Participatory system dynamics modelling for supporting decision-makers in enhancing urban flood resilience: the Thamesmead blue-green vision

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Coordinator: Prof. Michele Mossa

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ICAR02-Hydraulic and marine constructions and hydrology

DICATECh
Department of Civil, Environmental, Building Engineering and Chemistry

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Modellazione partecipativa System Dynamics per supportare i decisori nell'incrementare la resilienza del sistema urbano alle inondazioni: la visione Blu-Verde di Thamesmead

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Final Dissertation

PARTICIPATORY SYSTEM DYNAMICS MODELLING FOR SUPPORTING DECISION-MAKERS IN ENHANCING URBAN FLOOD RESILIENCE: THE THAMESMEAD BLUE-GREEN VISION

by

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EXTENDED ABSTRACT (ENG)

Several modelling tools commonly used for supporting flood risk assessment and management are highly effective in representing physical (hydrological) phenomena but provide a rather limited understanding of the multiple implications that flood risk and flood risk reduction measures have on highly complex systems such as urban areas. In fact, the dynamic and unstable evolution – characterised also by significant uncertainty – of flood risk in urban systems is typically neglected. A limited understanding of the complex set of interactions between flood risk and urban areas may result in an ineffective flood risk management. In this context, some studies highlighted the relevance of resilience-based approaches to increase the capability of urban systems to deal with complex and uncertain future threats.

The present work proposes an innovative modelling approach to support decision-makers, at a planning or strategic level, in managing urban flood risk while defining strategies for enhancing the resilience of the system. To this aim, the multi-dimensional implications of flood risk and of different flood risk management strategies are analysed and simulated. The adopted modelling approach is based on System Dynamics (SD) modelling principles and relies on the integration of scientific and stakeholder knowledge. The SD modelling approach is adopted because of its capacity of building a holistic system picture, while accounting for system structure and dynamic relations among multiple different urban components. Besides that, it allows the evaluation of different management solutions and the identification of suitable bundles of actions for both flood risk reduction and urban resilience increase. Both qualitative and quantitative SD modelling tools are used to fully exploit the abilities of the SD approach.

The obtained results revealed i) the relevance of SD modelling in evaluating the effectiveness of measures to reduce flood risk and increase the urban flood resilience ultimately providing actionable information for decision-makers; ii) the added value provided by the combination of scientific and stakeholder knowledge in the entire modelling process; iii) the ability of Blue-Green infrastructure to deliver both hydrological and non-hydrological (i.e., social and environmental) benefits to the system thus reducing flood risk and increasing urban resilience to flooding.

Reference is made to one of the case studies of the CUSSH and CAMELLIA projects, namely Thamesmead (London), a formerly inhospitable marshland currently undergoing a process of urban regeneration and increasingly vulnerable to flooding. While the proposed approach is appropriate in the context of the case study application, it can be adapted to ensure it is relevant to different contexts. Therefore, it represents an interesting opportunity for building a replicable approach to integrate urban development dynamics with flood risk, ultimately supporting decision-makers in identifying mitigation/prevention measures and understanding how they could help achieve multi-dimensional benefits.

Keywords: *Flood risk management; Resilience; Urban dynamics; System Dynamics modelling; Stakeholder engagement; Blue-Green infrastructure*

EXTENDED ABSTRACT (ITA)

Diversi strumenti di modellazione comunemente utilizzati per supportare la valutazione e la gestione del rischio di inondazione sono molto efficaci nel rappresentare i fenomeni fisici (idrologici), ma forniscono una comprensione piuttosto limitata delle molteplici implicazioni che il rischio di inondazione e le misure di riduzione del rischio hanno su sistemi altamente complessi come le aree urbane. Infatti, l'evoluzione dinamica e instabile - caratterizzata anche da una significativa incertezza - del rischio di inondazione nei sistemi urbani è generalmente trascurata. Una comprensione limitata del complesso insieme di interazioni tra rischio di inondazione e aree urbane può portare ad una sua inefficace gestione. In questo contesto, alcuni studi hanno evidenziato l'importanza di approcci basati sulla resilienza per aumentare la capacità dei sistemi urbani di affrontare minacce future complesse e incerte.

Il presente lavoro propone un approccio modellistico innovativo per supportare i decisori, a livello pianificatorio o strategico, nella gestione del rischio di inondazioni urbane e nella definizione di strategie per aumentare la resilienza del sistema. A tal fine, vengono analizzate e simulate le implicazioni multidimensionali del rischio di inondazione e delle diverse strategie di gestione. L'approccio di modellazione adottato si basa sui principi della System Dynamics (SD) e sull'integrazione della conoscenza scientifica e degli stakeholder. L'approccio di modellazione SD è stato adottato per la sua capacità di costruire una visione olistica del sistema, tenendo conto della sua struttura e delle relazioni dinamiche tra più componenti urbane diverse. Inoltre, consente di valutare diverse soluzioni di gestione e di identificare pacchetti di azioni idonei sia per la riduzione del rischio di inondazione che per l'aumento della resilienza urbana. Per sfruttare appieno le capacità dell'approccio SD vengono utilizzati strumenti di modellazione SD sia qualitativi che quantitativi.

I risultati ottenuti hanno rivelato i) l'importanza della modellazione SD nel valutare l'efficacia delle misure per ridurre il rischio di inondazioni e aumentare la resilienza alle inondazioni urbane, fornendo informazioni attuabili per i decisori; ii) il valore aggiunto fornito dalla combinazione della conoscenza scientifica e degli stakeholder nell'intero processo di modellazione; iii) la capacità delle infrastrutture Blu-Verdi di fornire benefici sia idrologici che non idrologici (cioè sociali e ambientali) al sistema, riducendo così il rischio di inondazioni e aumentando la resilienza urbana.

Specifico riferimento è fatto a uno dei casi di studio dei progetti CUSSH e CAMELLIA, ovvero Thamesmead (Londra), una palude un tempo inospitale attualmente sottoposta a un processo di rigenerazione urbana e sempre più vulnerabile alle inondazioni. Sebbene l'approccio proposto sia appropriato nel contesto dell'applicazione del caso di studio, può essere adattato per garantire la sua rilevanza in contesti diversi. Pertanto, rappresenta un'interessante opportunità per costruire un approccio replicabile per integrare le dinamiche di sviluppo urbano con il rischio di inondazione, supportando in ultima analisi i decisori nell'identificazione di misure di mitigazione/prevenzione e nella comprensione di come queste possano contribuire a ottenere benefici multidimensionali.

Parole chiave: *Gestione rischio inondazione; Resilienza; Dinamiche urbane; Modellazione System Dynamics; Coinvolgimento stakeholder; Infrastrutture Blu-Verdi*

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1. INTRODUCTION

1.1. Overview

Cities are complex systems which integrate economic, social, ecological, and human dimensions that depend on and cooperate with each other (Gao et al. 2022). In addition, their dynamic evolution is uncertain since they consist of situational and changing relations between the different elements they are characterised by (Mannucci et al. 2022). In these conditions, a change of one component can have unforeseen consequences for the whole system (Disse et al. 2020).

Flooding is one of the natural disasters that many cities may encounter. Urban surface water flooding originates when excess rainfall caused by short, intense precipitation events cannot infiltrate into the subsurface or drain via natural or artificial drainage systems (Riel, 2011), or when localised drainage capacity is exceeded by rainfall (Evans et al. 2004). As stated by Green et al. (2021), many severe urban flooding events are caused by coincident flooding in areas subjected to multiple flooding sources, i.e., drainage systems, sewer, river, groundwater, and sea. Large and long-lasting economic losses associated with damage to property, infrastructure, services, and human activities as well as water-borne diseases and loss of life may be caused by the occurrence of urban flooding (Tunstall et al. 2006; Bosher, 2014). The changes of climatic and socio-economic factors - e.g., variability of extreme events in frequency and intensity, population growth and distribution, widespread impermeable surfaces in disfavour of green permeable surfaces, and ageing infrastructure - are increasing the level of flood risk facing urban areas (Friedman, 2008). Therefore, flooding impacts on communities, economy, and built environment are expected to spread dramatically over time (Keesstra et al. 2018).

It goes without saying that decision and policy-makers cannot ignore the influences and interdependencies of all these factors and should move towards an adequate approach to flood risk management (Di Baldassarre et al. 2015). While the impacts of climate change on flood events are accounted for in the development and implementation of existing modelling approaches and tools for flood risk management, the dynamic nature of complex urban systems is largely ignored (Geltner and de Neufville, 2012; Perrone et al. 2020). This is a potential limit of the most widely used modelling tools and approaches for flood risk management in urban areas (McInerney, Lempert, and Keller, 2012). In fact, most of the existing literature on flood risk management limits the uncertainty analysis in non-stationary conditions to the one related to the phenomena (i.e., the hazard component of flood risk). On the contrary, very few works i) integrate the hydrological sub-system with others (such as the social, economic, and environmental) (Wamsler et al. 2013) and ii) consider the influence of different elements – e.g., built environment, population growth and distribution, infrastructures, green areas, etc. – on the impacts of extreme events in the urban system (Riddell et al. 2019). In general, a limited understanding of the complex interconnections between flood risk and urban dynamics could limit the knowledge of policy and decision-makers about the future and consequently affect the effectiveness of strategies – i.e., the sequence of actions – for flood risk reduction (Kwakkel et al. 2010; Walker et al. 2013a; Barendrecht et al. 2017). An example is the 'levee effect' observed in Vienna, i.e., the (unexpected) increase in exposure and/or vulnerability as more people moved into the floodplain of a river because of a false sense of security following an increase in protection level (Di Baldassarre et al. 2015). Pahl-Wostl et al. (2007) stated that the overall performance of the flood risk management system can be improved by adopting resilient-based approaches. In fact, these practices increase the system capability to deal with its complexities and the uncertainty of future threats (Pagano et al. 2017). Specifically, resilience thinking increases the system's ability to i) anticipate and absorb potential disruptions, ii) adapt to changes, iii) build the capacity to withstand the disruption or recover as quickly as possible after an impact (Francis & Bekera, 2014).

To deeply understand the complex set of interactions between flood risk and urban areas, there is a growing need to benefit from stakeholder involvement (Maskrey et al. 2016; Inam et al. 2017a, 2017b, 2017c; Perrone et al. 2020). In fact, it has recently been recognised as a central component for building cities' resilience to flooding (see e.g., Yusuf et al. 2018 and O'Donnell et al. 2018). Stakeholders are deemed legitimate participants to the identification of both problems and solutions (Pluchinotta et al. 2021a). Specifically, their involvement in the entire flood risk modelling process through the adoption of participatory techniques could i) enhance researchers' knowledge on local issues (Rich et al. 2018); ii) support decision-makers in the identification of suitable strategies to act on the system (Lopes and Videira, 2017); iii) promote awareness and motivation of those taking part in decision- or policy-making processes (Pluchinotta et al. 2018). Besides that, an increasing body of literature further suggests that the implementation of Blue-Green (BG) infrastructure that works synergistically with existing Grey infrastructure could increase urban flood resilience (see e.g., Pagano et al. 2019; O'Donnell et al. 2020b; Coletta et al. 2021; Green et al. 2021). In fact, BG infrastructure (e.g., wetlands, swales and trees) can expand the hydrological potential of Grey infrastructure (e.g., dams, embankments and levees), while delivering multiple co-benefits to the environment and society (O'Keeffe et al. 2022).

Starting from these premises, this work aims at developing an innovative approach to support decision-makers in enhancing urban flood resilience, accounting for the dynamic and complex nature of cities' interacting elements. To this aim, a System Dynamic (SD) modelling approach (see e.g., Sterman, 2000 and Simonovic, 2009), which also relies on the integration of scientific and stakeholder knowledge, is implemented. Due to its ability to adopt a whole-system approach and a social learning process (Bagheri, 2006; Sušnik et al. 2014, 2018), the SD modelling is widely considered efficient in addressing dynamically complex problems, including integrated water-related risks management (Ahmad and Simonovic, 2015; Karimlou et al. 2020). The method, although replicable in different study contexts, is developed and tested in one of the case studies of the CUSSH (Complex Urban Systems for Sustainability and Health)[1] and CAMELLIA (Community Water Management for a Liveable London)[2] projects, namely Thamesmead (London), perceived as being increasingly vulnerable to flooding.

The concept of resilience to flood events and the relation between it and flood risk management is explained in more detail in the following section. Then, the importance of stakeholder involvement throughout the decision-making process as well as of the integration of Blue-Green and Grey infrastructure to enhance urban flood resilience is illustrated. The last section is related to the outline of the main objective, the adopted approach, and the research questions of this thesis.

1.2. Flood resilience and its relation with flood risk management

Resilience is a discussed concept, with a variety of definitions and interpretations. Despite this, in the context of disaster resilience it can be defined as the "ability of a system, community or society to pursue its social, ecological and economic development objectives, while managing its disaster risks over time in a mutually reinforcing way" (Keating et al. 2016). Widely recognised in the literature is the distinction of three frameworks of system resilience, i.e., engineering resilience, ecological resilience, and socio-ecological (or evolutionary or adaptive) resilience, proposed by Holling (1996). Engineering resilience focuses on how fast a system returns to an original state after a stress and how large the disturbance needs to be before a system is pushed out of its previous state (i.e., the resistance of the system) (De Bruijn, 2004; Folke, 2006). This is often referred to as "bouncing back" (Dabson, 2015). This framework lacks the critical component of adaptation that is important for cities to learn how to better manage stresses and not to remain vulnerable to disaster if another shock occurs (Mitchell et al. 2012). This means that engineering resilience can have many proper applications in closed boundary problems rather than in complex, open systems such as cities (Liao, 2012). Ecological resilience, on the other hand, is the ability of a system to cope with disturbances changing the state of the equilibrium (Morrison et al. 2018). In complex systems the flooding event (i.e., the shock) changes the system in itself; it may for example change people's perception of risk. At the same time, the system reacts in unforeseen ways, such as policy interventions, subsidies, etc. (Disse et al. 2020). Socio-ecological (or evolutionary or adaptive) resilience does not involve one or more equilibrium states, but rather continuous adaptation and change (Davoudi, 2012). It is characterised by the ideas of "coping", "transformation" (Rodina, 2018) and "bouncing forward" (Dabson, 2015). This means that in case of flooding it is unlikely that communities return to the previous state. On the contrary, they make adaptations to improve conditions and prevent disasters caused by flooding from happening again. This conceptualization of resilience better represents the nature of human societies. These three frameworks are illustrated in Fig. 1 through the example of the ball and cup model used in resilience theory (Laboy and Fannon, 2016).

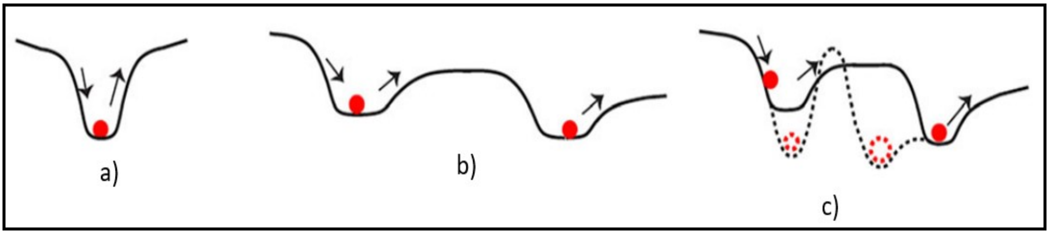


Fig. 1 - Ball and cup model of system stability in the three resilience frameworks. The red ball represents the system, while arrows disturbances. a) One stability domain (one valley) is represented; engineering resilience is defined by the slope of the sides of an individual valley. b) Two different stability domains (two valleys) are represented; a loss of the intervening hill in the middle represents a loss of ecological resilience. The system can potentially re-organize around the new stability domain and the movement of the ball in the horizontal direction is a measure of the change in ecological resilience. c) The adaptive nature of socio-ecological resilience is represented as the stability domain is shifting.

Considering that enhancing a system's resilience is forward-looking, it is important that the system must be resilient also into the future (in addition to current disturbances) (de Bruijn et al. 2017; Zevenbergen et al. 2020). To ensure that a system has multiple equilibria also in the long run, adaptation or transformation may be required (Folke et al. 2010). Walker et al. 2004 defined adaptation as the capacity of a system or its actors to influence resilience by changing parts of the system, while transformation as the capacity to create fundamentally new systems.

The resilience concept is increasingly appealing to policy and decision-makers because i) many policy documents (e.g., those from the European Union (EU, 2013) and UK Environment Agency (Dilley, 2016) and international agreements in three post-2015 agendas (e.g., the Sustainable Development Goals, the Sendai Framework for Disaster Risk Reduction) call for resilience; ii) it covers significant elements that are missed in approaches to the management of extreme weather events that are currently in use (Restemeyer et al. 2015). Specifically, these approaches are often risk-based – i.e., they consider the combination of the probability of a hazard and its consequences (UNISDR, 2009). The risk of extreme weather events, often expressed in terms of expected annual damage or number of casualties (Kind, 2014), can be evaluated by comparing them with acceptable risk levels or in an economic assessment. Reducing risks requires taking measures that reduce the hazard probability or its consequences. While the evaluation of the cost of the measures is relatively easy, their benefits are much harder to establish (Kenny, 2012). Furthermore, not all relevant potential impacts of measures can be expressed well in monetary terms, such as ecosystem quality and residents' well-being. In addition, a risk approach often ignores the overall system behaviour focusing on single elements of the system rather than considering the interrelations between all the sub-systems within the system (physical and societal) (Linkov et al. 2014). The future uncertainty generated by climatic and societal changes need also to be considered in disaster risk management. This means that adaptations may be required in systems (Milly et al. 2008). Therefore, some aspects are missing or oversimplified in risk-based approaches. In this context, resilience thinking can complement and improve them on the assumption that, since the risk cannot be perfectly known, it is better to act on the system by making it capable of absorbing shocks in a short time and with little loss of performance (Cea and Costabile, 2022). In fact, building resilience fits well with the increasingly complex, non-linear, and uncertain systems – such as cities – in the current situation and in future developments (Laurien et al. 2022).

De Bruijn et al. 2017 proposed five principles, which involve aspects missing in risk approaches, to enhance the resilience of societies to cope with extreme weather events. 1) Adopt a system's approach – i.e., study the system as a whole and view the different sub-systems and processes within the system as interlinked. As systems may be complex, the use of methods and techniques from the field of System Thinking, which can help to identify the key elements and linkages, are suggested (Meadows, 2008; Simonovic, 2011). As the systems are dynamic, feedback loops and changes over time also require attention. 2) Look at beyond-design events – i.e., think about the worst case, or even unimaginable scenarios because unexpected events can always happen because of inherent uncertainties in system behaviour and climate variability (Wasson, 2016). 3) Design and prepare systems according to the 'remain functioning' principle (also known as fail-safe principle) – i.e., design the systems in such a way that consequences of failure are manageable and not catastrophic. 4) Increase the recovery capacity – i.e., improve the socio-economic development level. Health improvement and education are sustainable development objectives that also increase a society's recovery (Asgary et al. 2012). 5) Remain resilient into the future – i.e., if necessary, to be flexible, to have the capacity to adapt and the willingness to transform in order to cope with uncertain changes (e.g., climate change and socio-economic developments). Scenario-analysis, exploratory modelling, and adaptation pathways (Hallegatte, 2009; Haasnoot et al. 2013; Walker et al. 2013) can help define the most suitable adaptation measures, adaptation rates and windows to initiate a transition to an entirely different policy. Several governments and aid agencies have developed indicator-based tools and methods to measure the resilience of communities to flood risk and to prioritise interventions and investments (Cutter, 2016). The indicators cover various social, natural, political, physical, financial, and human capacities of societies, and support decision-makers in understanding where the challenges and weaknesses of flood resilience are (Quinlan et al. 2016). However, there are still a couple of aspects that are not covered by these tools and that are fundamental when decision-makers need to choose what action should be taken first: 1) the interdependencies and cause-effect relations among different resilience components, and 2) how interventions influence the different resilience components including co-benefits (Mehryar and Surminski, 2022).

1.3. Stakeholder engagement in modelling for achieving urban flood resilience

To further understand how different factors interact and act on an urban system influencing flood risk as well as to set priorities for actions and investments, there is a growing need to benefit from different fields of knowledge in participatory modelling for achieving urban flood resilience (Hegger et al. 2012). This requires the integration of scientific (i.e., provided by models and data) and expert/stakeholder knowledge during the various stages of the process (Kloprogge and Sluijs, 2006; Voinov and Bousquet, 2010; Scrieciu et al. 2021). It is therefore about integrating the knowledge of researchers with that of stakeholders who are considered legitimate participants in the identification of problems and solutions (Pluchinotta et al. 2021a). In fact, stakeholders can expand the scientist's knowledge of the problems in the area, otherwise limited only to the literature reviews (Pagano et al. 2019; Giordano et al. 2020; Coletta et al. 2021; Scrieciu et al.

2021); besides that, stakeholders are affected by decisions and actions for flood resilience and often have different perceptions and preferences in how flood risk should be managed. Therefore, in an effective and inclusive decision-making process, it is essential to include such knowledge in modelling (Inam et al. 2015; Inam et al. 2017a, 2017b, 2017c; Di Baldassarre et al. 2019; Mehryar and Surminski, 2022). It was demonstrated in various studies that participatory decision-making processes increase fundamental aspects for societal resilience, such as legitimacy, acceptability, justice and equity of decisions and actions, communities' awareness about problems and solutions, learning, and willingness for community cooperation (Mehryar, 2019; Cattino and Reckien, 2021; Khatibi et al. 2021).

Stakeholder engagement could be achieved using participatory modelling techniques, i.e., building processes in which stakeholders are supported in the development and formalisation of conceptual models (Carmona et al. 2013; Voinov, 2016) and in the understanding of cross-sectoral connections and implications (Ahmad and Simonovic, 2015; Pasquier et al. 2020). Basically, they participate in different stages of the processes, from problem definition to model development and/or policy analysis (Voinov and Bousquet, 2010). For this purpose, different types of analytical and system tools can be used; the most common and widely used tools are System Dynamics (SD), Bayesian belief networks, fuzzy cognitive mapping, and agent-based modelling (Voinov, 2017).

Although more and more studies are emphasising the importance of developing methods for integrating stakeholder knowledge into the identification of flood related problems and flood risk management options (see e.g., Nutt, 2002; Tingsanchali, 2012; Edelenbos et al. 2017; Pagano et al. 2019; Perrone et al. 2020; Coletta et al. 2021), the level of stakeholder involvement in the context of flood modelling is still low (Wehn et al. 2015; Scaini et al. 2021), mainly due to time and funding constraints and the lack of trust that decision and policy-makers have in participatory approaches (Chilvers and Kearnes, 2016; Löschner et al. 2016).

1.4. Integration of Blue-Green and Grey infrastructure for increasing urban flood resilience

Rethinking and adapting cities approach to flood risk management implies a shift from the concept of flood defence (generated by the implementation of hard/Grey/engineering structures that protect cities from rivers and rising sea levels and remove surface water) to flood resilience (according to which urban spaces are designed to adapt to the increasing threat of urban flooding, while also providing environmental, social, and economic co-benefits) (O'Donnell et al. 2020). From this perspective, a transition from Grey - e.g., culverts, sewer systems, and urban drainage channels - to holistic, integrated Grey and Blue-Green (i.e., Hybrid) infrastructure solutions is needed (Lennon et al. 2014).

The term Blue-Green (BG) infrastructure generally refers to the use of natural processes to reduce the risk of surface water flooding while also providing multiple functions and services to people, the environment, and the economy (Green et al. 2021). It is seen as a subset of Nature-based Solutions (NBS) (Lafortezza et al. 2018) but, considering that the small differences between the two terms are beyond the scope of this work, BG infrastructure, NBS, non-traditional measures, and sustainable solutions will be used interchangeably; all of them will refer to the concept of measures that work with natural processes, deliver co-benefits, and "make space for water" (Burgess-Gamble et al. 2017). In urban areas, BG infrastructure is mainly designed to reduce the surface runoff induced by the increase of impervious areas using natural processes. Among these are gardens, green roofs, wetlands, detention basins, swales, green streets, rainwater harvesting systems, and permeable pavements (Vijayaraghavan et al. 2021); in Fig. 2 some examples of urban BG infrastructure at different scales are represented. For more detailed information on these sustainable solutions see e.g., Woods Ballard et al. (2015).

Fig. 2 – Examples of urban BG infrastructure at different scales. a) Wetland in Kington, Herefordshire[3]. b) Swale in Hastings, England[4]. c) Trees in London, England[5]. d) Permeable paving in Oregon, USA[6].

In addition, these solutions provide multiple social, environmental, and economic benefits and services, such as improving residents' well-being, creating attractive and aesthetically pleasing spaces, and increasing biodiversity (Fenner, 2017; Coletta et al. 2021). Thanks to their ability to manage surface water above-ground, BG infrastructure can also help e.g., extend the lifetime of ageing grey infrastructure, and limit the quantity of rainwater that travels through combined sewers. In addition, they are flexible for adaptation according to changing local conditions (Babovic et al. 2017) and their costs of annual maintenance are 17%–20% cheaper than Grey infrastructure (Duffy et al. 2008). For these reasons, BG infrastructure represent a sustainable option; therefore, the combination of Grey and Blue-Green infrastructure, represented in Fig. 3 on the next page through the Hybrid approach, is needed to achieve urban flood resilience (Browder et al. 2019; Alves, 2020; Kapetas & Fenner, 2020).

Despite all the positive aspects highlighted, BG measures are still being applied at a slow pace in cities and traditional Grey infrastructure continues to be widely preferred in urban areas (Qiao et al. 2018). This is related to the several barriers to their implementation, such as i) the absence of sufficient technical support and tools for decision-making, mainly regarding the evaluation and quantification of additional benefits (IPCC, 2012; Alves, 2020); ii) public acceptability and lack of stakeholder collaboration during their design and implementation (Wihlborg et al. 2019); iii) the uncertainty about their long-term performance and costs (Davis et al. 2015). Therefore, to increase the acceptance of BG infrastructure, the emphasis on the provision of multiple benefits, in addition to the support for flood protection, is fundamental (Kabisch et al. 2017a). In fact, Miller and Montalto (2019) demonstrated that local stakeholders' perception of co-benefits is an important driver of BG infrastructure application.

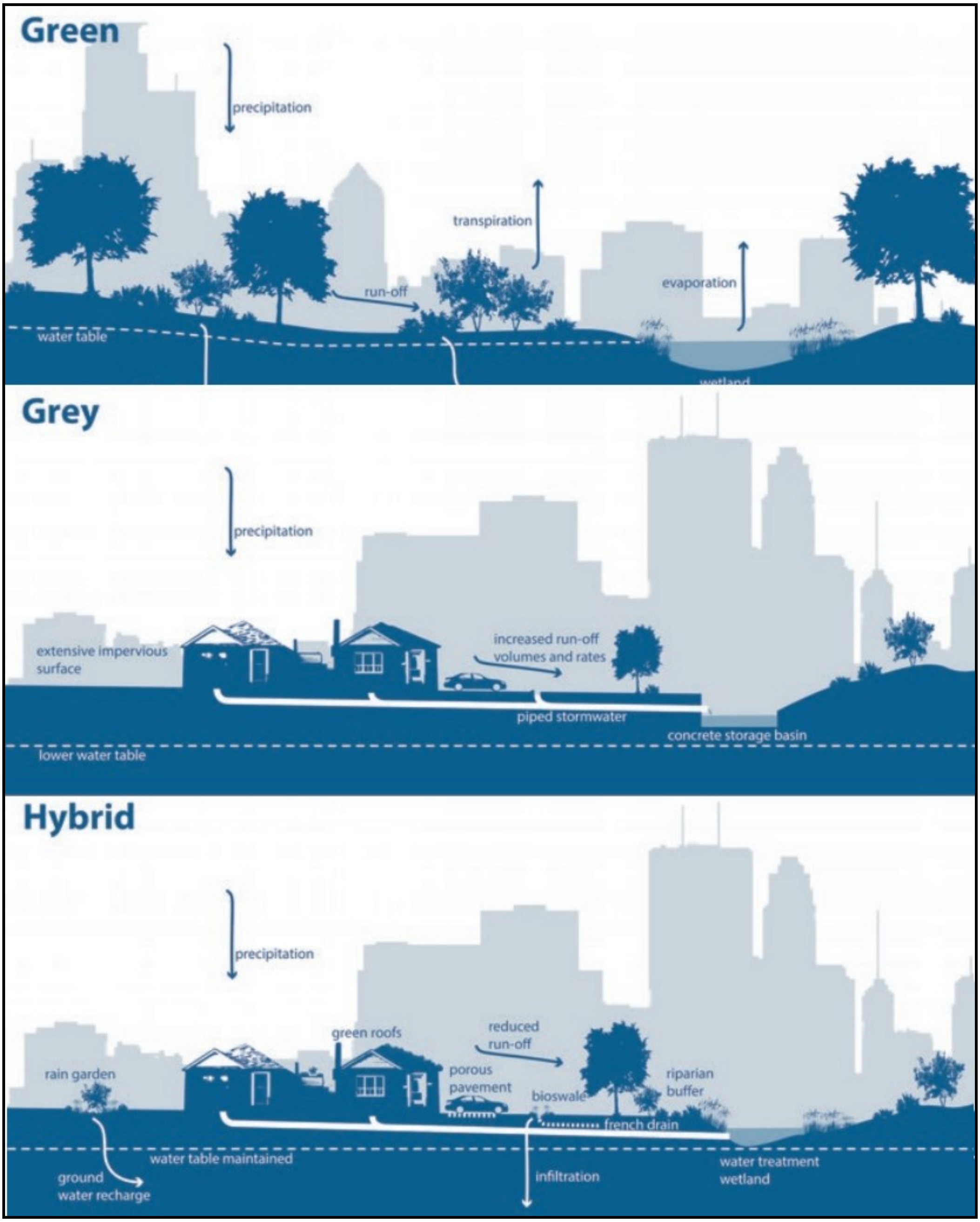


Fig. 3 – The three approaches for flood risk management: Green and Blue only, Grey only, and Hybrid (from Kabisch et al. 2017a – Chapter 6).

1.5. Objective, adopted approach, and research questions of the thesis

Based on the main literature gaps highlighted in the previous sub-sections, the main objective of the present work is to develop an approach capable of i) describing and modelling the global system behaviour, in a complex and dynamically evolving urban area; ii) evaluating the multi-dimensional impacts related to the implementation of BG measures in the system, considering both the impact on risk reduction and the co-benefits production; iii) find suitable bundles of solutions that can be adapted and adjusted over time; iv) integrating scientific and stakeholders' knowledge in the same model. Specifically, a participatory System Dynamics modelling approach is implemented for supporting decision-makers in enhancing urban flood resilience. In fact, System Dynamics can consider the interactions between different variables and sub-systems and help dealing with dynamic problems and their combined effects (consequently highlighting potential trade-offs and unintended consequences) (Senge and Sterman, 1992; Simonovic, 2009; Khan et al. 2009; Giordano et al. 2020). This modelling approach is especially applicable to water-related risk management problems (Guo et al. 2001; Stave, 2003; Simonovic and Ahmad, 2005; Videira et al. 2009; Zarghami and Akbariyeh, 2012; Ahmad and Simonovic, 2015; Pagano et al. 2019; Karimlou et al. 2020; Pluchinotta et al. 2021a) since it: i) can be integrated with results of sectoral models (Zomorodian et al. 2018); ii) enables the integration of scientific and stakeholder knowledge (Rich et al. 2018); iii) enables to investigate how complex systems evolve over time, considering quantitative and qualitative aspects (Simonovic, 2009); iv) helps understanding how variables within the system interact and how factors external to the system affect its complex dynamics (Mirchi et al. 2012); v) accounts for the systematic exploration of a very large number of possible future scenarios (Sterman, 2000); vi) provides aggregated information useful at a planning or strategic level (Phan et al. 2021). Background information on the System Dynamics approach is provided in Materials and Methods (Section 2).

Within this context, the present work aims to address the following main research question: to what extent can System Dynamics modelling support decision-makers, at a planning or strategic level, evaluating the effectiveness of measures to increase the urban flood resilience? Other research questions are: i) to what extent can the combination of scientific and stakeholder knowledge within the System Dynamics modelling contribute to a better understanding of flood risk and implications in urban settings as well as support actions selection ultimately increasing urban flood resilience?; ii) to what extent can the implementation of Blue-Green infrastructure in the system enhance urban flood resilience?

The manuscript is organised as follows. Section 2 describes the different steps of the methodology, developed as part of the urban regeneration projects CUSSH (Complex Urban Systems for Sustainability and Health) and CAMELLIA (Community Water Management for a Liveable London). Section 4 discusses the results obtained with specific reference to Thamesmead (London) (introduced in Section 3), an urban regeneration case study in which building resilience to flooding is considered a key issue for protecting both the community and the built environment. Section 5 shares the lessons learned from the implementation of the developed approach.

2. MATERIALS AND METHODS

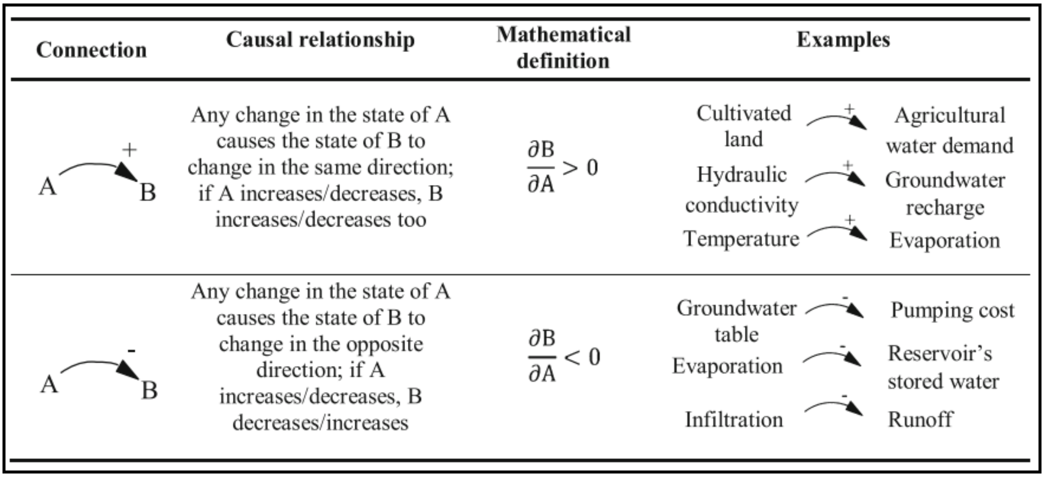
Background information on the System Dynamics approach is provided below (see Section 2.1). Subsequently, the adopted methodology is explained in detail (see Section 2.2). It aims at i) analysing flood risk and urban resilience to flooding accounting for the dynamic evolution of the urban system under changing climatic and socio-economic conditions; ii) supporting decision-makers in identifying strategies for reducing flood risk and enhancing urban flood resilience, while achieving multi-dimensional benefits. The common ground for the different phases of the methodological approach is the active participation of stakeholders, supported by different methods described in the following sections.

2.1. Background information on System Dynamics

System Dynamics (SD) is a computer-aided approach that facilitates holistic understanding of complex dynamics systems, and strategic decision-making (Forrester, 1961; Forrester 1969; Meadows et al. 1972; Richmond, 1993; Ford, 1999; Sterman 2000). Thanks to their ability of underlying feedback loops between the different components of the system, SD models support decision-makers in understanding the potential consequences of system perturbations. For this reason, they are a suitable tool for sustainable water resources planning and management at the strategic level (Simonovic, 2009).

The SD approach is a combination of System Thinking and Dynamic Simulation. System Thinking is a holistic approach to describe and understand the causality and interrelations between components within a system as well as influences from outside the system. Dynamic Simulation completes Systems

Thinking quantifying the interactions and simulating the behaviour of the system (Sterman, 2000). The modelling tool generally used in System Thinking is the Causal Loop Diagram (CLD), that is a qualitative map of the structure of feedback of the system. Specifically, a CLD represents the structure of an interconnected system and creates a shared understanding of the system amongst members of a discussion group (Coletta et al. 2021). It consists of variables connected by causal links (arrows). Each arrow is assigned a polarity, either positive (+) or negative (-), which describes what would happen to the structure of the system if there were changes. A positive link means that if the cause increases/decreases, the effect increases/decreases; conversely, a negative link means that if the cause increases/decreases, the effect decreases/increases (Abebe et al. 2021). Fig. 4 summarises the graphical notations and polarity of causal relationships.



Connection	Causal relationship	Mathematical definition	Examples
$A \xrightarrow{+} B$	Any change in the state of A causes the state of B to change in the same direction; if A increases/decreases, B increases/decreases too	$\frac{\partial B}{\partial A} > 0$	Cultivated land $\xrightarrow{+}$ Agricultural water demand Hydraulic conductivity $\xrightarrow{+}$ Groundwater recharge Temperature $\xrightarrow{+}$ Evaporation
$A \xrightarrow{-} B$	Any change in the state of A causes the state of B to change in the opposite direction; if A increases/decreases, B decreases/increases	$\frac{\partial B}{\partial A} < 0$	Groundwater table $\xrightarrow{-}$ Pumping cost Evaporation $\xrightarrow{-}$ Reservoir's stored water Infiltration $\xrightarrow{-}$ Runoff

Fig. 4 – Graphical notation and polarity of causal relationships (from Mirchi et al. 2012).

Delays can also be added and are represented by a perpendicular double bar on the arrow; they give systems inertia and create oscillations and trade-offs between the short-and long-term effects of policies (Sterman, 2000). In complex systems, the combination of positive and negative causal relationships in the CLD can form balancing (B) and/or reinforcing (R) feedback loops. The former generate balancing behaviour that acts as an equilibrator in a system; the latter contribute to the exponential behaviour of a system (Mirchi et al. 2012). As the behaviour of complex systems arises from such relationships, analysing the main feedback loops of the CLD allows the modeller to form hypotheses on the behavioural patterns of the system. This ultimately supports an understanding of what the main implications and potential impacts could be, avoiding undesirable future scenarios (e.g., Senge, 1994; Braun, 2002). The basic modes of behaviour in dynamic systems are: i) exponential growth/decline, created by self-reinforcing feedback loops; ii) goal seeking behaviour, that arises from balancing feedback loops; iii) oscillation, that can occur if there are delays in at least one of the links in a balancing loop, causes the system to constantly move above and then below its goal (i.e., the desired state of the system) (Sterman, 2000). Interactions of these fundamental modes cause three more complex patterns of behaviour, i.e., S-shaped Growth, S-shaped Growth with Overshoot, Overshoot and Collapse (e.g., see Mirchi et al. 2012 for further details).

