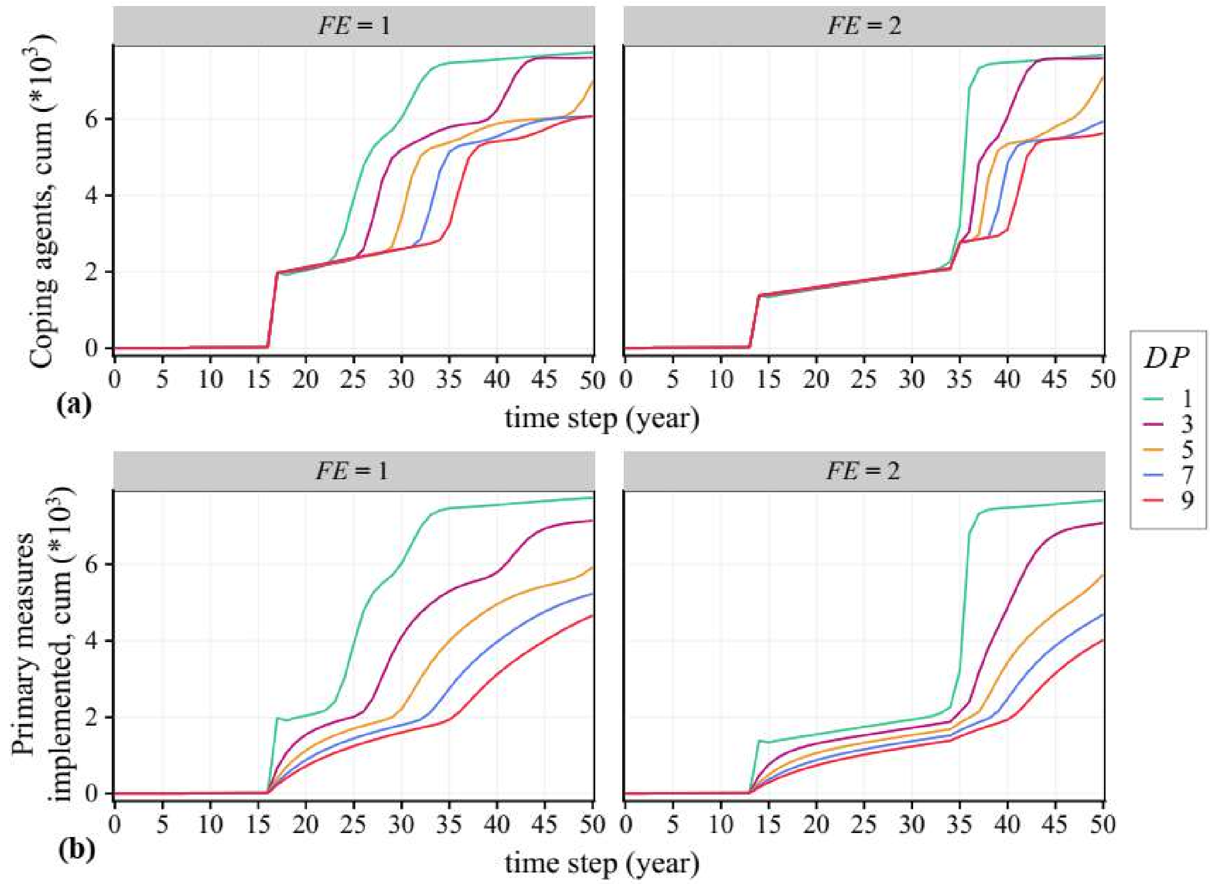

Figure 21. Impacts of the delay parameter on the adaptation behavior of agents. (a) shows the coping behavior of agents and (b) shows the cumulative number of agents that converted their coping behavior to action, i.e., implement primary adaptation measures. Simulations that generated the results are set with $SS = 2$. The left and right panels show simulation results with flood events scenarios of 1 and 2, respectively.

Impacts of secondary measure parameter: Figure 22 (a) shows that the cumulative number of agents that implemented secondary measure increases as the parameter value increases. But, the rate of increase in secondary measure implemented is marginal especially for $SMP \geq 0.4$, in both cases of subsidy levers. When flooded agents receive a subsidy, secondary measure implemented increases by about 1000 agents compared to the policy lever with no subsidy. Although the subsidy does not directly affect the implementation of secondary measures, it increases the implementation of primary measures, which in turn, increases secondary measure implemented. The only exception is when $SMP = 0$; in that case, no agent implement secondary measure despite the subsidy lever.

Similarly, Figure 22 (b) shows that the contents damage mitigated increases marginally with the increase in the SMP value. The damage mitigated when $SMP = 0$ is because some agents implemented flood adapted interior fittings, which are classified as primary measures, and these measures mitigate both building and contents damages. When there is a subsidy, the contents damage mitigated increases by about three folds for each of the SMP values, except $SMP = 0$, compared to the policy lever with no subsidy.

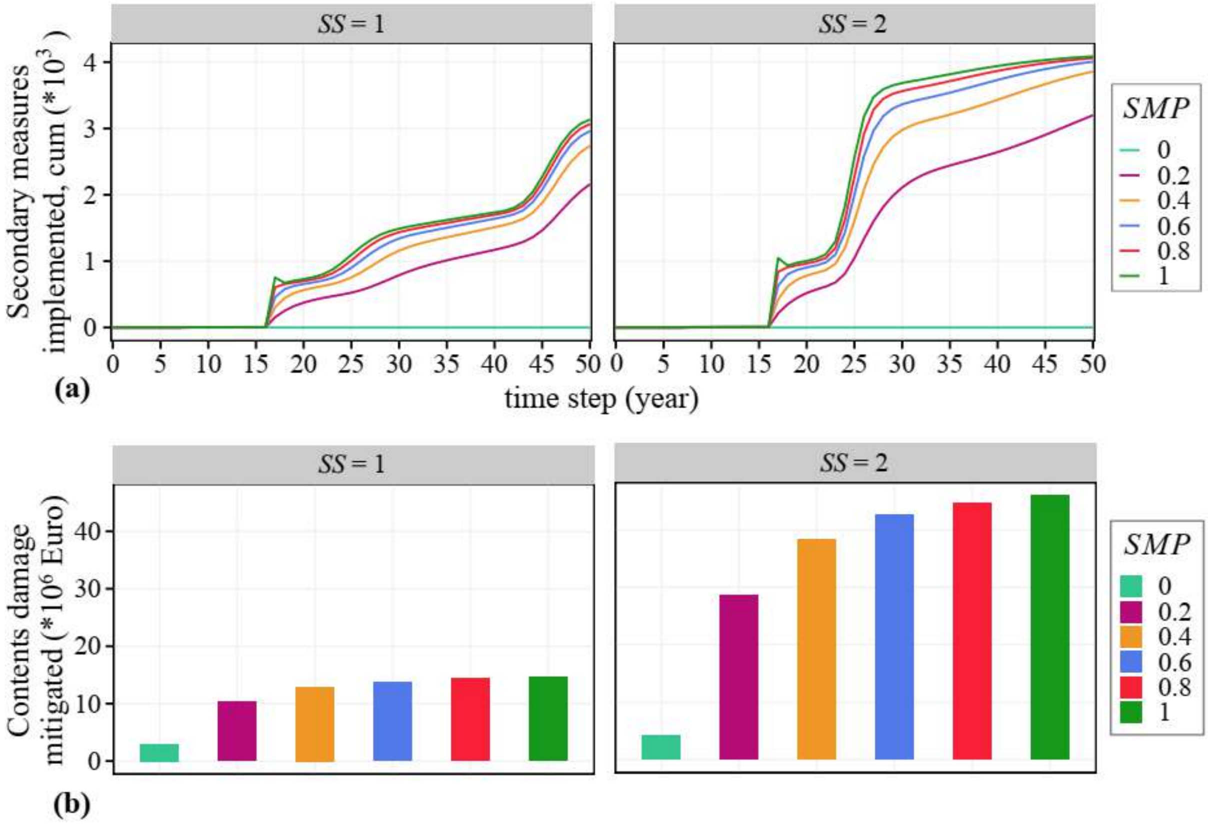

Figure 22. Impacts of the secondary measure parameter on the adaptation behavior of agents. (a) shows the cumulative number of secondary measures implemented, and (b) shows the potential contents damage mitigated. The left and right panels show simulation results without subsidies and with subsidies for flooded agents, respectively.

5.5 Extending CLAIM to model NBSs

Some of the important characteristics of CLAIM are that:

- CLAIM provides a *holistic* conceptualization and modelling of the human-flood interaction by incorporating the five main elements of a coupled human-flood system (i.e., agents, institutions, urban environment, physical processes that generate flood and external factors)
- CLAIM is designed to be as *generic* as possible so that it does not constrain the conceptualization of a specific case study. The level of representation of each element during conceptualization varies based on the problem that is modelled, the modeller's knowledge of the case study and the availability of data, among other factors.
- CLAIM provides the means to *explicitly* model the human and flood subsystems using knowledge from the respective domains, and link the two subsystems dynamically to study their interactions.