Stock and Flow (SF) model is instead the quantitative modelling tool used for Dynamic Simulation. As stated by Forrester (1961), stocks (levels), represented by rectangles, are measured at a particular moment of time, and represent any variable (either physical or not) that accumulates or depletes over time; flows (rates), represented by arrows and measured over a certain interval of time, change stocks over time. In particular, inflow adds to the stock, while outflow subtracts from the stock. These conventions were based on a hydraulic metaphor (see Fig. 5). "It is helpful to think of stocks as bathtubs of water. The quantity of water in the bathtub at any time is the accumulation of water flowing in through the tap less the water flowing out through the drain" (Sterman, 2000). Auxiliary variables (converters) are intermediary that can help describing the processes of the model. The relationships between the various elements in the model are depicted as arrows (connectors) (Forrester, 1961; Sterman, 2000; Pagano et al. 2019).

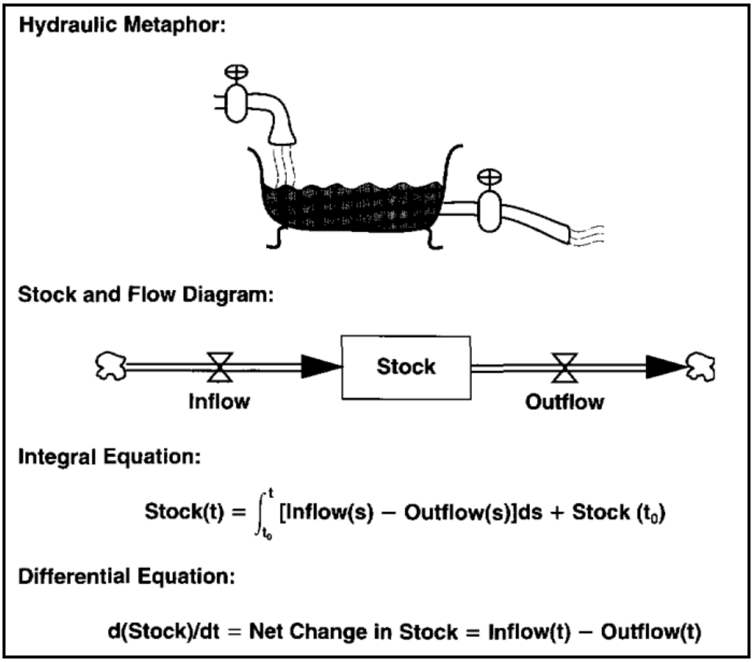


Fig. 5 – Four equivalent representations of stock and flow structure (from Sterman, 2000).

User-friendly software programs - e.g., STELLA (High Performance Systems, 1992), Powersim (Powersim Corp., 1996), and Vensim (Ventana Systems, 1996) – can be used for building both the qualitative and the quantitative models.

Over the last decade, several studies have reviewed the various works that have applied a SD approach to the management of water-related issues (e.g., Mirchi et al. 2012; Zarghami et al. 2018; Zomorodian et al. 2018; Pejic Bach et al. 2019; Mashaly and Fernald, 2020; Phan et al. 2021) and some gaps in its application have emerged. In particular, the following were discussed in the work of Perrone et al. (2020) as well as in the most recent literature review by Phan et al. (2021): i) few works have integrated scientific and stakeholder knowledge (Karimlou et al. 2020); ii) few sub-systems have been combined and explored (Davies and Simonovic, 2011); iii) the ability of System Thinking to improve understanding of multiple interactions in complex water systems has not been fully exploited (Zare et al. 2019); iv) many studies did not validate the models, affecting their reliability especially when social, economic, and political sub-systems, more difficult to predict than physically-based sub-systems, are included (Blair and Buytaert, 2016). Starting from these limits, the main methodological innovation proposed in this work is related to the development of an SD model that: i) integrates scientific and stakeholder knowledge during the entire modelling process; ii) integrates and explores different sub-systems; iii) fully exploits the ability of both System Thinking and Dynamic Simulation to support decision-makers in selecting measures for the improvement of urban flood resilience.

2.2. Overview of the proposed approach

This section provides a detailed description of the methodological framework adopted (schematised in Table 1), based on a multi-step process of knowledge gathering and on the SD principles (see e.g., Forrester, 1990; Sterman, 2000; Chu et al. 2010; Berariu et al. 2016; Giordano et al. 2017; Phan et al. 2018; Song et al. 2018; Wang et al. 2018 for other frameworks based on SD modelling). The proposed methodology allows for the integration of urban dynamics with flood risk, ultimately supporting decision-makers in identifying bundles of actions for enhancing urban flood resilience, while achieving multi-dimensional benefits. The framework uses the System Thinking and Dynamic Simulation approaches, integrating conceptual and numerical modelling tools with methods for the active participation of stakeholders. It represents an interesting opportunity for building a replicable approach, with appropriate changes and updates (e.g., the steps may not all be carried out), in different contexts.

Table 1. The implemented multi-step approach. The activities with their objectives, the tools/methods adopted, and the expected results are shown. The rows related to System Thinking are in blue, while those of Dynamic Simulation in green.

#	TASKS	AIMS	TOOLS/METHODS	OUTCOMES
1	Literature review and baseline analysis for preliminary Causal Loop Diagram (CLD) building	To build a preliminary CLD, based on the scientific knowledge and background information on the study area	• Literature review on urban flooding • Gathering information about the study area, e.g., from reports, existing models, etc.	A preliminary CLD on the study area, based on the scientific knowledge, focused on urban flood risk
2	Interviews with stakeholders for preliminary CLD improvement	To collect and structure stakeholder knowledge for improving the key cause-effect chains of the preliminary CLD	• Semi-structured interviews with stakeholders and email exchange • Analysis of semi-structured interviews • Integration of scientific and stakeholder knowledge	A CLD on urban flood risk which integrates scientific and stakeholder knowledge
3	CLD causal structure validation	To validate general structure and key CLD connections	Collective model testing and participatory exercises	Final structure of CLD
4	Behaviour Over Time (BOT) graphs construction with stakeholders	To collect stakeholder perception on the dynamic evolution of some key variables of the system	BOT graphs construction	Graphs on the dynamic evolution of the system based on stakeholder perception

5	CLD integration based on stakeholder-built BOT graphs	• To analyse the main dynamics and impacts of flood in the CLD • To integrate BOT graphs results into final CLD	BOT graphs and key CLD feedback loops analysis	Formulation of hypotheses on urban system dynamics and flood risk management policies
6	Transformation of the CLD into a Stock and Flow (SF) model related to the current system condition	• To identify stock, flow, auxiliary and input variables • To identify mathematical equations and parameters using literature, existing models, reports, databases, stakeholders' knowledge • To develop sub-models and calculate indices that provide aggregated information on system dynamics	• Literature review and collection of information to populate the model (e.g., from reports, existing models, etc.) • Interviews with stakeholders and email exchange	A SF model on urban flood risk which integrates scientific and stakeholder knowledge
7	SF model validation	• To validate the model through the analysis of the behaviour over time of key variables/ indices of the system	• Comparison of BOT graphs constructed by stakeholders and trends obtained by the model simulation for the same variables • Collective model testing	Final SF model on urban flood risk

			and participatory exercises to validate other variables	
8	Future scenarios building and analysis	• To develop future scenarios to discuss with stakeholders • To design possible other scenarios with stakeholders • To compare future scenarios • To choose the most suitable scenario and perform a sensitivity analysis to hypothesise which variables to monitor over time	• Literature review and interviews with stakeholders regarding the scenarios to be explored • Analysis of the urban system in the event of flooding by comparing future scenarios • Sensitivity analysis of the most suitable scenario	Suggestions on i) a suitable bundle of actions to be implemented and ii) variables to adapt and adjust for improving the resilience of the urban system to flooding

2.2.1. Task 1: Preliminary Causal Loop Diagram building

The aim of the first modelling activity (TASK 1) was to build, based on both scientific knowledge on the main physical phenomena and specific information on the case study, a preliminary CLD to explicitly relate the issue of flooding to the main urban dynamics of the area. Whereas often a CLD can be directly co-developed with the stakeholders (see e.g., Inam et al. 2015; Perrone et al. 2020), existing scientific papers and models were used in the present work to develop a model draft which was subsequently augmented with stakeholder knowledge. This choice helped significantly expanding the level of detail of the model. For this purpose, an in-depth analysis of i) the main variables involved in hydraulic flood models existing in the literature, with focus on urban areas and ii) background information on the study area, e.g., from reports, existing models, etc., was necessary. Scientific electronic databases (Scopus, Web of Sciences, and Google Scholar) were used to identify original research and academic papers on flood risk in urban contexts. Some keywords, such as "flooding", "flood risk", "cities", "urban dynamics", were combined to select relevant articles. Regarding the specificities of the case study, Google searches and email exchanges with involved stakeholders proved invaluable. When formal equations were identified within the selected scientific papers and/or existing models, their transformation into CLD cause-effect relationships was done under the assumption that: i) the terms of the equations represent variables, e.g., A and B; ii) the correlation between the variables depends on whether variable B modifies variable A; iii) if the variation of A with respect to B is greater than zero, the polarity of the connection is positive, whereas if the variation of A with respect to B is less than zero, the polarity of the connection is negative (Sterman, 2000). For example, in the equation that links runoff coefficient (C) to river peak discharge (Qp), if C increases (decreases), then Qp increases (decreases). This means that the variation of Qp with respect to C is greater than zero. This relationship can be represented in the CLD by an arrow, with positive polarity, that starts from the variable 'surface runoff' and arrives at the variable 'river peak discharge'.

2.2.2. Task 2 and 3: Stakeholder involvement and Causal Loop Diagram causal structure validation

TASK 2 mainly aims at gathering the stakeholder perception about flood risk and past flooding events in the chosen area and at integrating it into the CLD. Semi-structured interviews with stakeholders were conducted. Stakeholder interviews were used to elicit the perception of the system boundaries and individual problem framing, and provide useful insights to add, modify, or improve the cause-effect relationships of the diagram (Inam et al. 2015; Kotir et al. 2016; Pluchinotta et al. 2021b). With the support of an agenda, each question was associated with an objective. Specifically, the first question helped the modeller understand why it is important to investigate flooding in the area. The interviewer asked the respondents whether, to their knowledge, flooding events had occurred in the past. If they had occurred, subsequent questions had the following objectives: i) collecting information on past flooding events; ii) understanding what type of flooding the area is most susceptible to; iii) investigating damage due to flooding; iv) investigating the effectiveness of individual and collective flood risk prevention measures in the area; v) investigating what post-intervention measures had been taken. If, however, the interviewee did not recall past flood events, the objectives of the following questions were: i) understanding whether the non-occurrence of flood depended on the exposure of the system to risk, e.g., the absence of heavy or long-lasting rainfall, or on the effectiveness of risk mitigation measures, e.g., drainage systems; ii) understanding why it could be important to investigate flooding. The interview structure can be found in Section 10.1 of the Supplementary Material. The responses given by the stakeholders were then translated into variables and the causal interconnections into links in the CLD. For this purpose, the stakeholders' responses were analysed based on the identification and use of specific categories: i) cause variables; ii) effect variables; and iii) causal relationship type, i.e., positive or negative polarity (Kim and Andersen, 2012; Eker and Zimmermann, 2016). Table 2 below provides a couple of examples of this process. In case of divergences of problem frames, they were aligned promoting discussion between stakeholders during a participatory workshop aiming at validating the CLD causal structure (TASK 3).

Table 2. Examples of the analysis of the semi-structured interviews with stakeholders

QUOTES FROM THE INTERVIEWS	**CAUSE VARIABLE**	**EFFECT VARIABLE**	**RELATIONSHIP TYPE**
“With improved defences the risk of flooding from river is residual”	River defences effectiveness	River flood	Negative
“Part of the road floods almost to the extent that the whole road is underwater. It affects people's movements and lives in general”	Infrastructure damage	1. Productive activities operation 2. Economic losses 3. Residents’ health	1. Negative 2. Positive 3. Negative

As stated by Mirchi et al. (2012), in participatory System Dynamics modelling, the validation can be done with the involvement of a range of experts and stakeholders during different phases of the modelling process. For this reason, several works have validated their System Dynamics models on water problems through the consultation of stakeholders (see e.g., Susnik et al. 2012; Sahin et al. 2016; Bertone et al. 2019; Pagano et al. 2019), which is particularly relevant when expert knowledge is used for model building. In this work, a workshop was organised, and stakeholders were asked to provide comments on both specific parts of the model and the whole CLD structure. Adopting the semi-structured interview style, a facilitator presented the model to stakeholders by the division of the variables into thematic clusters and encouraged them to validate the uncertain connections. Specifically, relationships between variables on which the literature was insufficient or for which stakeholders expressed different views in TASK 2, were discussed. This provided the final architecture of the CLD, which thus integrates scientific and stakeholder knowledge. It is important to clarify that the CLD does not represent a precise and definitive view of the analysed system, but a description based on the knowledge available at that time. Therefore, it is a ‘shared’ working base and can be subject to updates and revisions.

2.2.3. Task 4: Behaviour Over Time graphs construction

TASK 4 represented an additional step of knowledge building through stakeholder engagement. While the previous activities (TASK 2 and 3, Section 2.2.2) concerned the collection of the stakeholders’ understanding of the cause-effect chains affecting flood risk, in this task their perception of the dynamic evolution of the urban system and flood risk was collected. A workshop was organised, and stakeholders drew and described the Behaviour Over Time (BOT) graphs of key variables under different conditions. These variables were the main elements of the urban system affected by flooding, for which data are limited or unavailable. Although in the literature the construction and analysis of BOT graphs mainly support the problem structuring phase before the CLD construction with stakeholders (see e.g., Cavana and Maani, 2007; Elias, 2012), in this work this exercise was performed afterwards as the preliminary CLD was built based on scientific knowledge. For this reason, the BOT graphs represented a further step of stakeholder knowledge elicitation, necessary for building the final CLD and therefore for the formulation of hypotheses about the dynamics of the urban system related to flooding. Indeed, BOT graphs have the potential to provide insights and inform future modelling and data collection priorities (Calancie et al. 2018). In addition, integrating a multiplicity of perspectives may help practitioners understand the consequences (intended or unintended) of potential interventions and could therefore formulate more realistic assumptions about the dynamics of the urban system (Hovmand et al. 2013). After giving an example of how to draw a BOT, a facilitator organised stakeholders into groups based on their expertise. In each group the facilitator asked stakeholders to draw each variable's BOT under three different future conditions: 1) desired future, i.e., the evolution of the variable as the stakeholders would prefer; 2) most likely future, i.e., the evolution that the variable is expected to have; 3) feared future, i.e., the evolution of the variable that stakeholders do not want. Such graphs were built highlighting - if possible - specific values and thresholds. The groups were then brought together, and each group briefly presented at least one BOT graph. Variables that were particularly difficult to quantify, e.g., variables that are intangible and related to attributes of human behaviour, were assigned to all groups. When the graphs drawn by the different groups on the same variables did not show relevant differences, the graph that contained most information and a higher-level of detail was chosen. In case of large differences, the various interpretations were evaluated by all stakeholders to reach a consensus. At the end of the workshop an evaluation form of the activity was submitted to the stakeholders to help the facilitator improve future participatory activities.

2.2.4. Task 5: Causal Loop Diagram integration

To formulate hypotheses on both urban system dynamics and the implementation of flood related policies, TASK 5 was based on the aggregation of the knowledge collected in the previous activities. Specifically, the CLD - and more precisely the information provided by the feedback loops - was integrated with the stakeholder-built BOT graphs.

As stated in Section 2.1, in complex systems, the combination of feedback loops creates different patterns of behaviour. Although one of the advantages of CLD is that the essential components and interactions in a system can be represented with simplifications (Haraldsson, 2004), Richardson (1997) and Lane (2008) demonstrated with some examples the impossibility of rigorously inferring dynamic behaviour from non-formal models, such as CLD. Indeed, considering that the behaviour depends upon rate-to-level links, hidden loops, and net rates, that are unspecified in CLD, traditional definitions in terms of behaviour (based on CLD polarities) affect the fairness of dynamic behaviour inferred from feedback loops. In addition, Schaffernicht (2010) stated that CLDs: i) draw attention on 'events', i.e., a discrete change in one of the aspects of behaviour, rather than on the behaviour itself; ii) show system structure only, leaving the behavioural aspects to the modeller; iii) do not represent aspects of the structure that help the modeller notice traps of behavioural inferences. These problems are exacerbated in the case of a multi-loop system, such as an urban one. To make the assumptions about the dynamic behaviour of the system deduced from the feedback loops of the CLD as reliable as possible, the potential of the CLD was expanded through its integration with the BOT graphs built by stakeholders.

2.2.5. Task 6: Stock and Flow model construction

TASK 6 represented the first step of the Dynamic Simulation approach as it involved the construction of the quantitative SF model starting from the CLD. In fact, the SF model can be considered as a kind of evolution of the CLD developed in the previous tasks.

The development of qualitative conceptual models is certainly essential to capture a clear picture of complex systems. By means of feedback loops analysis, modellers can prioritise the aspects to be studied in more detail thus ensuring an in-depth understanding of the problem (Richmond, 1993).

Nevertheless, the information provided by a qualitative model may not be enough to identify an adaptive strategy and to support its operationalization. In addition, although integrating the narratives of CLD with BOT graphs allows an improved understanding of the influence of the dynamics on key variables over time, a limitation exists - especially for very complex models - related to the importance of isolating these dynamics from the context of a more comprehensive model. SD quantitative models can help through the use of multiple sub-models aggregated in a single model, which integrate qualitative ('soft' or intangible) and quantitative variables ('hard' or physical) (Pagano et al. 2019). They allow for precise specification of all the system's parts and their interrelation and, although they may be affected by data-related uncertainty, they can reveal complex systems behaviour that could not be understood through qualitative diagramming (Homer and Oliva, 2001). Therefore, once reasonably simplified conceptual models of the system have been constructed, a successful application of system dynamics involves running simulations (Mirchi et al. 2012).

CLD's variables and causal relationships were translated into the common SF model sets, i.e., stocks, flows, auxiliary variables, converters, and connectors (see Section 2.1 for further details on diagramming notation) and hypotheses on the mathematical equations and parameters were formulated (Meinherz and Videira, 2018), integrating multiple sources of information (i.e., scientific/grey literature, reports, databases, and stakeholder consultation). BOT graphs were used at this stage for the identification of the initial value of key variables of the urban system for which there is a lack of data/information, or which are difficult to quantify. Given the complexity of the system, the model was organised into 'thematic' sub-models - closely interconnected - representing the main processes/elements involved in an urban system subject to flood risk. Specifically, sub-models related to flood risk assessment, tangible damage evaluation, and co-benefits analysis were developed (see Fig. 6 which describes the conceptual structure of the whole model, with a focus on interconnections). Although SD modelling provides a thorough understanding of complex systems (Senge and Sterman, 1992; Simonovic, 2009), the obtained information needs to be synthesised to be useful for planning and strategic purposes. In this work, the synthesis was carried out through the construction of indices that aggregate representative variables of the system behaviour; these included the hazard index, the vulnerability index, the risk index, and the urban performance index, computed on the basis of some studies (e.g., Kissi et al. 2015; Ntajal et al. 2016; Babanawo et al. 2022; Tingsanchali and Promping, 2022). This allowed combining the SD approach, which considers the interdependencies and cause-effect relationships between the different components of the system, with an index-based method for assessing the risk and resilience of the urban system to flooding. The following paragraphs provide more information on the main sub-models and indices developed.

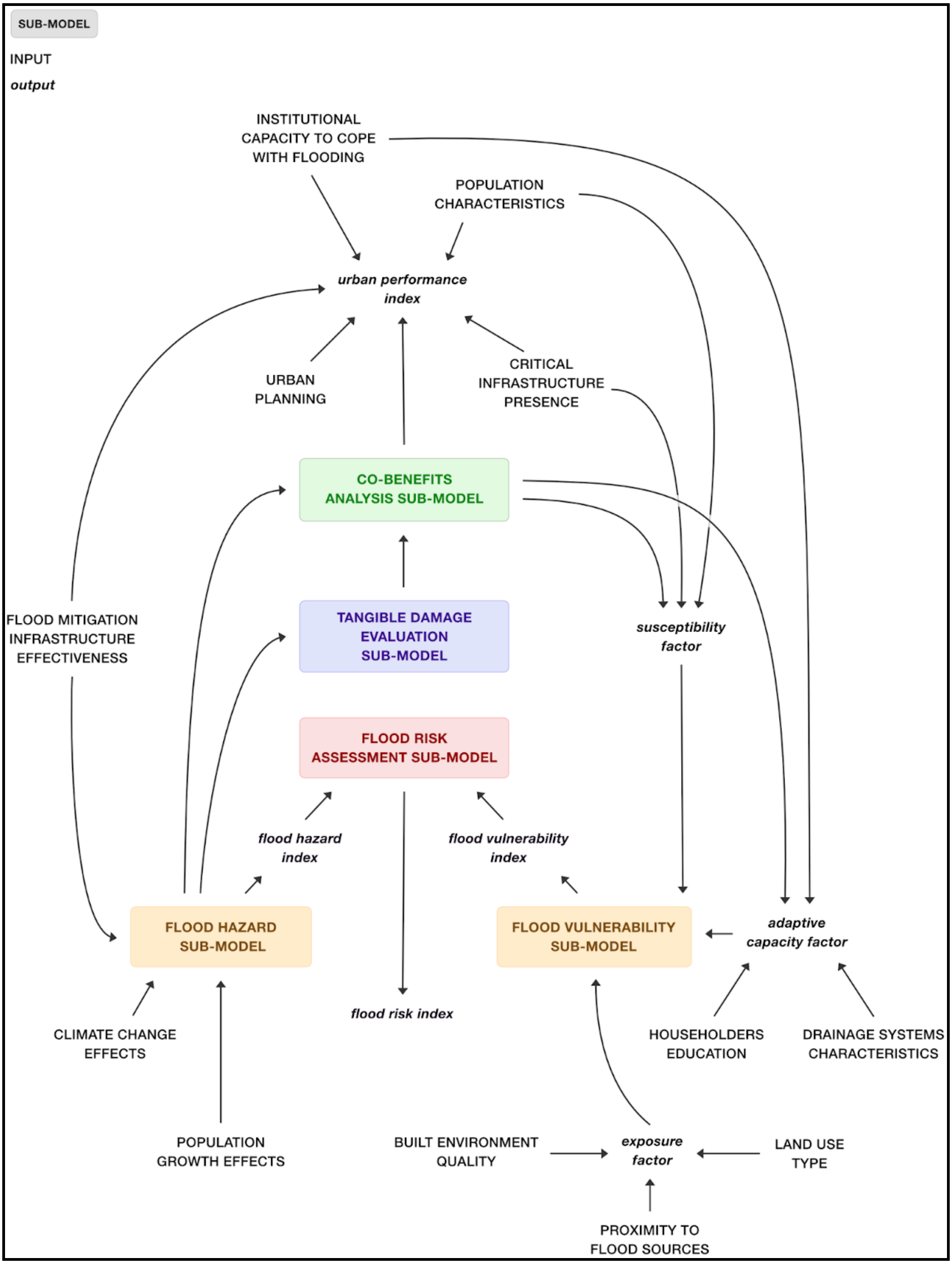


Fig. 6 – Interactions between the different SD sub-models developed for the analysis of urban flood resilience. The sub-models are in coloured rectangles, while the main inputs/outputs of the sub-models are respectively in capital letters and italics.

2.2.5.1. 'Flood risk assessment' sub-model and risk-based indices

The 'Flood risk assessment' sub-model provided a simplified risk evaluation, combining the flood hazard-related elements with the variables that describe the system's vulnerability to hazard.

The hazard part of the sub-model included all the examined flood sources and all the physical variables that condition urban flood depth, e.g., the precipitation and sea level rise (influenced by climate change), the imperviousness of the area (influenced by population growth), the surface runoff, the effectiveness of flood prevention/mitigation infrastructure (influenced by ageing and sediments build-up). Once the flood depths generated by the different flood sources were assessed, they were associated with a hazard class between 1 (very low/low) to 3 (high/very high) adapting what suggested by Tingsanchali and Promping (2022). To obtain a single flood hazard index (FHI) representing the global flood hazard of the urban system, the flood sources were assigned a weight (the sum of which did not exceed 1) based on both the literature and what stakeholders claimed during the individual interviews (TASK 2, Section 2.2.2) and the workshop for the validation of the CLD structure (TASK 3, Section 2.2.2). A weighted average was then performed. The weighting reflected the relative importance of each source regarding the global flood hazard of the area. Therefore, the assignment of the weights was linked to the capacity of the flood resource to create devastating impacts on the system; the greater the magnitude of the potential impact, the greater the weight assigned.

As for the vulnerability part of the sub-model, this was developed as the result of the interrelationships between exposure, susceptibility, and adaptive capacity to hazard. Specifically, exposure was understood as the predisposition of the system to be disrupted by a flooding event due to its location; the values that are present at the location where flooding can occur (e.g., goods and infrastructure) were characterised in terms of their quality or density. Susceptibility was related to system characteristics, including the social context of flood damage formation and the presence of critical infrastructure (e.g., hospitals, schools, electricity sub-stations); while the adaptive capacity variables referred to those aspects, mainly cultural and institutional, that condition the system's response to hazard. Adapting from Kissi et al. (2015), Ntajal et al. (2016), Babanawo et al. (2022), and Tingsanchali and Promping (2022), each element characterising the three components of vulnerability was assigned a class (between 1 and 3) and a weight, and a weighted average was performed. In this way, the exposure factor (E), the susceptibility factor (S), and the adaptive capacity factor (AC) were obtained. To calculate a single flood vulnerability index (FVI), the three factors were aggregated using the additive function w1*E+w2*S-w3*AC, with sum of weights (w1, w2, w3) not exceeding 1.

The flood risk index (FRI) was then computed as the product of the FHI and the FVI and classified into three ranges corresponding to very low/low (class 1) for $1 < FRI \leq 10$, medium (class 2) for $10 < FRI \leq 15$, high/very high (class 3) for $15 < FRI \leq 25$.

2.2.5.2. ‘Tangible damage evaluation’ sub-model

The damage sub-model focused on the evaluation of the effects of flooding on the built environment. Case specific depth (m) - damage (€/m2) curves were applied to describe the primary impacts of flooding on residential buildings, businesses, transport services, and recreational facilities. Once the damage on each component of the built environment was calculated, classes 1 (very low/low) to 3 (high/very high) were assigned adapting what suggested by Tingsanchali and Promping (2022). To obtain a global damage class for the built environment, the highest damage class among the cited impacts was chosen thus reasoning in favour of safety.

2.2.5.3. 'Co-benefits analysis' sub-model

The 'Co-benefits analysis' sub-model aimed to investigate the additional positive effects that planning and/or policy measures might have on social, environmental, and economic aspects of the urban system (e.g., residents' well-being; ecosystem quality; attractiveness of the area). Although evidence has demonstrated that co-benefits may represent the main driver for solutions - and mainly sustainable solutions - implementation (Larson and Perrings, 2013; McVittie et al. 2018), only a few works have explicitly considered the co-benefits analysis for measures selection and design (see e.g., Alves et al. 2018; Coletta et al. 2021). Once identified, the co-benefits were transformed into stocks as they are variables whose memory needs to be preserved over time. As they are generally intangible variables: i) they were expressed in dimensionless terms; ii) their starting value was defined through BOT graphs constructed by stakeholders (TASK 4, Section 2.2.3) or literature; iii) they were measured on a scale from 0 to 1 (or 100 in % terms), where 0 corresponds to the minimum level and 1 to the maximum level.

2.2.5.4. Urban performance index

To provide a comprehensive overview of the urban resilience to flooding, an urban performance index was calculated. Indeed, measuring resilience can lead to a better understanding of the potential performance of districts in the time of an adverse event (Moghadas et al. 2019). Based on several studies that have applied an index-based approach for measuring the urban performance in the face of flooding (e.g., Cutter et al. 2008; Cutter et al. 2010; Verrucci et al. 2012; Batica et al. 2013; Cutter et al. 2014; Joerin et al. 2014; Rockefeller, 2015; Figureido et al. 2018; Moghadas et al. 2019; Feofilovs et al. 2020; Satour et al. 2021; Marasco et al. 2022), system characteristics related to five resilience dimensions (social, economic, institutional, infrastructural, and environmental) were used to quantify community disaster resilience. In this study, the social resilience analysed the context-related capacities of different population groups within urban districts that can effectively respond in time of flooding; the economic dimension measured the vitality and resourcefulness of the community economy. The institutional resilience was measured based on the attributes connected with planning, preparedness initiatives and institutional capacity to cope with flooding; the infrastructural resilience was about the attributes or qualities of physical assets leading to response and recovery capacity. The environmental dimension considered the qualities of the urban environment that can increase or reduce the flooding risk. Variables of the urban system related to these dimensions were selected, and classes (between 1 and 3) and weights were assigned to perform an aggregated weighted average and obtain a global urban performance index.

2.2.6. Task 7: Stock and Flow model validation

TASK 7 involved the validation of the SF model constructed in TASK 6. A conceptual validation through stakeholder knowledge was carried out. BOT graphs drawn by stakeholders (TASK 4, Section 2.2.3) - and specifically the most likely behaviour over time of key variables of the system - were used to ensure that the model was appropriate. In addition, specific inputs/outputs of the model were validated with stakeholders applying the semi-structured interview style during a workshop. As for the inputs, stakeholders were asked whether they agreed with the assigned values; regarding outputs, whether they agreed with the behaviour over time. In both moments, stakeholders were encouraged to justify their responses. Outputs for which BOTs were built (TASK 4, Section 2.2.3) were only shown in case of deviation from the most likely future drawn by stakeholders. Stakeholder suggestions were implemented and the final SF model on urban flood risk, which integrates scientific and stakeholder knowledge, was obtained.

2.2.7. Task 8: Future scenarios building and analysis

TASK 8 provided suggestions on the most suitable bundle of actions to implement to increase the resilience of the urban system to flooding.

The SF model obtained from the previous tasks was used with a twofold objective: i) for the assessment of the long-term impacts of the baseline conditions; ii) for a scenario analysis, useful to analyse the potential effect of the introduction of specific measures on urban flood resilience.

Based on its expertise and the desired futures drawn by stakeholders (TASK 4, Section 2.2.3), the modeller developed different flood risk management scenarios. These scenarios were then discussed with stakeholders using semi-structured interviews during a workshop. Specifically, a facilitator described the meaning of each scenario compared to the baseline situation and stakeholders were asked to express their opinion about the behaviour of the key variables of the system in each developed scenario. A second session focused on the co-design of additional scenarios to be tested in the model for improved risk management. Stakeholders were asked to collectively select other factors/measures that may contribute to obtain the future scenarios they desire. A facilitator wrote detailed notes of what the stakeholders mentioned. Subsequently, the modeller implemented the stakeholders' suggestions and combined the developed scenarios in order to propose suitable bundles of actions that can be adapted and adjusted over time. The results were then discussed with other experts considering the trend of the main variables of the SF model with respect to the baseline scenario. The most suitable scenario for the area was chosen and used as a benchmark for sensitivity analysis (SA). SA was performed to understand which variables impact most on the resilience of the urban system (Mirchi et al. 2012). The effect of single parameter variation was analysed by individually altering the standard value of each parameter with up- and down-variations of 50% in a series of separate runs, while holding all other terms constant (Mateus & Franz, 2015). This helped to suggest to decision-makers i) which factors or associated processes in the urban system they should monitor over time as they have more impact on urban flood resilience, and consequently ii) on which aspects to intervene to adapt and adjust strategies and objectives with a view to improving urban flood resilience.

3. THE THAMESMEAD CASE STUDY FROM THE FLOOD RISK ANALYSIS PERSPECTIVE

The methodology proposed in Section 2 has been applied to the Thamesmead (TM) case study, a former inhospitable marshland in south-east London, drained in the 1960s when the Greater London Council bought it with the aim of transforming the land into an attractive residential area (Markowitz, 2017). Unfortunately, that potential was never fully realised. A new regeneration plan renewed the interest in flood risk in the area.

The area (Fig. 7) is located between the London Borough of Bexley and the Royal Borough of Greenwich. It is bordered by Woolwich to the southwest, Belvedere and Erith to the southeast, and the tidal River Thames to the north.

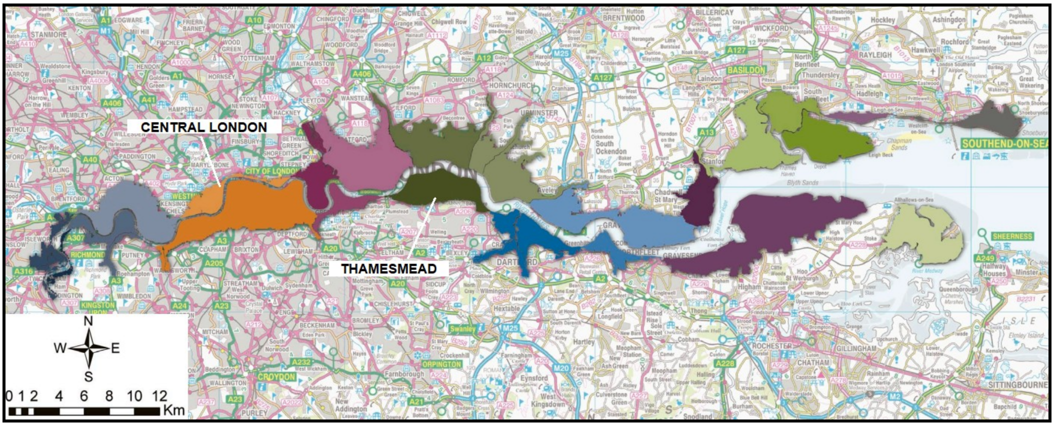


Fig. 7 – Overview of the study area in relation to central London (adapted from EA, 2012). The coloured areas are the eight Thames Estuary 2100 flood risk action zones.

The information in this section was mainly gathered from the Thames Estuary 2100 Plan (EA, 2012), the Living in the Landscape Framework (Peabody, 2021), the Charlton to Bexley Riverside Integrated Water Management

Strategy (AECOM, 2017), and from semi-structured interviews or personal correspondence with stakeholders. In this regard, additional details are included in the Section 10.2 of the Supplementary Material.

TM consists of 40.000 people, 16.000 households and approx. 1000ha. Since 2014, the 65% of the housing estate is owned by Peabody Trust, which set out an ambitious 30-year vision for TM as London's new town. This will make the area experience significant growth, with averaged projections of 14.140 additional residents and 4.850 new jobs over the next 20 years. The vision is based on some tenets, mainly related to the importance of nature, connectivity, inclusion, and safety as well as resilience to climate change impacts. Based on that, building resilience to flooding is considered a key issue for protecting both the local community and the built environment in TM by the stakeholders. The area, in which there are 21 schools, six care homes, and over 100 electricity sub-stations, is vulnerable to four, closely related, types of flooding mechanisms: tidal, fluvial, pluvial, and groundwater flood. The following paragraphs illustrate the main characteristics of the area in relation to the different sources of flooding.

3.1. Tidal river flood risk in Thamesmead

The area is located within the portion of the River Thames where it is tidal, and hence subject to tides. Specifically, the tide rises and falls twice a day by up to 7m. In addition, the Thames estuary is prone to an increase in water levels caused by a North Sea surge. For this reason, TM benefits from the Thames Tidal Defences and, specifically, from a River Wall and two sections of embankment. The breach modelling showed that although the risk of tidal flooding is residual, the consequence of a breach or overtopping of the defences would be significant. It should be considered that the combined effect of defences degradation caused by ageing and climate change, may affect the standard of protection that they can provide (EA, 2010). These might eventually have to be improved or replaced. However, according to the Thames Estuary 2100 Plan, the Thames Defences - with continued maintenance and planned improvements, and with later modification (after 2070) - could continue to provide protection to London and the estuary through to the end of the century.

3.2. Fluvial flood risk in Thamesmead

The Wickham Valley watercourse (also known as the Butts canal) is a main river that flows northwards and enters a culvert to the south of TM, which discharges into the Southmere Lake. Southmere Lake is connected to the TM lakes and canals surface water drainage network, which is London's largest Sustainable urban Drainage System, and eventually discharges into the River Thames. Located to the east of TM, the Erith Marshes system of ditches and dykes, along with the lakes and canals system, dominates the drainage system of the area. In both networks, represented in Fig. 8, the water levels are controlled by sluices and pumping stations.

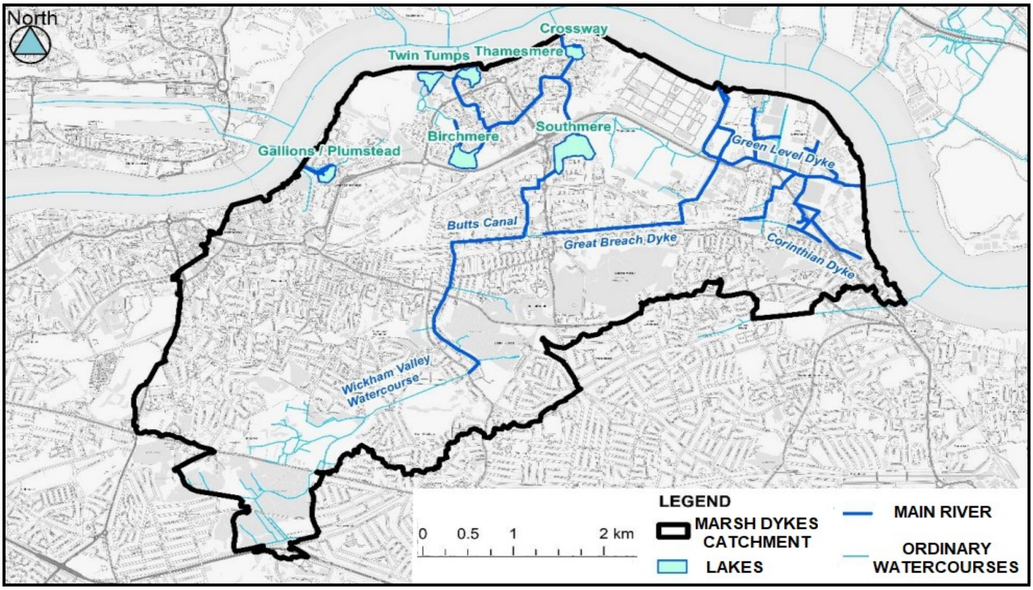


Fig. 8 – Locations of the drainage systems in the Marsh Dykes catchment, i.e., the entire area of reclaimed marshland (adapted from JBA, 2020).

3.2.1. Gravity outfalls

There are three locations in the study area where flows can exit the system under low tide conditions via gravity outfalls, i.e., Plumstead Sluice, Abbey Sluice and Great Breach Dyke. The location of these outfalls is shown in Fig. 9.

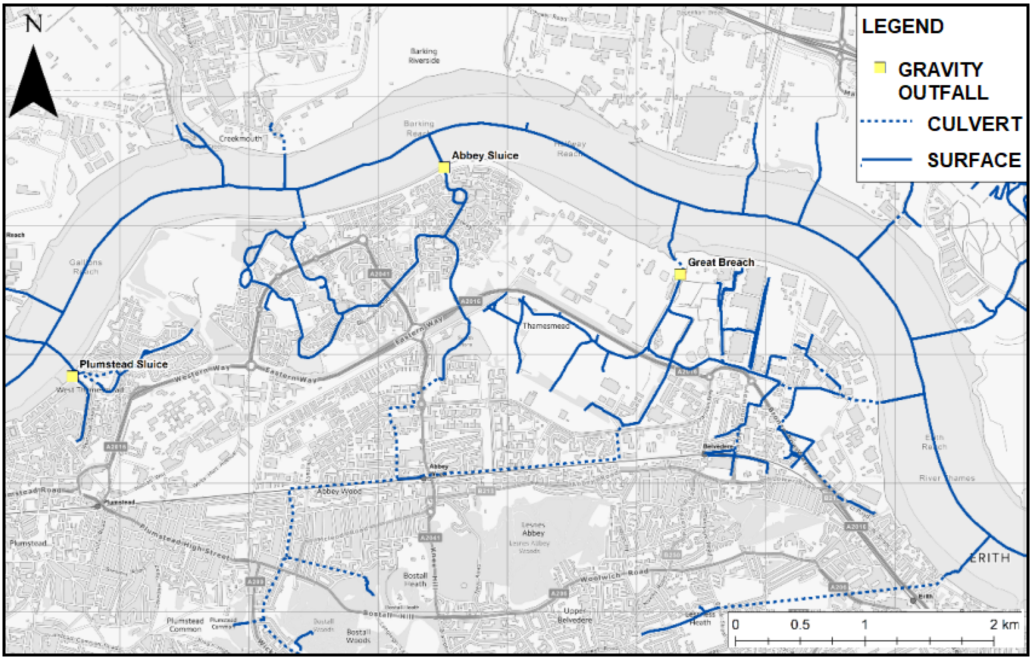


Fig. 9 – Locations of Gravity Outfalls in the study area (adapted from JBA, 2020).

Plumstead Sluice and Abbey Sluice take flows respectively from the Gallions Lake and the Crossway Lake to the River Thames. They maintain the water level in the lakes and connected canals at -0.762mAOD, which corresponds to their constant standing water level (URS Scott Wilson, 2012). The Great Breach gravity outfall is at the same location as the Great Breach pumping station and takes fluvial flows to the River Thames during low tide conditions.

3.2.2. Pumping stations

Due to the tidal fluctuations of the Thames, the sluice outflows can become tidelocked. In such circumstances, the pumps operate in four pumping stations, i.e., Great Breach, i.e., Green Level, Lake 5 (Plumstead) and Lake 4 (Thamesmere), to pass flow to the River Thames. As fluvial pumping stations are inland, they can be identified as defences in addition to the tidal flood defences (Fig. 10).

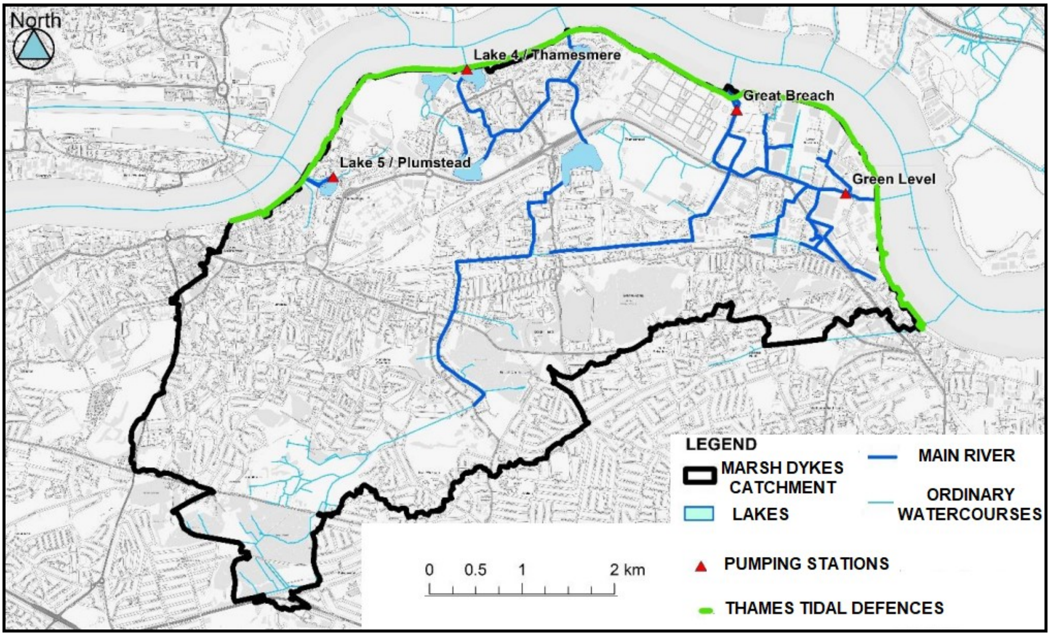


Fig. 10 – Defences included within the Marsh Dykes catchment, i.e., the entire area of reclaimed marshland (adapted from JBA, 2020).

3.3. Pluvial flood risk in Thamesmead

The study area is covered by the Crossness sewer network, which is largely a combined system with some areas of separated sewer, i.e., foul and storm water sewers, with the latter discharging into the lakes and canals system (Fig. 11). Several sewer flooding episodes were recorded within the last 10 years.

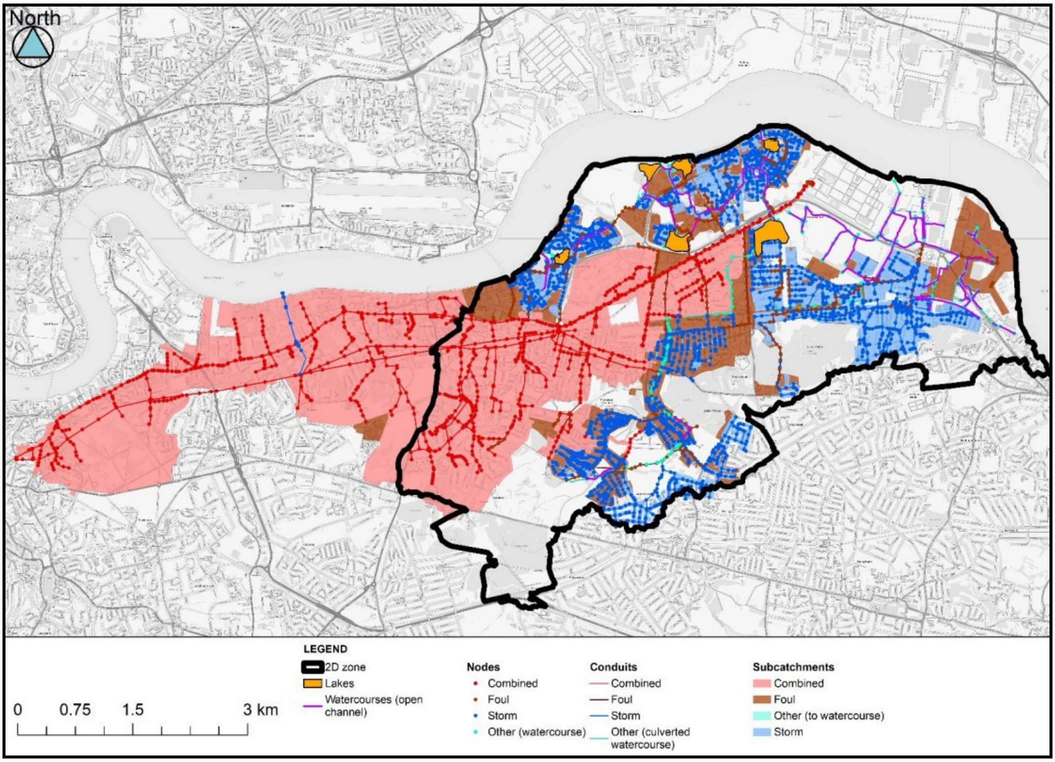


Fig. 11 – Crossness sewer network within the Marsh Dykes catchment, i.e., the entire area of reclaimed marshland (adapted from JBA, 2020).

3.4. Groundwater flood risk in Thamesmead

The study area consists primarily of reclaimed marshland and therefore has a high water table. Most of the bedrock in the area is comprised of Thanet Sand Formation. There is an area of Chalk to the northwest and a small area of Chalk to the south. The eastern part is underlain by Lambeth Group (Fig. 12). Therefore, the base geology is relatively permeable, and the area is considered to have potential for groundwater flooding.

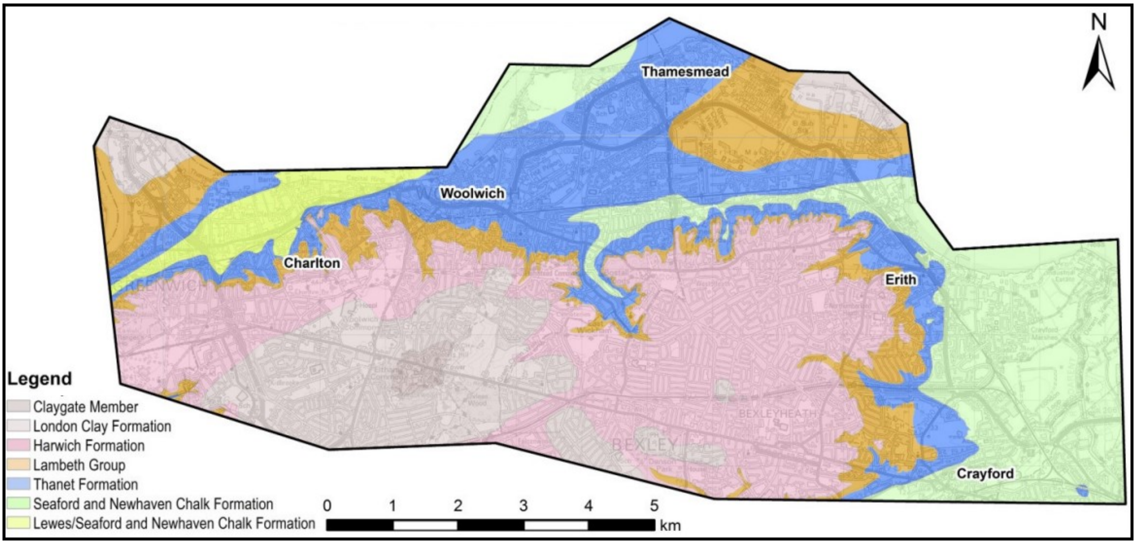


Fig. 12 – Geology of the Opportunity Areas in south-east London, among which is Thamesmead (adapted from AECOM, 2017).

Some models that consider flood risk from these different sources (mainly pluvial, fluvial, and tidal flooding) have already been developed. However, an analysis of their interaction with other aspects (environmental, economic, and social aspects) is still missing. In addition, no information on the condition of the sewer network and canals was contained within these models. Therefore, it has been assumed that they are in good working condition and are hydraulically efficient. Furthermore, the various discussions with stakeholders (see Sections 10.1, 10.2, 10.4, 10.5, 10.7 and 10.8 of the Supplementary Material) revealed that flooding events in the area are strictly linked to both the stormwater and the lakes and canals systems due to their ageing and the sediment build-up. The groundwater and tidal river, through interactions with these systems, contribute to exacerbating the situation. Stakeholders therefore expressed the need for approaches that assess the combined effect of these flood resources in the area. However, according to them, drainage networks should be both improved by adding mainly BG infrastructure and maintained in existing parts to avoid breaks or blockages.

Besides that, the stakeholders specified that pluvial and groundwater flood monitoring warning systems are lacking as well as that residents' awareness of flood risk should be increased.

4. RESULTS

The main results obtained from the application of the methodological framework presented in Section 2 to the Thamesmead case study are presented below. The first part of the Section relates to the description of the outputs of the implementation of the System Thinking approach (see Section 4.1 and 4.2), while the second part is about what obtained from the Dynamic Simulation (see Section 4.3 and 4.4).

4.1. Thamesmead flood Causal Loop Diagram construction

The final version of the CLD related to the TM study area is shown in Fig. 13. The variables in red identify the four main types of flooding mechanisms (i.e., tidal river flood, groundwater flood, fluvial flood, and pluvial flood) to which the area is vulnerable. The variables in orange identify the main issues/elements that are currently explored within the CUSSH and CAMELLIA projects and that represent a 'basis' for the developed model (see Davies et al. 2021); those in grey define the main measures/actions that, based on literature, stakeholder knowledge, and the ongoing regeneration projects, could be implemented in the area. The links between variables within feedback loops (endogenous variables) are black to distinguish them from the simple causal relationships (in blue and grey). A full list of the variables used in the CLD, along with a description, is provided in the Section 10.3 of the Supplementary Material.

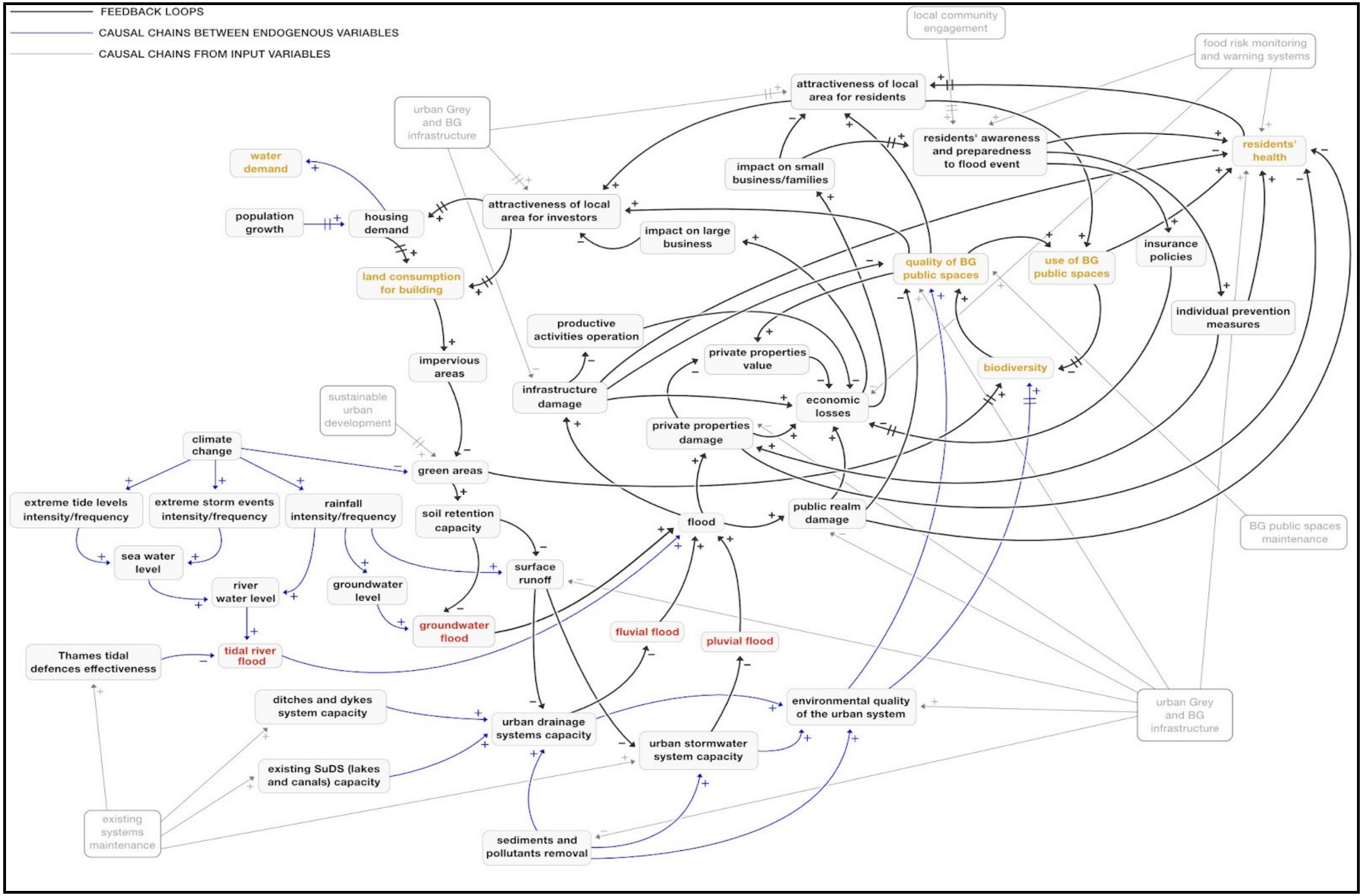


Fig. 13 - Thamesmead flood CLD.

The CLD in Fig. 13 was obtained using the Vensim® software, following TASKS 1, 2, and 3 described in Section 2.2. The information needed to build the preliminary TM urban flood risk CLD (TASK 1, Section 2.2.1) has been taken from i) literature review on hydraulic flood models variables, e.g., soil retention capacity and surface runoff, and the topics of flood risk and its effects on urban systems in general; ii) other TM CLDs already developed through three previous stakeholders workshops (between January and July 2020) on the quality of the built environment and BG spaces for other ongoing modelling activities within the CUSSH and CAMELLIA projects (see Pluchinotta et al. 2021b for further details); iii) existing water management reports through London and the Thames estuary obtained from involved stakeholders (see Section 10.2 of the Supplementary Material). As far as the improved CLD version which includes stakeholder knowledge (TASK 2, Section 2.2.2) is concerned, it was obtained from the analysis of both four rounds of semi-structured interviews of approximately 1 h duration (see Section 10.1 of Supplementary Material) and the review of past flooding events in the area with experts.

The validation of both some key connections and the general structure of the improved CLD with stakeholders during an online workshop (approximate duration 1 h) held on 9 September 2021 allowed producing the final version of the CLD structure (TASK 3, Section 2.2.2). CLD validation was based on the use of semi-structured interviews. Full details on the workshop agenda used for the TM CLD causal structure validation and on the stakeholders involved in the workshop are in Sections 10.4 and 10.5 of the Supplementary Material respectively.

With the aim of identifying and labelling features in the variable set and being also consistent with the analysis of the other CLDs on the quality of built/BG environment already developed for the case study, the TM CLD variables were coded into first order thematic clusters identified by the CUSSH/CAMELLIA team (see Pluchinotta et al. 2021b for further details). Four coders carried out the attribution of thematic clusters to the CLD flood variables. Fifteen variables were attributed to the ‘water management’ sector; thirteen variables were included in the ‘socio-economic aspects’ cluster. In the ‘natural capital’, ‘climate’, and ‘built environment’ sectors, five, four, and three variables have been allocated respectively. The remaining variables of the flood CLD were instead distributed, for a maximum number of two variables per sector, between the clusters ‘people's use of spaces’, ‘health’, ‘participation’, ‘maintenance’, ‘governance’, and ‘sustainability driven design’. Fig. 14 shows the TM flood CLD with the first order thematic clusters highlighted.

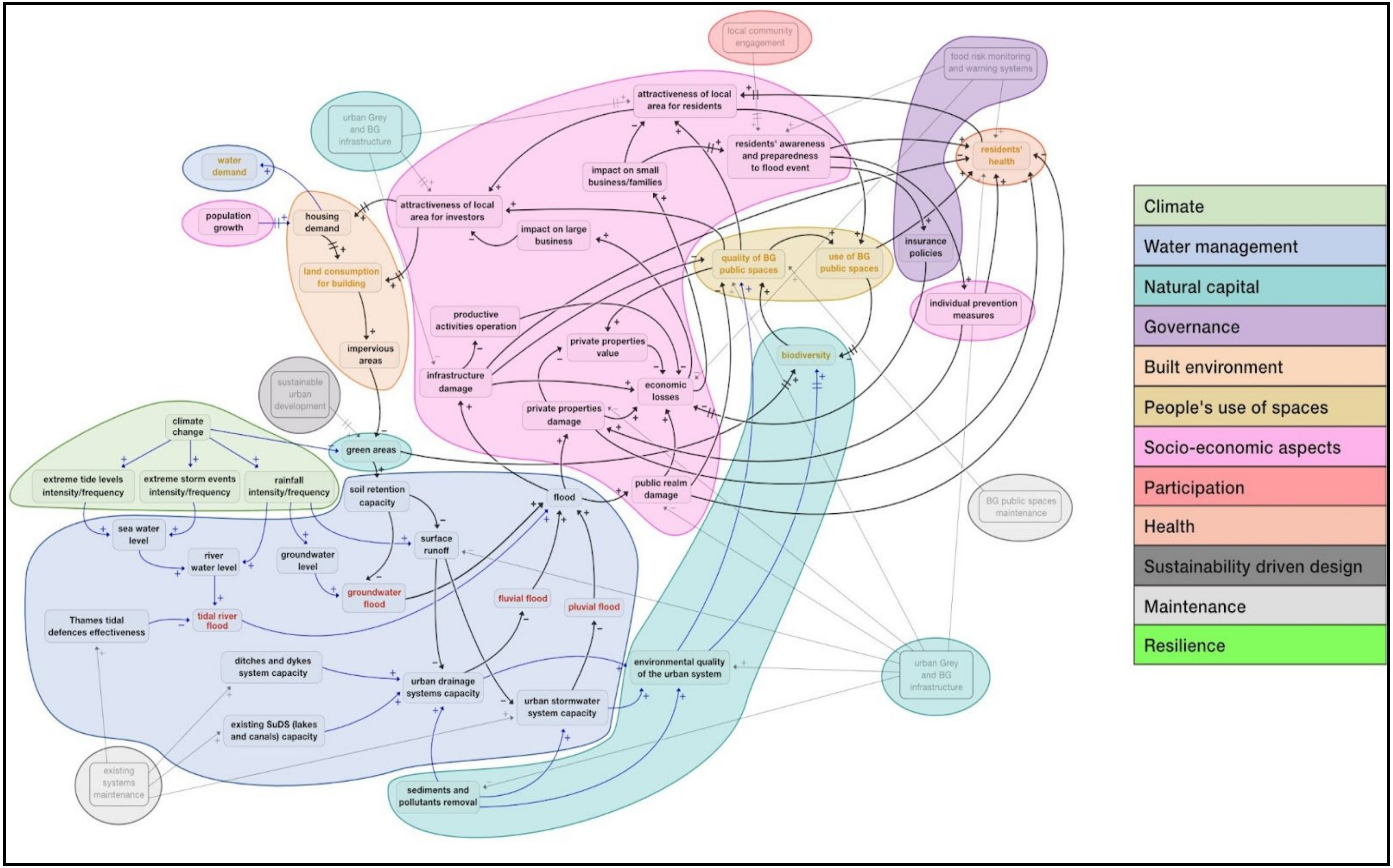


Fig. 14 - Thamesmead flood CLD with thematic clusters highlighted.

The second part of the online workshop held on 9 September 2021 (approximate duration of 1 h) and oriented to the analysis of the BOT graphs of key variables of the system (TASK 4, Section 2.2.3). Full details on the workshop agenda used for the BOT graphs construction are included in Section 10.4 of the Supplementary Material. Using Jamboard, the digital interactive whiteboard developed by Google, the stakeholders were asked to represent and describe, with the help of facilitators, the behaviour over time of the variables ‘infrastructure/public realm damage’ and ‘private properties damage’ due to flooding, ‘quality of BG public spaces’, ‘attractiveness of local area’, and ‘residents’ health’ under the three different conditions introduced in Section 2.2.3 of the methodological framework (i.e., desired future, most likely future, and feared future). The variables listed above were chosen for a twofold reason. First, they represent some of the objectives set by Peabody's ambitious Plan for regeneration in TM (namely, minimizing flood damage, achieving an attractive neighbourhood and high-quality BG public spaces, and improving the well-being of residents). Second, the possibility of finding data that describe them over time is limited. The seven stakeholders who participated in the workshop were divided into two groups in relation to their expertise and interests. The first group with four stakeholders was responsible for representing the variables 'infrastructure/public real damage' and 'private properties damage'; the second group worked on the graphs of the variables 'attractiveness of local area' and 'residents' health'. The variable 'quality of BG public spaces' was assigned to both groups, because it was considered particularly difficult to represent due to the absolute lack of data in the literature. The time horizon considered in the graphs was from 2010 until 2050, i.e., the end of the regeneration Plan.

4.2. Causal Loop Diagram integration based on Behaviour Over Time graphs

In this section, the mechanisms of the CLD which have the same variables as the BOT graphs are analysed and enriched to hypothesize the dynamic behaviour of the variables. TASK 5 of the methodological framework (Section 2.2.4) focused on formulating hypotheses on both urban system dynamics and the implementation of policies in the context of flood risk.

Within the flood CLD, through the application of function 'loops' in Vensim® software, 396 feedback loops directly involving the variable 'flood' have been identified. Specifically, 132 involve 'pluvial flood', ‘groundwater flood’, and 'fluvial flood'. The loops that are produced are mainly balancing loops. No feedback loops involve the variable ‘tidal river flood’.

The loops chosen for the analysis and integration with BOT graphs are those that contain a greater number of variables identified as important by the stakeholders in previous activities carried out within the CUSSH and CAMELLIA projects (‘land consumption for building’, ‘biodiversity’, ‘use of BG public spaces’, ‘economic losses’, ‘impact on small business/families’). The variables involved in each feedback loop, the related dynamics activated within the system, and the behaviour mode are included in Section 10.6 of the Supplementary Material. For the sake of brevity, only the most relevant CLD-BOT graphs’ integrations are presented below. These involve the feedback loops B1 and B2, whose dynamics mainly relate to the variables 'infrastructure damage' and 'public realm damage', and the B4 and B5, whose dynamics are related to 'attractiveness of the local area' and 'quality of BG public spaces' respectively.

4.2.1. Infrastructure and public realm damage

Firstly, two balancing loops with time delays involving the 'infrastructure damage' (B1) as well as the 'public realm damage' (B2) are isolated and shown in Fig. 15. The minimization of both classes of damage is a key objective for the area.

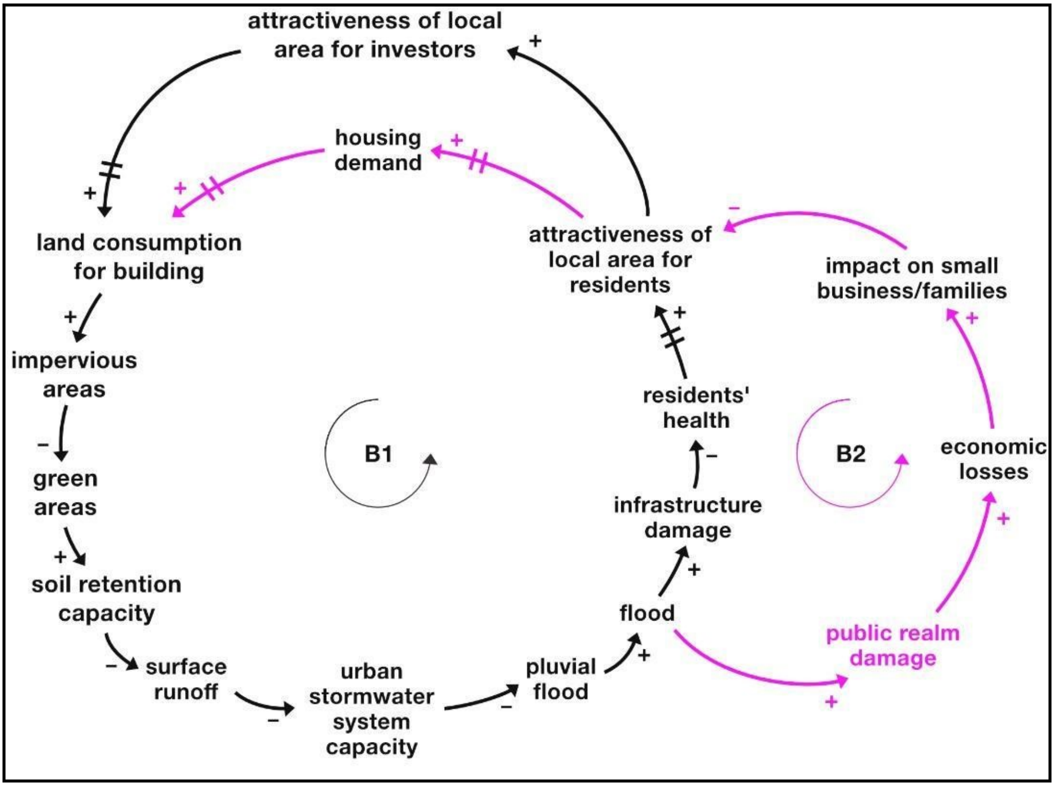


Fig. 15 –Infrastructure and public realm damage feedback loops (respectively B1 and B2). Loop B1 is the one in black, while loop B2 is the one in pink. The variables 'land consumption for building', 'impervious areas', 'green areas', 'soil retention capacity', 'surface runoff', 'urban stormwater system capacity', and 'pluvial flood' are in common between the two loops. Changing times (delays) are represented by bars on the arrows.

Specifically, the black balancing loop B1 shows that an increase of 'flood' may lead to an increase of 'infrastructure damage' with a consequent reduction of 'residents' health' and the attractiveness of the area. Considering the balancing loop B2 (pink), if ‘flood’ increases, the ‘public realm damage’ and ‘economic losses’ increase, reducing the attractiveness of the area. In both loops a reduction of the attractiveness of the area might lead to a decrease of ‘land consumption for building’, resulting in an increase of ‘soil retention capacity’ and a reduction of flood risk. These are two balancing feedback loops with delays that might create oscillating behaviour in the system in relation to the achievement of the established objective, i.e., the minimization of the 'infrastructure/public real damage'. This means that flood damage to infrastructure and the public realm may either increase or decrease in different conditions. Both loops are closely interconnected due to shared variables (‘flood’, ‘attractiveness of local area for residents’, ‘land consumption for building’, ‘impervious areas’, ‘green areas’, ‘soil retention capacity’, ‘surface runoff’, ‘urban stormwater system capacity’, and ‘pluvial flood’). Thus, if one of the two types of damage is reduced, the other one could be reduced as well.

Fig. 16a shows the feared future (yellow line) and the most likely future (red line) of the variables 'infrastructure damage' and 'public realm damage' as perceived (and drawn) by stakeholders; according to them, both trends may increase over time due to the impacts of climate change.

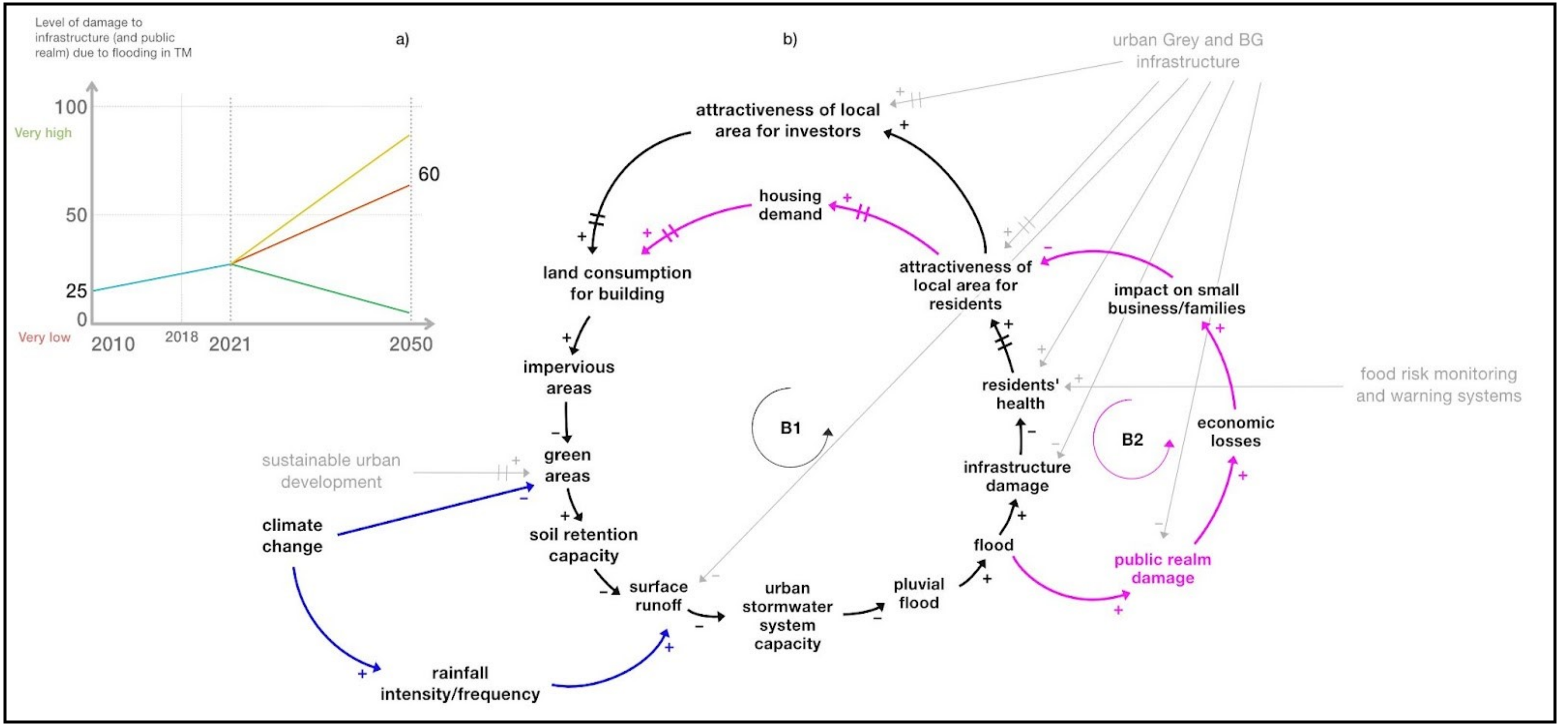


Fig. 16 - a) BOT graph of the variables 'infrastructure/public realm damage' created by the stakeholders during a participatory workshop. The blue line represents the past behaviour of the variable, the yellow, red, and green ones respectively the feared, most likely, and desired future. b) Infrastructure and public realm damage feedback loops (respectively B1 and B2). Loop B1 is the one in black, while loop B2 is the one in pink. The variables 'land consumption for building', 'impervious areas', 'green areas', 'soil retention capacity', 'surface runoff', 'urban stormwater system capacity', and 'pluvial flood' are in common between the two loops. The variables in grey are measures/actions; simple causal relationships between variables outside the feedback loops (exogenous variables) are in blue. Changing times (delays) are represented by bars on the arrows.

Considering the effect of the variable ‘climate change’ on the loops (Fig. 16b), it can be observed that a large increase of the variable may lead to a significant decrease of 'green areas' and a large increase of 'surface runoff' with a consequent increase of 'infrastructure damage' and 'public realm damage' and thus a linear upward trend of the variables (instead of oscillatory as would result from the analysis of the loops alone in Fig. 15). Depending on the severity of the effect of ‘climate change’ on ‘green areas’ and ‘surface runoff’, the feared and most likely future may be obtained. According to the stakeholders, by activating flood risk mitigation/prevention measures in the system, the variables ‘infrastructure damage’ and ‘public realm damage’ may behave similarly to the desired future (green line, Fig. 16a), which is linearly decreasing. In fact, adding some interventions in the loops simultaneously (see Fig. 16b) may generate the desired dynamics and thus move from an oscillatory to a linear trend of damage minimization. For example, the introduction of ‘Grey and BG infrastructure’ may allow the rebalancing of the system thanks to an effect on the ‘infrastructure damage’ and ‘public realm damage’ variables. In the long term, further corrective measures, such as ‘sustainable urban development’, should be activated to ensure that the system does not move away from the target of damage minimization (and therefore from the desired future). Indeed, short-term damage management (e.g., through the introduction of 'Grey and BG infrastructure') may lead to an increase of the attractiveness of the area and of ‘land consumption for building’, which, if not effectively controlled, risks reducing ‘soil retention capacity’, which is increasingly exacerbated by ‘climate change’, and once again unbalancing the system.

4.2.2. Attractiveness of local area and quality of Blue and Green public spaces

Fig. 17 includes two balancing feedback loops with time delays (B4 and B5) related to the 'attractiveness of local area' and 'quality of BG public spaces'. Key objectives for the area are the achievement of an attractive neighbourhood and high-quality BG public spaces.

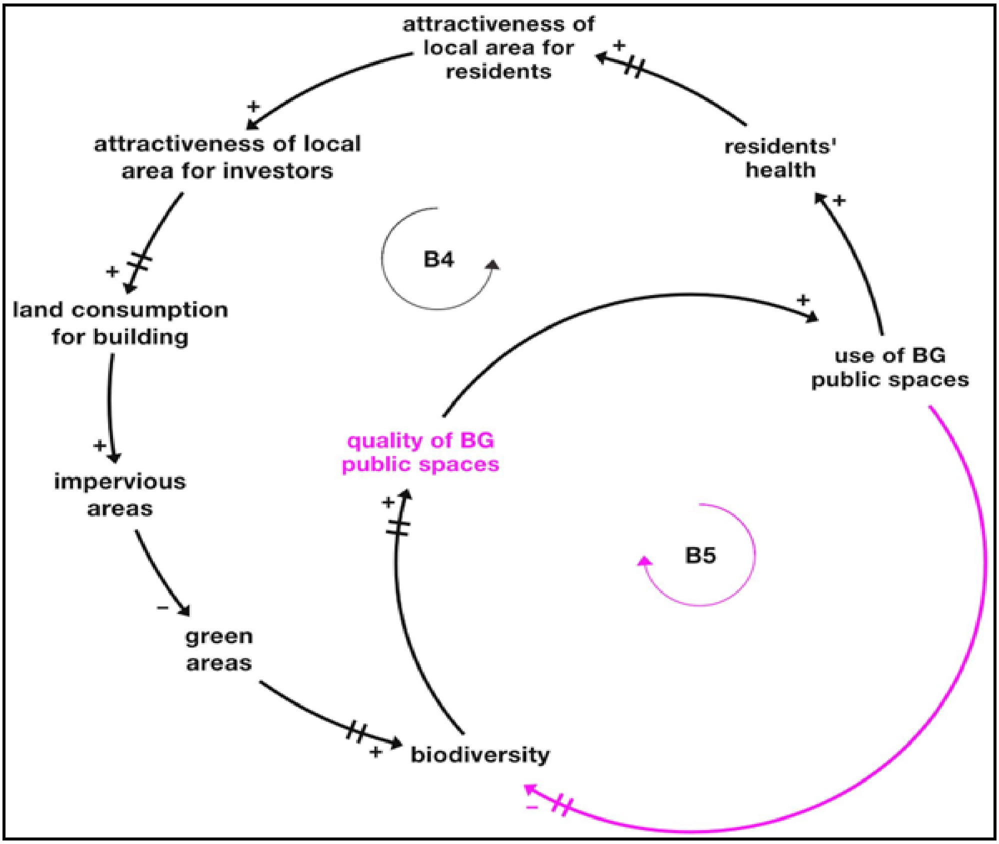


Fig. 17 –Attractiveness of local area and quality of BG public spaces feedback loops (respectively B4 and B5). Loop B4 is the one in black, while loop B5 is the one in pink. The variables 'biodiversity', 'quality of BG public spaces', and 'use of BG public spaces' are in common between the two loops. Changing times (delays) are represented by bars on the arrows.