The holistic, generic and explicit design of CLAIM is an advantage in extending its use for modelling NBSs as a bridge between the human and nature (or environment) interaction. For example, in the case of Sint Maarten, a bigger flood event may cause major flooding as shown in Figure 23. To reduce the risk of such flooding, the government may implement NBS measures such as a detention basin and channel restorations as shown in Figure 24 and Figure 25. These measures are considered as policy implementations, which a government agent executes before (as in a proactive planning) or after (as in a reactive planning) in an ABM. The government agent may also draft a policy so that individual agents must implement green roofs when they build new houses. The green roofs can also be introduced as shared strategies in which household agents implement the measures when the majority of the agents in the island implement the measure. In such a case, agent interaction can be conceptualised using a network analysis.

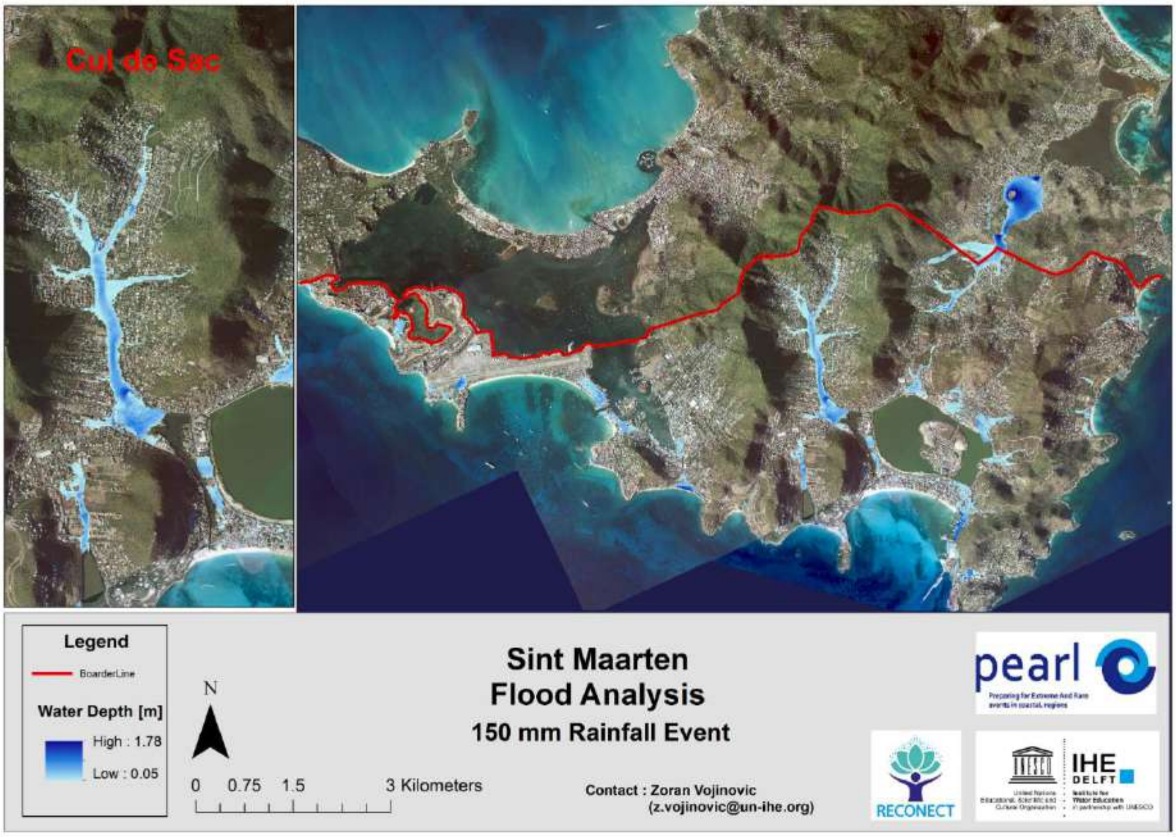

Figure 23. Flood map for a 150mm/hr rainfall event in the Caribbean island of Sint Maarten. The left panel shows the Cul de Sac area, which suffers major floodings.

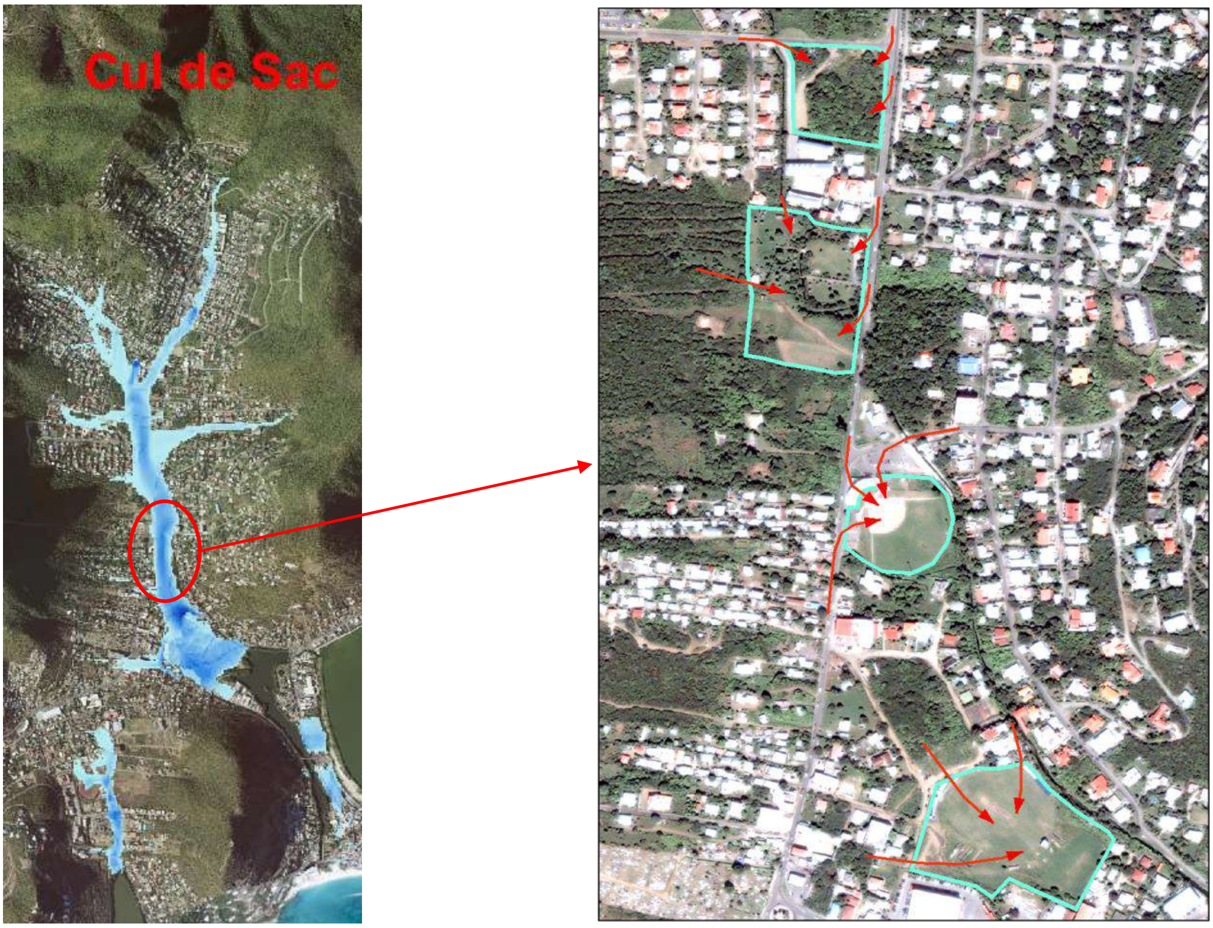

Figure 24. Potential locations of detention basins in the Cul de Sac area, Sint Maarten

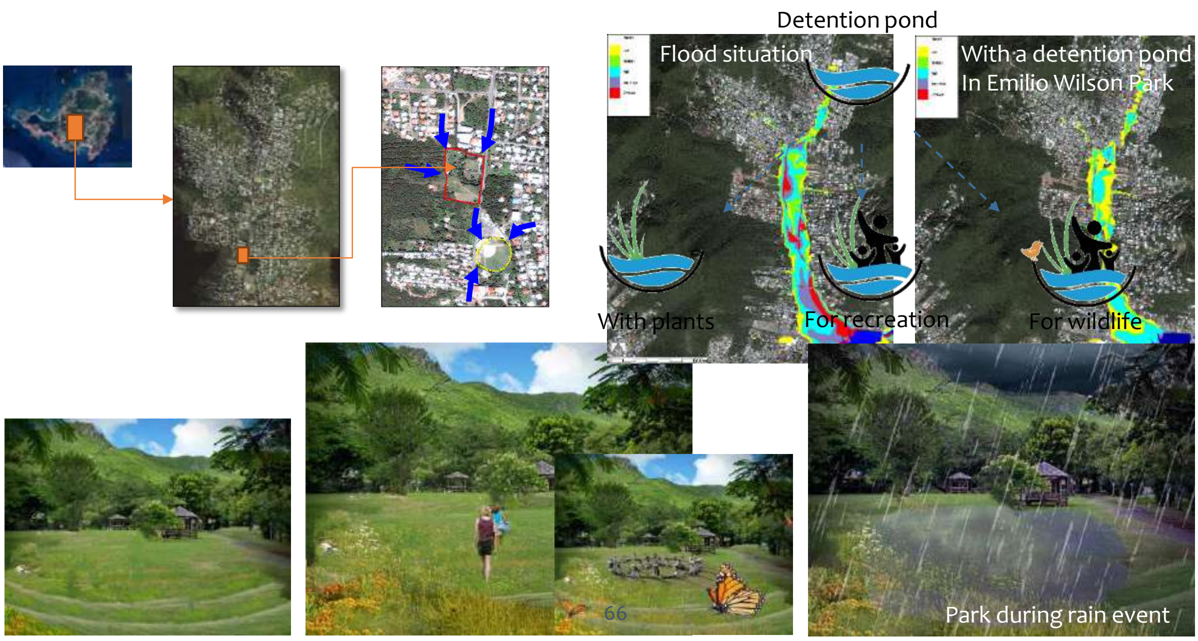

Figure 25. Examples of detention basins in the Cul de Sac area, Sint Maarten

If the NBS are multi-purpose, for example if they are implemented to mitigate multiple hazards or if they are also used for an ecological service, all related institutions can be conceptualised with CLAIM. For example, Figure 26 shows potential large scale NBS measures such as seagrass bed restoration, mangrove restoration and artificial reefs can be used to mitigate coastal flooding while providing necessary ecological services in Sint Maarten.

Figure 26. Examples of NBS measures along the coastline area, Sint Maarten

CLAIM can be used as a prototype to conceptualize the interaction of humans (decisions, actions) with all the hydro-meteorological hazards, ecosystem services and the NBS. For example, in a human-flood-ecosystem interaction study, one way of extending CLAIM is by incorporating *coastal ecosystem* and *ecological processes* as illustrated by Figure 27. The coastal ecosystem, especially the near-shore ecosystem, is where mangroves and seagrass grow and coral reefs are constructed to reduce coastal flooding in urban areas. The coastal ecosystem can be described by ecological processes such as physical, chemical and biological processes. These processes include energy flux (such as photosynthesis), carbon flux and nutrients flux. These processes are important in providing *ecological services*. *Agents* affect the coastal ecosystem through their action such as pollution and over utilization of services. These actions are governed by institutions such as coastal zone management and water quality management policies (for example, the EU Water Framework Directive[7], the EU Recommendation on Integrated Coastal Zone Management[8] and the US Shore Protection Act[9]). The ecosystems also define agents' states through the services (for example, the amount of fish an agent catches or mangrove woods harvested).

[7] https://ec.europa.eu/environment/water/water-framework/index_en.html
[8] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32002H0413
[9] https://www.epa.gov/laws-regulations/summary-shore-protection-act

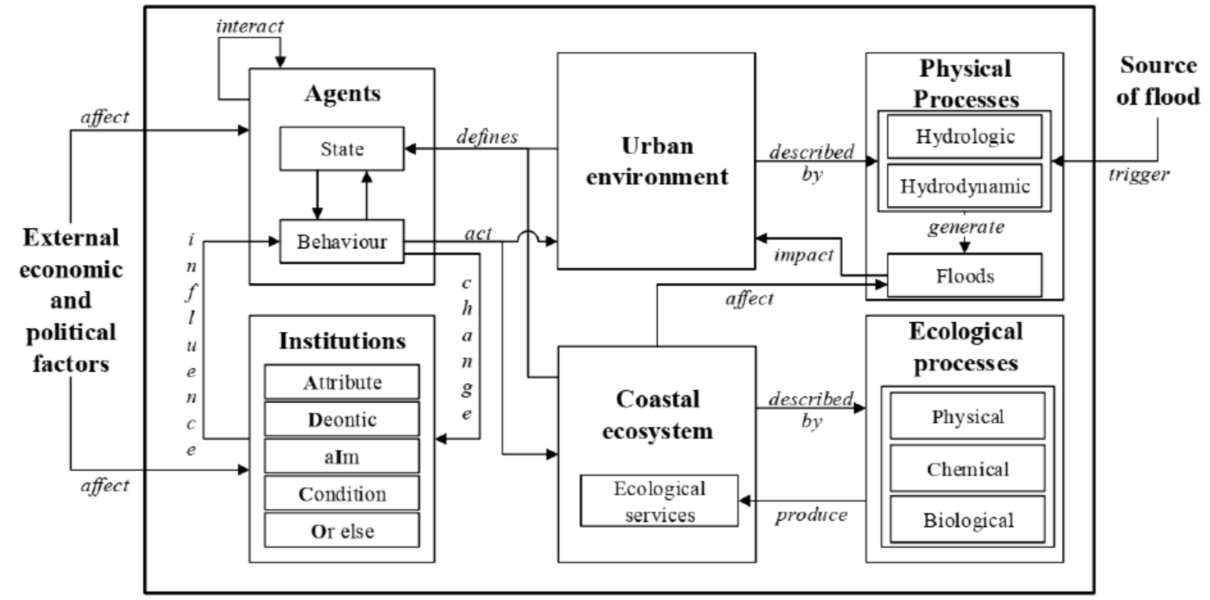

Figure 27. Extended CLAIM framework showing interactions among humans (agents and institutions), their urban environment, coastal ecosystem, the ecological processes that produce ecological services, the physical processes that generate flood, and external factors.

6 Outlook of CAS application to NBS

After developing conceptual models, converting such models to an ABM software is a daunting task. The main reason is the “nature” of the ABM modelling paradigm. In hydrodynamic modelling, 2D surface water flow in any case study can be modelled using the shallow water equations – a mass equation and two momentum equations in the x and y directions. If a modeller knows the initial conditions, the boundary conditions and the model parameter values of any study area, an off-the-shelf hydrodynamic modelling software such as MIKE21 solves the equations numerically and provide outputs such as water level and discharge at each computational cell. Unfortunately, there is no universal way of describing human behaviour in an ABM, especially considering heterogeneous agents and their interactions. In fact, there is no such ABM software. There are only ABM development environments such as NetLogo and Repast Simphony that gives the platform to write lines of codes that describe the conceptual model. Thus, developing ABM software requires a “certain” level of programming skills. In relation to that, using different ABM development platform requires knowledge of different programming languages. For example, NetLogo uses a simplified logo language while Repast Simphony uses the Java programming language. Besides, as every case is different, the modeller needs to develop the ABM software for every case.

In addition, modelling human-water interactions certainly requires an understanding of the scientific knowledge such as the phenomena to be modelled (for example, a flood event and its impact), underlying physical laws and scientific concepts (for example, flow equations and protection motivation theory) and statistical methods to analyse model outputs. However, subjective considerations that are gained through observation and experience are also important. In coupled ABM-flood modelling, the level of subjective considerations while developing the individual models varies considerably. In numerical flood modelling, as there are governing shallow water equations that define 1D and 2D flows, the room for subjectivity is relatively low. Modellers may benefit from prior experience but model schematization, including time and space discretization, should satisfy stability conditions. In contrast, the ABM paradigm requires more personal judgement, creativity and imagination than hydrodynamic modelling. Starting from the model conceptualization to the software implementation and results analysis, the ABM is prone to the subjective interpretation of the modeller. An element one modeller considers as an important aspect can be conceptualised as an assumption by another, which would essentially create a different model. Hence, an ABM model development would benefit from a team of modellers and problem owners participating in every stage to reduce the subjective bias of a single modeller.

Another important aspect is conceptualizing and modelling two complex subsystems, i.e., the human and flood subsystems, which in turn comprise further complex subsystems requires a 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). Data for model validation is also a significant aspect to consider when setting up such models. In addition to the large data sets needed to build each model, running simulations may require substantial computational resources in which both models contribute. Urban flood modelling using 2D hydrodynamic models present a high computational cost due to the smaller time step required to overcome simulation instability. Whereas, in the case of ABMs, the computational demand is related to a large number of repetitions and experiments required to evaluate the model setup.

Visualization and stakeholder's engagement

As part of this work, we also aim to build an interactive visualisation tool akin to a decision support system or possibly a serious game accessible from one's computer at home. This visualisation tool would be invaluable because it would allow participants to explore the whole array of policies available to different types of agents, and understand their combined effects on the system.

We plan to use one of the partners past experience developing similar tools, i.e. the Millbrook serious game (Khoury et al., 2018) shown in Figure 28 where participants were able to observe that changing crops in the neighbouring farms is cheaper and has a much greater effect than changing the water pipe infrastructure under the village to contain future flooding events.