The loops show how ‘attractiveness of local area’ and ‘quality of BG public spaces’ may increase or decrease as variables belonging to other thematic clusters, i.e., built environment, natural capital, and space use, change. Focusing on the black balancing loop B4, if ‘land consumption for building’ increases, ‘green areas’ may decrease as well as ‘biodiversity’, leading, in the long run, to a reduction in the attractiveness of the area in general and consequently in the ‘land consumption for building’. The pink balancing loop B5 shows instead what happens to the system if ‘biodiversity’ decreases or increases. If ‘biodiversity’ decreases, the quality and use of BG public spaces may also decrease, leading to an increase in ‘biodiversity’ over time. These are two balancing feedback loops with delays that might lead to oscillation in the system in relation to the achievement of the established objectives (i.e., the achievement of an attractive neighbourhood and high-quality BG public spaces). Both loops (and therefore both goals) are closely interconnected since they have three variables in common (‘biodiversity’, ‘quality of BG public spaces’, and ‘use of BG public spaces’). In particular, the achievement of the objective ‘attractiveness of local area’ may imply the non-achievement of the objective ‘high-quality BG public spaces’.

In Fig. 18a/b the feared futures (yellow lines) of the variables were represented by stakeholders with a low but (quite) constant trend due to both a lack of money for new investments and the effect of interventions first implemented in 2018.

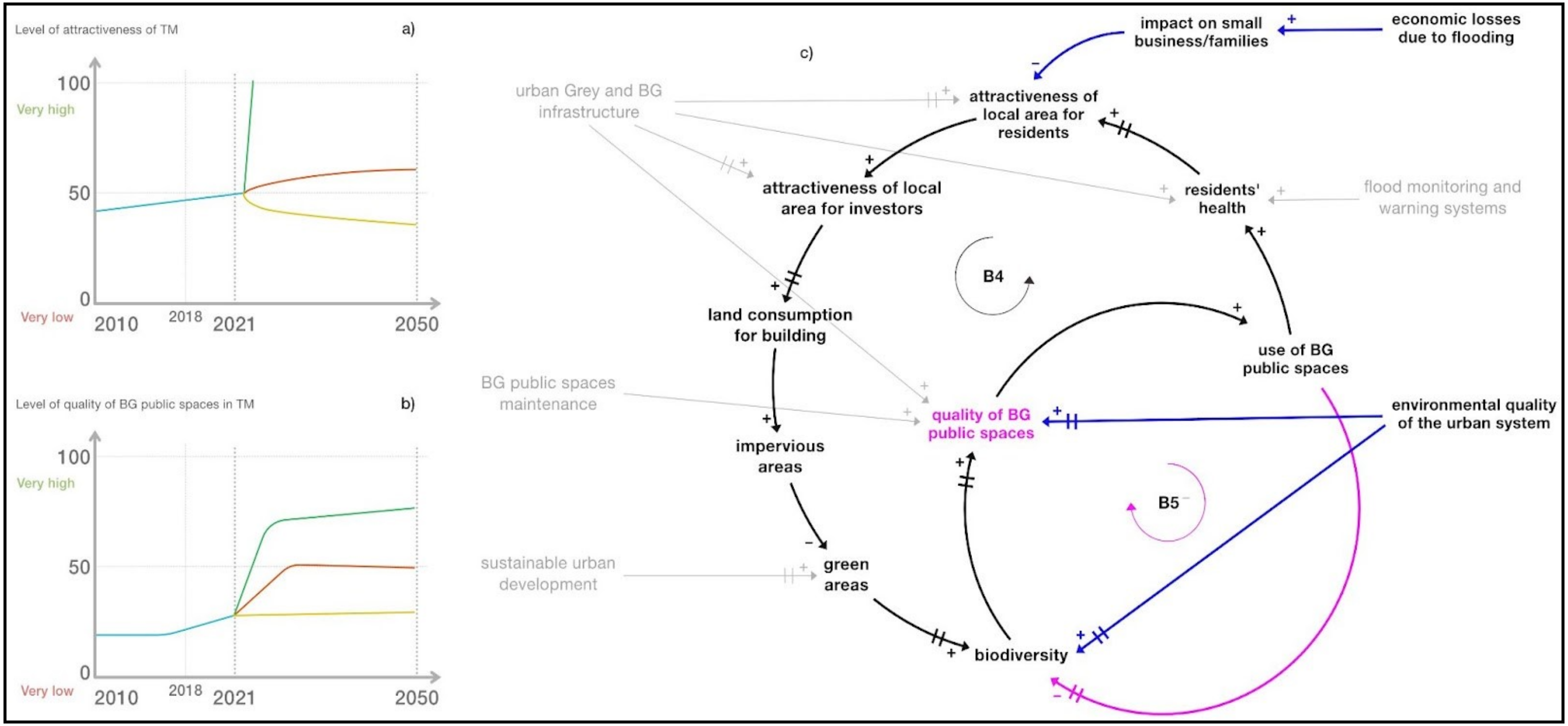


Fig. 18 - a) BOT graph of the variable 'attractiveness of local area' created by the stakeholders during a participatory workshop. b) BOT graph of the variable 'quality of BG public spaces' created by the stakeholders during a participatory workshop. In both graphs the blue line represents the past behaviour of the variable, the yellow, red, and green ones respectively the feared, most likely, and desired future. c) Attractiveness of local area and quality of BG public spaces feedback loops (respectively B4 and B5). Loop B4 is the one in black, while loop B5 is the one in pink. The variables 'biodiversity', 'quality of BG public spaces', and 'use of BG public spaces' are in common between the two loops. The variables in grey are measures/actions; simple causal relationships between variables outside the feedback loops (exogenous variables) are in blue. Changing times (delays) are represented by bars on the arrows.

To guarantee that the CLD correctly represents the constant trend of the feared futures it is necessary to consider simultaneously in Fig. 18c: i) the effect on the loops of external variables, such as 'impact on small business/families' due to 'economic losses' caused by flooding for loop B4 and 'environmental quality of the urban system' for loop B5, and ii) the maintenance of pre-existing measures. According to stakeholders, by activating flood risk mitigation/prevention measures, the variables ‘attractiveness of local area’ and ‘quality of BG public spaces’ may behave similarly to either the most likely futures (red lines) or the desired futures (green lines) in Fig. 18a/b. The CLD can integrate this perception (see Fig. 18c), provided that several actions, such as 'sustainable urban development' and ‘urban Grey and BG infrastructure’, are implemented simultaneously. Indeed, 'sustainable urban development' might lead to an increase in ‘green areas’ and ‘biodiversity’ over time, continuing to guarantee, in the long run, the achievement of both objectives, while ‘urban Grey and BG infrastructure’ directly act on both variables. The difference between the desired and most likely futures depends on the degree to which the measures are activated. In particular, in the case of the desired futures, all the measures are applied and/or fully functioning and effective; while in the case of the most likely futures not all measures are applied, or they are not fully functioning and effective.

Although the desired future of the variable 'attractiveness of local area' suggests that very high levels of attractiveness may be achieved in a very short time (Fig. 18a), it was specified by stakeholders that residents may not want the neighbourhood to be too attractive because this would result in an exponential increase in housing prices. Therefore, ideally, the CLD narrative should represent a desired future in which the degree of attractiveness grows with time but not excessively. To this end, implementing measures that rapidly increase attractiveness could go against the wishes of residents.

4.3. Thamesmead flood Stock and Flow model construction

The quantitative SD model on flood risk in TM was obtained using the Vensim® software and following TASKS 6 and 7 described in Section 2.2. Information on the mathematical equations and parameters to build the TM flood risk SF model (TASK 6, Section 2.2.5) was taken from i) literature review and ii) existing datasets, hydraulic/hydrological models, and water management reports from involved stakeholders (see Section 10.2 of the Supplementary Material). Regarding stakeholder validation of specific inputs/outputs of the model (TASK 7, Section 2.2.6), an online workshop (approximate duration 1 h) was held on 27 October 2022. The SF model was validated through semi-structured interviews. Full details on the workshop agenda used for the TM SF model validation and on the stakeholders involved in the workshop are in Sections 10.7 and 10.8 of the Supplementary Material respectively.

The model ran over a time scale of 78 years, accounting for the evolution of the neighbourhood from 2022 to 2100. This allowed for considering both the period covered by the Peabody regeneration Plan (ending in 2050) and the entire future time horizon considered by the flood risk management Plan (TE2100 Plan) developed by the Environmental Agency. The simulation was based on a daily time step because this represents the best compromise between the one generally used for analysing urban drainage systems (i.e., sub-hourly/hourly) and the one used for computing river and groundwater dynamics (monthly and/or yearly).

Specific dynamics were isolated and arranged in specific sub-models - i.e., ‘Flood hazard’, ‘Tangible damage evaluation’, ‘Co-benefits analysis’, ‘Flood vulnerability’, and ‘Flood risk assessment’ – simplifying the representation, without losing the advantages of an aggregated structure. Aggregated indices – i.e., flood hazard index, flood vulnerability index, flood risk index, and urban performance index - were calculated to obtain information on the urban system of use at a planning and/or strategic level. In the next paragraphs a simplified version of each developed SD sub-model is described, while the mathematical equations, data, and initial values behind the model are included in Section 10.9 of the Supplementary Material.

4.3.1. ‘Flood hazard’ sub-model description

The ‘Flood hazard’ sub-model related to the TM study area is shown in Fig. 19. It consists of six sections identified in the Figure with grey shapes, namely ‘land consumption’, ‘water balance’, ‘groundwater level’, ‘tidal river flood’, ‘pluvial flood’, and ‘fluvial flood’. The variables in red identify the simulated flooding mechanisms.

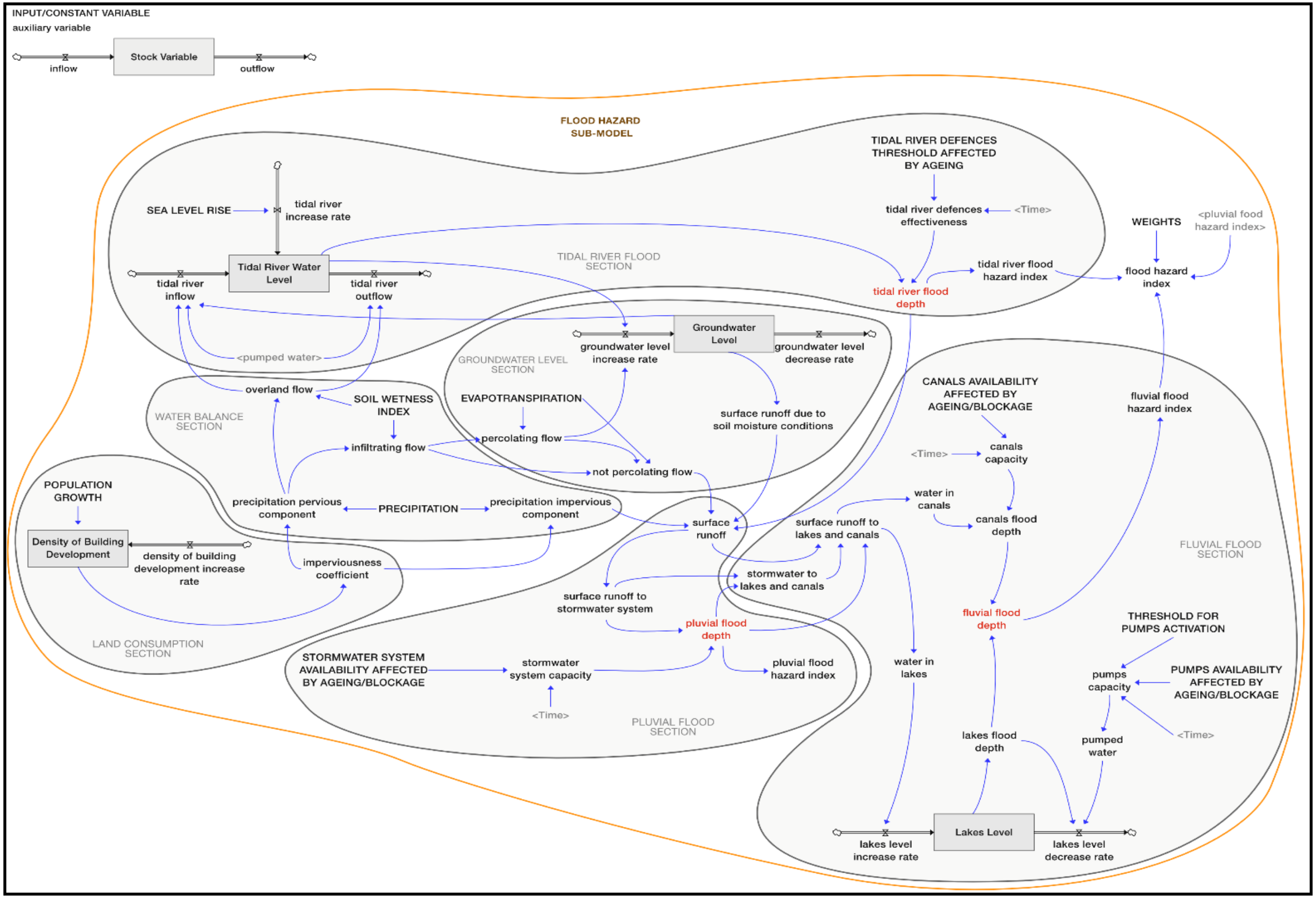


Fig. 19 – Thamesmead 'Flood hazard' sub-model. Sub-model sections are represented with grey shapes, while variables in red are the simulated flooding mechanisms.

This sub-model provided a simplified hazard assessment, combining the effects of climate change and population growth, and the effectiveness of flood mitigation infrastructure. The effect of climate change was taken into account through a specific subset of parameters, i.e., ‘precipitation’, ‘evapotranspiration’, and ‘sea level rise’ (respectively in sections ‘water balance’, ‘groundwater level’, and ‘tidal river flood’ in Fig. 19). For these variables, climate change projections on a regional scale with reference to a 90% probability level under the high emission future scenario were considered (see Murphy et al. 2009). To include the probabilistic component in the hazard assessment, the precipitation dataset was enriched with 2, 5, 10, 30, 50, 100 and 500- year return period events. The effect of population growth planned by Peabody was expressed through changes in the ‘density of building development’ over time (see section ‘land consumption’ in Fig. 19). Population projections (Askew, 2018) were used to this end. The effectiveness of flood mitigation infrastructure was described referring to the capacity of both the stormwater system and the drainage systems, affected not only by the ageing of the infrastructure but also by frequent sediment build-up (see the sections ‘pluvial flood’ and ‘fluvial flood in Fig. 19). For this purpose, future projections of systems clogging were developed based on past flooding episodes. The deterioration of the Thames defences was also considered (see the ‘tidal river flood’ section in Fig. 19).

The ‘Flood hazard’ sub-model’ main purpose was to calculate an aggregated flood hazard index. To compute the flood hazard index, the hazard from each flood source was assessed, while considering the role of interconnections. Since, according to stakeholders, flooding events occur mainly with reference to drainage systems, the ‘groundwater level’ was used to evaluate the degree of soil saturation and consequently the amount of water that contributes, together with the ‘precipitation impervious component’, to the ‘surface runoff’ feeding the drainage systems (see the interaction between the ‘groundwater level’ and ‘pluvial flood’ sections in Fig. 19). At the same time, the groundwater level was used to assess the ‘tidal river level’, which, for the sake of simplicity, was modelled at high tide. The amount of water flooding from the tidal river Thames was considered as an additional contribution to the ‘surface runoff’ (see the interaction between the ‘groundwater level’ and ‘tidal river flood’ sections in Fig. 19).

4.3.2. ‘Tangible damage evaluation’ and ‘Co-benefits analysis’ sub-models description

The ‘Tangible damage evaluation’ and the ‘Co-benefits analysis’ sub-models are shown in Fig. 20. The former (circled in blue in Fig. 20) was built on the basis of the flood depths calculated in the ‘Flood hazard’ sub-model and allowed a simplified assessment of flooding’s impacts on the built environment. The latter (circled in green in Fig. 20), closely related to the ‘Tangible damage evaluation’ sub-model, consists of four sections represented with grey shapes, namely ‘ecosystem quality’, ‘residents’ well-being’, ‘attractiveness for companies’, and ‘community flood risk perception’.

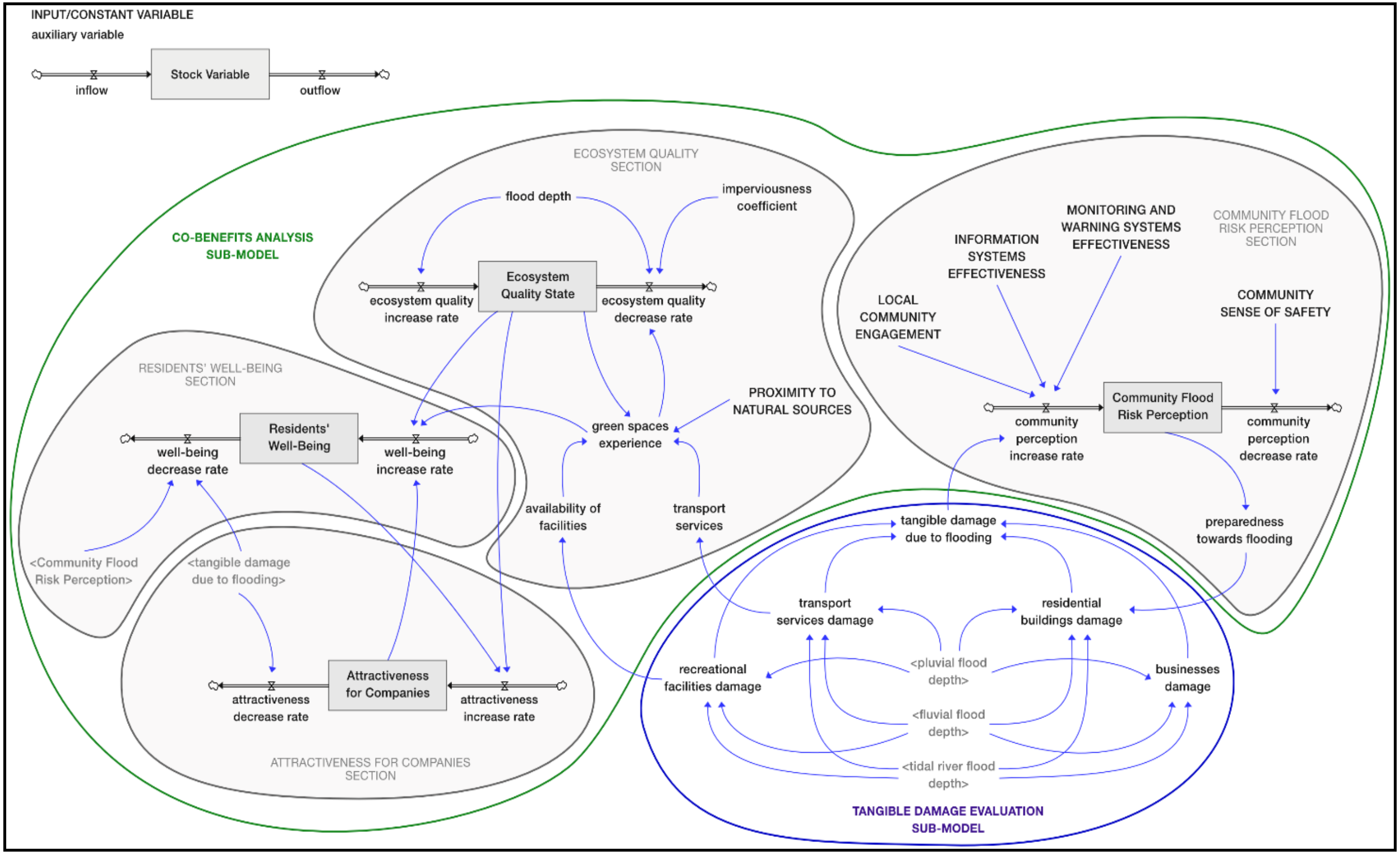


Fig. 20 – Thamesmead 'Tangible damage evaluation' and 'Co-benefits analysis' sub-models. The former is circled in blue, while the latter in green. Sub-model sections are represented with grey shapes.

The ‘Ecosystem quality state’ (see the ‘ecosystem quality’ section in Fig. 20) represents the quality of the urban natural space, which in turn depends on biodiversity and access. In particular, biodiversity is conditioned by ‘flood depth’ and ‘imperviousness coefficient’, while access depends on ‘proximity to natural sources’, ‘availability of facilities’, and ‘transport services’ (O’Keeffe et al. 2022). ‘Ecosystem quality state’ increases both ‘attractiveness for companies’ and ‘residents’ well-being’ (see ‘residents’ well-being’ and ‘attractiveness for companies’ sections in Fig. 20). The latter is decreased by ‘community flood risk perception’ (see the ‘community flood risk perception’ section in Fig. 20), which denotes the level of awareness and preparedness of people with respect to flood risk. This can be improved through specific strategies (e.g., ’local community engagement’, information systems, and monitoring and warning systems) and affects the damage due to flooding.

4.3.3. ‘Flood vulnerability’ and ‘Flood risk assessment’ sub-models description

The ‘Flood vulnerability’ and the ‘Flood risk assessment’ sub-models are shown in Fig. 21. The former (circled in orange in Fig. 21) consists of three sections represented with grey shapes, namely ‘flood exposure’, ‘flood susceptibility’, and ‘flood adaptive capacity’. The latter (circled in red in Fig. 21) includes both the ‘Flood hazard’ and ‘Flood vulnerability’ sub-models.

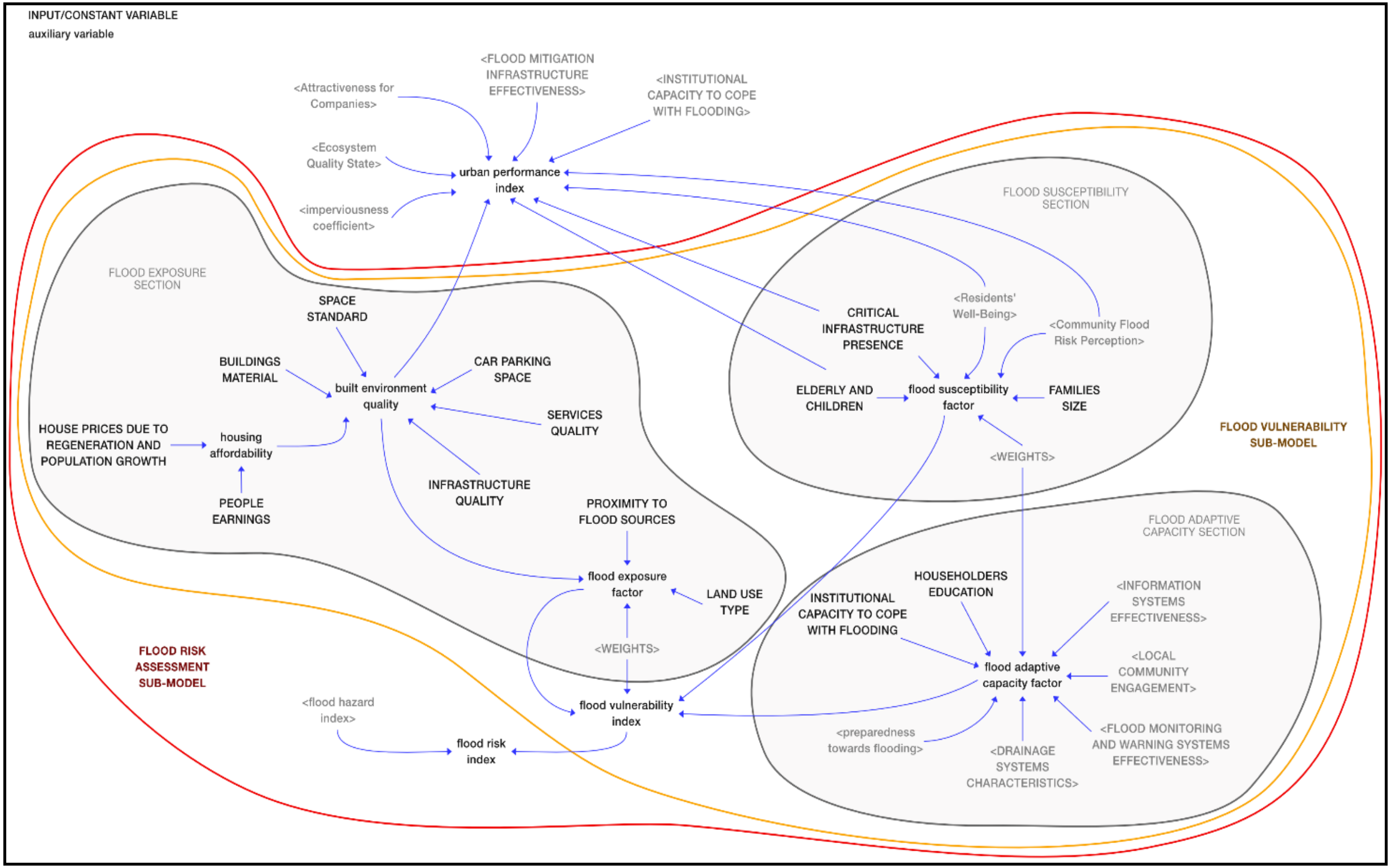


Fig. 21 – Thamesmead 'Flood vulnerability' and 'Flood risk assessment' sub-models. The former is circled in orange, while the latter in red. Sub-model sections are represented with grey shapes.

The ‘Flood vulnerability’ sub-model provided a simplified vulnerability assessment, combining the ‘flood exposure factor’, ‘flood susceptibility factor’, and ‘flood adaptive capacity factor’. The ‘flood exposure factor’ depends on ‘proximity to flood sources’, ‘land use type’, and ‘built environment quality’, which is in turn conditioned by the quality of buildings, infrastructure, and services in the area (see the ‘flood exposure’ section in Fig. 21). The ‘flood susceptibility factor’ and the ‘flood adaptive capacity factor’ are closely connected with the ‘Co-benefits analysis’ sub-model. The former includes the variables ‘residents’ well-being’ and ‘community flood risk perception’ as well as the social characteristics of the system (‘elderly and children’ and ‘families size’) and the ‘critical infrastructure presence’ (see the ‘flood susceptibility’ section in Fig. 21). The latter is affected instead by variables that condition the system's response to hazard (e.g., ‘information systems effectiveness’, ‘flood monitoring and warning systems effectiveness’, and ‘local community engagement’) (see the ‘flood adaptive capacity’ section in Fig. 21). The combination of the three factors allowed calculating the ‘flood vulnerability index’, which together with the ‘flood hazard index’ gave a simplified estimation of the ‘flood risk index’ (see the ‘Flood risk assessment’ sub-model in Fig. 21). The urban resilience to flooding was evaluated through the ‘urban performance index’ affected by i) the main co-benefits (i.e., ‘ecosystem quality state’, ‘attractiveness for companies’, ‘residents’ well-being’, and ‘community flood risk perception’), ii) the strategies for improving community flood risk perception (e.g., 'flood monitoring and warning systems effectiveness'), iii) the variables related to urban planning (i.e., ‘built environment quality’ and ‘imperviousness coefficient’), and iv) the population characteristics, such as the presence of ‘elderly and children’.

4.4. Future scenarios building and analysis for Thamesmead

Considering the ability of the SF models to produce graphs representing the evolution of system variables over time, the TM SF model was used with the aim of identifying, through scenario analysis, the impact that different flood risk management actions would have on the model's output variables (TASK 8, Section 2.2.7). Different scenarios were proposed and co-designed with stakeholders during an online workshop (approximate duration 1 h) held on 27 October 2022. Full details on the workshop agenda used for scenarios building and on the involved stakeholders are in Sections 10.7 and 10.8 of the Supplementary Material respectively. The trends of the key variables of the SF model (i.e., ‘flood hazard index’, ‘tangible damage due to flooding’, ‘ecosystem quality state’, ‘residents’ well-being’, ‘community flood risk perception’, ‘attractiveness for companies’, ‘flood vulnerability index’, ‘flood risk index’, and ‘urban performance index’) were compared with each other under different conditions using the baseline scenario as a reference. The developed scenarios are described below, while Table 3 shows the variables that were changed in each scenario.

Baseline Scenario

This scenario described the most likely evolution of the system if the main input variables (e.g., precipitation, evapotranspiration, sea level, population, built environment quality) change according to the climate change projections and the regeneration plan proposed by Peabody. For the purposes of this scenario, no modifications were made to the parameters of the flood mitigation infrastructure. This means that they were only maintained when necessary (e.g., in case of sediment build-up).

Scenario 1 - 'Replacing infrastructure at lifecycle end'
In this scenario, stormwater and drainage systems were replaced at the end of their service life (approximately 40 years). Based on this, changes in the parameters of the systems were made in 2046 and 2087.

Scenario 2 - 'Planned ordinary maintenance'
In this scenario, stormwater and drainage systems were regularly maintained from 2030 onwards. The effects of periodically cleaning the systems and the subsequent extension of their service life (about 10 years) were evaluated.

Scenario 3 - 'BG infrastructure implementation'
In line with the vision of Peabody's regeneration plan for TM, this scenario examined the role that BG infrastructure can play in addressing flooding and improving co-benefits (e.g., ecosystem quality and residents' well-being). The hydrological benefit of BG infrastructure measured through surface runoff reduction and biodiversity performance were implemented from 2030 onwards. Specifically, intensive Blue/Green roofs, urban green avenue/woodlands, wetlands, parks, and lake and canal naturalisation were introduced.

Table 3. Summary of the changed variables in the modelled scenarios. Where numerical values of the variables are proposed, a qualitative description of their meaning is indicated. As for variables that are not constant over time, see Section 10.10 of the Supplementary Material for further details.

VARIABLE	**BASELINE SCENARIO**	**SCENARIO 1**	**SCENARIO 2**	**SCENARIO 3**
Stormwater system capacity	Variable with time	Variable with time	Variable with time	Variable with time
Canals capacity	Variable with time	Variable with time	Variable with time	Variable with time
Pumps capacity	Variable with time	Variable with time	Variable with time	Variable with time
Community sense of safety	1 (low class)	Variable with time	Variable with time	Variable with time
Citizens' involvement	1 (low class)	1 (low class)	1 (low class)	Variable with time
Wetlands hydrological performance	—	—	—	Variable with time
Urban green avenue/woodland hydrological performance	—	—	—	Variable with time
Intensive Blue/Green roofs hydrological performance	—	—	—	Variable with time
Parks hydrological performance	—	—	—	Variable with time
Lakes and canals naturalization	—	—	—	Variable with time

Proximity to natural spaces	0.5 (medium level)	0.5 (medium level)	0.5 (medium level)	Variable with time
Wetlands biodiversity performance	—	—	—	Variable with time
Urban green avenue/woodland biodiversity performance	—	—	—	Variable with time
Intensive Blue/Green roofs biodiversity performance	—	—	—	Variable with time
Parks biodiversity performance	—	—	—	Variable with time

4.4.1. Scenario analysis and comparison

The effectiveness of different measures with respect to key SF model variables was compared. To provide a general idea of the behaviour of the variables over time, annual averages and maxima were calculated. For the sake of brevity, the maximum values of the variables ‘flood hazard index’, ‘residential buildings damage’, ‘flood vulnerability index’, and ‘flood risk index’ (most relevant for a comprehensive flood risk analysis) were only reported in this work. As for the co-benefits (i.e., ‘ecosystem quality state’, ‘residents’ well-being’, ‘community flood risk perception’, and ‘attractiveness for companies’) and the ‘urban performance index’, the average values were represented. However, the maximum and minimum values of each variable, albeit with some variations, showed limited differences.

Model outputs are described below by key variables. With the exceptions of ‘residential buildings damage’ which is presented in euros per square metre (euro/sqm), outputs are dimensionless and range from 1 (low) to 3 (high) if they are indices and from 0 (minimum level) to 1 (maximum level) if they are co-benefits.

‘Flood hazard index’ and ‘residential buildings damage’

As for the variable ‘flood hazard index’ (see Fig. 22a), the baseline case shows an increase over time mainly due to the malfunctioning of drainage systems due to sediment build-up and systems ageing; the surge around 2090 can be attributed to the deterioration of the Thames defences. The contribution of the maintenance carried out in Scenarios 2 and 3 is positive with regard to the reduction of the ‘flood hazard index’ for about ten years due to the extension of the service life of the drainage systems. When the service life of the systems is over, the implementation of the BG infrastructure (Scenario 3) is no longer sufficient to reduce the index compared to the baseline. Similar considerations can be extended to the variable 'residential buildings damage' (see Fig. 22b). With reference to the behaviour of ‘flood hazard index’ and ‘residential buildings damage’, none of the scenarios succeed in mitigating the impact caused around 2090 by the deterioration of the Thames defences. In fact, the index reaches at least medium values (i.e., 2), while the value of damage rises above 100 euro/sqm. Looking at the variable ‘residential buildings damage’, there is a greater impact in the case of Scenario 2. The reason for this can be attributed to the replacement of the drainage systems which, functioning correctly, would discharge the accumulated water into the tidal river Thames. Therefore, the combined effect of the sea level rise, deterioration of defences and discharge of water into the river by the drainage systems could create greater damage in Scenario 2 around 2090. Actions should therefore be taken to counteract the deterioration of defences and/or its effects.

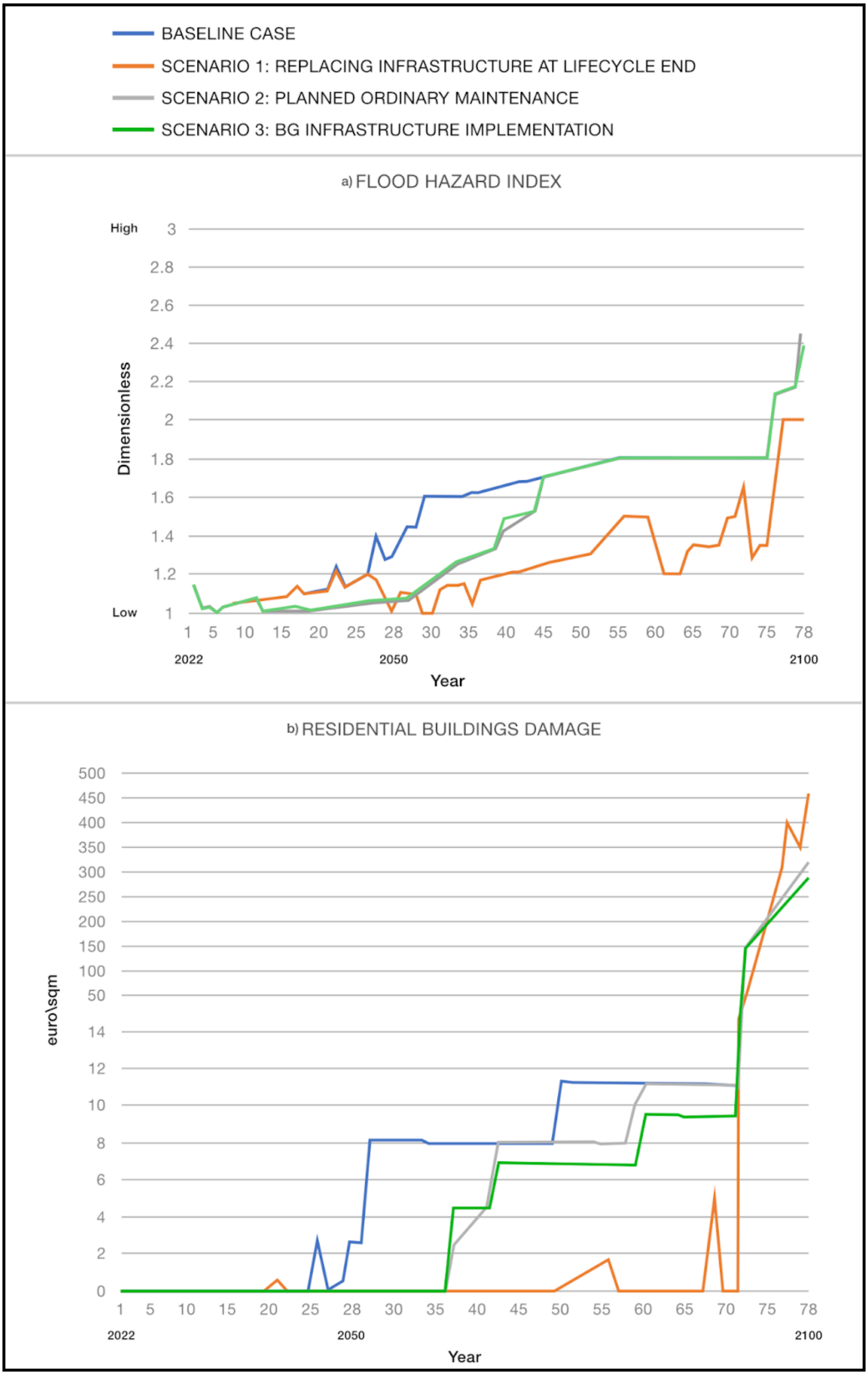


Fig. 22 – a) 'flood hazard index' and b) 'residential buildings damage' outputs generated by the model during Scenarios 1–3 using the baseline case as reference.

'Community flood risk perception'

The trend of the variable 'community flood risk perception' (see Fig. 23) in Scenario 1 gets worse compared to the baseline. This could be due to both the increased sense of safety that the replacement of drainage systems could bring as well as the general reduction of tangible damage. On the contrary, in Scenario 3 the community perception improves compared to the baseline mainly because the implementation of BG infrastructure provides a greater involvement of citizens and thus a greater awareness of the flood risk in the area.

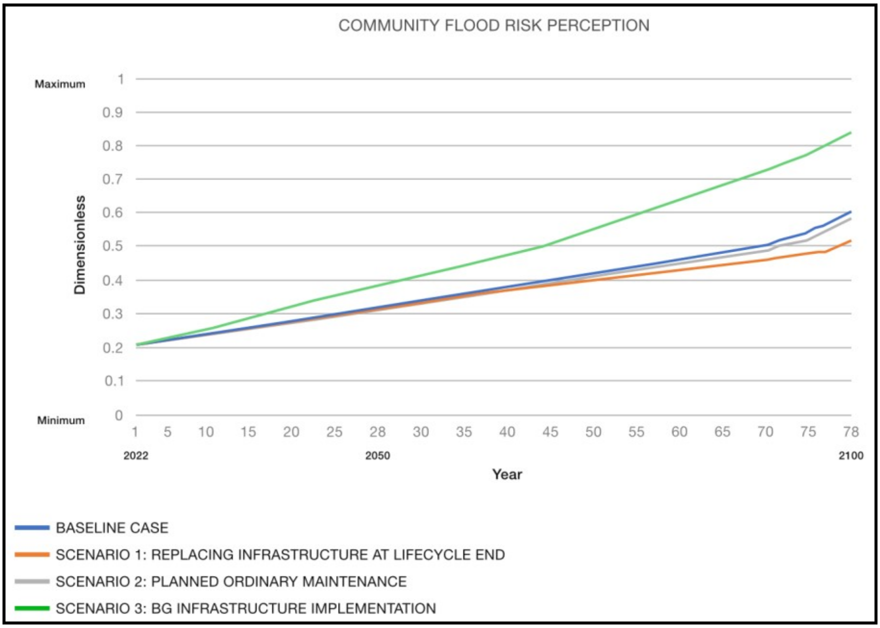


Fig. 23 – 'Community flood risk perception' outputs generated by the model during Scenarios 1–3 using the baseline case as reference.

'Ecosystem quality', 'residents' well-being' and 'attractiveness for companies'

In Scenarios 1 and 2 the variables 'ecosystem quality' and 'residents' well-being' show no major differences from the baseline. However, in Scenario 3 there is an increase of the two co-benefits probably because of the growth of the variable 'green spaces experience' due to the implementation of BG infrastructure (see Fig. 24a/b). ‘Attractiveness for companies’ does not change significantly between scenarios.

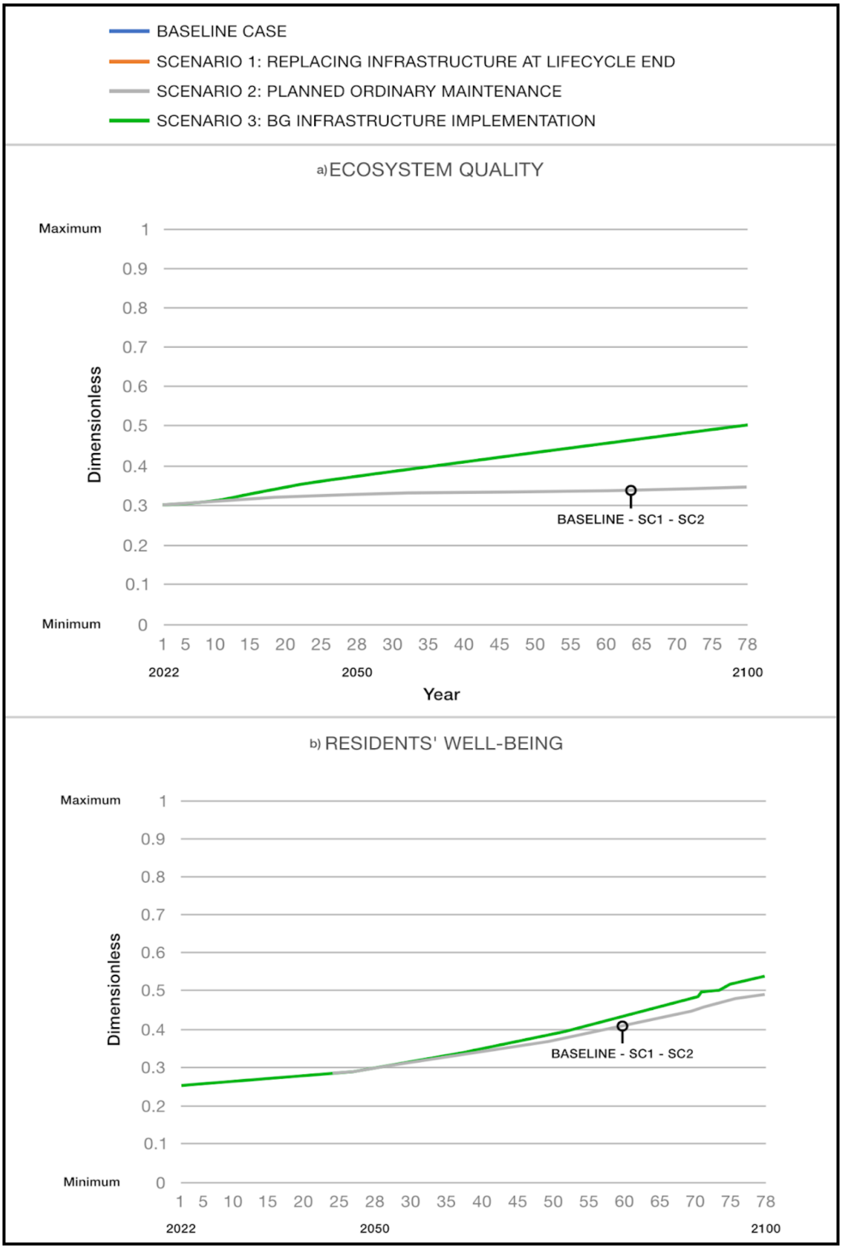


Fig. 24 – a) ‘ecosystem quality’ and b) ‘residents’ well-being’ outputs generated by the model during Scenarios 1–3 using the baseline case as reference. Where scenarios overlap, their labels are placed and separated by a hyphen (-).

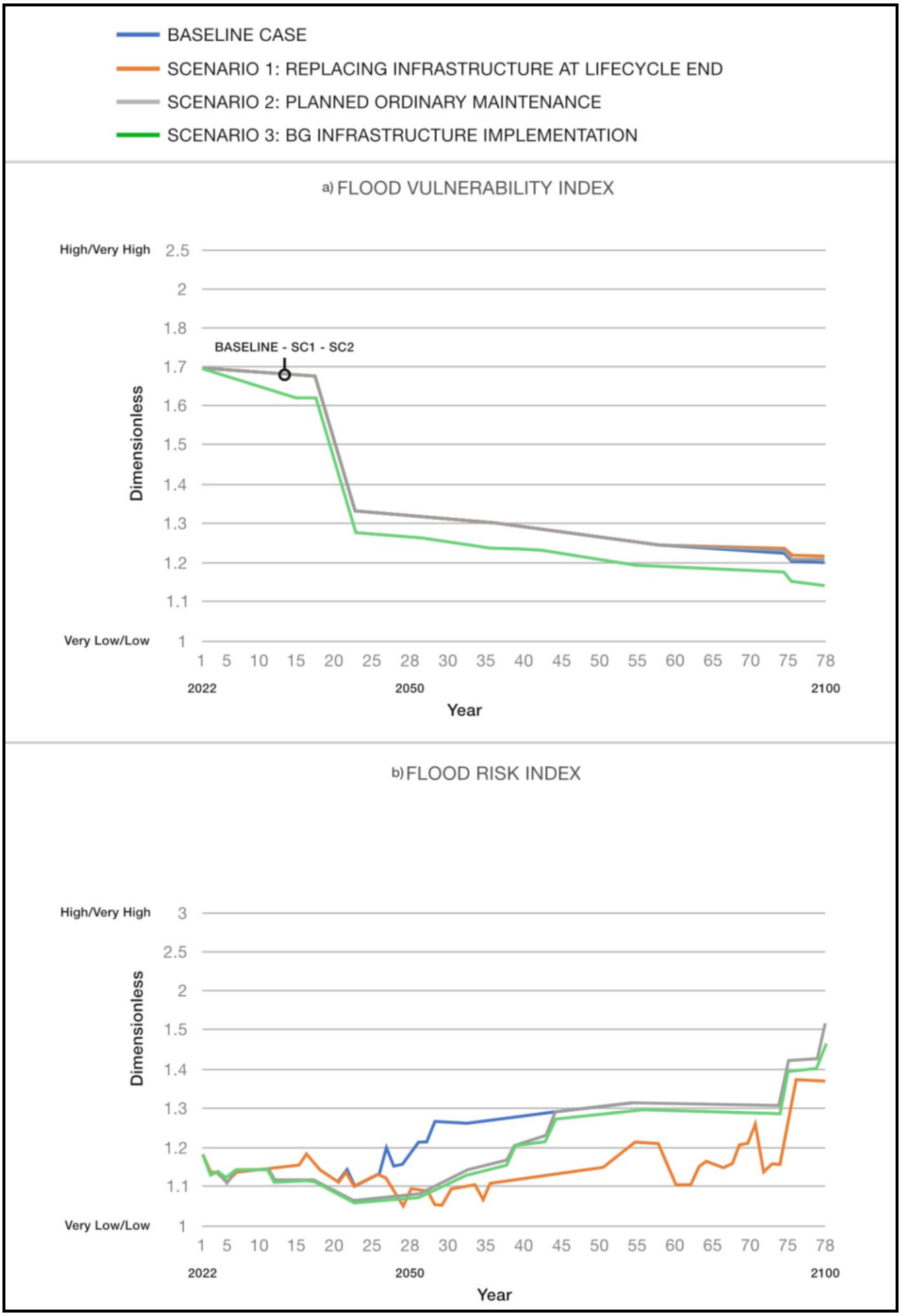


Fig. 25 – a) 'flood vulnerability index' and b) 'flood risk index' outputs generated by the model during Scenarios 1–3 using the baseline case as reference. Where scenarios overlap, their labels are placed and separated by a hyphen (-).

‘Flood vulnerability index’ and ‘flood risk index’

The ‘flood vulnerability index’ does not show notable changes in Scenarios 1 and 2 with respect to the baseline in which the trend is expected to decrease over time due to the positive effect of the regeneration plan on the quality of the built environment (i.e., buildings, transport services, infrastructure). In Scenario 3, although the variations with respect to the baseline are small, the variable shows the most desirable outcome due to the increase of co-benefits (see Fig. 25a above). The limited change of the 'flood vulnerability index' over time in the different scenarios means that the 'flood risk index' is more susceptible to the fluctuations of the 'flood hazard index' (see Fig. 22a and Fig. 25b above). Provided that the drainage system works, the risk is reduced in all the three scenarios with respect to the current situation. In the long run, Scenario 1 shows better impacts.

‘Urban performance index’

The behaviour of the variable 'urban performance index' (see Fig. 26) does not change in the different scenarios until around 2030, which corresponds to the implementation of the management measures. From 2030 onwards, the urban performance improves in all the scenarios compared to the baseline. However, while the performance in Scenario 2 returns to that of the baseline around 2065, in Scenarios 1 and 3 it continues to be more desirable. In Scenario 1 this depends on the improvement in the effectiveness of flood mitigation infrastructure, while in Scenario 3 on the increase of co-benefits.

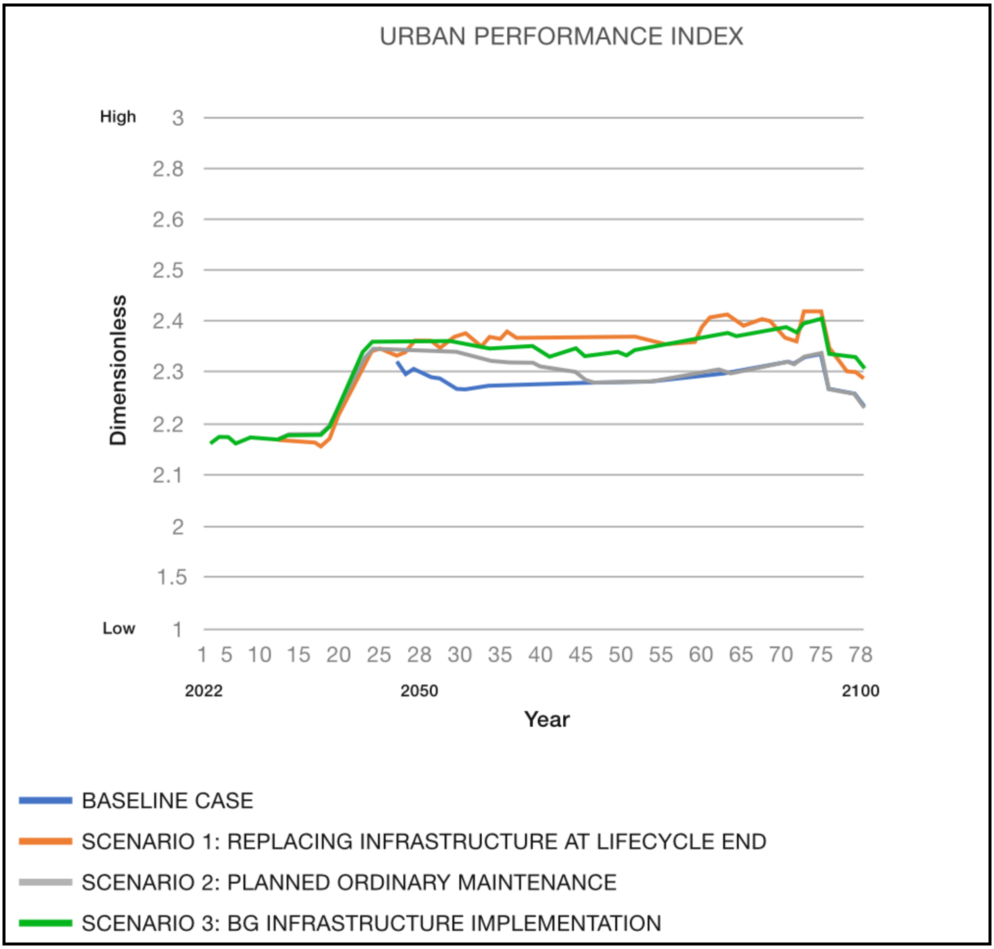


Fig. 26 – ‘Urban performance index’ outputs generated by the model during Scenarios 1–3 using the baseline case as reference.

4.4.2. Bundles of actions comparison

Starting from the considerations in the previous paragraph, further scenarios were developed. Specifically, combining the actions proposed in Scenarios 1-3 over time, the implementation of bundles of corrective actions was proposed. The developed scenarios are described below.

Scenario 4 - 'BG infrastructure implementation + planned ordinary maintenance'
This scenario proposes the implementation of BG infrastructure from 2030 (as in Scenario 3) and ordinary maintenance actions from 2050 (as in Scenario 2).

Scenario 5 - 'Replacing infrastructure at lifecycle end + Thames defences extraordinary maintenance'
This scenario proposes the replacement of the stormwater and drainage systems in 2046 and 2087 (as in Scenario 1) and the modification of the Thames defences around 2090.

Scenario 6 - 'Scenario 4 + Scenario 5'
This scenario suggests the implementation of the bundle of actions of Scenario 4 and, from 2070 onwards, that of Scenario 5.

Scenario 7 - 'Scenario 6 + BG infrastructure increase'
This scenario proposes the implementation of the same actions of Scenario 6, while doubling the areas of the BG infrastructure.

Model outputs are described below by key variables.

'Flood hazard index' and 'residential buildings damage'

The behaviour over time of the variable 'flood hazard index' (see Fig. 27a) in Scenario 4 shows an improvement with respect to the baseline provided the drainage systems are functioning. In Scenario 5 the index value consistently remains below 1.5 due to the modifications to the Thames defences. Despite the doubling of the BG infrastructure areas, the behaviour of the variable does not change significantly in Scenario 7 compared to Scenario 6. This confirms what was stated in relation to Scenario 3 in the previous paragraph, namely that the proper functioning of the Grey infrastructure (i.e., drainage systems) is essential for flood risk mitigation and that the implementation of BG infrastructure, while providing hydrological benefits, would not be sufficient on its own to contain surface runoff. In addition, the almost non-existent variation between the two scenarios suggests that the areas that have been allocated to BG infrastructure in the Peabody regeneration Plan (used in Scenario 6) are sufficient to improve the hydrological performance of the urban system with respect to flooding and therefore that there would be no need to invest in expanding the BG areas.

As for tangible damage to buildings, an improvement in all scenarios compared to the baseline can be observed in Fig. 27b. In the long term, only the scenarios in which the modification of the Thames defences was planned (i.e., Scenarios 5, 6 and 7) show a greater limitation of damage.

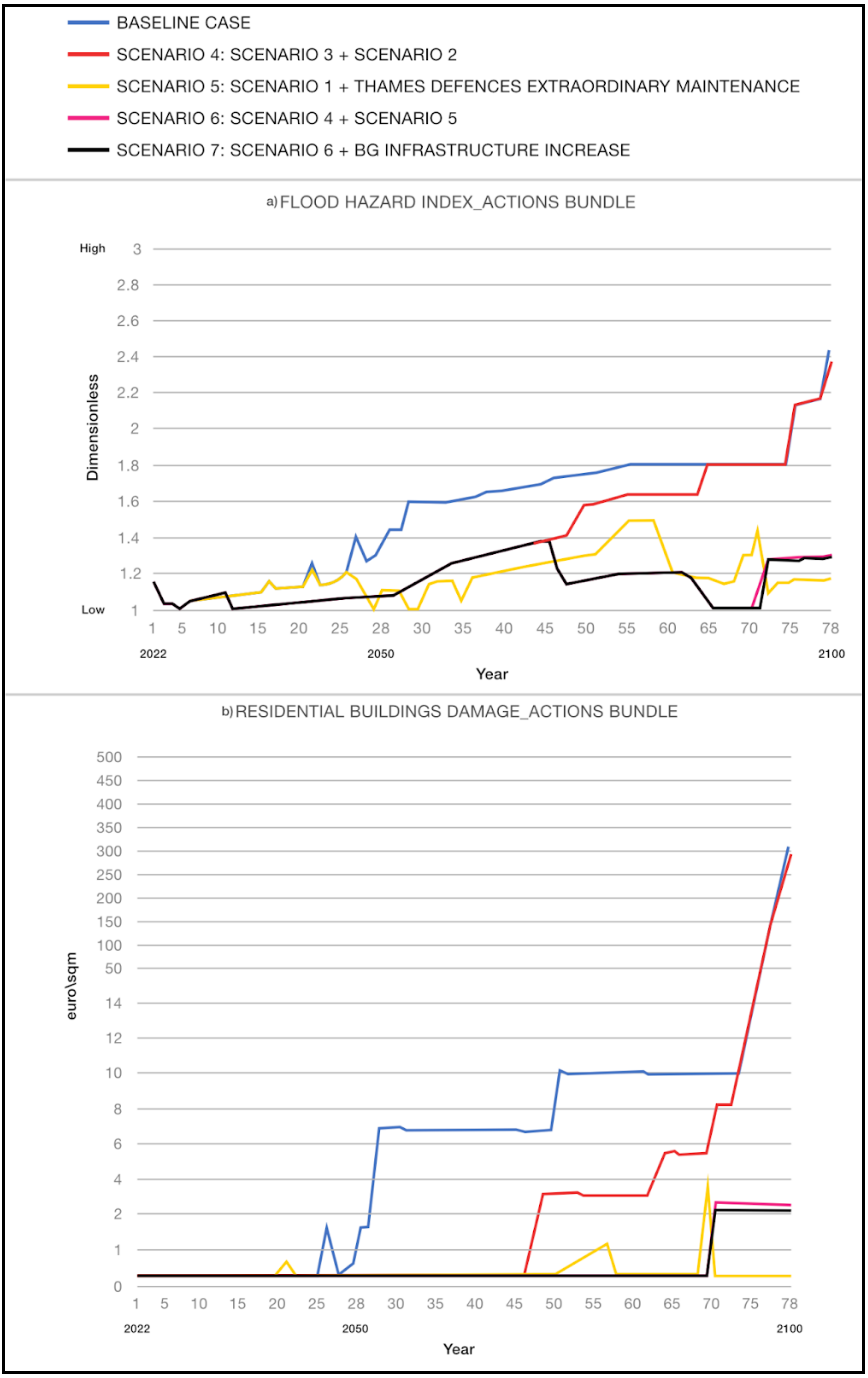


Fig. 27 – a) 'flood hazard index' and b) 'residential buildings damage' outputs of Scenarios 4–7 using the baseline case as reference. Where scenarios overlap, their labels are placed and separated by a hyphen (-).

'Community flood risk perception'

Compared to the baseline, the trend of the variable 'community flood risk perception' (see Fig. 28) has lower values in Scenario 5 because of the reduction of the damage to the built environment and the increase of the sense of safety of the community. In Scenarios 4, 6 and 7 the variable reaches higher values thanks to the involvement of the community in the implementation of BG measures. The decrease of the community's sense of safety due to the deterioration of the Thames defences reflects an increase in 'community flood risk perception' around 2090 in Scenario 4.

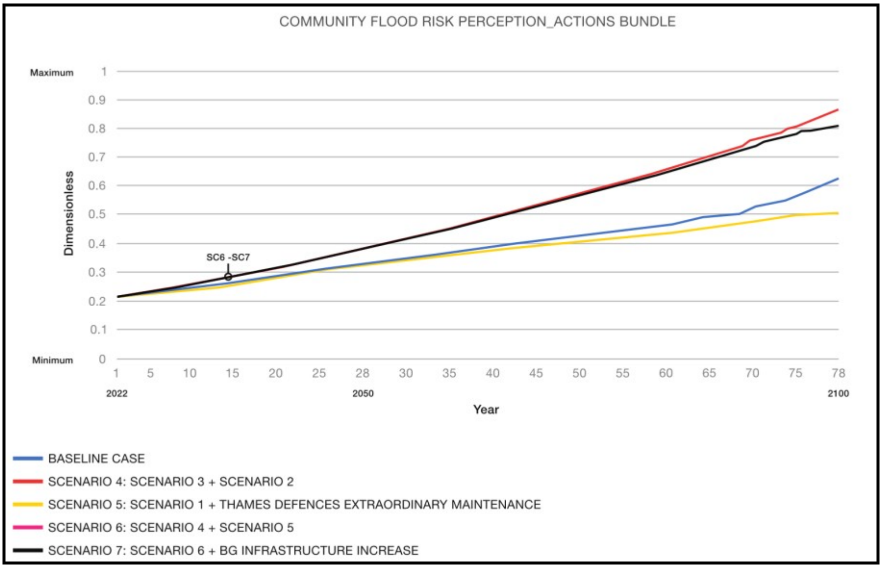


Fig. 28 – 'Community flood risk perception' outputs of the Scenarios 4–7 using the baseline case as reference.

'Ecosystem quality' and 'residents' well-being'

As for the trend of the variables 'ecosystem quality' and 'residents' well-being' (Fig. 29a/b), in all scenarios that provide for the implementation of BG infrastructure (i.e., Scenarios 4, 6 and 7) they reach higher values than the baseline; in Scenario 5 there are no significant differences from the baseline. In Scenario 7, the trend of the variable 'ecosystem quality' is higher than in Scenario 6 due to the expansion of the BG areas.

Fig. 29 – a) 'ecosystem quality' and b) 'residents' well-being' outputs of the Scenarios 4–7 using the baseline case as reference. Where scenarios overlap, their labels are placed and separated by a hyphen (-).

‘Flood vulnerability index’ and ‘flood risk index’

As stated in the Section 4.4.1, the variable ‘flood vulnerability index’ tends to decrease over time thanks to the improvements of the Peabody regeneration Plan on the built environment (see Fig. 31a). While Scenario 5 reproduces similar values for the variable with respect to the baseline scenario, the implementation of BG measures in Scenarios 4, 6 and 7 has a greater effect on ‘flood vulnerability index’ e.g., thanks to the increase of ‘community flood risk perception’. As for 'flood risk index' (Fig. 31b), the most suitable Scenarios are 6 and 7, i.e., those in which the implementation of BG and both ordinary and extraordinary maintenance of the drainage systems were planned. This confirms that implementing BG measures alongside Grey measures brings benefits and co-benefits to the system.

‘Urban performance index’

‘Urban performance index’ improves in all scenarios compared to the baseline (see Fig. 32). In Scenario 4 due to the implementation of BG measures, which provide co-benefits (e.g., ‘residents’ well-being’ and ‘ecosystem quality’ increase), and in Scenario 5 due to higher ‘flood mitigation infrastructure effectiveness’. In Scenarios 6 and 7 the improvement depends on both the implementation of BG measures and increased effectiveness of flood infrastructure. However, the bundles of actions proposed with Scenarios 6 and 7 turn out to be the most suitable and do not differ much from each other.

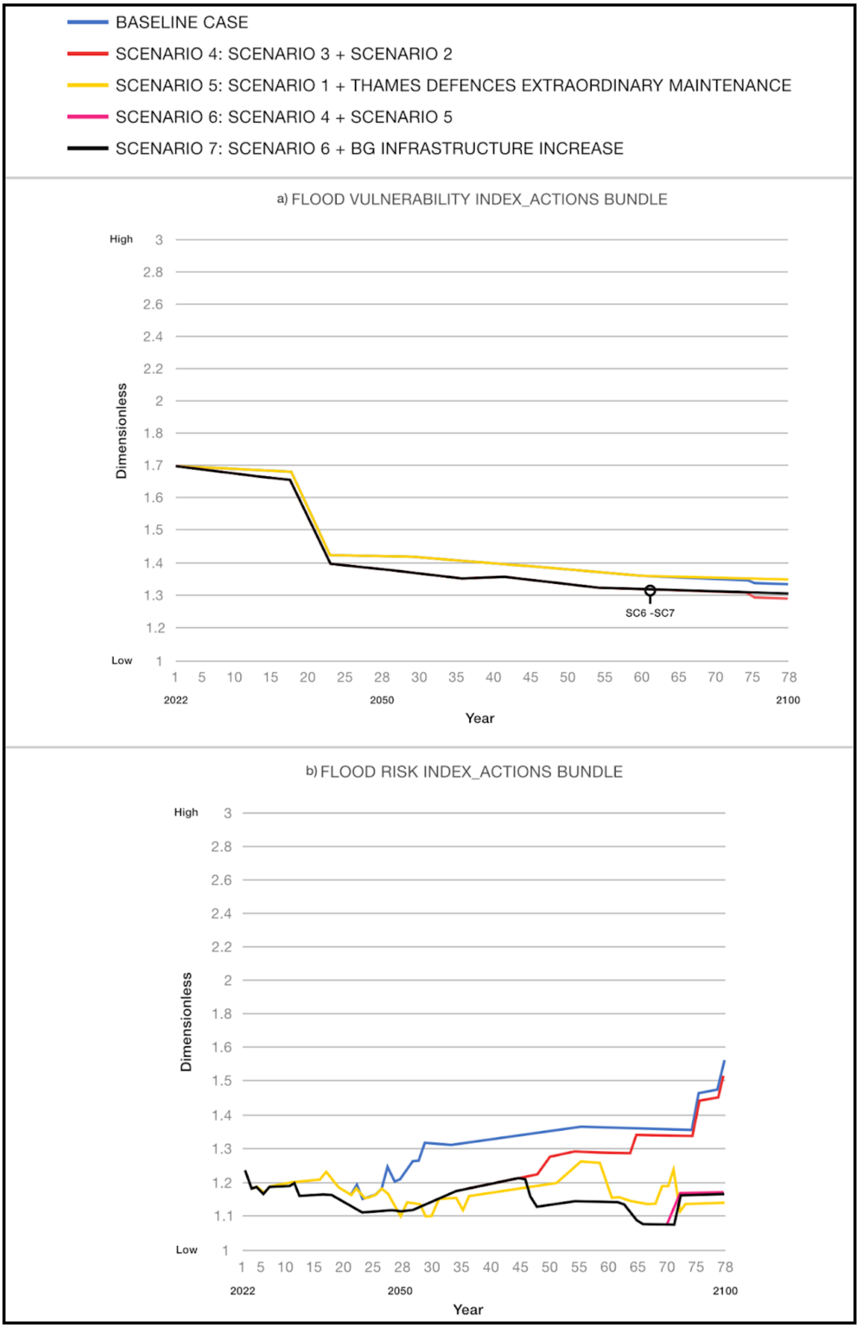


Fig. 31 – a) 'flood vulnerability index' and b) 'flood risk index' outputs of Scenarios 4–7 using the baseline case as reference. Where scenarios overlap, their labels are placed and separated by a hyphen (-).

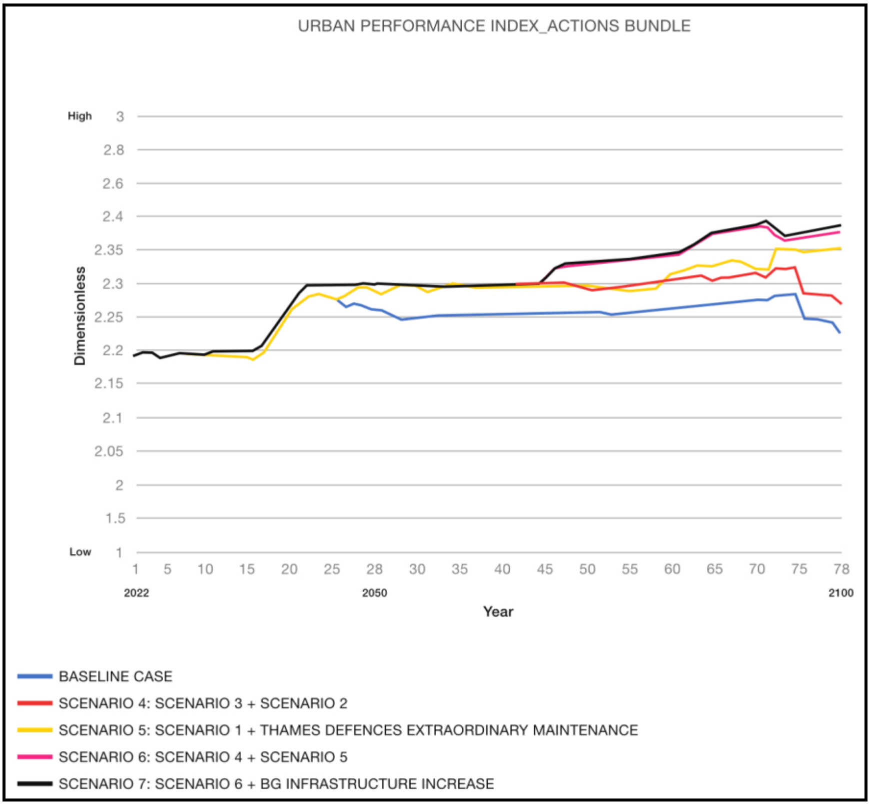


Fig. 32 – 'Urban performance index' outputs generated by the model during Scenarios 4–7 using the baseline case as reference.

4.4.3. Sensitivity analysis

A sensitivity analysis was performed with reference to Scenario 6 focusing on key variables and investigating the influence of single variables on the 'urban performance index'. Specifically, these variables – namely 'precipitation', 'population growth', 'critical infrastructure presence', 'population characteristics', 'local community engagement', 'co-benefits', 'institutional capacity to cope with flooding', 'built environment quality', and 'flood mitigation infrastructure' – were adjusted individually from 0.5 to 1, incrementing/decrementing by 0.5. For the sake of brevity, Fig. 33 shows the difference between the values of 'urban performance index'. In Scenario 6 and in scenarios obtained by changing the parameters by 50%. The Figure is representative of the influence that the individual parameters have on flood resilience with respect to Scenario 6.

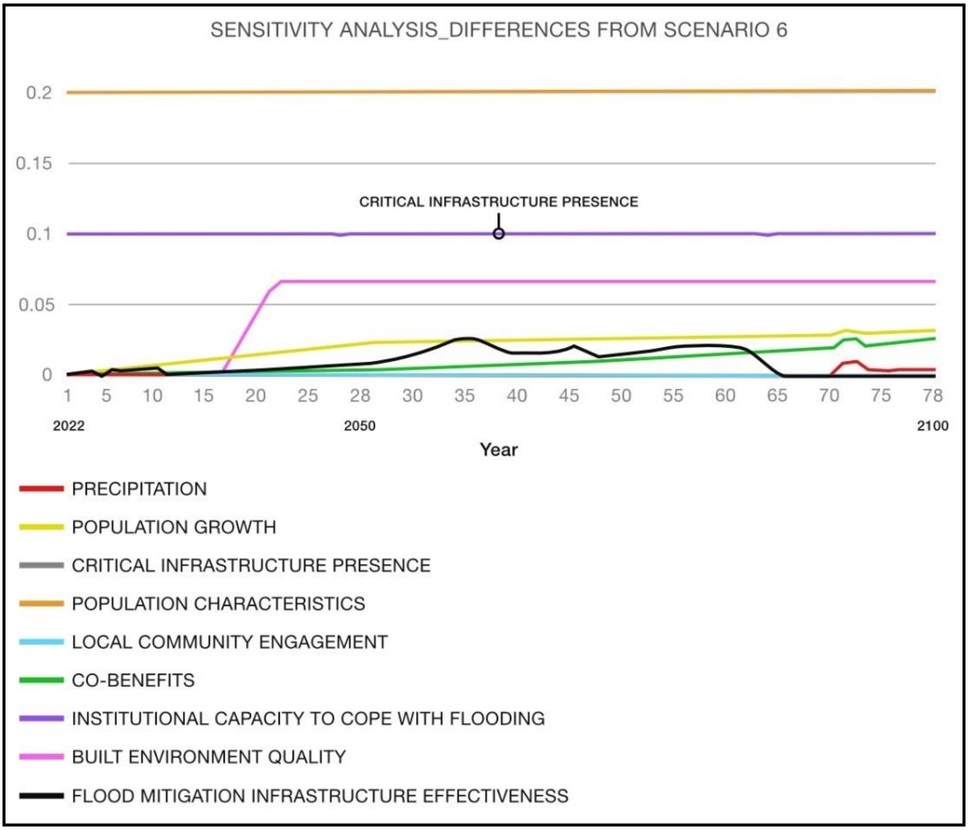


Fig. 33 – Sensitivity analysis related to ‘urban performance index’ – Differences between Scenario 6 and single parameters variation.

‘Population characteristics’, ‘critical infrastructure presence’, and ‘institutional capacity to cope with flooding’ seem to be the variables that influence most the ‘urban performance index’ with respect to Scenario 6. Since they are constant variables within the model, the represented differences do not change over time. As the other parameters vary with time, the differences are not constant. Changes in ‘population growth’, ‘flood mitigation infrastructure effectiveness', and 'co-benefits', while affecting urban system resilience, do not lead to significant changes with respect to Scenario 6. This could mean that the implementation of the bundle of actions provided by Scenario 6, which already acts mainly on 'co-benefits' and 'flood mitigation infrastructure effectiveness', should be enhanced with measures capable to affect other factors such as 'population characteristics', 'critical infrastructure presence', and 'institutional capacity to cope with flooding' to further improve the urban resilience to flooding.

5. DISCUSSION

This Section critically discusses to what extent the research activities presented in Section 4 contribute to progress on the issues raised by the research questions identified in the Introduction (Section 1). The encountered difficulties and the limitations of this work are subsequently illustrated.

5.1. Research findings

To what extent can System Dynamics modelling support decision-makers, at a planning or strategic level, evaluating the effectiveness of measures to increase the urban flood resilience?

The urban system is complex and uncertain, and its interacting elements (economic, social, ecological, and human) can be influenced by the impacts of flooding events, in turn exacerbated by the changes of climatic and socio-economic factors (e.g., variability of precipitation intensity and frequency, and population growth). Compared to purely hydrological models for flood risk management (see e.g., Milly et al. 2008; Salas et al. 2014; Serinaldi et al. 2018; Villarini et al. 2018), this work adopts a holistic perspective centred on the concept of resilience, including in the analysis multiple dynamic mechanisms influencing flood risk at urban scale. A system-based approach was adopted, and the hydrological sub-system and processes were integrated with others (such as the social, economic, and environmental). For this purpose, SD is used and the full potentialities of both System Thinking and Dynamic Simulation are exploited. Firstly, the use of a CLD enables the mapping and visualisation of the interactions between different system components, ultimately helping to describe the complex set of interconnections and loops affecting its dynamic evolution. Using the CLD to explore the system's structure also provides insights into behavioural trends of the system's elements. Compared to more recent works on flood risk analysis (e.g., Dzulkarnain et al. 2019; Fenner et al. 2019), this work introduces two elements of innovation related to i) the detailed analysis of the feedback loops with focus on their impacts on key variables, and ii) the validation of the model causal structure and the construction of BOT graphs for key variables with stakeholders after CLD development. Specifically, the construction of BOT graphs expanded the potential of feedback loops in hypothesising system behaviour providing valuable support to decision-makers in identifying different flood risk mitigation/prevention actions and their potential impacts on the system as a whole. Secondly, the construction of the SF model starting from the CLD provided a deeper understanding of the flood risk and its impacts by isolating the main dynamics of the system into 'thematic' sub-models and analysing them individually, while capturing a clear picture of the entire system. In addition, the ability of the SF model to analyse not only quantitative ('hard' or physical), but also qualitative ('soft' or intangible) aspects reveals complex systems behaviour. For example, the development of the 'Co-benefits analysis' sub-model allows the investigation of the relationship between 'ecosystem quality state', 'residents' well-being' and 'attractiveness for investors', obtaining useful information for the development of other sub-models, such as the 'flood vulnerability sub-model'. Besides that, the integrated evaluation of the BG infrastructure potential in terms of risk reduction, co-benefits production and urban flood resilience increase demonstrates the suitability of the SF model in overcoming the lack of structured representations of existing frameworks' multi-dimensionality (see e.g., Kabisch et al. 2016 and Calliari et al. 2019). In this direction, the scenario analysis assesses the impact of different resilience-enhancing actions on the model's key variables. To this aim, the development of indices summarising the information obtained in the SF model has proved to be useful. Suitable bundles of actions are thus identified and their effectiveness, potential consequences, side effects and synergistic effects can be modelled and visualised. This allows the characterization of the feasibility and relevance of the selected strategies in view of the main objective (i.e., managing flood risk and improving urban flood resilience), while understanding the multi-dimensional implications they have. For example, through the analysis of hazard, vulnerability, risk, and urban performance indices, it was observed that the scenario involving the coupling of BG infrastructure and planned extraordinary and ordinary maintenance, is the one that in the long-term provides the highest benefits and co-benefits to the system. Lastly, through the sensitivity analysis, the SF model provides information on which factors or associated processes in the urban system have more impact on flood resilience and thus should be monitored over time and modified adapting and adjusting strategies and decision-makers' objectives. Just to provide an example, it was found that aspects such as 'population characteristics', 'critical infrastructure presence' and 'institutional capacity to cope with flooding' may have a high impact on system resilience, and therefore strategies involving these factors should be considered.

Based on these considerations, it is therefore possible to state that SD modelling is a valuable support for decision-makers at a planning or strategic level. Although it does not produce mathematically refined results, SD modelling provides a broader view of the system and allows comparisons of different solutions and strategies when compared to classical hydrological modelling.

To what extent can the combination of scientific and stakeholder knowledge within the System Dynamics modelling contribute to a better understanding of flood risk and implications in urban settings as well as support actions selection ultimately increasing urban flood resilience?