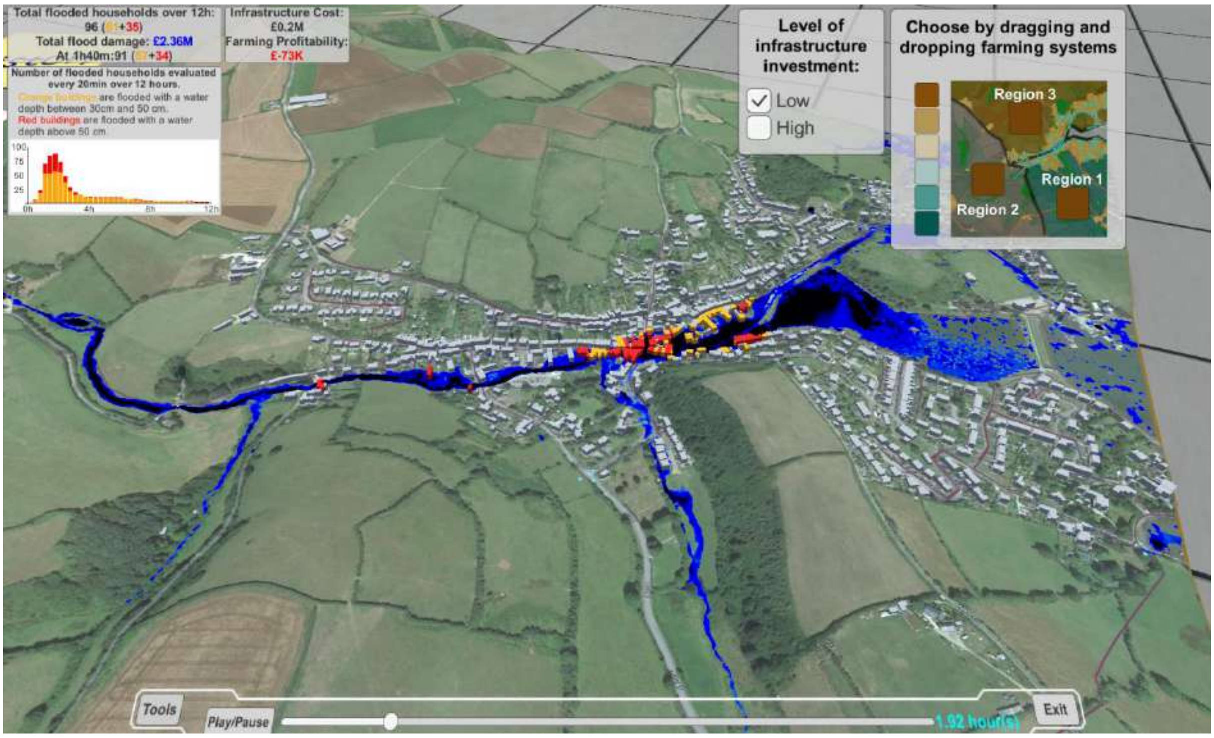

Figure 28. The Millbrook Serious Game screenshot – developed in 2017 by the University of Exeter

Initially, the visualisation can be built by using the data and modelling results derived from the Hamburg case study. Once the prototype is sufficiently refined, the visualisation can then be reasonably extended to cover a second case study with additional specifics such as the work being done for Saint Maarten.

In the context of such as decision support system, we want to look at the resulting consequences of applying policies over decades of interactions between several interdependent systems. There is therefore more to be gained by connecting various relatively “shallow” models with relatively low precision rather limiting ourselves to fewer computationally expensive models with greater individual accuracy that will be lost as soon as it is combined with other less reliable measurements. After all, the added value resides mainly in the integration of the multi-disciplinary aspects of the problem i.e. combining together rough estimations of ecosystem diversity, return of investment, flood damages, and socio-economic indicators that just give “order of magnitude” type of results.

We suggest a prototype combining different domains that could for example reflect the various types of agents present in the CLAIM system and their respective means of actuation e.g. for institutions it could be different taxes, for urban planning agents, different surfaces of non-permeable pavement allowed in one area, etc.

Examples of domains that can be considered are:

- Acceptance and adoption of technology
- Stakeholders behaviour for technology implementation
- Habitat enhancement/ benefits with NBS implementation – nesting models with different scales (space and time)
- Biodiversity
- Pollution control
- LUCC models – large scale for flood control (hurricane effects) – Mangroves and coastal measures

Although the area presented in the visualisation would be localised to the case study, the time line considered could focus on short term consequences (one year) perhaps of greater interest to residents, medium term consequences (5 years) that could relate to return on investment periods for businesses, and finally longer term consequences (20 years or more) that could describe impact on ecosystems and more global aspects of the system under stress.

The format of a Serious Game would make participatory modelling and engagement easier for a greater audience. Similarly, the relatively low degree of specialisation required to run “shallow” models and combine their outputs would mean that fairly generic research skills such as some experience converting data formats using scripting languages like Python would be sufficient to build the model behind the visualisation. Finally, the abundance of free software development tools makes the construction of either an online interactive visualisation or a downloadable application extremely cost effective.

References

Abar, S., Theodoropoulos, G.K., Lemarinier, P., O'Hare, G.M.P., 2017. Agent Based Modelling and Simulation tools: A review of the state-of-art software. Computer Science Review 24, 13–33. https://doi.org/10.1016/j.cosrev.2017.03.001

Abdou, M., Hamill, L., Gilbert, N., 2012. Designing and Building an Agent-Based Model, in: Heppenstall, A.J., Crooks, A.T., See, L.M., Batty, M. (Eds.), Agent-Based Models of Geographical Systems. Springer, Dordrecht, The Netherlands, pp. 141–165. https://doi.org/10.1007/978-90-481-8927-4_8

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. Environmental Modelling & Software 111, 483–492. https://doi.org/10.1016/j.envsoft.2018.10.015

Ahmed, E., Hashish, A.H., 2006. On modelling the immune system as a complex system. Theory Biosci. 124, 413–418. https://doi.org/10.1016/j.thbio.2005.07.001

Allen, P.M., Strathern, M., Baldwin, J., 2008. Complexity: the Integrating Framework for Models of Urban and Regional Systems, in: Albeverio, S., Andrey, D., Giordano, P., Vancheri, A. (Eds.), The Dynamics of Complex Urban Systems: An Interdisciplinary Approach. Physica-Verlag, Heidelberg, Germany, pp. 21–41.

An, L., 2012. Modeling human decisions in coupled human and natural systems: Review of agent-based models. Ecological Modelling, Modeling Human Decisions 229, 25–36. https://doi.org/10.1016/j.ecolmodel.2011.07.010

Axelrod, R., 2006. Agent-based Modeling as a Bridge Between Disciplines, in: L. Tesfatsion, K.L. Judd (Eds.), Handbook of Computational Economics. Elsevier, pp. 1565–1584.

Balci, O., 1989. How to assess the acceptability and credibility of simulation results. In Proceedings of the 1989 Winter Simulation Conference. p. 62-71, New York, NY, USA.

Ball, P., 2012. Why society is a complex matter : Meeting twenty-first century challenges with a new kind of science. Springer, Berlin, Heidelberg.

Bankes, S.C., 2002. Agent-based modeling: A revolution? PNAS 99, 7199–7200. https://doi.org/10.1073/pnas.072081299

Barreteau, O., Bousquet, F., 2000. SHADOC: a multi-agent model to tackle viability of irrigated systems. Ann Oper Res, 94, 139–162

Barreteau, O., Bousquet, F., Millier, C., Weber, J., 2004. Suitability of multi-agent simulations to study irrigated system viability: application to case studies in the Senegal River valley. Agr Syst, 80, 255–275

Bar-Yam, Y., 1997. Dynamics of complex systems, Studies in Nonlinearity. Addison-Wesley, Reading, MA, USA.

Behdani, B., 2012. Evaluation of paradigms for modeling supply chains as complex socio-technical systems, in: Laroque, C., Himmelspach, J., Pasupathy, R., Rose, O., Uhrmacher, A.M. (Eds.), Proceedings of the 2012 Winter Simulation Conference (WSC). Presented at the Proceedings of the 2012 Winter Simulation Conference (WSC), Berlin, Germany, pp. 1–15. https://doi.org/10.1109/WSC.2012.6465109

Belete, G.F., Voinov, A., Laniak, G.F., 2017. An overview of the model integration process: From pre-integration assessment to testing. Environmental Modelling & Software 87, 49–63. https://doi.org/10.1016/j.envsoft.2016.10.013

Berkes, F., 2011. Restoring Unity. In World Fisheries (eds T.J. Pitcher, R.E. Ommer, R.I. Perry, K. Cochrane and P. Cury). https://doi.org/10.1002/9781444392241.ch2

Bettencourt, L.M.A., 2015. Cities as Complex Systems, in: Furtado, B.A., Sakowski, P.A.M., Tóvolli, M.H. (Eds.), Modeling Complex Systems for Public Policies. Institute for Applied Economic Research (IPEA), Brasília, Brazil, pp. 217–236.