The multi-step process of knowledge gathering and structuring in the form of both a CLD and a SF model provides a better understanding, compared to purely hydrological models, of how different factors interact within an urban system influencing flood risk and resilience. The iterative integration of scientific and stakeholder knowledge allows the peculiarities of the case study to be accounted for. More specifically, as for the System Thinking phase, a set of semi-structured interviews expanded scientists' knowledge on flood risk in the area and allowed including 'non-hydraulic' aspects in a preliminary version of the CLD as well as highlighting critical interconnections among variables, such as between the 'urban drainage systems capacity' (Water management thematic cluster) and 'environmental quality of urban systems' (Natural capital thematic cluster). Once the qualitative model integrates scientific and stakeholder knowledge, participatory activities are used for CLD validation. Indeed, during a workshop, stakeholders were asked to revise some connections between variables (mainly "soft" variables) and highlighted further aspects of fundamental importance that required integration. Subsequently, stakeholder involvement in the construction of the BOT graphs helped define hypotheses on the future dynamics of key variables, e.g., 'infrastructures/public realm damage' and 'attractiveness of local area', useful for the subsequent quantitative modelling phase. With these graphs as a starting point, the modeller can make reliable assumptions about both the dynamics of the urban system and the implementation of policies relating to flooding.

As for the Dynamic Simulation phase, stakeholder contribution was necessary not only in the collection of data to transform the qualitative model into a quantitative one, but also in the validation of input and output variables for the SF model. Participatory modelling techniques were used for this purpose. For instance, the BOT graphs drawn by stakeholders about co-benefits were crucial in defining their initial value in the SF model and then simulating their trend. In addition, stakeholders enabled the development of suitable scenarios for flood risk management and flood resilience increase. Specifically, they support the modeller in selecting actions (mainly BG infrastructure) and strategies to be implemented in the

SF model based on the wide range of objectives and investments foreseen in the regeneration Plan.

To what extent can the implementation of Blue-Green infrastructure in the system enhance urban flood resilience?

Starting from the assumption that rethinking cities approach to flood risk management implies a shift to the flood resilience concept through the implementation of BG infrastructure (see e.g., Wihlborg et al. 2019 and Alves, 2020), a tool is developed to support decision-makers in evaluating and quantifying their multi-dimensional effectiveness. The scenarios analysis confirms, following an increasing body of literature, the ability of BG infrastructure to provide not only hydrological benefits (mainly about the reduction of surface runoff) but also multiple social and environmental benefits (i.e., the co-benefits) which are often even more relevant. For example, the implementation of different BG infrastructure (such as wetlands, blue/green roofs, woodlands) may increase the 'ecosystem quality state' and the 'residents' well-being' thanks to the possibility of more 'green spaces experience'. Besides that, their development asks for more 'local community engagement' thus improving the 'community perception of flood risk'. Nevertheless, the model also shows that the BG infrastructure implementation would not be sufficient on its own to both reduce flood risk and enhance urban flood resilience. For this reason, the combined effects of BG and well-functioning Grey infrastructure implementation is examined. From a hydrological point of view, BG solutions extend the service life of ageing stormwater and drainage systems reducing the quantity of 'surface runoff' and sediments they have to manage.

Therefore, considering that Hybrid infrastructure (integrated Grey and Blue-Green solutions) support urban systems in adapting to the increasing threat of flooding, while also providing environmental, social, and economic co-benefits, their resilience-enhancing ability is confirmed. In further evidence of this assertion, the scenarios analysis demonstrates the increase of the urban performance index (i.e., urban resilience measure in this work) when BG infrastructure is implemented along with existing Grey measures.

5.2. Summary of the main challenges

The limited literature on the integration between system variables pertaining to different components of flood risk (hazard, exposure, and vulnerability) was a limit in CLD construction, as there was not a consolidated methodological approach to consider. In particular, the most difficult issue was the connection between technical (e.g., related to the characterisation of the flood phenomenon) and 'soft' variables (e.g., environmental and social). Difficulties were also experienced in the transition from CLD to the SF model, especially with regard to the collection of some data and the quantification of the connections between technical and 'soft' variables. In this regard, further consultations with stakeholders and targeted interviews were helpful.

Despite the fundamental contribution of stakeholders, the time and workload needed for the organisation of interviews and workshops (as in every participatory activity) increased the time needed for model building. However, co-developing models with the stakeholders has a huge benefit related to the amount of expert knowledge that can be included in the model. Furthermore, arranging online meetings that could meet the needs of all stakeholders was difficult and, in general, could limit the level of interaction among stakeholders. However, online meetings allowed progress with the activities during the COVID-19 pandemic.

One of the biggest challenges was encouraging stakeholders’ participation, to ensure continuity between workshops. In addition, effectively communicating the purpose of the model to stakeholders was often challenging, especially as understanding the applicability and limitations of an SD model is not always straightforward. For this purpose, sharing some briefing notes on the model before meetings has been helpful to support a better comprehension and a more effective contribution to activities. In general, the feedback from stakeholders on the content of the workshops was positive; particularly, they appreciated the opportunity to reflect on shared interests for the area and to be informed on the perspectives of other stakeholders. The coding of the interviews and workshops also proved to be time-consuming. In general, stakeholders shared a lot of information with the modeller, requiring an iterative approach to identify, select, and validate relevant information.

5.3. Limitations

The limitations of the participatory SD model presented in this work are mainly related to the introduction of some simplifications in the quantification of variables and their connections due to lack of data. Although this is a drawback of the work, the possibility of analysing the system also through simplifications is one of the strengths of the SD approach. Even if the current structure of the model is adequate for the analysis presented, future developments should further explore processes such as the relationship between the effects of climate change and the reduction of green areas, the decrease of private property values due to flooding damage, and the distinction between the attractiveness of the area for residents and investors. The lack of an explicit representation of spatial processes is also a key constraint for SD modelling. This means that it is not possible to fully account for the spatial scale for BG infrastructure effectiveness assessment and trade-offs analysis. In fact, as stated by several authors (see e.g., Howe et al. 2014; Golden and Hoghooghi, 2018; Zhang and Chui, 2019), BG infrastructure effects may be variable at different spatial scales. For this reason, combining the quantitative SD model and spatially distributed modelling approach could help to address this issue. In addition, although the SD model could support decision-makers at a planning or strategic level, it has limited applicability in the analysis of individual or micro-scale dynamics, which could be useful at other stages of the design process. Furthermore, a thorough analysis and comparison of strategies in terms of benefits and costs has to be supported by other methodologies, such as Cost-Benefit Analysis and Multiple-Criteria Decision Analysis. The need to combine SD modelling with other decision support approaches should therefore be considered.

6. CONCLUSIONS

The effectiveness of existing modelling tools for supporting flood risk management in urban areas is limited because they often focus on purely hydrological issues, neglect the dynamic interaction with key elements of the urban system (e.g., built environment, population growth and distribution, infrastructures, green areas, etc.). In fact, the poor understanding of the complex interconnections between flooding and urban dynamics could affect the effectiveness of strategies for flood risk reduction. In this context, resilience thinking can expand the potentialities of risk-based approaches focusing on system capability of absorbing shocks, under highly uncertain conditions. To this aim, this work adopts SD modelling tools for explicitly including flood risk resilience and flood risk mitigation in the analysis of urban development dynamics, ultimately providing an improved understanding of system state and system evolution that can be useful for decision-makers at a planning or strategic level. Specific reference is made to one of the case studies of the CUSSH and CAMELLIA projects, namely Thamesmead (London, UK), perceived as being increasingly vulnerable to flooding. However, the developed methodological approach is suitable for replication in other contexts.

More specifically, using CLD as a tool for qualitative modelling, allowed to: i) integrate hydrological aspects related to flood risk with other aspects (social, economic, and environmental) that are highly relevant to analyse urban dynamics (in the present work, with specific reference to a regeneration process); ii) explicitly integrate the flood phenomenon (and flood reduction measures) with the characteristics of the affected system, thus making preliminary assumptions on the behaviour of key system variables.

Subsequently, the SF quantitative modelling provided i) a deeper understanding of complex systems behaviour and ii) the identification of suitable bundles of actions in view of managing flood risk and improving urban flood resilience. Specifically, the effectiveness of the implementation of Blue-Green infrastructure (under different scenarios that include coupling with grey infrastructures) was evaluated.

The adopted methodology heavily relies on participatory activities and pursues the combination of scientific and stakeholder knowledge. The obtained results show that looking at flood risk in a broader sense and integrating different types of knowledge supports more realistic insights into the dynamics of the urban system with respect to flooding, thus providing decision-makers with a holistic perspective on system state and on the impacts of different actions on system resilience. In addition, the assumption of an increasing body of literature on the ability of BG infrastructure to provide hydrological, social, and environmental benefits, if combined with well-functioning Grey infrastructure, is confirmed.

7. NOTES

1. Project, ref. no. 209387/Z/17/Z, https://projectcussh.org/
2. Project ref. no. NE/S003495/1, https://www.camelliawater.org/
3. http://www.susdrain.org/case-studies/case_studies/surgery_kington_herefordshire.htm
4. http://www.susdrain.org/case-studies/case_studies/hollington_primary_school_hastings.html
5. https://www.itreetools.org/resources/reports/VictoriaUK_BID_iTree.pdf
6. https://www.portlandoregon.gov/bes/article/77074

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9. REFERENCES

Abebe, Y., Adey, B.T., Tesfamariam, S., 2021. Sustainable funding strategies for stormwater infrastructure management: A system dynamics model. Sustain. Cities Soc., 64, 102485.

AECOM, 2017. Charlton to Bexley Riverside Integrated Water Management Strategy.

Ahmad, S. S., Simonovic, S. P., 2015. System dynamics and hydrodynamic modelling approaches for spatial and temporal analysis of flood risk. Int. J. River Basin Manag., 13(4), 443–461. https://doi.org/10.1080/15715124.2015.1016954.

Alves, A., Gersonius, B., Sanchez, A., Vojinovic, Z., Kapelan, Z., 2018. Multi-criteria approach for selection of green and grey infrastructure to reduce flood risk and increase CO benefits. Water Resour. Manag. 32, 2505–2522. https://doi.org/10.1007/s11269-018-1943-3.

Alves, A., 2020. Combining green-blue-grey infrastructure for flood mitigation and enhancement of co-benefits. CRC Press / Balkema - Taylor & Francis Group.

Asgary, A., Anjum, M.I., Azimi, N., 2012. Disaster recovery and business continuity after the 2010 flood in Pakistan: case of small businesses. Int. J. Disaster Risk Reduct. 2, 46–56. http://dx.doi.org/10.1016/j.ijdrr.2012.08.001.

Askew, P., 2018. Creating value for people in thamesmead - well being and green infrastructure. Valuing Landscape Conference.

Babanawo, D., Mattah, P.A.D., Agblorti, S.K.M., Brempong, E.K., Mattah, M.M., Aheto, D.W., 2022. Local Indicator-Based Flood Vulnerability Indices and Predictors of Relocation in the Ketu South Municipal Area of Ghana. Sustainability, 14, 5698. https://doi.org/10.3390/su14095698.

Babovic, F., Babovik, V., & Mijic, A., 2017. Antifragility and the development of urban water infrastructure. Int. J. Water Resour. Dev., 34(4), 499–509. https://doi.org/10.1080/07900627.2017.1369866.

Bagheri, A., 2006. Sustainable Development: Implementation in Urban Water Systems. Department of Water Resources Engineering, Lund Institute of Technology, Lund University.

Barendrecht, M.H., Viglione, A., Blöschl, G., 2017. A dynamic framework for flood risk. Water Secur., 1, 3-11. https://doi.org/10.1016/j.wasec.2017.02.001.

Batica, J., Gourbesville, P., Hu, F., 2013.Methodology for flood resilience index. International Conference on Flood Resilience: Experiences in Asia and Europe, Exeter, United Kingdom.

Berariu, R., Fikar, C., Gronalt, M., Hirsch, P., 2016. Training decision-makers in flood re sponse with system dynamics. Disaster Prev. Manag. An Int. J. 25, 118–136. https://doi.org/10.1108/DPM-06-2015-0140.

Bertone, E., Sahin, O., Richards, R., Roiko, A., 2019. Assessing the impacts of extreme weather events on potable water quality: the value to managers of a highly participatory, integrated modelling approach. H2Open J. 2 (1), 9–24. https:// doi.org/10.2166/h2oj.2019.024.

Blair, P., Buytaert, W., 2016. Socio-hydrological modelling: a review asking "why, what and how? Hydrol. Earth Syst. Sci., 20 (1), 443–478. https://doi.org/10.5194/hess-20- 443-2016.

Bond, L., Kearns, A., Mason, P., Tannahill, C., Egan, M., Whitely, E., 2012. Exploring the relationships between housing, neighbourhoods and mental wellbeing for residents of deprived areas. BMC Public Health, 12:48. https://doi.org/10.1186/1471-2458-12-48.

Bosher, L., 2014. Built-in resilience through disaster risk reduction: Operational issues. Build. Res. Inf., 42, 240–254. https://doi.org/10.1080/09613218.2014.858203.

Bradford, R.A., O'Sullivan, J.J., van der Craats, I.M., Krywkow, J., Rotko, P., Aaltonen, J., Bonaiuto, M., De Dominicis, S., Waylen, K., and Schelfaut, K.,

2012. Risk perception – issues for flood management in Europe. Nat. Hazards Earth Syst. Sci., 12, 2299–2309. https://doi.org/10.5194/nhess-12-2299-2012, 2012.

Bratman, G.N., Anderson, C.B., Berman, M.G., Cochran, B., de Vries, S., Flanders, J., Folke, C., Frumkin, H., Gross, J. J., Hartig, T., Kahn Jr., P.H., Kuo, M., Lawler, J.J., Levin, P.S., Lindahl, T., Meyer-Lindenberg, A., Mitchell, R., Ouyang, Z., Roe, J., Scarlett, L., Smith, J.R., van den Bosch, M., Wheeler, B.W., White, M.P., Zheng, H., Daily, G.C., 2019. Nature and mental health: An ecosystem service perspective. Sci. Adv. 5, eaax0903.

Braun, W., 2002. The system archetypes. System, 27.

Brooks, K.N., Ffolliott, P.F., Magner, J.A., 2013. Infiltration, Pathways of Water Flow, and Recharge. Chapter 5. Hydrology and the Management of Watersheds, Fourth Edition.

Browder, G., Ozment, S., Rehberger Bescos, I., Gartner, T., Lange, G-M., 2019. INTEGRATING GREEN AND GAY: Creating Next Generation Infrastructure. World Bank and World Resources institute: Washington, DC.

Burgess-Gamble, L., Ngai, R., Wilkinson, M., Nisbet, T., Pontee, N., Harvey, R., Kipling, K., Addy, S., Rose, S., Maslen, S., Jay, H., Nicholson, A., Pahge, T., Jonczyk, J., & Quinn, P. (2017). Working with natural processes–Evidence directory. Environmental Agency, Report No. SC150005. Environment Agency.

Butler, D., Digman, C.J., Makropoulos, C., Davies, J.W., 2018. Urban Drainage, fourth edition. Taylor & Francis Group, LLC.

Calancie, L., Anderson, S., Branscomb, J., Apostolico, A. A., Lich, K. H., 2018. Using behavior over time graphs to spur systems thinking among public health practitioners. Prev. Chronic Dis., 15(2), 1–8. https://doi.org/10.5888/pcd15.170254.

Calliari, E., Staccione, A., Mysiak, J., 2019. An assessment framework for climate-proof nature-based solutions. Sci. Total Environ. 656, 691–700. https://doi.org/10.1016/j.scitotenv.2018.11.341.

Carmona, G., Varela-Ortega, C., Bromley, J., 2013. Participatory modelling to support decision making in water management under uncertainty: Two comparative case studies in the Guadiana river basin, Spain. J. Environ. Manage., 128, 400-412.

Cattino, M., Reckien, D., 2021. Does public participation lead to more ambitious and transformative local climate change planning? Curr. Opin. Environ. Sustain., 52, 100-110. https://doi.org/10.1016/j.cosust.2021.08.004.

Cavana R, Maani K., 2000. A methodological framework for integrating systems thinking and system dynamics. In: Proceedings of the 18th International Conference of the System Dynamics Society.

Cea, L., Costabile, P., 2022. Flood Risk in Urban Areas: Modelling, Management and Adaptation to Climate Change. A Review. Hydrology, 9, 50. https://doi.org/10.3390/hydrology9030050.

Chilvers, J., Kearnes, M., 2016. Science, democracy and emergent publics. In: Chilvers, J., Kearnes, M. (Eds.), Remaking Participation: Science, Environment and Emergent Publics. Routledge, Abingdon, pp. 1–28.

Chu, H.J., Chang, L.C., Lin, Y.P., Wang, Y.C., Chen, Y.W., 2010. Application of system dynamics on shallow multipurpose artificial lakes: a case study of detention pond at Tai Taiwan. Environ. Model. Assess. 15, 211–221. https://doi.org/10.1007/s10666-009-9196-4.

Coletta, V.R., Pagano, A., Pluchinotta, I., Fratino, U., Scrieciu, A., Nanu, F., Giordano, R., 2021. Causal Loop Diagrams for supporting Nature Based Solutions participatory design and performance assessment. J. Environ. Manage., 280, 111668. https://doi.org/10.1016/j.jenvman.2020.111668.

Cologna, V., Bark, R.H., Paavola, J., 2017. Flood risk perceptions and the UK media: Moving beyond "once in a lifetime" to "Be Prepared" report ing. Clim. Risk Manag., 17, 1-10. http://dx.doi.org/10.1016/j.crm.2017.04.005.

Coxon, G., Addor, N., Bloomfield, J.P., Freer, J., Fry, M., Hannaford, J., Howden, N.J.K., Lane, R., Lewis, M., Robinson, E.L., Wagener, T., Woods, R., 2020. CAMELS-GB: Hydrometeorological time series and landscape attributes for 671 catchments in Great Britain.

Cutter, S.L., Barnes, L., Berry, M., Burton, C., Evans, E., Tate, E., Webb, J., 2008. A place-based model for understanding community resilience to natural disasters, Glob. Environ. Chang. 18, 598–606. https://doi.org/10.1016/j.gloenvcha.2008.07.013.

Cutter, S.L., Burton, C.G., Emrich, C.T., 2010. Disaster resilience indicators for benchmarking baseline conditions, J. Homel. Secur. Emerg. Manag. 7, 14. https://doi.org/10.2202/1547-7355.1732.

Cutter, S.L., Ash, K.D., Emrich, C.T., 2014. The geographies of community disaster resilience. Global Environ. Change, 29, 65-77. https://doi.org/10.1016/j.gloenvcha.2014.08.005.

Cutter, S.L., 2016. The landscape of disaster resilience indicators in the USA. Nat. Hazards, 80, 741–758. https://doi.org/10.1007/s11069-015-1993-2.

Dabson, B., 2015. Planning for a More Resilient Future. A Guide to Regional Approaches. Technical Report. National Association of Development Organizations (NADO) Research Foundation. https://doi.org/10.13140/RG.2.1.2434.2480.

Davies, E.G.R., Simonovic, S.P., 2011. Global water resources modeling with an integrated model of the social–economic–environmental system. Adv. Water Resour., 34, 684–700. https://doi.org/10.1016/j.advwatres.2011.02.010.

Davies, M., Belesova, K., Crane, M., et al., 2021. The CUSSH programme: supporting cities’ transformational change towards health and sustainability. Wellcome Open Res., 6:100. doi:10.12688/wellcomeopenres.16678.2.

Davis, M., Krüger, I., Hinzmann, M., 2015. Coastal Protection and Suds-Nature-Based Solutions Available at: www.recreate-net.eu.

Davoudi, S., et al., 2012. Resilience: A Bridging Concept or a Dead End? Plan. Theory Pract., 13, 2, 299–333. https://doi.org/10.1080/14649357.2012.677124.

De Bruijn, K.M., 2004. Resilience and flood risk management. Water Policy, 6, 53–66. https://doi.org/10.2166/wp.2004.0004.

De Bruijn, K.M., Buurman, J., Mens, M., Dahm, R., Klijn, F, 2017. Resilience in practice: Five principles to enable societies to cope with extreme weather events. Environ Sci Policy, 70, 21-30. http://dx.doi.org/10.1016/j.envsci.2017.02.001.

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Yan, K., Brandimarte, L., & Blöschl, G., 2015. Perspectives on sociohydrology: Capturing feedbacks between physical and social processes. Water Resour. Res., 51, 4770–4781. https://doi.org/10.1002/2014WR016416.

Di Baldassarre, G., Sivapalan, M., Rusca, M., Cudennec, C., Garcia, M., Kreibich, H., et al. 2019. Sociohydrology: Scientific challenges in addressing the sustainable development goals. Water Resour. Res., 55, 6327–6355. https://doi.org/10.1029/2018WR023901.

Dilley, P., 2016. Environment Agency Head Calls for Focus on Resilience. http://www.building.co.uk/environment-agency-head-calls-for-focus-on-resilience/5079494.article.

Disse, M., Johnson, T.G., Leandro, J., Hartmann, T., 2020. Exploring the relation between flood risk management and flood resilience. Water Secur., 9, 100059. https://doi.org/10.1016/j.wasec.2020.100059.

Duffy, A., Jefferies, C., Waddell, G., Shanks, G., Blackwood, D., & Watkins, A., 2008. A cost comparison of traditional drainage and SUDS in Scotland. Water Sci. Technol., 57, 1451–1459. https://doi.org/10.2166/wst.2008.262.

Dzulkarnain, A., Suryani, E., Aprillya, M. R., 2019. Analysis of flood identification and mitigation for disaster preparedness: A system thinking ap proach. Procedia Comput. Sci., 161, 927–934. https://doi.org/10.1016/j.procs.2019.11.201.

Edelenbos, J., Van Buuren, A., Roth, D., Winnubst, M., 2017. Stakeholder initiatives in flood risk management: exploring the role and impact of bottom-up initiatives in three 'Room for the River' projects in the Netherlands. J. Environ. Plann. Manage. https://doi.org/10.1080/09640568.2016.1140025.

Eker, S., Zimmermann, N., 2016. Using Textual Data in System Dynamics Model Conceptualization. Systems, 4(3), 28. https://doi.org/10.3390/systems4030028.

Elias, A. A., 2012. A system dynamics model for stakeholder analysis in environmental conflicts. J. Environ. Plan. Manag., 55(3), 387–406. https://doi.org/10.1080/09640568.2011.604191.

Environment Agency, 2010. The Thames Barrier project pack 2010.

Environment Agency, 2012. Managing flood risk through London and the Thames estuary. Thames Estuary 2100 Plan.

EU, 2013. The EU Strategy on adaptation to climate change.

Evans, E., Ashley, R., Hall, J., Penning-Rowsell, E., Sayers, P., Thorne, C., & Watkinson, A., 2004. Foresight future flooding, volume I and volume II. Office of Science and Technology.

Fenner, R., 2017. Spatial evaluation of multiple benefits to encourage multifunctional design of sustainable drainage in blue-green cities. Water, 9, 953. https://doi.org/10.3390/w9120953.

Fenner, R., O'Donnell, E., Ahilan, S., Dawson, D., Kapetas, L., Krivtsov, V., Ncube, S., Vercruysse, K., 2019. Achieving urban flood resilience in an uncertain future. Water (Switzerland), 11(5), 1–9. https://doi.org/10.3390/w11051082.

Feofilovs, M., Romagnoli, F., Gotangco, C.K., Josol, J.C., Jardeleza, J.M.P., Litam, J.E., Campos, J.I. and Abenojar, K., 2020. Assessing resilience against floods with a system dynamics approach: a comparative study of two models. Int. J. Disaster Resil. Built Environ., Vol. 11 No. 5, 615-629. https://doi.org/10.1108/IJDRBE-02-2020-0013.

Figureido, L., Honiden, T., Schumann, A., 2018. Indicators for Resilient Cities. OECD Regional Development Working Papers. https://doi.org/10.1787/20737009.

Folke, C., 2006. Resilience: the emergence of a perspective for social-ecological systems analyses. Global Environ. Change, 16, 253–267. http://dx.doi.org/ 10.1016/j.gloenvcha.2006.04.002.

Folke, C., S. R. Carpenter, B. Walker, M. Scheffer, T. Chapin, and J. Rockström. 2010. Resilience thinking: integrating resilience, adaptability and transformability. Ecol. Soc., 15(4): 20. http://www.ecologyandsociety.org/vol15/iss4/art20/.

Ford, A., 1999. Modeling the environment. Island Press, Washington.

Forrester, J., 1961. Industrial dynamics. MIT Press, Cambridge.

Forrester, J., 1969. Urban dynamics. MIT Press, Cambridge.

Forrester, J.W., 1990. Principles of Systems. Productivity, Portland.

Foudi, S., Oses-Eraso, N., Galarraga, I., 2017. The effect of flooding on mental health: Lessons learned for building resilience, Water Resour. Res., 53. http://dx.doi.org/10.1002/2017WR020435.

Francis, R., & Bekera, B., 2014. A metric and frameworks for resilience analysis of engineered and infrastructure systems. Reliab. Eng. Syst. Safety, 121, 90–103. https://doi.org/10.1016/j.ress.2013.07.004.

French, C.E., Waite, T.D., Armstrong, B., et al., 2019. Impact of repeat flooding on mental health and health-related quality of life: a cross-sectional analysis of the English National Study of Flooding and Health. BMJ Open, 9:e031562. http://dx.doi.org/10.1136/bmjopen-2019-031562.

Friedman, T., 2008. Hot, Flat & Crowded. New York: Farrar, Straus and Giroux.

Frumkin, H., 2003. Healthy Places: Exploring the Evidence. Reviewing the evidence. Am. J. Public Health, 93,9.

Gao, M., Wang, Z., Yang, H., 2022. Review of Urban Flood Resilience: Insights from Scientometric and Systematic Analysis. Int. J. Environ. Res. Public Health, 19, 8837. https://doi.org/10.3390/ ijerph19148837.

Geltner, D., de Neufville, R., 2012. Uncertainty, Flexibility, Valuation & Design: How 21st Century Information & Knowledge Can Improve 21st Century Urban Development. In Royal Institution of Chartered Surveyors Global Symposium. Adelaide.

Giordano, R., Pagano, A., Pluchinotta, I., del Amo, R.O., Hernandez, S.M., Lafuente, E.S., 2017. Modelling the complexity of the network of interactions in flood emergency management: the Lorca flash flood case. Environ. Model. Softw. 95, 180–195. https://doi.org/10.1016/j.envsoft.2017.06.026.

Giordano, R., Pluchinotta, I., Pagano, A., Scrieciu, A., Nanu, F., 2020. Enhancing nature-based solutions acceptance through stakeholders' engagement in co-benefits identification and trade-offs analysis. Sci. Total Environ., 713, 136552. https://doi.org/10.1016/j.scitotenv.2020.136552.

Golden, H.E., Hoghooghi, N., 2018. Green infrastructure and its catchment-scale effects: an emerging science. Wiley Interdiscip. Rev. Water 5 (1), e1254.

Green, D., O'Donnell, E., Johnson, M., Slater, L., Thorne, C., Zheng, S., Stirling, R., Chan, F. K. S., Li, L., & Boothroyd, R. J., 2021. Green infrastructure: The future of urban flood risk management? Wiley Interdiscip. Rev. Water, 8(6), e21560. https://doi.org/10.1002/wat2.1560.

Guo, H.C., Liu, L., Huang, G.H., Fuller, G.A., Zou, R., Yin, Y.Y., 2001. A system dynamics approach for regional environmental planning and management: a study for the Lake Erhai Basin. J. Environ. Manag., 61 (1), 93–111. https://doi.org/10.1006/jema.2000.0400.

Gustard, A.; Bullock, A.; Dixon, J. Low Flow Estimation in the United Kingdom; Institute of Hydrology: Wallingford, UK, 1992.

Haasnoot, M., Kwakkel, J.H., Walker, W.E., ter Maat, J., 2013. Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. Global Environ. Change 23, 485–498. http://dx.doi.org/10.1016/j.gloenvcha.2012.12.006.

Hall, S., Madden, D., 2018. Housing the city, learning from Thamesmead.

Hallegatte, S., 2009. Strategies to adapt to an uncertain climate change. Global Environ. Change 19, 240–247. http://dx.doi.org/10.1016/j.gloenvcha.2008.12.003.

Hamidi, A.R., Jing, L., Shahab, M., Azam, K., Atiq Ur Rehman Tariq, M., Ng, A.W.M., 2018. Flood Exposure and Social Vulnerability Analysis in Rural Areas of Developing Countries: An Empirical Study of Charsadda District, Pakistan. Water, 14, 1176. https://doi.org/10.3390/w14071176.

Haraldsson, H. V., 2018. Causal Loop Diagrams - Archetypes. Idea, January 2004, 1–5.

Hegger, D., Lamers, M., Van Zeijl-Rozema, A., & Dieperink, C., 2012. Conceptualising joint knowledge production in regional climate change adaptation projects: Success conditions and levers for action. Environ. Sci. Policy, 18, 52–65. https://doi.org/10.1016/j.envsci.2012.01.002.

High Performance Systems (1992) Stella II: an introduction to systems thinking. High Performance Systems, Inc, Hanover, New Hampshire.

Holling, C.S., 1996. Engineering resilience versus ecological resilience. In: Schulze, P. (Ed.), Engineering Within Ecological Constraints. National Academy Press, Washington, pp. 31–44.

Homer, J., Oliva, R., 2001. Maps and models in system dynamics: a response to Coyle. Syst. Dyn. Rev., 17(4):347–356. https://doi.org/10.1002/sdr.224.

Hovmand, P.S., Etiënne, Rouwette, A.J.A., Andersen, D.F., Richardson, G.P., Kraus, A., 2013. Scriptapedia, 1–88.

Howe, C., Suich, H., Vira, B., and Mace, G.M., 2014. Creating Win-Wins from Trade-Offs? Ecosystem Services for Human Well-Being: A Meta-

Analysis of Ecosystem Service Trade-Offs and Synergies in the Real World. Glob. Environ. Change, 28, 263–275. https://doi.org/10.1016/j.gloenvcha.2014.07.005.

Inam, A., Adamowski, J., Halbe, J., Prasher, S., 2015. Using causal loop diagrams for the initialization of stakeholder engagement in soil salinity management in agricultural watersheds in developing countries: a case study in the Rechna Doab watershed, Pakistan. J. Environ. Manage. 152, 251–267. https://doi.org/10.1016/j.jenvman.2015.01.052.

Inam, A., Adamowski, J., Prasher, S., Halbe, J., Malard, J., Albano, R., 2017a. Coupling of a distributed stakeholder-built system dynamics socio-economic model with SAHYSMOD for sustainable soil salinity management - part 1: model development. J. Hydrol. 551, 596–618. https://doi.org/10.1016/j.jhydrol.2017.03.039.

Inam, A., Adamowski, J., Prasher, S., Halbe, J., Malard, J., Albano, R., 2017b. Coupling of a distributed stakeholder-built system dynamics socio-economic model with SAHYSMOD for sustainable soil salinity management - part 2: model coupling and application. J. Hydrol. 551, 278–299. https://doi.org/10.1016/j.jhydrol.2017.03.040.

Inam, A., Adamowski, J., Prasher, S., Albano, R., 2017c. Parameter estimation and uncertainty analysis of Spatial Agro Hydro Salinity Model (SAHYSMOD) in semi-arid climate of Rechna Doab, Pakistan. Environ. Modell. Software 186–211. https://doi.org/10.1016/j.envsoft.2017.04.002.

IPCC, 2012. Managing the Risks of Extreme Events and Disasters To Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (and PMM C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, ed.). Cambridge University Pres: Cambridge and New York. https://doi.org/10.1017/CBO9781139177245.

JBA consulting, 2020. Marsh Dykes Modelling. Technical Modelling Report.

Joerin, J., Shaw, R., Takeuchi, Y., Krishnamurthy, R., 2014. The adoption of a Climate Disaster Resilience Index in Chennai, India. Disasters, 38(3): 540−561. https://doi.org/10.1111/disa.12058.

Jones, M.A., Hughes, A.G., Jackson, C.R., Van Wonderen, J.J, 2012. Geol. Soc. Spec. Publ., 364, 99-111. https://doi.org/10.1144/SP364.8.

Kabisch, N., Stadler, J., Korn, H., Bonn, A., 2016. Nature-based solutions to climate change mitigation and adaptation in urban areas. Ecol. Soc. 21, 39. https://doi.org/10.5751/ES-08373-210239.

Kabisch N, Korn H, Stadler J, Bonn A. 2017a. Nature - based Solutions to Climate Change Adaptation in Urban Areas. Springer.

Kapetas L, Fenner R., 2020. Integrating blue-green and grey infrastructure through an adaptation pathways approach to surface water flooding. Phil. Trans. R. Soc., A 378: 20190204. http://dx.doi.org/10.1098/rsta.2019.0204.

Karimlou, K., Hassani, N., Rashidi Mehrabadi, A., Nazari, M.R., 2020. Developing a model for decision-makers in dynamic modeling of urban water system management. Water Resour. Manag. 34 (2), 481–499. https://doi.org/10.1007/s11269-019-02428-z.

Keating, A., Campbell, K., Mechler, R., Magnuszewski, P., Mochizuki, J., Liu, W., Szoenyi, M. and McQuistan, C., 2016. Disaster resilience: what it is and how it can engender a meaningful change in development policy. Dev. Policy Rev., 35 65–91.

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. Sci. Total Environ, 610–611, 997–1009. https://doi.org/10.1016/j. scitotenv.2017.08.077.

Kelly, L., Kalin, R.M., Bertram, D., Kanjaye, M., Nkhata, M., Sibande, H., 2019. Quantification of Temporal Variations in Base Flow Index Using Sporadic River Data: Application to the Bua Catchment, Malawi. Water, 11(5), 901. https://doi.org/10.3390/w11050901.

Khan, S., Yufeng, L., Ahmad, A., 2009. Analysing complex behaviour of hydrological systems through a system dynamics approach. Environ. Model. Softw., 24(12), 1363–1372. https://doi.org/10.1016/j.envsoft.2007.06.006.

Khatibi, F.S., Dedekorkut-Howes, A., Howes, M., Torabi, E., 2021. Can public awareness, knowledge and engagement improve climate change adaptation policies? Discov. Sustain. 2, 1–24. https://doi.org/10.1007/s43621-021-00024-z.

Kim, H., Andersen, D.F., 2012. Building confidence in causal maps generated from purposive text data: mapping transcripts of the Federal Reserve. Syst. Dyn. Rev., 28 (4), 311–328.

Kind, J.M., 2014. Economically efficient flood protection standards for the Netherlands. J. Flood Risk Manage. 7, 103–117. http://dx.doi.org/10.1111/jfr3.12026.

Kissi, A.E., Abbey, G.A., Agboka, K. and Egbendewe, A., 2015. Quantitative Assessment of Vulnerability to Flood Hazards in Downstream Area of Mono Basin, South-Eastern Togo: Yoto District. Journal of Geographic Information System, 7, 607-619. http://dx.doi.org/10.4236/jgis.2015.76049.

Kloprogge, P., Sluijs, J.P.V.D., 2006. The inclusion of stakeholder knowledge and perspectives in integrated assessment of climate change. Clim. Change, 75 (3), 359–389. https://doi.org/10.1007/s10584-006-0362-2.

Kotir, J. H., Smith, C., Brown, G., Marshall, N., & Johnstone, R., 2016. A system dynamics simulation model for sustainable water resources management and agricultural development in the Volta River Basin, Ghana. Sci. Total Environ., 573, 444–457. https://doi.org/10.1016/j.scitotenv.2016.08.081.

Kwakkel, J.H., Walker, W.E., Marchau, V.A.W.J., 2010. Classifying and communicating uncertainties in model-based policy analysis. Int. J. Technol. Policy Manag. https://doi.org/10.1504/IJTPM.2010.036918.

Laboy, M., Fannon, D., 2016. Resilience theory and praxis: a critical framework for architecture. Enquiry, 13, 39–52. https://doi.org/10.17831/enq:arcc.v13i2.405.

Lafortezza R, Davies C, Sanesi G, Konijnendijk CC (2013) Green Infrastructure as a tool to support spatial planning in European urban regions. iForest, 6:102. https://doi.org/10.3832/ifor0723-006.

Landcom, 2011. Residential density guide. For Landcom project teams.

Lane, D.C., 2008. The Emergence and use of diagramming in system dynamics: a critical account. Syst. Res. Behav. Sci., 25: 3–23.

Larson, E.K., Perrings, C., 2013. The value of water-related amenities in an arid city: the case of the Phoenix metropolitan area. Landsc. Urban Plann. 109 https://doi.org/ 10.1016/j.landurbplan.2012.10.008.

Laurien, F., Martin, J.C.G., Mehryar, S., 2022. Climate and disaster resilience measurement: Persistent gaps in multiple hazards, methods, and practicability. Clim. Risk Manag., 37, 100443. https://doi.org/10.1016/j.crm.2022.100443.

Lechowska, E., 2018. What determines flood risk perception? A review of factors of flood risk perception and relations between its basic elements. Nat. Hazards, 94:1341–1366. https://doi.org/10.1007/s11069-018-3480-z.

Lee, J., Perera, D., Glickman, T., Taing, L., 2020. Water-related disasters and their health impacts: A global review. Progress in Disaster Science, 8, 100123. https://doi.org/10.1016/j.pdisas.2020.100123.

Lemaire, G.G., Carnohan, S.A., Grand, S., Mazel, V., Bjerg, P.L., McKnight, U.S., 2021. Data-Driven System Dynamics Model for Simulating Water Quantity and Quality in Peri-Urban Streams. Water, 13, 3002. https://doi.org/10.3390/w13213002.

Lennon, M., Scott, M., & O'Neill, E., 2014. Urban design and adapting to flood risk: The role of green infrastructure. J. Urban Des., 19(5), 745–758. https://doi.org/10.1080/13574809.2014.944113?journalCode=cjud20#.VHBsqsmsnK0.

Liao, K-H., 2012. A theory on urban resilience to floods—a basis for alternative planning practices Ecol. Soc., 17(4): 48. http://dx.doi.org/10.5751/ES-05231-170448.

Linkov, I., et al., 2014. Changing the resilience paradigm. Nat. Clim. Change 4, 407– 409. http://dx.doi.org/10.1038/nclimate2227.

Liu, D., Li, M., Li, Y., Chen, H., 2022. Assessment of Public Flood Risk Perception and Influencing Factors: An Example of Jiaozuo City, China. Sustainability, 14, 9475. https://doi.org/10.3390/su14159475

Lopes, R., Videira, N., 2017. Modelling feedback processes underpinning management of ecosystem services: the role of participatory systems mapping. Ecosyst. Serv. 28, 28–42. https://doi.org/10.1016/j.ecoser.2017.09.012.