Birkland, T.A., 2016. An introduction to the policy process: Theories, concepts, and models of public policy making. 4th Edition. Routledge, NY, USA.
Blair, P., Buytaert, W., 2016. Socio-hydrological modelling: a review asking “why, what and how?” Hydrol. Earth Syst. Sci. 20, 443–478. https://doi.org/10.5194/hess-20-443-2016
Boccara, N., 2004. Modeling complex systems, Graduate Texts in Contemporary Physics. Springer, New York, NY, USA.
Bollinger, L.A., Davis, C.B., Nikolic, I., 2013. An Agent-Based Model of a Mobile Phone Production, Consumption and Recycling Network, in: van Dam, K.H., Nikolic, Igor, Lukszo, Z. (Eds.), Agent-Based Modelling of Socio-Technical Systems, Agent-Based Social Systems. Springer Netherlands, Dordrecht, The Netherlands, pp. 221–243. https://doi.org/10.1007/978-94-007-4933-7_8
Bollinger, L.A., Nikolić, I., Davis, C.B., Dijkema, G.P.J., 2015. Multimodel Ecologies: Cultivating Model Ecosystems in Industrial Ecology. Journal of Industrial Ecology 19, 252–263. https://doi.org/10.1111/jiec.12253
Bolton, R., Foxon, T.J., 2015. A socio-technical perspective on low carbon investment challenges – Insights for UK energy policy. Environmental Innovation and Societal Transitions 14, 165–181. https://doi.org/10.1016/j.eist.2014.07.005
Bonabeau, E., 2002. Agent-based modeling: Methods and techniques for simulating human systems. PNAS 99, 7280–7287. https://doi.org/10.1073/pnas.082080899
Bostrom, R., and Heinen, J., 1977. MIS Problems and Failures: A Socio-Technical Perspective, Part II: The Application of Socio-Technical Theory. MIS Quarterly, 1(4), 11-28. https://doi.org/10.2307/249019
Brent, D.A., Gangadharan, L., Lassiter, A., Leroux, A. and Raschky, P.A., 2017. Valuing environmental services provided by local stormwater management. Water Resources Research, 53, 4907-4921. https://doi.org/10.1002/2016WR019776
Brouwers, L. and M. Boman, 2010. “A Computational Agent Model of Flood Management Strategies.” In H. A. do Prado, A. J. Barreto Luiz and H. C. Filho, eds., Computational Methods for Agricultural Research: Advances and Applications, pages 296–307. IGI Global, Hershey, USA.
Carter, B., 2014. Inclusive Institutions: Topic Guide.
Chan, S., 2001. Complex adaptive systems. ESD. 83 Research Seminar in Engineering Systems. Massachusetts Institute of Technology. pp. 1-9.
Cioffi-Revilla, C., 2014. Introduction to computational social science: Principles and Applications. London and Heidelberg: Springer.
Clarke, K.C., 2014. Cellular automata and agent-based models, in Fischer, M.M. and Nijkamp, P. (Eds), Handbook of regional science. Springer Berlin Heidelberg, pp.1217-1233.
Cohen-Shacham, E., Walters, G., Janzen, C. and Maginnis, S. (eds.), 2016. Nature-based Solutions to address global societal challenges. IUCN, Gland, Switzerland. http://dx.doi.org/10.2305/IUCN.CH.2016.13.en
Costanza, R., d'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'neill, R.V., Paruelo, J. and Raskin, R.G., 1997. The value of the world's ecosystem services and natural capital. Nature, 387, 253-260.
Crawford, S.E.S., Ostrom, E., 1995. A Grammar of Institutions. American Political Science Review 89, 582–600. https://doi.org/10.2307/2082975
Crooks, A.T., Castle, C.J.E., 2012. The Integration of Agent-Based Modelling and Geographical Information for Geospatial Simulation, in: Heppenstall, A.J., Crooks, A.T., See, L.M., Batty, M. (Eds.), Agent-Based Models of Geographical Systems. Springer, Dordrecht, The Netherlands, pp. 219–251. https://doi.org/10.1007/978-90-481-8927-4_12

Crooks, A.T., Heppenstall, A.J., 2012. Introduction to Agent-Based Modelling, in: Heppenstall, A.J., Crooks, A.T., See, L.M., Batty, M. (Eds.), Agent-Based Models of Geographical Systems. Springer, Dordrecht, The Netherlands, pp. 85–105.

Dawson, R.J., Peppe, R., Wang, M., 2011. An agent-based model for risk-based flood incident management. Nat Hazards 59, 167–189. https://doi.org/10.1007/s11069-011-9745-4

Detsis, V., Briassoulis, H., Kosmas, C., 2017. The Socio-Ecological Dynamics of Human Responses in a Land Degradation-Affected Region: The Messara Valley (Crete, Greece). Land 6, 45. https://doi.org/10.3390/land6030045

DHI, 2017a. MIKE FLOOD: 1D-2D User Manual. MIKE Powered by DHI, Hørsholm, Denmark.

DHI, 2017b. MIKE11: A Modelling System for Rivers and Channels - Reference Manual. MIKE Powered by DHI, Hørsholm, Denmark.

DHI, 2017c. MIKE21 Flow Model FM: Hydrodynamic Module User Guide. MIKE Powered by DHI, Hørsholm, Denmark.

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Salinas, J.L., Blöschl, G., 2013. Socio-hydrology: conceptualising human-flood interactions. Hydrol. Earth Syst. Sci. 17, 3295–3303. https://doi.org/10.5194/hess-17-3295-2013

Dijkema, G.P.J., Lukszo, Z., Weijnen, M.P.C., 2013. Introduction, in: van Dam, K.H., Nikolic, I., Lukszo, Zofia (Eds.), Agent-Based Modelling of Socio-Technical Systems, Agent-Based Social Systems. Springer Netherlands, Dordrecht, The Netherlands, pp. 1–8. https://doi.org/10.1007/978-94-007-4933-7_1

Drummond, M.A., Auch, R.F., Karstensen, K.A., Sayler, K.L., Taylor, J.L., Loveland, T.R., 2012. Land change variability and human–environment dynamics in the United States Great Plains. Land Use Policy 29, 710–723. https://doi.org/10.1016/j.landusepol.2011.11.007

Dubbelboer, J., I. Nikolic, K. Jenkins and J. Hall, 2017. An Agent-Based Model of Flood Risk and Insurance. JASSS 20 (1), 6. DOI: 10.18564/jasss.3135.

Dye, T.R., 2013. Understanding public policy. 14th Editions. Pearson, Englewood Cliffs, NJ.

Essenfelder, A.H., Pérez-Blanco, C.D., Mayer, A.S., 2018. Rationalizing Systems Analysis for the Evaluation of Adaptation Strategies in Complex Human-Water Systems. Earth’s Future 6, 1181–1206. https://doi.org/10.1029/2018EF000826

EU, 2013. Mapping and Assessment of Ecosystems and their Services: An analytical framework for ecosystem assessments under Action 5 of the EU Biodiversity Strategy to 2020. Technical Report - 2013 – 067. European Union. https://ec.europa.eu/environment/nature/knowledge/ecosystem_assessment/pdf/MAESWorkingPaper2013.pdf

EU, 2015. Towards an EU Research and Innovation policy agenda for Nature-Based Solutions & Re-Naturing Cities Final Report of the Horizon 2020 Expert Group on 'Nature-Based Solutions and Re-Naturing Cities'. European Union

Felgenhauer, T. and Webster, M., 2013. Multiple adaptation types with mitigation: a framework for policy analysis. Global Environmental Change, 23(6), 1556-1565.

Feuillette, S., Bousquet, F., Le Goulven, P., 2003. SINUSE: a multi-agent model to negotiate water demand management on a free access water table. Environ Model Software 18, 413–427

Filatova, T., Verburg, P.H., Parker, D.C., Stannard, C.A., 2013. Spatial agent-based models for socio-ecological systems: Challenges and prospects. Environmental Modelling & Software, Thematic Issue on Spatial Agent-Based Models for Socio-Ecological Systems 45, 1–7. https://doi.org/10.1016/j.envsoft.2013.03.017

Forrester, J.W., 2007. System dynamics—a personal view of the first fifty years. System Dynamics Review, 23(2/3), 345-358. https://doi.org/10.1002/sdr.382

Frantzeskaki, N., 2019. Seven lessons for planning nature-based solutions in cities. Environmental science & policy, 93, 101-111. https://doi.org/10.1016/j.envsci.2018.12.033

Furtado, B.A., Sakowski, P.A.M. and Tóvolli, M.H., 2015. A Complexity approach for public policies, in: Furtado, B.A., Sakowski, P.A.M. and Tóvolli, M.H. (Eds.), Modeling complex systems for public policies. IPEA, Brasilia, Br, pp. 17–35

Ge, J., & Polhill, G. (2020). Agent-based Models of Coupled Social and Natural Systems. In N. Sang (Ed.), Modelling Nature-based Solutions: Integrating Computational and Participatory Scenario Modelling for Environmental Management and Planning (pp. 56-81). Cambridge: Cambridge University Press. doi:10.1017/9781108553827.003

Gentile, J.E., Glazner, C., and Koehler, M., 2015. Simulation models for public policy, in: Furtado, B.A., Sakowski, P.A.M., Tóvolli, M.H. (Eds.), Modeling Complex Systems for Public Policies. Institute for Applied Economic Research (IPEA), Brasília, Brazil, pp. 73–83.