Löschner, L., Nordbeck, R., Scherhaufer, P., Seher, W., 2016. Scientist–stakeholder workshops: a collaborative approach for integrating science and decision-making in Austrian flood-prone municipalities. Environ. Sci. Policy, 55, 345–352. https://doi. org/10.1016/j.envsci.2015.08.003.

Maher, C., Gormally, M., Williams, C., Skeffington, M.S., 2014. Atlantic floodplain meadows: influence of hydrological gradients and management on sciomyzid (Diptera) assemblages. J. Insect. Conserv., 18:267–282.

Mannucci, S., Rosso, F., D'Amico, A., Bernardini, G., Morganti, M., 2022. Flood Resilience and Adaptation in the Built Environment: How Far along Are We? Sustainability, 14, 4096. https://doi.org/10.3390/su14074096. https://doi. org/10.1007/s10841-014-9630-z.

Marasco, S., Kammouh, O., Cimellaro, G.P., 2022. Disaster resilience quantification of communities: A risk-based approach. Int. J. Disaster Risk Reduct., 70, 102778. https://doi.org/10.1016/j.ijdrr.2021.102778.

Markowitz, A., 2017. The making, unmaking, and remaking of Thamesmead. UCL DPU Working Paper No. 193.

Mashaly, A. F., Fernald, A. G., 2020. Identifying capabilities and potentials of system dynamics in hydrology and water resources as a promising modeling approach for water management. Water (Switzerland), 12(5). https://doi.org/10.3390/w12051432.

Maskrey, S.A., Mount, N.J., Thorne, C.R., Dryden, I., 2016. Participatory modelling for stakeholder involvement in the development of flood risk management interventions options. Environ. Modell. Software 82, 275–294. https://doi.org/10.1016/j.envsoft.2016.04.027.

Mateus, M. D., & Franz, G., 2015. Sensitivity analysis in a complex marine ecological model. Water, 7, 2060–2081. http://dx.doi.org/10.3390/w7052060.

McInerney, D. J., Lempert, R. J., Keller, K., 2012. What are Robust Strategies in the Face of Uncertain Climate Threshold Responses?: Robust Climate Strategies. Climatic Change, 112 (3–4): 547–568. https://doi:10.1007/s10584-011-0377-1.

McVittie, A., Cole, L., Wreford, A., Sgobbi, A., Yordi, B., 2018. Ecosystem-based solutions for disaster risk reduction: lessons from European applications of ecosystem-based adaptation measures. Int. J. Disaster Risk Reduction 32, 42–54. https://doi.org/ 10.1016/j.ijdrr.2017.12.014.

Meadows, D.H., Meadows, D.L., Randers, J., Behrens, W.W., 1972. The limits to growth. Universe Books, New York.

Meadows, D.H., 2008. Thinking in Systems: a Primer. Chelsea Green Publishing, Vermont.

Mehryar, S., Sliuzas, R., Schwarz, N., Sharifi, A., van Maarseveen, M., 2019. From individual fuzzy cognitive maps to agent based models: modeling multi-factorial and multi-stakeholder decision-making for water scarcity. J. Environ. Manag. 250, 109482. https://doi.org/10.1016/j.jenvman.2019.109482.

Mehryar, S., Surminski, S., 2022. Investigating flood resilience perceptions and supporting collective decision-making through fuzzy cognitive mapping. Sci. Total Environ., 837, 155854. http://dx.doi.org/10.1016/j.scitotenv.2022.155854.

Meinherz, F., Videira, N., 2018. Integrating qualitative and quantitative methods in partic ipatory modeling to elicit behavioral drivers in environmental dilemmas: the case of air pollution in Talca, Chile. Environ. Manag. 62, 260–276. https://doi.org/10.1007/s00267-018-1034-5.

Messner, F., Meyer, V., 2006. Flood damage, vulnerability and risk perception – challenges for flood damage research. Flood Risk Management: Hazards, Vulnerability and Mitigation Measures, 149–167.

Miles, D., 2012. Population density, house prices and mortgage design. S.J.P.E., 59(5).

Miller, S.M., Montalto, F.A., 2019. Stakeholder perceptions of the ecosystem services provided by Green Infrastructure in New York City. Ecosyst. Serv., 37:100928. https://doi.org/10.1016/j.ecoser.2019.100928.

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., Stouffer, R.J., 2008. Stationarity is dead: whither water management? Science 319, 573–574. http://dx.doi.org/10.1126/science.1151915.

Mirchi, A., Madani, K., Watkins, D., Ahmad, S., 2012. Synthesis of system dynamics tools for holistic conceptualization of water resources problems. Water Resour. Manag., 26(9), 2421–2442.

Moghadas, M., Asadzadeh, A., Vafeidis, A., Fekete, A., Kötter, T., 2019. A multi-criteria approach for assessing urban flood resilience in Tehran, Iran. Int. J. Disaster Risk Reduct., 35, 101069. https://doi.org/10.1016/j.ijdrr.2019.101069.

Morrison, A., Westbrook, C.J., Noble, B.F., 2018. A review of the flood risk management governance and resilience literature. Flood Risk Manage., 11, 291–304. https://doi.org/10.1111/jfr3.12315.

Mulder, C.H., 2006. The relationship between population and housing. Sixty-ninth session of the UNECE Committee on Housing and Land Management, Key note presentation.

Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Boorman, P.M., Booth, B.B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., Betts, R.A., Brown, S.J., Howard, T.P., Humphrey, K.A., McCarthy, M.P., McDonald, R.E., Stephens, A., Wallace, C., Warren, R., Wilby, R., Wood, R.A., 2009. UK Climate Projections Science Report: Climate change projections. Met Office Hadley Centre, Exeter.

Nasiri, H., Yusof, M.J.M., Ali, T.A.M., Hussein, M.K.B., 2017. District food vulnerability index: urban decision-making tool. Int. J. Eng. Res., 7, 10.

Ntajal, J., Lamptey, B.L., MianikpoSogbedji, J., 2016. Flood Vulnerability Mapping in the Lower Mono River Basin in Togo, West Africa. Int. J. Sci. Eng. Res., 7.

Nutt, P.C., 2002. Why Decisions Fail: Avoiding the Blunders and Traps that Lead to Debacles. Berrett-Koehler Publishers, San Francisco, CA. https://doi.org/10.5465/ame.2003.9474995.

O’Donnell, E., Lamond, J. & Thorne, C. 2018. Learning and action alliance framework to facilitate stakeholder collaboration and social learning in urban flood risk management. Environ. Sci. Policy, 80, 1–8. https://doi:10.1016/j.envsci.2017. 10.013.

O'Donnell, E., Thorne, C., Ahilan, S., Arthur, S., Birkinshaw, S., Butler, D., Dawson, D., Everett, G., Fenner, R., Glenis, V., Kapetas, L., Kilsby, C., Krivtsov, V., Lamond, J., Maskrey, S., O'Donnell, G., Potter, K., Vercruysse, K., Vilcan, T., & Wright, N., 2020. The blue-green path to urban flood resilience. Blue-Green Systems, 2, 28–45. https://doi.org/10.2166/bgs.2019.199.

O'Donnell, E., & Thorne, C., 2020b. Urban flood risk management: The blue-green advantage. In C. Thorne (Ed.), Blue-green cities: Integrating urban flood risk management with green infrastructure. ICE Publishing. https://doi.org/10.1680/bgc.64195.001.

O’Keeffe, J., Pluchinotta, I., De Stercke, S., Hinson, C., Puchol-Salort, P., Mijic, A., Zimmermann, N., Collins, A.M., 2022. Evaluating natural capital performance of urban development through system dynamics: A case study from London. Sci. Total Environ., 153673. https://doi.org/10.1016/j.scitotenv.2022.153673.

Pagano, A., Pluchinotta, I., Giordano, R., Vurro, M., 2017. Drinking water supply in resilient cities: notes from L'Aquila earthquake case study. Sustain. Cities Soc. 28, 435–449. https://doi.org/10.1016/j.scs.2016.09.005.

Pagano, A., Pluchinotta, I., Pengal, P., Cokan, B., & Giordano, R., 2019. Engaging stakeholders in the assessment of NBS effectiveness in flood risk reduction: A participatory System Dynamics Model for benefits and co-benefits evaluation. Sci. Total Environ., 690, 543–555. https://doi.org/10.1016/j.scitotenv.2019.07.059.

Pahl-Wostl, C., Sendzimir, J., Jeffrey, P., Aerts, J., Berkamp, G., and Cross, K., 2007. Managing change toward adaptive water management through social learning. Ecol. Soc., 12(2): 30. http://www.ecologyandsociety.org/vol12/iss2/art30/.

Papagiannaki, K., Kotroni, V., Lagouvardos, K., Papagiannakis, G., 2019. How awareness and confidence affect flood-risk precautionary behavior of Greek citizens: the role of perceptual and emotional mechanisms. Nat. Hazards Earth Syst. Sci., 19, 1329–1346. https://doi.org/10.5194/nhess-19-1329-2019.

Pasquier, U., Few, R., Goulden, M. C., Hooton, S., He, Y., & Hiscock, K. M., 2020. “We can’t do it on our own!”—Integrating stakeholder and scientific knowledge of future flood risk to inform climate change adaptation planning in a coastal region. Environ. Sci. Policy, 103, 50–57. https://doi.org/10.1016/j.envsci.2019.10.016.

Peabody, 2021. Leaving in the Landscape.

Pejic Bach, M., Tustanovski, E., Ip, A. W. H., Yung, K. L., & Roblek, V., 2020. System dynamics models for the simulation of sustainable urban development: A review and analysis and the stakeholder perspective. Kybernetes, 49(2), 460–504. https://doi.org/10.1108/K-04-2018-0210.

Perrone, A., Inam, A., Albano, R., Adamowski, J., Sole, A., 2020. A participatory system dynamics modeling approach to facilitate collaborative flood risk management: A case study in the Bradano River (Italy). J. Hydrol., 580. https://doi.org/10.1016/j.jhydrol.2019.124354.

Phan, T.D., Smart, J.C.R., Sahin, O., Capon, S.J., Hadwen, W.L., 2018. Assessment of the vul nerability of a coastal freshwater system to climatic and non-climatic changes: a sys tem dynamics approach. J. Clean. Prod. 183, 940–955. https://doi.org/10.1016/j.jclepro.2018.02.169.

Phan, T. D., Bertone, E., Stewart, R. A., 2021. Critical review of system dynamics modelling applications for water resources planning and management. Clean. Env. System., 2. 100031. https://doi.org/10.1016/j.cesys.2021.100031.

Pluchinotta, I., Pagano, A., Giordano, R., Tsoukiàs, A., 2018. A system dynamics model for supporting decision-makers in irrigation water management. J. Environ. Manag. 223, 815–824. https://doi.org/10.1016/j.jenvman.2018.06.083.

Pluchinotta, I., Pagano, A., Vilcan, T., Ahilan, S., Kapetas, L., Maskrey, S., Krivtsov, V., Thorne, C., & O'Donnell, E., 2021a. A participatory system dynamics model to investigate sustainable urban water management in Ebbsfleet Garden City. Sustain. Cities Soc, 67. https://doi.org/10.1016/j.scs.2021.102709.

Pluchinotta, I., Salvia, G., Zimmermann, N., 2021b. The importance of eliciting stakeholders' system boundary perceptions for problem structuring and decision-making. Eur. J. Oper. Res. https://doi.org/10.1016/j.ejor.2021.12.029.

Powersim Corporation, 1996. Powersim 2.5 reference manual. Powersim Corporation Inc., Herndon, Virginia.

Qiao, X.J., Kristoffersson, A., Randrup, T.B., 2018. Challenges to implementing urban sustainable stormwater management from a governance perspective: A literature review. J. Clean. Prod., 196: 943–952. https://doi.org/10.1016/j.jclepro.2018.06.049.

Quinlan, A.E., Berbés-Blázquez, M., Haider, L.J., Peterson, G.D., 2016. Measuring and assessing resilience: broadening understanding through multiple disciplinary perspectives. J. Appl. Ecol., 53, 677–687. https://doi.org/10.1111/1365-2664.12550.

Restemeyer, B., Woltjer, J., van den Brink, M., 2015. A strategy-based framework for assessing the flood resilience of cities – a Hamburg case study. Plann. Theory Pract. 16, 45–62. http://dx.doi.org/10.1080/14649357.2014.1000950.

Rich, K.M., Rich, M., Dizyee, K., 2018. Participatory systems approaches for urban and peri-urban agriculture planning: the role of system dynamics and spatial group model building. Agric. Syst. 160, 110–123. https://doi.org/10.1016/j.agsy.2016.09.022.

Richardson, G.P., 1997. Problems in causal loop diagrams revisited. Syst. Dyn. Rev., 13: 24.

Richmond, B., 1993. Systems thinking: critical thinking skills for the 1990ies and beyond. Syst. Dyn. Rev., 9(2):113–133.

Riddell, G.A., van Delden, H., Maier, H.R., Zecchin, A.C., 2019. Exploratory scenario analysis for disaster risk reduction: Considering alternative pathways in disaster risk assessment. Int. Jour. Disast. Risk. Red. https://doi.org/10.1016/j.ijdrr.2019.101230.

Riel, W. V., 2011. Exploratory study of pluvial flood impacts in Dutch urban areas. Deltares.

Robin, C., Beck, C., Armstrong, B., Waite, T.D., Rubin, G.J., English National Study of Flooding and Health Study Group, Oliver, I., 2020. Impact of flooding on health-related quality of life in England: results from the National Study of Flooding and Health. Eur. J. Public Health, 30(5), 942–948. https://doi.org/10.1093/eurpub/ckaa049.

Rockefeller, ARUP, City Resilience Index, 2015. https://assets.rockefellerfoundation.org/app/uploads/20160201132303/CRI-Revised-Booklet1.pdf.

Rodina, L., 2018. Defining “water resilience”: debates, concepts, approaches and gaps. Wiley Interdiscip. Rev. Water, 6.2. https://doi.org/10.1002/wat2.1334.

Sahin, O., Siems, R.S., Stewart, R.A., Porter, M.G., 2016. Paradigm shift to enhanced water supply planning through augmented grids, scarcity pricing and adaptive factory water: a system dynamics approach. Environ. Model. Software 75, 348–361. https://doi.org/10.1016/j.envsoft.2014.05.018.

Salas, J.D., Obeysekera, J., 2014. Revisiting the Concepts of Return Period and Risk for Nonstationary Hydrologic Extreme Events. J. Hydrol. Eng.

Salvia, G., Pluchinotta, I., Tsoulou, I., Moore, G., Zimmermann, N., 2022. Understanding Urban Green Space Usage through Systems Thinking: A Case Study in Thamesmead, London. Sustainability, 14, 2575. https://doi.org/10.3390/su14052575.

Satour, N., Raji, O., El Mocayd, N., Kacimi, I., and Kassou, N., 2021. Spatialized flood resilience measurement in rapidly urbanized coastal areas with complex semi-arid environment in Northern Morocco. Nat. Hazards Earth Syst. Sci., 21, 1101–1118, https://doi.org/10.5194/nhess-21-1101-2021, 2021.

Scaffernicht, M., 2010. Causal Loop Diagrams Between Structure and Behaviour: A Critical Analysis of the Relationship Between Polarity, Behaviour and Events. Syst. Res., 27, 653-666. https://doi.org/10.1002/sres.1018.

Scaini, A., Stritih, A., Brouillet, C., Scaini, C., 2021. Flood Risk and River Conservation: Mapping Citizen Perception to Support Sustainable River Management. Front. Earth Sci., 9, 1–14. https://doi.org/10.3389/feart.2021.675131.

Scrieciu, A., Pagano, A., Coletta, V. R., Fratino, U., Giordano, R., 2021. Bayesian Belief Networks for Integrating Scientific and Stakeholders’ Knowledge to Support Nature-Based Solution Implementation. Front. Earth Sci., 9, 1–18. https://doi.org/10.3389/feart.2021.674618.

Senge, P. M., Sterman, J. D., 1992. Systems Thinking and Organizational Learning - Acting Locally and Thinking Globally in the Organization of the Future (Reprinted from European Journal Operational-Research, 1992). Transforming Organizations, 59, 353–371.

Senge, P.M., 1994. The Fifth Discipline: The Art and Practice of The Learning Organization. Currency Doubleday, New York.

Serinaldi, F., Kilsby, C.G., 2018. Unsurprising Surprises: The Frequency of Record-breaking and Overthreshold Hydrological Extremes Under Spatial and Temporal Dependence. Wat. Resour. Res.

Simonovic, S.P., Ahmad, S., 2005. Computer-based model for flood evacuation emergency planning. Nat. Hazard, 34(1):25–51.

Simonovic, S.P., 2009. Managing Water Resources: Methods and Tools for a System Approach. UNESCO, Earthscan.

Simonovic, S.P., 2011. Systems Approach to Management of Disasters: Methods and Applications. Wiley, New Jersey. http://dx.doi.org/10.1002/9780470890363.

Song, K., You, S., Chon, J., 2018. Simulation modeling for a resilience improvement plan for natural disasters in a coastal area. Environ. Pollut. 242, 1970–1980. https://doi.org/10.1016/j.envpol.2018.07.057.

Staśko, S., Tarka, R., Olichwer, T., 2012. Groundwater recharge evaluation based on the infiltration method. Intern. Assoc. Hydrogeol. Selected Papers 17:189–197.

Stave, K. A., 2003. A system dynamics model to facilitate public understanding of water management options in Las Vegas, Nevada. J. Environ. Manage, 67(4), 303–313. https://doi.org/10.1016/S0301-4797(02)00205-0.

Sterman, J.D., 2000. Systems Thinking and Modeling for a Complex World. McGraw-Hill, New York.

Sušnik, J., Vamvakeridou-Lyroudia, L.S., Savic, D.A., Kapelan, Z., 2012. Integrated system dynamics modelling for water scarcity assessment:

case study of the kairouan region. Sci. Total Environ. 440, 290–306. https://doi.org/10.1016/j.scitotenv.2012.05.085.

Sušnik, J., Vamvakeridou-Lyroudia, L. S., Baumert, N., Kloos, J., Renaud, F., La Jeunesse, I., Mabrouk, B., et al., 2014. Interdisciplinary assessment of sea-level rise and climate change impacts on the lower Nile delta, Egypt. Sci. Total Environ., 503-504, 279–288. https://doi.org/10.1016/j.scitotenv.2014.06.111.

Sušnik, J., Chew, C., Domingo, X., Mereu, S., Trabucco, A., Evans, B., et al., 2018. Multi-Stakeholder Development of a Serious Game to Explore the Water-Energy-Food-Land-Climate Nexus: The SIM4NEXUS Approach. Water, 10(2), 139. https://doi.org/10.3390/w10020139.

Systems V., 1996. Vensim user's guide. Ventana Systems Inc, Belmont, Massachusetts.

Talbot, C.J., Bennett, E.M., Cassell, K., Hanes, D.M., Minor, E.C., Paerl, H., Raymond, P.A., Vargas, R., Vidon, P.G., Wollheim, W., Xenopoulos, M.A., 2018. The impact of flooding on aquatic ecosystem services. Biogeochemistry, 141(3):439-461. https://doi.org/10.1007/s10533-018-0449-7.

The Land Trust, 2018. The economic value of our green spaces.

Thompson, J.R., 2012. Modelling the impacts of climate change on upland catchments in southwest Scotland using MIKE SHE and the UKCP09 probabilistic projections. Hydrology Research, 43.4. https://doi.org/10.2166/nh.2012.105.

Tingsanchali, T., 2012. Urban flood disaster management. Procedia Eng., 32, 25–37. https://doi.org/10.1016/j.proeng.2012.01.1233.

Tingsanchali, T., Promping, T., 2022. Comprehensive Assessment of Flood Hazard, Vulnerability, and Flood Risk at the Household Level in a Municipality Area: A Case Study of Nan Province, Thailand. Water, 14, 161. https://doi.org/10.3390/w14020161.

Tunstall, S., Tapsell, S., Green, C., Floyd, P., & George, C., 2006. The health effects of flooding: Social research results from England and Wales. J. Water Health, 4, 365–380. https://doi.org/10.2166/wh.2006.031.

UNISDR, 2009. UNISDR Terminology on Disaster Risk Reduction. United Nations. International Strategy for Disaster Reduction, Geneva.

URS Scott Wilson, 2012. Tilfen Land. Lakes and Canals Capacity Assessment, Stage 3.

Verrucci, E., Rossetto, T., Twigg, J., 2012. Multi-disciplinary indicators for evaluating the seismic resilience of urban areas, 15th World Conference on Earthquake Engineering.

Videira, N., Antunes, P., Santos, R., 2009. Scoping river basin management issues with participatory modelling: the Baixo Guadiana experience. Ecol. Econ. 68, 965e978. https://doi.org/10.1016/j.ecolecon.2008.11.008.

Villarini, G., Bales, J., Bates, P. D., Krajewski, W. F., Serinaldi, F., Smith, J. A., 2009a. Flood frequency analysis for nonstationary annual peak records in an urban drainage basin. Advances in Water Resour.

Vijayaraghavan, K., Basanta, K. B., Adam, M. G., Soh, S. H., Tsen-Tieng, D. L., Davis, A. P., Chew, H. S., Tan, P. Y., Babovic, V., & Balasubramanian, R., 2021. Bioretention systems for stormwater management: Recent advances and future prospects. J. Environ. Manage., 292, 112766. https://doi.org/10.1016/j.jenvman.2021.112766.

Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. Environ. Model. Softw., 25(11), 1268–1281. https://doi.org/10.1016/j.envsoft.2010.03.007.

Voinov, A., Kolagani, N., McCall, M. K., Glynn, P. D., Kragt, M. E., Ostermann, F. O., Pierce, S. A., & Ramu, P., 2016. Modelling with stakeholders - Next generation., Environ. Model. Softw., 77, 196–220. https://doi.org/10.1016/j.envsoft.2015.11.016.

Voinov, A., 2017. Participatory Modeling for Sustainability. Encyclopedia of Sustainable Technologies, no. November: 33–39. https://doi.org/10.1016/B978-0-12-409548-9.10532-9.

Walker, B.H, Holling, C.S., Carpenter, S.R., and Kinzig. A., 2004. Resilience, adaptability and transformability in social–ecological systems. Ecol. Soc., 9(2):5. http://www.ecologyandsociety.org/vol9/iss2/art5.

Walker, W., Haasnoot, M., Kwakkel, J., 2013a. Adapt or perish: a review of planning approaches for adaptation under deep uncertainty. Sustainability. https://doi.org/10.3390/su5030955.

Wamsler, C., Brink, E., Rivera, C., 2013. Planning for climate change in urban areas: From theory to practice. J. Clean. Prod., 50, 68–81. https://doi.org/10.1016/j.jclepro.2012.12.008.

Wang, H., Zhang, J., Zeng, W., 2018. Intelligent simulation of aquatic environment eco nomic policy coupled ABM and SD models. Sci. Total Environ. 618, 1160–1172. https://doi.org/10.1016/j.scitotenv.2017.09.184.

Wasson, R.J., 2016. Uncertainty, ambiguity and adaptive flood forecasting. Policy Soc. http://dx.doi.org/10.1016/j.polsoc.2016.06.002.

Wehn, U., Rusca, M., Evers, J., Lanfranchi, V., 2015. Participation in Flood Risk Management and the Potential of Citizen Observatories: A Governance Analysis Environ. Sci. Pol., 48 225–236. https://doi:10.1016/j.envsci.2014.12.017.

Wihlborg, M., Sörensen, J., Alkan Olsson, J., 2019. Assessment of barriers and drivers for implementation of blue-green solutions in Swedish municipalities. J. Environ. Manage., 233: 706–718. https://doi.org/10.1016/j.jenvman.2018.12.018.

Winter, T.C., Harvey, J.W., Franke, O.L., Alley, W.M., 1998. Ground Water and Surface Water: A Single Resource. U.S. Geological Survey Circular, 1139,

Woods Ballard, B., Wilson, S., Udale-Clarke, H., Illman, S., Scott, T., Ashley, R., et al. 2015. CIRIA report C753 The SuDS Manual.

Yan, Z., Teng, M., He, W., Liu, A., Li, Y., Wang, P., 2019. Impervious surface area is a key predictor for urban plant diversity in a city undergone rapid urbanization. Sci. Total Environ., 650, 335-342. https://doi.org/10.1016/j.scitotenv.2018.09.025.

Yusuf, J-E., St. John III, B., Covi, M., Nicula, G., 2018. Engaging Stakeholders in Planning for Sea Level Rise and Resilience. J. contemp. water res. educ., 164, 112-123. https://doi.org/10.1111/j.1936-704X.2018.03287.x.

Zare, F., Elsawah, S., Bagheri, A., Nabavi, E., Jakeman, A.J., 2019. Improved integrated water resource modelling by combining DPSIR and system dynamics conceptual modelling techniques. J. Environ. Manag. 246, 27–41. https://doi.org/10.1016/ j.jenvman.2019.05.033.

Zarghami, M., Akbariyeh, S., 2012. System dynamics modeling for complex urban water systems: application to the city of Tabriz, Iran. Resour. Conserv. Recycl. 60, 99–106. https://doi.org/10.1016/j.resconrec.2011.11.008.

Zarghami, S. A., Gunawan, I., Schultmann, F., 2018. System Dynamics Modelling Process in Water Sector: a Review of Research Literature. Syst. Res. Behav. Sci., 35(6), 776–790. https://doi.org/10.1002/sres.2518.

Zevenbergen, C., Gersonius, B., Radhakrishan, M., 2020. Flood resilience. Phil. Trans. R. Soc. A, 378: 20190212. http://dx.doi.org/10.1098/rsta.2019.0212.

Zhang, K., Chui, T.F.M., 2019. Linking hydrological and bioecological benefits of green infrastructures across spatial scales-a literature review. Sci. Total Environ. 646, 1219–1231.

Zhang, Y., Li, Z., Ge, W., Chen, X., Xu, H., Guan, H., 2021. Evaluation of the impact of extreme floods on the biodiversity of terrestrial animals. Sci. Total Environ., 790, 148227. https://doi.org/10.1016/j.scitotenv.2021.148227.

Zhou, Y., Liu, Z., Liu, S., Zhao, J., Li, W., Zhang, J., Chen, A.S., 2013. Flood damage assessment of Vizhuang, Beijing. International Conference on

Flood Resilience: Experiences in Asia and Europe, 5-7 September, Exeter, United Kingdom.

Zomorodian, M., Lai, S. H., Homayounfar, M., Ibrahim, S., Fatemi, S. E., El-Shafie, A., 2018. The state-of-the-art system dynamics application in integrated water resources modeling. J. Environ. Manage., 227, 294–304. https://doi.org/10.1016/j.jenvman.2018.08.097.

10. SUPPLEMENTARY MATERIAL

This section includes additional details related to (1) semi-structured interviews, (2) interviews/correspondences and engaged stakeholders, (3) Thamesmead flood Causal Loop Diagram (CLD) variables definitions, (4) the workshop agenda on the CLD causal structure validation and Behaviour Over Time (BOT) graphs construction, (5) stakeholders involved in the first workshop, (6) short description of the main feedback loops, (7) the workshop agenda on the Stock and Flow (SF) model validation and scenarios design, (8) stakeholders involved in the second workshop, (9) mathematical equations, initial values and data sources behind the SF model, (10) values of the changed variables in the different scenarios.

10.1. Semi-structured interviews guideline on flood risk and past flooding events

Each question is associated with an objective. Depending on the answer to question 1, the interview proceeded differently (asking questions 2 to 10 if stakeholder answers yes or 11 and 12 if stakeholders answer no to question 1). Similarly, to the first question, the final questions (i.e., 13 and 14) are the same for all experts.

#	QUESTION	OBJECTIVE
1	Based on your own knowledge, have flooding events occurred in the area in the past?	Understand why it is important to investigate flooding in the area
	YES	
2	When?	Collect information on past flooding events

3	Do you think flooding may be a risk currently and/or in the future? • If so, why? Are there transformations (e.g., urban transformations, climate change) taking place that may involve this? • If not, why?	Understand why it is important to investigate flooding in the area
4	What kind of flood events were these (i.e., pluvial flooding, river flooding, groundwater flooding)? What do you think were the causes? (e.g., drainage systems did not work, it rained for many days)	Understand what type of flooding the area is most susceptible to
5	Has there been any damage to the built environment (e.g., buildings and road, electrical, gas, and telecommunication infrastructure)? • If so, what type of damage occurred (e.g., buildings filled with water, roads were inaccessible, electricity went off)? Was there any damage to the basements or ground floors of buildings? • If so, were the basements protected in any way?	Investigate damage to the built environment due to flooding
6	Have productive activities been affected? How? Did flooding affect the price of dwellings? How?	Investigate damage to economy due to flooding
7	During the flood events, what was the role of the Sustainable Urban Drainage Systems (network lakes, canals)? • Did they work properly? If not, why? Was it a design or management problem?	Investigate the performance of drainage systems in the area when the event took place
8	Were there warning and monitoring systems in place? • If so, which ones (e.g., rainfall monitoring/forecasting, water level and velocity sensors in the river)? Why did they not work? Have you been alarmed in time by someone?	Investigate whether there were any warning and monitoring systems in the area and their effectiveness when the event took place

9	Have individual prevention measures been implemented? - If so, what kind (e.g., leaving the ground floor of buildings vacant)? - Why did they not work? Have collective prevention measures been implemented? - If so, what kind (e.g., ensure the functionality of drainage systems)? - Why did they not work?	Investigate whether any prevention measures were implemented and their effectiveness when the event took place
10	What post-event intervention measures have been taken? Were they measures to restore the damaged system (e.g., rebuild buildings and infrastructure, improve drainage systems) or measures to prevent damage in the event of future flooding (e.g., activities to engage the community, insurance, and sustainable land use policies)? - If so, who intervened? (e.g., municipality, national government)	Investigate what was done after the event and with which funds
	NO	
11	Do you think that no flood events have occurred in the past because the system is not exposed to risk (e.g., there is never heavy or long-lasting rainfall) or because risk mitigation measures (e.g., drainage systems) are effective?	Understand the susceptibility of the area to flooding and investigate the performance of mitigation measures in the area
12	Do you think that currently and/or in the future there may be flood risk in the area? - If so, why? Are there transformations (e.g., urban transformations, climate change) taking place that may involve this thus changing the system's risk levels? - If not, why?	Understand why it is important to investigate flooding
	FINAL QUESTIONS FOR EVERYONE	
13	(if appropriate) Is there anyone else you think we could usefully speak to?	Stakeholder snowballing
14	Thank you for your time. Is there anything else you would like to tell me about the topics we discussed today, on flood risk and flood events in the area?	Wrap up

10.2. Details on interviews/correspondences and engaged stakeholders

INTERVIEW / CORRESPONDENCE REFERENCE	INTERVIEW / CORRESPONDENCE DATE	STAKEHOLDER ORGANIZATION	STAKEHOLDER ROLE
Int. 1	23/02/2021	Environmental Non-Governmental Organisation	Senior Manager
Int. 2	26/02/2021	Local Authority	Flood Risk and Development Manager
Int. 3	31/03/2021	Housing Association/Developers	Director
Int. 4	28/05/2021	Company of consulting and engineering/ architectural design	Director
[redacted]			
Correspondence 1	16/02/2021	Housing Association/Developers	Sustainability Manager
Correspondence 2	23/02/2021	Environmental Non-Governmental Organisation	Senior Manager
Correspondence 3	1/03/2021	Local Authority	Flood Risk and Development Manager
Correspondence 4	23/03/2021	Local Authority	Project Officer

10.3. Flood Causal Loop Diagram variables definitions

VARIABLE	DESCRIPTION
climate change	State of change in the climatic conditions over time that is identified as changes in the mean and/or the variability of its properties, that

	persists for an extended period
extreme tide levels intensity/ frequency	Magnitude and occurrence rate per year of exceedance of tide threshold levels
extreme storm events intensity/ frequency	Magnitude and occurrence rate per year of storm events extremes in the historical distribution
rainfall intensity/frequency	Magnitude and return period of precipitation events
soil retention capacity	Soil ability to storage water and make it sufficiently available for plant use
surface runoff	Precipitation runoff over the landscape
urban stormwater system capacity	The water volume that the sewage system can take without surcharging or flooding
existing SuDS (lakes and canals) capacity	Remaining volume of the networks of the existing Sustainable urban Drainage Systems (SuDS)
urban drainage systems capacity	The amount of water that can be stored by drainage systems (both ditches/dykes system and SuDS) without surcharging or flooding
groundwater level	The upper level of an underground surface in which the soil is permanently saturated with water
river water level	A measure of the depth of water in a river relative to an arbitrary point (e.g., the riverbed)
ditches and dykes system capacity	Available volume of ditches and dykes system
sediments and pollutants removal	Interception and filtration of sediments and pollutants present in the water and/or air
Thames tidal defences effectiveness	The capability of Thames tidal defences of producing the desired protection reducing, or ideally preventing, damage by flood water
sea water level	The level corresponding to the surface of the sea at mean level between high and low tide
flood	A temporary coverage with water of an area not normally covered by water
pluvial flood	Type of flooding that results from the lack of urban stormwater system capacity
groundwater flood	Type of flooding occurring when the natural water level below ground rises to well above what can be accommodated

tidal river flood	Type of flooding, usually very sudden, that results from the sea
fluvial flood	Type of flooding occurring when urban drainage systems no longer have capacity
environmental quality of the urban system	The combination of water, air, and soil quality, and the aesthetic and ecosystemic value of the area
green areas	All urban land covered by vegetation of any kind
impervious areas	Surfaces, completely human-created, that allow little or no stormwater infiltration into the ground
housing demand	A market driven concept that relates to the type and number of houses that households will choose to occupy based on preference and ability to pay
population growth	The increase in the number of individuals in the population
infrastructure damage	All detrimental effects on basic structures and facilities (highways, electrical, gas, and telecommunication) provoked by flooding
public realm damage	All detrimental effects on all parts of the built environment where the public has free access (streets, squares, parks, open spaces, waterfronts, and public transit systems) provoked by flooding
private properties damage	All detrimental effects provoked by flooding on the interiors and structures of properties owned by private parties
private properties value	The worth of a piece of real estate based on the price that a buyer and seller agree upon, determined by what the market bears
economic losses	The value of direct (e.g., cost of repairs) and indirect (e.g., lost income losses) financial losses due to flooding
productive activities operation	The functioning of activities that have economic value in the marketplace
attractiveness of local area for residents	The feature that makes the area appealing to residents and meets their needs
attractiveness of local area for investors	The quality of the area that make it interesting to investors

impact on large businesses	Financial effect on large businesses
impact on small businesses/families	Financial effect on small businesses and families
insurance policies	Insurance tools that limit the impacts of hazards on insured people, objects, or organizations through the transfer of these impacts to an insurer who will provide for economic compensation
individual prevention measures	Self-insurance initiatives against flooding
residents’ awareness and preparedness to flood event	The extent of common knowledge about flooding risk and the actions that can be taken to reduce exposure and vulnerability to it, as well as capabilities and actions of community to effectively anticipate, respond to, and recover from, the impacts of flooding events
quality of BG public spaces	Distinctive attribute of the benefits Blue and Green (BG) public spaces provide, which might be important determinants for how and how frequently people use them and for human well-being
biodiversity	Coexistence, in the same ecosystem, of a variability of living organisms from all sources, within species and between species
use of BG public spaces	Attendance degree of BG public spaces by people
residents’ health	State of citizens' physical and mental well-being
land consumption for building	The conversion of land with healthy soil and intact habitats into areas for urban human settlements
water demand	The volume of water requested by users to satisfy their needs
urban grey and BG infrastructure (permeable pavements, attenuation tank, green roofs, swales, retention areas) implementation and maintenance	Development and functional preservation of grey and green measures
existing systems maintenance	The art of keeping existing systems in condition to fulfil adequately the purposes for which they were intended

BG public spaces maintenance	Set of activities necessary to keep blue and green public spaces in good condition and in full working order
sustainable urban development	The persecution of urban form that synthesises land development and nature preservation and places the protection of natural systems into a state of vital equipoise
flood risk monitoring and warning systems	Tools and systems supporting operate during the flooding event
local community engagement	The process of working collaboratively with and through groups of residents affiliated by interest or similar situations to address issues affecting their well-being

10.4. Workshop agenda of Thamesmead CLD causal structure validation and BOT graphs construction with stakeholders

Date: 9/09/2021
Time: 2h
Location: online, using Microsoft Teams
Aims

- To present the flood CLD
- To validate the general structure and specific elements
- To build the BOT of some key variables

TIME	ACTIVITY	OBJECTIVE
10 min	Welcome and introduction	Warm up for orientation and goal clarification
3 min	Flood CLD presentation	Presentation of the modelling process, prepare the participants for the next activities
47 min	Flood CLD validation (semi-structured interviews style)	To reach consensus over the model structure
5 min	BOT activities presentation	Activity clarification
30 min	BOT graphs construction (5 variables)	—
10 min	BOT presentation	To share BOT graphs cre-

		ated by each group
10 min	Evaluation Next steps and closing	—

10.5. List of the stakeholders involved in the first workshop

STAKEHOLDER	ORGANIZATION	ROLE
Stakeholder 1	Housing Association/Developers	Director
Stakeholder 2	Housing Association/Developers	Head of Landscape & Placemaking
Stakeholder 3	Local Authority	Flood Risk and Development Manager
Stakeholder 4	Environmental Non-Governmental Organisation	Senior Manager
Stakeholder 5	Company of consulting and engineering/ architectural design	Director
Stakeholder 6	Local Authority	Project Manager
Stakeholder 7	Local Authority	Manager of Operations

10.6. Short description of the main feedback loops

LOOP	DYNAMICS	INTERNAL VARIABLES	BEHAVIOUR MODE
B1	infrastructure damage	• residents' health • attractiveness of local area for residents • attractiveness of local area for investors • land consumption for building • impervious areas • green areas • soil retention capacity • surface runoff • urban stormwater system capacity • pluvial flood	oscillation

		• flood • infrastructure damage	
B2	public realm damage	• economic losses • impact on small business/families • attractiveness of local area for residents • housing demand • land consumption for building • impervious areas • green areas • soil retention capacity • surface runoff • urban stormwater system capacity • pluvial flood • flood • public realm damage	oscillation
B3	private properties damage	• economic losses • impact on small business/families • residents' awareness and preparedness to flood event • individual prevention measures • private properties damage	oscillation
B4	attractiveness of local area	• land consumption for building • impervious areas • green areas • biodiversity • quality of BG public spaces • use of BG public spaces • residents' health • attractiveness of local area for residents'	oscillation

		• attractiveness of local area for investors	
B5	quality of BG public spaces	• use of BG public spaces • biodiversity • quality of BG public spaces	oscillation
R	residents' health	• attractiveness of local area for residents • use of BG public spaces • residents' health	exponential growth/decline