Ghorbani, A., 2013. Structuring Socio-technical Complexity: Modelling Agent Systems using Institutional Analysis. Delft University of Technology, Delft, The Netherlands.

Ghorbani, A., Bots, P., Dignum, V., Dijkema, G., 2013. MAIA: a Framework for Developing Agent-Based Social Simulations. JASSS 16, 9. https://doi.org/10.18564/jasss.2166

Gilbert, N. and Troitzsch, K., 2005. Simulation for the social scientist. 2nd Edition, Open University Press, Berkshire, England.

Gilbert, N., Terna, P., 2000. How to build and use agent-based models in social science. Mind & Society 1, 57–72. https://doi.org/10.1007/BF02512229

Glaser, M., Christie, P., Diele, K., Dsikowitzky, L., Ferse, S., Nordhaus, I., Schlüter, A., Schwerdtner Mañez, K., Wild, C., 2012. Measuring and understanding sustainability-enhancing processes in tropical coastal and marine social–ecological systems. Current Opinion in Environmental Sustainability, Aquatic and marine systems 4, 300–308. https://doi.org/10.1016/j.cosust.2012.05.004

Gordon, D.M., 2002. The organization of work in social insect colonies. Complexity 8, 43–46. https://doi.org/10.1002/cplx.10048

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S.K., Huse, G., Huth, A., Jepsen, J.U., Jørgensen, C., Mooij, W.M., Müller, B., Pe'er, G., Piou, C., Railsback, S.F., Robbins, A.M., Robbins, M.M., Rossmanith, E., Rüger, N., Strand, E., Souissi, S., Stillman, R.A., Vabø, R., Visser, U., DeAngelis, D.L., 2006. A standard protocol for describing individual-based and agent-based models. Ecological Modelling 198, 115–126. https://doi.org/10.1016/j.ecolmodel.2006.04.023

Grimm, V., Berger, U., DeAngelis, D.L., Polhill, J.G., Giske, J., Railsback, S.F., 2010. The ODD protocol: A review and first update. Ecological Modelling 221, 2760–2768. https://doi.org/10.1016/j.ecolmodel.2010.08.019

Gurung, T.R., Bousquet, F., Trébuil, G., 2006. Companion modeling, conflict resolution, and institution building: sharing irrigation water in the Lingmuteychu watershed, Bhutan. Ecol Soc, 11(2), 36

Haasnoot, M., Kwakkel, J.H., Walker, W.E., 2012. Designing Adaptive Policy Pathways for Sustainable Water Management under Uncertainty: Lessons Learned from Two Cases Paper presented at the Third International Engineering Systems Symposium CESUN 2012, Delft, the Netherlands, 18-20 June, 2012

Haer, T., Botzen, W. J. W. and Aerts, J. C. J. H., 2016. The effectiveness of flood risk communication strategies and the influence of social networks - Insights from an agent-based model. Environ. Sci. Policy, 60, 44-52. DOI: 10.1016/j.envsci.2016.03.006.

Harden, C.P., 2012. Framing and Reframing Questions of Human-Environment Interactions. Ann. Assoc. Am. Geogr. 102, 737–747. https://doi.org/10.1080/00045608.2012.678035

Heckbert, S., Baynes, T., Reeson, A., 2010. Agent-based modeling in ecological economics. Annals of the New York Academy of Sciences 1185, 39–53. https://doi.org/10.1111/j.1749-6632.2009.05286.x
Hoffmann, M., Kelley, H., Evans, T., 2002. Simulating land-cover change in south-central Indiana: an agent-based model of deforestation and afforestation. In: Janssen MA (ed) Complexity and ecosystem management: the theory and practice of multi-agent systems. Edward Elgar, Cheltenham, 218–247
Holland, J.H., 2006. Studying Complex Adaptive Systems. Jrl Syst Sci & Complex 19, 1–8. https://doi.org/10.1007/s11424-006-0001-z
Holland, J.H., 2014. Complexity: A Very Short Introduction. Oxford University Press, Oxford, United Kingdom.
Janssen, M.A., 2007. Coordination in irrigation systems: an analysis of the Lansing–Kremer model of Bali. Agr Syst, 93, 170–190
Jenkins, K., Surminski, S., Hall, J. and Crick, F. 2017. Assessing surface water flood risk and management strategies under future climate change: Insights from an Agent-Based Model. Sci. Total Environ., 595 (Supplement C), 159–168. DOI: 10.1016/j.scitotenv.2017.03.242.
Jennings, N.R., Wooldridge, M.J., 1998. Applications of Intelligent Agents, in: Jennings, N.R., Wooldridge, M.J. (Eds.), Agent Technology: Foundations, Applications, and Markets. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 3–28. https://doi.org/10.1007/978-3-662-03678-5_1
Jepson, W., Brown, H.L., 2014. ‘If No Gasoline, No Water’: Privatizing Drinking Water Quality in South Texas Colonias. Environ Plan A 46, 1032–1048. https://doi.org/10.1068/a46170
Karsten, H., Richard, G. and Vanek, S., 2018. Future of food. InTeGrate. https://serc.carleton.edu/196845. Accessed on Jan 29, 2013
Kay, A. 2006. The dynamics of public policy: theory and evidence. Edward Elgar Publishing, Cheltenham, UK.
Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., Cerdà, A., 2018. The superior effect of nature based solutions in land management for enhancing ecosystem services. Science of the Total Environment, 610, 997-1009. https://doi.org/10.1016/j.scitotenv.2017.08.077
Kelly, R.A., Jakeman, A.J., Barreteau, O., Borsuk, M.E., ElSawah, S., Hamilton, S.H., Henriksen, H.J., Kuikka, S., Maier, H.R., Rizzoli, A.E., van Delden, H., Voinov, A.A., 2013. Selecting among five common modelling approaches for integrated environmental assessment and management. Environmental Modelling & Software 47, 159–181. https://doi.org/10.1016/j.envsoft.2013.05.005
Khoury, M., Gibson, M.J., Savic, D., Chen, A.S., Vamvakeridou-Lyroudia, L., Langford, H., Wigley, S., 2018. A Serious Game Designed to Explore and Understand the Complexities of Flood Mitigation Options in Urban–Rural Catchments. Water 10 (12), 1885. https://doi.org/10.3390/w10121885
Koutiva, I., Makropoulos, C., 2016. Modelling domestic water demand: An agent based approach. Environmental Modelling & Software 79, 35–54. https://doi.org/10.1016/j.envsoft.2016.01.005
Kravari, K., Bassiliades, N., 2015. A Survey of Agent Platforms. JASSS 18, 11. https://doi.org/10.18564/jasss.2661
Kreibich, H., Thieken, A.H., 2009. Coping with floods in the city of Dresden, Germany. Nat Hazards 51, 423–436. https://doi.org/10.1007/s11069-007-9200-8
Kroes, P., Franssen, M., Poel, I. van de, Ottens, M., 2006. Treating socio-technical systems as engineering systems: some conceptual problems. Systems Research and Behavioral Science 23, 803–814. https://doi.org/10.1002/sres.703

Kuil, L., Carr, G., Viglione, A., Prskawetz, A., Blöschl, G., 2016. Conceptualizing socio-hydrological drought processes: The case of the Maya collapse. Water Resources Research 52, 6222–6242. https://doi.org/10.1002/2015WR018298

Laniak, G.F., Olchin, G., Goodall, J., Voinov, A., Hill, M., Glynn, P., Whelan, G., Geller, G., Quinn, N., Blind, M., Peckham, S., Reaney, S., Gaber, N., Kennedy, R., Hughes, A., 2013. Integrated environmental modeling: A vision and roadmap for the future. Environmental Modelling & Software, Thematic Issue on the Future of Integrated Modeling Science and Technology 39, 3–23. https://doi.org/10.1016/j.envsoft.2012.09.006

Lansing, J.S., Kremer, J.N., 1993. Emergent properties of Balinese water temple networks: coadaptation on a rugged fitness landscape. Am Anthropol, 95(1), 97–114

Lavalle, C., Barredo, J.I., McCormick, N., Engelen, G., White, R., Uljee, I., 2004. The MOLAND model for urban and regional growth forecast: A tool for the definition of sustainable development paths. EUR 21480 EN, JRC, European Commission. http://www.riks.nl/resources/papers/EUR_21480_2004_Moland_model.pdf

Le Bars, M., Attonaty, J-M., Ferrand, N., Pinson, S., 2005. An agent-based simulation testing the impact of water allocation on farmers' collective behaviors. Simulation, 81(3), 223–235

Levin, S.A., 1998. Ecosystems and the Biosphere as Complex Adaptive Systems. Ecosystems 1, 431–436. https://doi.org/10.1007/s100219900037

Li, W., Li, Y., 2012. Managing Rangeland as a Complex System: How Government Interventions Decouple Social Systems from Ecological Systems. Ecology and Society 17. https://doi.org/10.5751/ES-04531-170109

Lindeman, R.L. (1942), The Trophic-Dynamic Aspect of Ecology. Ecology, 23, 399-417. https://doi.org/10.2307/1930126

Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., Pell, A.N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C.L., Schneider, S.H., Taylor, W.W., 2007a. Complexity of Coupled Human and Natural Systems. Science 317, 1513–1516. https://doi.org/10.1126/science.1144004

Liu, J., Dietz, T., Carpenter, S.R., Folke, C., Alberti, M., Redman, C.L., Schneider, S.H., Ostrom, E., Pell, A.N., Lubchenco, J. and Taylor, W.W., 2007b. Coupled human and natural systems. AMBIO: a journal of the human environment, 36(8), 639-649. https://doi.org/10.1579/0044-7447(2007)36[639:CHANS]2.0.CO;2

Liu, X. and S. Lim, 2018. An agent-based evacuation model for the 2011 Brisbane City-scale riverine flood. Nat. Hazards, 94 (1), 53–70. DOI: 10.1007/s11069-018-3373-1.

Lowe, R., Urich, C., Domingo, N. Sto., Mark, O., Deletic, A. and Arnbjerg-Nielsen, K., 2017. Assessment of urban pluvial flood risk and efficiency of adaptation options through simulations — A new generation of urban planning tools. J. Hydrol., 550, 355–367. DOI: 10.1016/j.jhydrol.2017.05.009.

Lyytimäki, J. and Assmuth, T., 2015. Down with the flow: public debates shaping the risk framing of artificial groundwater recharge. GeoJournal 80, 113–127. https://doi-org.tudelft.idm.oclc.org/10.1007/s10708-014-9540-3

Macal, C.M., North, M.J., 2010. Tutorial on agent-based modelling and simulation. J of Sim 4, 151–162. https://doi.org/10.1057/jos.2010.3

Manson, S., An, L., Clarke, K.C., Heppenstall, A., Koch, J., Krzyzanowski, B., Morgan, F., O'Sullivan, D., Runck, B.C., Shook, E. and Tesfatsion, L., 2020. Methodological Issues of Spatial Agent-Based Models. Journal of Artificial Societies and Social Simulation, 23 (1). DOI: 10.18564/jasss.4174

Markard, J., Suter, M., Ingold, K., 2016. Socio-technical transitions and policy change – Advocacy coalitions in Swiss energy policy. Environmental Innovation and Societal Transitions 18, 215–237. https://doi.org/10.1016/j.eist.2015.05.003

Mayer, A. L., Shuster, W. D., Beaulieu, J. J., Hopton, M. E., Rhea, L. K., Roy, A. H., and Thurston, H. W., 2012. Building Green Infrastructure via Citizen Participation: A Six-

Year Study in the Shepherd Creek (Ohio). Environmental Practice, 14, 57–67. https://doi.org/10.1017/s1466046611000494
Medina, N., Sanchez, A., Vojinovic, Z, I Nikolic, Y. Abebe. 2020. Agent-Based Models for Water-Related Disaster Risk Management: A state-of-the-art review. International Journal of Disaster Risk Reduction. Submitted -Under Review.
Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC.
Miller, J.H., Page, S.E., 2007. Complex Adaptive Systems: An Introduction to Computational Models of Social Life. Princeton University Press, Princeton, New Jersey.
Mitchell, M., 2009. Complexity: A Guided Tour. Oxford University Press, New York, NY, USA.
Moritz, M., Laborde, S., Phang, S.C., Ahmadou, M., Durand, M., Fernandez, A., Hamilton, I.M., Kari, S., Mark, B., Scholte, P. and Xiao, N., 2016. Studying the Logone floodplain, Cameroon, as a coupled human and natural system. African Journal of Aquatic Science, 41(1), 99-108. http://dx.doi.org/10.2989/16085914.2016.1143799
Munich RE, 2012. 50th Anniversary of the North Sea Flood of Hamburg. Press Dossier, Munich RE.
Mustafa, A., M. Bruwier, P. Archambeau, S. Erpicum, M. Pirotton, B. Dewals and J. Teller, 2018. Effects of spatial planning on future flood risks in urban environments. J. Environ. Manage. 225, 193–204. DOI: 10.1016/j.jenvman.2018.07.090.
Naulin, M., Kortenhaus, A., Oumeraci, H., 2012. Reliability analysis and breach modelling of sea/estuary dikes and coastal dunes in an integrated risk analysis. Coastal Engineering Proceedings 61. https://doi.org/10.9753/icce.v33.management.61
Nesshöver, C., Assmuth, T., Irvine, K.N., Rusch, G.M., Waylen, K.A., Delbaere, B., Haase, D., Jones-Walters, L., Keune, H., Kovacs, E. and Krauze, K., 2017. The science, policy and practice of nature-based solutions: An interdisciplinary perspective. Science of the Total Environment, 579, 1215-1227. https://doi.org/10.1016/j.scitotenv.2016.11.106
Nikolai, C., Madey, G., 2009. Tools of the Trade: A Survey of Various Agent Based Modeling Platforms. JASSS 12, 2. http://jasss.soc.surrey.ac.uk/12/2/2.html
Nikolic, I., Kasmire, J., 2013. Theory, in: van Dam, K.H., Nikolic, I., Lukszo, Z. (Eds.), Agent-Based Modelling of Socio-Technical Systems, Agent-Based Social Systems. Springer, Dordrecht, Dordrecht, The Netherlands, pp. 11–71. https://doi.org/10.1007/978-94-007-4933-7_2
Nikolic, I., van Dam, K.H., Kasmire, J., 2013. Practice, in: van Dam, K.H., Nikolic, I., Lukszo, Z. (Eds.), Agent-Based Modelling of Socio-Technical Systems, Agent-Based Social Systems. Springer, Dordrecht, Dordrecht, The Netherlands, pp. 73–137. https://doi.org/10.1007/978-94-007-4933-7_3
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 Adaptive Systems Modeling 1, 3. https://doi.org/10.1186/2194-3206-1-3
North, M.J., Macal, C.M., 2007. Managing Business Complexity: Discovering Strategic Solutions with Agent-Based Modeling and Simulation, 1st Edition. ed. Oxford University Press, New York.
Odum, E.P., 1953. Fundamentals of ecology. Saunders Co., Philadelphia, USA and London, UK
Ostrom, E., 2009. A General Framework for Analyzing Sustainability of Social-Ecological Systems. Science 325, 419–422. https://doi.org/10.1126/science.1172133
Panebianco, S., Pahl-Wostl, C., 2006. Modelling socio-technical transformations in wastewater treatment—A methodological proposal. Technovation 26, 1090–1100. https://doi.org/10.1016/j.technovation.2005.09.017
Pettersen, K.A., McDonald, N., Engen, O.A., 2010. Rethinking the role of social theory in socio-technical analysis: a critical realist approach to aircraft maintenance. Cogn Tech Work 12, 181–191. https://doi.org/10.1007/s10111-009-0133-8

Purnomo, H., Guizol, P., 2006. Simulating forest plantation co-management with a multi-agent system. Math Comput Model, 44, 535–552.
Purnomo, H., Mendoza, G.A., Prabhu, R., Yasmi, Y., 2005. Developing multi-stakeholder forest management scenarios: a multi-agent system simulation approach applied in Indonesia. Forest Policy Econ, 7(4), 475–491
Pyka, A., Grebel, T., 2006. Agent-Based Modelling — A Methodology for the Analysis of Qualitative Development Processes, in: Billari, F.C., Fent, T., Prskawetz, A., Scheffran, J. (Eds.), Agent-Based Computational Modelling, Contributions to Economics. Physica-Verlag HD, Germany, pp. 17–35.
Qin, H.P., Su, Q. and Khu, S.T., 2011. An integrated model for water management in a rapidly urbanizing catchment. Environmental modelling & software, 26(12), 1502-1514. https://doi.org/10.1016/j.envsoft.2011.07.003
Qureshi, Z.H., 2007. A Review of Accident Modelling Approaches for Complex Socio-technical Systems, in: Proceedings of the Twelfth Australian Workshop on Safety Critical Systems and Software and Safety-Related Programmable Systems - Volume 86, SCS '07. Australian Computer Society, Inc., Darlinghurst, Australia, pp. 47–59.
Railsback, S.F., Grimm, V., 2012. Agent-Based and Individual-Based Modeling: A Practical Introduction. Princeton University Press, Princeton, New Jersey, USA.
Railsback, S.F., Lytinen, S.L., Jackson, S.K., 2006. Agent-based Simulation Platforms: Review and Development Recommendations. SIMULATION 82, 609–623. https://doi.org/10.1177/0037549706073695
Rand, W., 2015. Complex Systems: Concepts, Literature, Possiblities and Limitations, in: Furtado, B.A., Sakowski, P.A.M., Tóvolli, M.H. (Eds.), Modeling Complex Systems for Public Policies. Institute for Applied Economic Research (IPEA), Brasília, Brazil, pp. 37–54.
Randrup, T.B., Buijs, A., Konijnendijk, C.C. and Wild, T., 2020. Moving beyond the nature-based solutions discourse: introducing nature-based thinking. Urban Ecosystems, 23(4), 919-926. https://doi.org/10.1007/s11252-020-00964-w
Reuter, P., 2009. The unintended consequences of drug policies: Report 5. RAND Corporation, Santa Monica, CA, USA. https://www.rand.org/pubs/technical_reports/TR706.html
Rotmans, J., Van Asselt, M., 1996. Integrated assessment: A growing child on its way to maturity. Climatic Change 34, 327–336. https://doi.org/10.1007/BF00139296
Sang, N. (Ed.). (2020). Modelling Nature-based Solutions: Integrating Computational and Participatory Scenario Modelling for Environmental Management and Planning. Cambridge: Cambridge University Press. doi:10.1017/9781108553827
Santé, I., García, A.M., Miranda, D. and Crecente, R., 2010. Cellular automata models for the simulation of real-world urban processes: A review and analysis. Landscape and Urban Planning, 96(2), 108-122. https://doi.org/10.1016/j.landurbplan.2010.03.001
Schlüter, M., Mcallister, R.R.J., Arlinghaus, R., Bunnefeld, N., Eisenack, K., Hölker, F., Milner-Gulland, E.J., Müller, B., Nicholson, E., Quaas, M., Stöven, M., 2012. New Horizons for Managing the Environment: A Review of Coupled Social-Ecological Systems Modeling. Natural Resource Modeling 25, 219–272. https://doi.org/10.1111/j.1939-7445.2011.00108.x
Schneider, A.L. and Ingram H., 1997. Policy design for democracy. University Press of Kansas, Lawrence, KS, USA
Schulze, J., Müller, B., Groeneveld, J. and Grimm, V., 2017. Agent-based modelling of social-ecological systems: Achievements, challenges, and a way forward. Journal of Artificial Societies and Social Simulation, 20(2), 8.
Sivapalan, M., Blöschl, G., 2015. Time scale interactions and the coevolution of humans and water. Water Resour. Res. 51, 6988–7022. https://doi.org/10.1002/2015WR017896
Smith, A., Stirling, A., 2010. The Politics of Social-ecological Resilience and Sustainable Socio-technical Transitions. Ecology and Society 15.

Sobiech, C., 2012. Agent-Based Simulation of Vulnerability Dynamics: A Case Study of the German North Sea Coast. Springer, Berlin Heidelberg.
Stanilov, K., 2012. Space in Agent-Based Models, in: Heppenstall, A.J., Crooks, A.T., See, L.M., Batty, M. (Eds.), Agent-Based Models of Geographical Systems. Springer, Dordrecht, The Netherlands, pp. 253–269. https://doi.org/10.1007/978-90-481-8927-4_13
Tansley, A.G., 1935. The use and abuse of vegetational concepts and terms. Ecology, 16(3), 284-307.
Teschner, N., Orenstein, D.E., Shapira, I., Keasar, T., 2017. Socio-ecological research and the transition toward sustainable agriculture. International Journal of Agricultural Sustainability 15, 99–101. https://doi.org/10.1080/14735903.2017.1294841
Tonn, G. L. and S. D. Guikema, 2017. An Agent-Based Model of Evolving Community Flood Risk. Risk Anal., 38 (6), 1258-1278. DOI: 10.1111/risa.12939.
Turner, V.K., Jarden, K. and Jefferson, A., 2016. Resident perspectives on green infrastructure in an experimental suburban stormwater management program. Cities and the Environment (CATE), 9(1), Article 4. http://digitalcommons.lmu.edu/cate/vol9/iss1/4
Ujeyl, G., Rose, J., 2015. Estimating Direct and Indirect Damages from Storm Surges: The Case of Hamburg—Wilhelmsburg. Coastal Engineering Journal 57, 1540006-1-1540006–26. https://doi.org/10.1142/S0578563415400069
van Buuren, A., Driessen, P. P. J., van Rijswick, M., Rietveld, P., Salet, W., Spit, T., and Teisman, G., 2013.Towards adaptive spatial planning for climate change: balancing between robustness and flexibility. Journal forEuropean Environmental & Planning Law, 10(1), 29-53. https://doi.org/10.1163/18760104-01001003
Venkataramanan, V., Lopez, D., McCuskey, D.J., Kiefus, D., McDonald, R.I., Miller, W.M., Packman, A.I. and Young, S.L., 2020. Knowledge, attitudes, intentions, and behavior related to green infrastructure for flood management: A systematic literature review. Science of The Total Environment, 720, 137606. https://doi.org/10.1016/j.scitotenv.2020.137606
Verhoog, R., Ghorbani, A., Dijkema, G.P.J., 2016. Modelling socio-ecological systems with MAIA: A biogas infrastructure simulation. Environmental Modelling & Software 81, 72–85. https://doi.org/10.1016/j.envsoft.2016.03.011
Viero, D.P., Roder, G., Matticchio, B., Defina, A., Tarolli, P., 2019. Floods, landscape modifications and population dynamics in anthropogenic coastal lowlands: The Polesine (northern Italy) case study. Science of The Total Environment 651, 1435–1450. https://doi.org/10.1016/j.scitotenv.2018.09.121
Voinov, A., Shugart, H.H., 2013. 'Integronsters', integral and integrated modeling. Environmental Modelling & Software, Thematic Issue on the Future of Integrated Modeling Science and Technology 39, 149–158. https://doi.org/10.1016/j.envsoft.2012.05.014
Vojinovic, Z., Tutulic, D., 2009. On the use of 1D and coupled 1D-2D modelling approaches for assessment of flood damage in urban areas. Urban Water Journal 6, 183–199. https://doi.org/10.1080/15730620802566877
Vojinovic, Z., van Teeffelen, J., 2007. An integrated stormwater management approach for small islands in tropical climates. Urban Water Journal 4, 211–231. https://doi.org/10.1080/15730620701464190
Wang, S., Fu, B., Zhao, W., Liu, Y. and Wei, F., 2018. Structure, function, and dynamic mechanisms of coupled human–natural systems. Current Opinion in Environmental Sustainability, 33, 87-91. https://doi.org/10.1016/j.cosust.2018.05.002
Watson, M., 2012. How theories of practice can inform transition to a decarbonised transport system. Journal of Transport Geography, Special Section on Theoretical Perspectives on Climate Change Mitigation in Transport 24, 488–496. https://doi.org/10.1016/j.jtrangeo.2012.04.002

Werner, B.T., McNamara, D.E., 2007. Dynamics of coupled human-landscape systems. Geomorphology, 38th Binghamton Geomorphology Symposium: Complexity in Geomorphology 91, 393–407. https://doi.org/10.1016/j.geomorph.2007.04.020
Wescoat, J.L., Siddiqi, A., Muhammad, A., 2018. Socio-Hydrology of Channel Flows in Complex River Basins: Rivers, Canals, and Distributaries in Punjab, Pakistan. Water Resources Research 54, 464–479. https://doi.org/10.1002/2017WR021486
Wilensky, U., Rand, W., 2015. An Introduction to Agent-Based Modeling: Modeling Natural, Social, and Engineered Complex Systems with NetLogo. The MIT Press, Cambridge, Massachusetts.
Wolfram, S., 2002. A new kind of science. Wolfram Media, Champaign, IL.
Woodward, A., Smith, K.R., Campbell-Lendrum, D., Chadee, D.D., Honda, Y., Liu, Q., Olwoch, J., Revich, B., Sauerborn, R., Chafe, Z. and Confalonieri, U., 2014. Climate change and health: on the latest IPCC report. The Lancet, 383(9924), 1185-1189.
Zhang, S.X. and Babovic, V., 2011. An evolutionary real options framework for the design and management of projects and systems with complex real options and exercising conditions. Decision Support Systems, 51(1), 119-129.
Ziegler, J.P., Golebie, E.J., Jones, S.E., Weidel, B.C., Solomon, C.T., 2017. Social-ecological outcomes in recreational fisheries: the interaction of lakeshore development and stocking. Ecological Applications 27, 56–65. https://doi.org/10.1002/eap.1433