10.7. Workshop agenda of Thamesmead SF model validation and scenarios design with stakeholders

Date: 27/10/2022
Time: 2h30
Location: online, using Microsoft Teams
Aims*:*

- To briefly present the flood risk SD simulation model
- To validate specific inputs/outputs of the model
- To show and discuss the developed future scenarios impacting key system elements
- To discuss other factors/measures that may contribute to future scenarios

TIME	ACTIVITY	OBJECTIVE
10 min	Welcome and introduction	Warm up for orientation and goals clarification
15 min	Flood simulation model presentation	• Summary of the modelling process • Presentation of the simulation model • Preparation of participants for the next activities
45 min	Validation of specific inputs/outputs of the model in the current condition (semi-structured interviews style)	To reach consensus over the model
40 min	Discussion on the developed future scenarios (semi-structured interviews style)	Reaching consensus on the developed future scenarios and their influencing factors/measures

TIME	ACTIVITY	OBJECTIVE
20 min	Design of possible other scenarios to be tested afterwards (semi-structured interviews style)	• Elicitation of stakeholders' ideas for scenarios to be tested that could include specific problem framing • Knowledge expansion
10 min	Evaluation Next steps and closing	—

10.8. List of the stakeholders involved in the second workshop

STAKEHOLDER	ORGANIZATION	ROLE
Stakeholder 1	Housing Association/Developers	Director
Stakeholder 2	Local Authority	Flood Risk and Development Manager
Stakeholder 3	Environmental Non-Governmental Organisation	Senior Manager
Stakeholder 4	Company of consulting and engineering/ architectural design	Director
Stakeholder 5	Company of consulting and engineering/ architectural design	Catchment Partnership Development Officer
Stakeholder 6	Local nature conservation charity	Conservation ecologist

10.9. Mathematical equations, initial values, and data sources behind the SF model

Initial Time 1 (01/01/2022)

Final Time 28835 (31/12/2100)

Time Step 1

Units for time Day

VARIABLE	VARIABLE TYPE	EQUATION OR VALUE	INTIAL /CONSTANT VALUE	DATA SOURCES
LAND CONSUMPTION SECTION				
RESIDENTIAL DENSITY GROWTH RATE DUE TO POPULATION GROWTH *(dwellings/(Day*ha))*	Lookup	[(1,0)-(22266,0.003)], (1,0),(1460,0.0028), (3285,0.0028), (5110,0.0028), (6935,0.0028), (8760,0.0028), (10950,0), (12775,0), (14600,0), (16425,0), (18250,0), (20075,0), (21900,0), (23725,0), (25550,0), (27375,0)		• Mulder, 2006 • Landcom, 2011 • Hall and Madden, 2018 • Peabody, 2021
fraction of residential density growth *(dwellings/(Day*ha))*	Auxiliary	RESIDENTIAL DENSITY GROWTH RATE DUE TO POPULATION GROWTH (Time)		
density of building development increase rate *(dwellings/(Day*ha))*	Inflow	fraction of population growth		• Landcom, 2011
Density of Building Development *(dwellings/ha)*	Stock	density of building development increase rate	20.7	• Hall and Madden, 2018
DENSITY APPROXIMATION FOR IMPERVIOUSNESS *(ha/dwellings)*	Constant		1	• Butler et al. 2018
STATISTICAL COEFFICIENT (Dmnl)	Constant		6.4	• Butler et al. 2018
percentage imperviousness (Dmnl)	Auxiliary	STATISTICAL COEFFICIENT*SQRT(Density of Building Development*DENSITY APPROXIMATION FOR IMPERVIOUSNESS)		• Butler et al. 2018

PERCENTAGE BASE VALUE (Dmnl)	Constant		100	
imperviousness coefficient (Dmnl)	Auxiliary	percentage imperviousness/PERCENTAGE BASE VALUE		
WATER BALANCE SECTION				
PRECIPITATION *(mm/Day)*	Data		Precipitation data	• Murphy et al. 2009 • Coxon et al. 2020 • https://nrfa.ceh.ac.uk/data/search
FULL IMPERVIOUSNESS COEFFICIENT *(Dmnl)*	Constant		1	• Lemaire et al. 2021
precipitation's pervious component *(mm/Day)*	Auxiliary	PRECIPITATION*(FULL IMPERVIOUSNESS COEFFICIENT-imperviousness coefficient)		• Lemaire et al. 2021
precipitations' impervious component *(mm/Day)*	Auxiliary	PRECIPITATION*imperviousness coefficient		• Lemaire et al. 2021
DESIGN SOIL WETNESS INDEX *(Dmnl)*	Constant		0.45	• Butler et al. 2018
infiltrating flow *(mm/Day)*	Auxiliary	precipitation's pervious component*(FULL IMPERVIOUSNESS COEFFICIENT-SOIL WETNESS INDEX)		• Lemaire et al. 2021
overland flow *(mm/Day)*	Auxiliary	precipitation's pervious component* SOIL WETNESS INDEX		• Lemaire et al. 2021
GROUNDWATER LEVEL SECTION				
EVAPOTRANSPIRATION *(mm/Day)*	Data		Evapotranspiration data	• Thompson, 2012 • Coxon et al. 2020 • https://nrfa.ceh.ac.uk/data/search

WATER PERCOLATING PERCENTAGE DUE TO GROUND TYPE *(mm/Day)*	Constant		0.5	• Jones et al. 2012 • Stàsko et al. 2012 • Brooks, 2013 • Butler et al. 2018
percolating flow *(mm/Day)*	Auxiliary	IF THEN ELSE(infiltrating flow>EVAPOTRANSPIRATION, (infiltrating flow-EVAPOTRANSPIRATION)*WATER PERCOLATING PERCENTAGE DUE TO GROUND TYPE , 0)		• Brooks, 2013
groundwater level increase rate *(mm/Day)*	Inflow	percolating flow		
Groundwater Level *(mm)*	Stock		29760	• Groundwater levels data from EA • EA, 2009 • PBA, 2017
LAG TIME OF CONTRIBUTION *(Day/Dmnl)*	Constant		12	• Winter et al. 1998
FRACTION OF BASEFLOW FROM GROUNDWATER *(Dmnl)*	Constant		0.00013	• https://nrfa.ceh.ac.uk/data/station/meanflow/39001 • Gustard et al. 1992 • Kelly et al. 2019
groundwater contribution to tidal river *(mm/Day)*	Auxiliary	(FRACTION OF BASEFLOW FROM GROUNDWATER*Tidal River Water Level)/LAG TIME OF CONTRIBUTION		• https://pubs.usgs.gov/circ/circ1186/html/gen_facts.html • https://www.usgs.gov/special-topics/water-science-school/science/rivers-contain-groundwater • http://www.columbia.edu/~vjd1/streams_basic.htm • Kelly et al. 2019

groundwater level decrease rate *(mm/Day)*	Ouflow	groundwater contribution to tidal river		
surface runoff due to soil moisture conditions *(mm/Day)*	Auxiliary	IF THEN ELSE(Groundwater Level>=GROUNDWATER THRESHOLD, percolating flow , 0)		
not percolating flow *(mm/Day)*		IF THEN ELSE(infiltrating flow>EVAPOTRANSPIRATION, infiltrating flow-EVAPOTRANSPIRATION-percolating flow , 0)		
PLUVIAL FLOOD SECTION				
surface runoff *(mm/Day)*	Auxiliary	precipitation's impervious component+not percolating flow+surface runoff due to soil moisture conditions+tidal river flood depth		
FRACTION OF SURFACE RUNOFF AVAILABLE FOR SURFACE SYSTEM *(Dmnl)*	Constant		0.474	• JBA, 2020
surface runoff to stormwater system *(mm/Day)*	Auxiliary	surface runoff*FRACTION OF SURFACE RUNOFF AVAILABLE FOR SEWERAGE SYSTEM		
STORMWATER SYSTEM AVAILABILITY AFFECTED BY AGEING/BLOCKAGE *(mm/Day)*	Lookup	[(0,0)-(22266,200)],(1,5),(3,104),(179,4.9),(181,103),(729,4.8),(731,97),(879,4.7),(881,95),(1094,4.6),(1096,94),(1244,4.5),(1246,92),(1460,4.4),(1462,90),(1609,4.3),(1701,89),(1824,4.2),(1826,86),(1974,4.1),(1976,85),(2189,4),(2191,83),(2339,3.9),(2341,81),(2554,3.8),(2556,79),(2704,3.7),(2706,78),(2919,3.6),(2921,76),(3069,3.5),(3071,74),(3284,3.4),(3286,72),(3434,3.3),(3436,71),(3649,3.2),(3651,68),(3799,3.1),(3801,67),(4014,3),(4016,65),(4164,2.9),(4166,63),(4379,2.8),(4381,61),(4529,2.7),		• JBA, 2020 • https://www.water-technology.net/projects/crossness-sewage-treatment-works-upgrade/Thamesmead Bexley Flooding Database.xls

		(4531,60),(4744,2.6),(4746,58),(4894,2.5),(4896,56),(5110,2.4),(5112,54),(5259,2.3),(5261,53),(5474,2.1),(5476,50),(5839,2),(5841,47),(5989,1.9),(5991,45),(6204,1.8),(6206,43),(6354,1.7),(6356,41),(6569,1.6),(6571,39),(6719,1.5),(6721,37),(6935,1.4),(6937,35),(7084,1.3),(7086,33),(7299,1.2),(7301,31),(7449,1.1),(7451,29),(7664,1),(7666,27),(7814,0.9),(7816,25),(8029,0.8),(8031,23),(8179,0.7),(8181,21),(8394,0.6),(8396,19),(8544,0.5),(8546,17),(8760,0),(8762,15),(8909,0),(8911,13),(9124,0),(9126,11),(9274,0),(9276,9),(9489,0),(9491,7),(9639,0),(9641,5),(9854,0),(9856,3),(10004,0),(10006,1),(10219,0),(10221,0),(10950,0),(12775,0),(14600,0),(16425,0),(18250,0),(20075,0),(21900,0),(23725,0),(25550,0),(27375,0)		
stormwater system capacity *(mm/Day)*	Auxiliary	STORMWATER SYSTEM AVAILABILITY AFFECTED BY AGEING/BLOCKAGE (Time)		
pluvial flood depth *(mm/Day)*	Auxiliary with Lookup	surface runoff to stormwater system-stormwater system capacity ([(-100,0)-(100,100)],(-70,0),(-60,0),(-50,0),(-40,0),(-30,0),(-20,0),(-10,0),(1,0),(0,0),(1,1),(10,10),(20,20),(30,30),(40,40),(50,50),(60,60),(70,70))		
stormwater to lakes and canals *(mm/Day)*	Auxiliary	IF THEN ELSE(pluvial flood depth=0, surface runoff to stormwater system , surface runoff to stormwater system-pluvial flood depth)		
DELAY IN STORMWATER DISCHARGE INTO LAKES AND CANALS	Constant		1	

(Day)				
delayed stormwater discharge into lakes and canals *(mm/Day)*	Auxiliary	DELAY1(stormwater to lakes and canals, DELAY IN STORMWATER DISCHARGE INTO LAKES AND CANALS)		
pluvial flood hazard index *(Dmnl)*	Auxiliary with Lookup	surface runoff to stormwater system-stormwater system capacity ([(0,0)-(19,10)],(-60,1),(-10,1.5),(0,1.5),(0.72,2),(4.32,2),(5.04,2),(14.4,2),(15.12,2.5),(16.2,2.5),(16.56,3),(18,3),(18.72,3))		- Tingsanchali and Promping, 2022
FLUVIAL FLOOD SECTION				
FRACTION OF SURFACE RUNOFF AVAILABLE FOR LAKES AND CANALS *(Dmnl)*	Constant		0.526	- JBA, 2020
surface runoff to lakes and canals *(mm/Day)*	Auxiliary	(surface runoff*FRACTION OF SURFACE RUNOFF AVAILABLE FOR LAKES AND CANALS)+pluvial flood depth+delayed stormwater discharge into lakes and canals		
THAMESMEAD AREA *(sqm)*	Constant		10.2	- Peabody, 2021
LAKES AREA *(sqm)*	Constant		7	- JBA, 2020
water in lakes *(mm/Day)*	Auxiliary	(LAKES AREA*surface runoff to lakes and canals)/THAMESMEAD AREA		
water in SUDS increase rate *(mm/Day)*	Inflow	water in lakes		
Water in SUDS *(mm)*	Stock	water in SUDS increase rate-water in SUDS decrease rate	0	- Peabody, 2021 - GLC Paper on Surface Water Drainage

				• URS Scott Wilson, 2012
water in canals *(mm/Day)*	Auxiliary	surface runoff to lakes and canals		
CANALS AVAILABILITY AFFECTED BY AGEING/BLOCKAGE *(mm/Day)*	Lookup	[(0,0)-(22266,20000)],(1,760),(1460,685),(3285,548),(5110,411),(6935,274),(8760,137),(10950,0),(12775,0),(14600,0),(16425,0),(18250,0),(20075,0),(21900,0),(23725,0),(25550,0),(27375,0)		• JBA, 2020 • Peabody, 2021 • GLC Paper on Surface Water Drainage • URS Scott Wilson, 2012
canals capacity *(mm/Day)*	Auxiliary	CANALS AVAILABILITY AFFECTED BY AGEING/BLOCKAGE (Time)		
canals flood depth *(mm/Day)*	Auxiliary with Lookup	canals capacity-water in canals ([(-995,0)-(100,1000)],(-995,995),(-650,650),(-595,595),(-400,400),(-300,300),(-250,250),(0,0),(100,0))		
canals flood hazard index *(Dmnl)*	Auxiliary with Lookup	water in canals-canals capacity ([(0,0)-(99,10)],(-300,1),(-200,1),(-100,1.5),(0,1.5),(3.8,2),(22.8,2),(26.6,2),(76,2),(79.8,2.5),(85.5,2.5),(87.4,3),(95,3),(98.8,3))		• Tingsanchali and Promping, 2022
PUMPS AVAILABILITY AFFECTED BY AGEING/BLOCKAGE *(mm/Day)*	Lookup	[(0,0)-(22266,5000)],(1,4450),(1460,4005),(3285,3560),(5110,3115),(6935,2670),(8760,2225),(10950,1780),(12775,1335),(14600,890),(16425,445),(18250,0),(20075,0),(21900,0),(23725,0),(25550,0),(27375,0)		• JBA, 2020
pumps capacity *(mm/Day)*	Auxiliary	PUMPS AVAILABILITY AFFECTED BY AGEING/BLOCKAGE (Time)		
THRESHOLD FOR PUMPS ACTIVATION *(mm)*	Constant		150	• GLC Paper on Surface Water Drainage

water to pumping stations *(mm/Day)*	Auxiliary	IF THEN ELSE(Water in SUDS>=THRESHOLD FOR PUMPS ACTIVATION, Water in SUDS/DAY , 0)		
pumped water *(mm/Day)*	Auxiliary	IF THEN ELSE(water to pumping stations<=pumps capacity, water to pumping stations , pumps capacity)		
SUDS THRESHOLD *(mm/Day)*	Constant		760	- GLC Paper on Surface Water Drainage
SUDS flood depth *(mm/Day)*	Auxiliary	IF THEN ELSE(water to pumping stations-pumped water>SUDS THRESHOLD, (water to pumping stations-pumped water-SUDS THRESHOLD), 0)		
SUDS flood hazard index *(Dmnl)*	Auxiliary with Lookup	(water to pumping stations-pumped water)-SUDS THRESHOLD ([(0,0)-(99,10)],(-300,1),(-200,1),(-100,1.5),(0,1.5),(3.8,2),(22.8,2),(26.6,2),(76,2),(79.8,2.5),(85.5,2.5),(87.4,3),(95,3),(98.8,3))		- Tingsanchali and Promping, 2022
fluvial flood hazard index (Dmnl)	Auxiliary	MAX(canals flood hazard index,SUDS flood hazard index)		
TIDAL RIVER FLOOD SECTION				
SEA LEVEL RISE *(mm/Day)*	Lookup	[(0,0)-(22266,10)],(1,0.01),(1825,0.01),(3650,0.01),(5475,0.023),(7300,0.023),(9125,0.023),(10950,0.023),(12775,0.023),(14965,0.023),(16790,0.023),(18615,0.03),(20440,0.03),(22266,0.03)		- EA, 2010
sea level increase rate *(mm/Day)*	Auxiliary	SEA LEVEL RISE (Time)		
tidal river increase rate *(mm/Day)*	Inflow	sea level increase rate		

tidal river inflow *(mm/Day)*	Inflow	delayed pumped water discharge into river+overland flow		
tidal river outflow *(mm/Day)*	Outflow	DELAY1(delayed pumped water discharge into river+overland flow, 1)		
Tidal River Water Level *(mm)*	Stock	tidal river increase rate+tidal river inflow-tidal river outflow	15000	• EA, 2010 • EA, 2012
TIDAL RIVER DEFENCES THRESHOLD AFFECTED BY AGEING *(mm)*	Lookup	[(0,0)-(22266,30000)],(1,18600),(1460,18400),(3285,18200),(5110,18000),(6935,17800),(8760,17600),(10950,17400),(12775,17200),(14600,17000),(16425,16800),(18250,16600),(20075,16400),(21900,16200),(23725,16000),(25550,15800),(27375,15600)		• https://www.gov.uk/government/publications/thames-estuary-2100-te2100/thames-estuary-2100-key-findings-from-the-monitoring-review • https://www.ice.org.uk/what-is-civil-engineering/what-do-civil-engineers-do/thames-barrier#:~:text=Construction%20began%20in%201974.,by%20the%20Queen%20in%201984.&text=The%20Thames%20Barrier%20is%20the,defence%20barrier%20in%20the%20world. • http://www.floodsite.net/html/cd_task17-19/thamesmead_embayment.html • https://www.constructex.co.uk/thamesmead-flood-wall • AECOM, 2017 • EA, 2012 • Peabody, 2021
tidal river defences effectiveness *(mm)*	Auxiliary	TIDAL RIVER DEFENCES THRESHOLD AFFECTED BY AGEING (Time)		

tidal river flood depth *(mm)*	Auxiliary	tidal river defences effectiveness-Tidal River Water Level ([(-8000,0)-(7000,8000)],(-5000,5000),(-4000,4000),(-3000,3000),(-2000,2000),(-1000,1000),(0,0),(1000,0),(2000,0),(3000,0),(4000,0),(5000,0))		
tidal river flood hazard index *(Dmnl)*	Auxiliary with Lookup	Tidal River Water Level-tidal river defences effectiveness ([(-3000,0)-(3000,10)],(-3000,1),(-2000,1),(-1000,1.5),(-500,1.5),(0,1.5),(200,2),(700,2),(600,2),(2100,2.5),(2250,2.5),(2300,3),(2500,3),(2600,3))		• Tingsanchali and Promping, 2022
FLOOD HAZARD SUB-MODEL				
PLUVIAL FLOOD WEIGHT *(Dmnl)*	Constant		0.3	
weighted pluvial flood hazard index *(Dmnl)*	Auxiliary	pluvial flood hazard index*PLUVIAL FLOOD WEIGHT		
TIDAL RIVER FLOOD DEPTH *(Dmnl)*	Constant		0.4	
weighted tidal river flood hazard index *(Dmnl)*	Auxiliary	TIDAL RIVER FLOOD WEIGHT*tidal river flood hazard index		
FLUVIAL FLOOD WEIGHT *(Dmnl)*	Constant		0.3	
weighted fluvial flood hazard index *(Dmnl)*	Auxiliary	FLUVIAL FLOOD WEIGHT*fluvial flood hazard index		

flood hazard index *(Dmnl)*	Auxiliary	weighted pluvial flood hazard index+weighted fluvial flood hazard index+weighted tidal river flood hazard index		- Tingsanchali and Promping, 2022
TANGIBLE DAMAGE EVALUATION SUB-MODEL				
buildings damage due to pluvial flooding *(euro/sqm)*	Auxiliary with Lookup	pluvial flood depth ([(0,0)-(6000,2000)], (0,0),(500,716.04),(1000,859),(1500,931),(2000,1002),(2500,1074),(3000,1217))		- Zhou et al. 2013
buildings damage due to fluvial flooding *(euro/sqm)*	Auxiliary with Lookup	fluvial flood depth ([(0,0)-(6000,2000)], (0,0),(500,716.04),(1000,859),(1500,931),(2000,1002),(2500,1074),(3000,1217))		- Zhou et al. 2013
buildings damage due to tidal river flooding *(euro/sqm)*	Auxiliary with Lookup	tidal river flood depth ([(0,0)-(6000,2000)], (0,0),(500,716.04),(1000,859),(1500,931),(2000,1002),(2500,1074),(3000,1217))		- Zhou et al. 2013
buildings damage due to flooding *(euro/sqm)*	Auxiliary	buildings damage due to pluvial flooding+ buildings damage due to fluvial flooding +buildings damage due to tidal river flooding		
buildings damage due to preparedness *(euro/sqm)*	Auxiliary	SIMULTANEOUS (buildings damage due to flooding-(effect of households' preparedness on damage*buildings damage due to flooding),1)		
residential buildings damage class *(Dmnl)*	Auxiliary with Lookup	buildings damage due to preparedness ([(0,0)-(11000,200)], (0,1),(108,1),(135,2),(271,2),(298,3))		- Tingsanchali and Promping, 2022

businesses damage due to pluvial flooding *(euro/sqm)*	Auxiliary with Lookup	pluvial flood depth ([(0,0)-(6000,2000)], (0,0),(500,572),(1000,1073),(1500,1359), (2000,1573),(3000,1717))		• Zhou et al. 2013
business damage due to fluvial flooding *(euro/sqm)*	Auxiliary with Lookup	fluvial flood depth ([(0,0)-(6000,2000)], (0,0),(500,572),(1000,1073),(1500,1359), (2000,1573),(3000,1717))		• Zhou et al. 2013
business damage due to tidal river flooding *(euro/sqm)*	Auxiliary with Lookup	tidal river flood depth ([(0,0)-(6000,2000)], (0,0),(500,572),(1000,1073),(1500,1359), (2000,1573),(3000,1717))		• Zhou et al. 2013
business damage due to flooding *(euro/sqm)*	Auxiliary	businesses damage due to pluvial flooding+businesses damage due to fluvial flooding +businesses damage due to tidal river flooding		
business damage class *(Dmnl)*	Auxiliary with Lookup	business damage due to flooding ([(0,0)-(11000,200)], (0,1),(108,1),(135,2),(271,2),(298,3))		• Tingsanchali and Promping, 2022
recreational facilities damage due to pluvial flooding *(euro/sqm)*	Auxiliary with Lookup	pluvial flood depth ([(0,0)-(3000,2000)], (0,0),(500,437),(1000,728),(1500,1020), (2000,1093),(2500,1166),(3000,1239))		• Zhou et al. 2013
recreational facilities damage due to fluvial flooding *(euro/sqm)*	Auxiliary with Lookup	fluvial flood depth ([(0,0)-(3000,2000)], (0,0),(500,437),(1000,728),(1500,1020), (2000,1093),(2500,1166),(3000,1239))		• Zhou et al. 2013

recreational facilities damage due to tidal river flooding *(euro/sqm)*	Auxiliary with Lookup	tidal river flood depth ([(0,0)-(3000,2000)], (0,0),(500,437),(1000,728),(1500,1020), (2000,1093),(2500,1166),(3000,1239)		• Zhou et al. 2013
recreational facilities damage due to flooding *(euro/sqm)*	Auxiliary	recreational facilities damage due to pluvial flooding+recreational facilities damage due to fluvial flooding +recreational facilities damage due to tidal river flooding		
recreational facilities damage class *(Dmnl)*	Auxiliary with Lookup	recreational facilities damage due to flooding ([(0,0)-(22,10)],(12,1),(13,2),(20,2),(22,3))		• Tingsanchali and Promping, 2022
transport services damage due to pluvial flooding *(euro/sqm)*	Auxiliary with Lookup	pluvial flood depth ([(0,0)-(3000,900)], (0,0),(500,291),(1000,437),(1500,583), (2000,655),(2500,728),(3000,801))		• Zhou et al. 2013
transport services damage due to fluvial flooding *(euro/sqm)*	Auxiliary with Lookup	fluvial flood depth ([(0,0)-(3000,900)], (0,0),(500,291),(1000,437),(1500,583), (2000,655),(2500,728),(3000,801))		• Zhou et al. 2013
transport services damage due to tidal river flooding *(euro/sqm)*	Auxiliary with Lookup	tidal river flood depth ([(0,0)-(3000,900)], (0,0),(500,291),(1000,437),(1500,583), (2000,655),(2500,728),(3000,801))		• Zhou et al. 2013
transport services damage due to flooding *(euro/sqm)*	Auxiliary	transport services damage due to pluvial flooding+transport services damage due to fluvial flooding +transport services damage due to tidal river flooding		

transport services damage class (Dmnl)	Auxiliary with Lookup	transport services damage due to flooding ([(0,0)-(20,10)],(12,1),(13,2),(14,3),(20,2))		• Tingsanchali and Promping, 2022
tangible damage class due to flooding *(Dmnl)*	Auxiliary	SIMULTANEOUS(MAX(businesses damage class, MAX(recreational facilities damage class, MAX(residential buildings damage class, transport services damage class)))),1)		
ECOSYSTEM QUALITY SECTION				
effect of damage on transport services *(Dmnl)*	Auxiliary with Lookup	transport services damage class ([(0,0)-(10,10)],(1,0),(2,0.5),(3,1))		
TRANSPORT SERVICES *(Dmnl)*	Lookup	[(0,0)-(22266,10)], (1,0.1),(1460,0.1),(3285,0.1),(5110,0.1), (6935,0.5),(8760,0.5),(10950,0.7),(12775,0.7), (14600,0.7),(16425,0.7),(18250,0.7), (20075,0.7),(21900,0.7),(23725,0.7), (25550,0.7),(27375,0.7)		• O’Keeffe et al. 2022
transport services over time *(Dmnl)*	Auxiliary	TRANSPORT SERVICES (Time)		
transport services due to damage *(Dmnl)*	Auxiliary	transport services over time-(effect of damage on transport services*transport services over time)		
effect of damage on facilities availability *(Dmnl)*	Auxiliary with Lookup	recreational facilities damage class ([(0,0)-(10,10)],(1,0),(2,0.5),(3,1))		
AVAILABILITY OF FACILITIES *(Dmnl)*	Constant		0.1	• O’Keeffe et al. 2022
availability of facilities due to damage *(Dmnl)*	Auxiliary	AVAILABILITY OF FACILITIES-(AVAILABILITY OF FACILITIES*effect of damage on facilities availability)		

PROXIMITY TO NATURAL SPACES *(Dmnl)*	Constant		0.5	• O’Keeffe et al. 2022
NUMBER OF VABIALES ON GREEN SPACES EXPERIENCE *(Dmnl)*	Constant		4	
green spaces experience *(Dmnl)*	Auxiliary	(Ecosystem Quality State+PROXIMITY TO NATURAL SPACES+availability of facilities due to damage+transport services due to damage)/NUMBER OF VABIALES ON GREEN SPACES EXPERIENCE		• O’Keeffe et al. 2022
Ecosystem Quality State *(Dmnl)*	Stock	ecosystem quality state increase rate-ecosystem quality state decrease rate	0.3	• Stakeholders’ BOT graphs (Workshop n.1)
effect of low flood depth on ecosystem quality *(Dmnl)*	Auxiliary with Lookup	flood hazard index ([[(0,0)-(10,10)],(2,0.5),(2.5,0),(3,0))		• Maher et al.2014
ecosystem quality state increase rate *(Dmnl/Day)*	Inflow	Ecosystem Quality State*effect of low flood depth on ecosystem quality/DAYS		
effect of high flood depth on ecosystem quality *(Dmnl)*	Auxiliary with Lookup	flood hazard index ([[(0,0)-(10,10)],(2,0),(2.5,0),(3,0.53))		• Talbot et al. 2018 • Zhang et al. 2021 • Peabody, 2021
effect of imperviousness on ecosystem quality *(Dmnl)*	Auxiliary with Lookup	Imperviousness coefficient ([[(0,0)-(10,10)],(0.2,0),(0.4,0),(0.6,0.25),(0.8,0.5),(1,0.75))		• Yan et al. 2019 • O’Keeffe et al. 2022

ecosystem quality state decrease rate *(Dmnl/Day)*	Outflow	(Ecosystem Quality State*effect of imperviousness on ecosystem quality/DAYS)+(Ecosystem Quality State *effect of high flood depth on ecosystem quality /DAYS)+(Ecosystem Quality State*green spaces experience/DAYS)		
COMMUNITY FLOOD RISK PERCEPTION SECTION				
INFORMATION SYSTEMS EFFECTIVENESS CLASS *(Dmnl)*	Constant		1	• Stakeholders’ individual interviews
INFORMATION SYSTEMS EFFECTIVENESS WEIGHT IN PERCEPTION *(Dmnl)*	Constant		0.1	
information systems effectiveness class in perception *(Dmnl)*	Auxiliary	INFORMATION SYSTEMS EFFECTIVENESS CLASS*INFORMATION SYSTEMS EFFECTIVENESS WEIGHT IN PERCEPTION		
CITIZENS' INVOLVEMENT CLASS *(Dmnl)*	Constant		1	• Stakeholders’ individual interviews
DELAY IN CITIZENS' INVOLVEMENT *(Day)*	Constant		365	
CITIZENS' INVOLVEMENT WEIGHT *(Dmnl)*	Constant		0.35	
local community engagement class *(Dmnl)*	Auxiliary	DELAY1(CITIZENS' INVOLVEMENT CLASS*CITIZENS' INVOLVEMENT WEIGHT, DELAY IN CITIZENS' INVOLVEMENT)		

FLOOD MONITORING AND WARNING SYSTEMS EFFECTIVENESS CLASS *(Dmnl)*	Constant		2	- Stakeholders' individual interviews
FLOOD MONITORING AND WARNING SYSTEMS EFFECTIVENESS WEIGHT IN PERCEPTION *(Dmnl)*	Constant		0.1	
monitoring and warning systems effectiveness class in perception *(Dmnl)*	Auxiliary	FLOOD MONITORING AND WARNING SYSTEMS EFFECTIVENESS CLASS*FLOOD MONITORING AND WARNING SYSTEMS EFFECTIVENESS WEIGHT IN PERCEPTION		
DAMAGE DUE TO FLOODING WEIGHT IN PERCEPTION *(Dmnl)*	Constant		0.35	
COMMUNITY SENSE OF SAFETY CLAS *(Dmnl)*	Constant		1	- Stakeholders' individual interviews
COMMUNITY SENSE OF SAFETY WEIGHT IN PERCEPTION *(Dmnl)*	Constant		0.1	
community sense of safety class in perception *(Dmnl)*	Auxiliary	COMMUNITY SENSE OF SAFETY CLASS*COMMUNITY SENSE OF SAFETY WEIGHT IN PERCEPTION		
Community Flood Risk Perception *(Dmnl)*	Stock	community perception increase rate-community perception decrease rate	1	- Bradford et al. 2012 - Lechowska, 2018

community perception increase rate *(Dmnl/Day)*	Inflow	(damage class due to flooding in perception+local community engagement class+monitoring and warning systems effectiveness class in perception+information systems effectiveness class in perception)/DAYS		
community perception decrease rate *(Dmnl/Day)*	Outflow	community sense of safety class in perception/DAYS		
COMMUNITY FLOOD RISK PERCEPTION WEIGHT IN PREPAREDNESS *(Dmnl)*	Constant		0.6	• Cologna et al. 2017 • Papagiannaki et al. 2019 • Liu et al. 2022
community flood risk perception in preparedness *(Dmnl)*	Auxiliary	Community Flood Risk Perception*COMMUNITY FLOOD RISK PERCEPTION WEIGHT IN PREPAREDNESS		
DAMAGE DUE TO FLOODING WEIGHT IN PREPAREDNESS *(Dmnl)*	Constant		0.3	• Cologna et al. 2017 • Papagiannaki et al. 2019 • Liu et al. 2022
COMMUNITY SENSE OF SAFETY WEIGHT IN PREPAREDNESS *(Dmnl)*	Constant		0.1	• Cologna et al. 2017 • Papagiannaki et al. 2019 • Liu et al. 2022
community sense of safety class in preparedness *(Dmnl)*	Auxiliary	COMMUNITY SENSE OF SAFETY CLASS*COMMUNITY SENSE OF SAFETY WEIGHT IN PREPAREDNESS		
class of preparedness towards flooding *(Dmnl)*	Auxilary	SIMULTANEOUS(community flood risk perception in preparedness+community sense of safety class in preparedness+damage class due to flooding in preparedness,1)		

effect of households' preparedness on damage *(Dmnl)*	Auxiliary with Lookup	class of preparedness towards flooding ([(0,0)-(10,10)], (1,0),(1.5,0.075),(2,0.15),(2.5,0.225),(3,0.3))		- Messner and Meyer, 2006
RESIDENTS' WELL-BEING SECTION				
effect of ecosystem quality on residents' well-being *(Dmnl)*	Auxiliary	IF THEN ELSE(Ecosystem Quality State>ECOSYSTEM QUALITY STATE INITIAL VALUE, 0.15 , 0)		- Bratman et al. 2019 - Salvia et al. 2022
effect of green spaces experience on well-being *(Dmnl)*	Auxiliary with Lookup	green spaces experience ([(0,0)-(10,10)],(0,0),(0.5,0.5),(1,1))		- Bratman et al. 2019 - Salvia et al. 2022
effect of attractiveness on residents' well-being *(Dmnl)*	Auxiliary with Lookup	Attractiveness for Companies ([(0,0)-(10,10)],(0.1,0.15),(0.5,0.25),(1,0.5))		
Residents' Well-Being *(Dmnl)*	Stock	well-being increase rate - well-being decrease rate	0.25	- Stakeholders' BOT graphs (Workshop n.1)
well-being increase rate *(Dmnl/Day)*	Inflow	IF THEN ELSE(Attractiveness for Companies>ATTRACTIVENESS FOR COMPANIES INITIAL VALUE, (effect of attractiveness on residents' well-being *Residents' Well-Being /DAYS)+(effect of green spaces experience on well-being *Residents' Well-Being)/DAYS+(effect of ecosystem quality on residents' well-being*Residents' Well-Being)/DAYS, (effect of green spaces experience on well-being *Residents' Well-Being)/DAYS)+(effect of ecosystem quality on residents' well-being*Residents' Well-Being)/DAYS		- Bratman et al. 2019

effect of flood hazard on well-being *(Dmnl)*	Auxiliary with Lookup	flood hazard index ([[(0,0)-(10,10)],(1,0),(2,0),(2.5, 0.17),(3,0.25))		- Foudi et al. 2017
effect of flood perception on well-being *(Dmnl)*	Auxiliary with Lookup	Community Flood Risk Perception ([[(0,0)-(10,10)],(1,0.29),(2,0.23),(3,0.18))		- Foudi et al. 2017
effect of damage on well-being *(Dmnl)*	Auxiliary with Lookup	tangible damage class due to flooding ([[(0,0)-(10,10)],(1,0.19),(2,0.25),(3,0.32))		- Foudi et al. 2017
well-being decrease rate *(Dmnl/Day)*		(Residents' Well-Being*effect of flood hazard on well-being/DAYS)+(Residents' Well-Being*effect of damage on well-being /DAYS)+(Residents' Well-Being*effect of flood perception on well-being/DAYS)		- Foudi et al. 2017 - French et al. 2019 - Lee et al. 2020 - Robin et al. 2020
ATTRACTIVENESS FOR COMPANIES SECTION				
effect of ecosystem quality on attractiveness *(Dmnl)*	Auxiliary	IF THEN ELSE(Ecosystem Quality State>ECOSYSTEM QUALITY STATE INITIAL VALUE, 0.15 , 0)		- https://www.wur.nl/en/show-longread/Seven-Reasons-to-Invest-in-a-Green-City.htm - The Land Trust, 2018
effect of residents' well-being on attractiveness *(Dmnl)*	Auxiliary	IF THEN ELSE("Residents' Well-Being">"RESIDENTS' WELL-BEING INITIAL VALUE", 0.15 , 0)		- Frumkin,2003 - Bond et al. 2012
effect of damage on attractiveness *(Dmnl)*	Auxiliary with Lookup	tangible damage class due to flooding ([[(0,0)-(10,10)],(1,0),(2,0.5),(3,1))		- Bond et al. 2012
ATTRACTIVENESS FOR COMPANIES INITIAL VALUE *(Dmnl)*	Constant		0.5	- Stakeholders’ BOT graphs (Workshop n.1)

Attractiveness for Companies *(Dmnl)*		attractiveness for companies increase rate-attractiveness for companies decrease rate		
attractiveness for companies increase rate *(Dmnl/Day)*	Inflow	(effect of ecosystem quality on attractiveness*Attractiveness for Companies /DAYS)+("effect of residents' well-being on attractiveness"*Attractiveness for Companies/DAYS)		
attractiveness for companies decrease rate *(Dmnl/Day)*	Outflow	effect of damage on attractiveness*Attractiveness for Companies/DAYS		
FLOOD EXPOSURE SECTION				
BUILDINGS MATERIAL CATEGORY *(Dmnl)*	Lookup	[(0,0)-(22266,10)], (1,2),(1460,2),(3285,2),(5110,2),(6935,3), (8760,3),(10950,3),(12775,3),(14600,3), (16425,3),(18250,3),(20075,3),(21900,3), (23725,3),(25550,3),(27375,3)		• Hall and Madden, 2018 • Validation workshop with stakeholders (Workshop n.2)
buildings material class *(Dmnl)*	Auxiliary	BUILDINGS MATERIAL CATEGORY (Time)		
EARNINGS GROWTH RATE *(Dmnl)*	Lookup	[(0,0)-(22266,10)], (1,0.008),(1460,0.008),(3285,0.008), (5110,0.008),(6935,0.008),(8760,0.008), (10950,0.008),(12775,0.008),(14600,0.008), (16425,0.008),(18250,0.008),(20075,0.008), (21900,0.008),(23725,0.008),(25550,0.008), (27375,0.008)		• Hall and Madden, 2018
HOUSE PRICES CHANGE RATE DUE TO REGENERATION AND POPULATION GROWTH *(Dmnl)*	Lookup	[(0,0)-(14965,10)], (1,0.015),(1460,0.057),(3285,0.05), (5110,0.043),(6935,0.035),(8760,0.028), (10950,0.015), (12775,0.062), (14600,0.06), (16425,0.057),(18250,0.055),(20075,0.05), (21900,0.048),(23725,0.042),(25550,0.038), (27375,0.032)		• Miles,2012 • Hall and Madden, 2018 • Peabody,2021 • https://www.investopedia.com /ask/answers/040215/how-does-law-supply-and-demand-

				affect-housing-market.asp#:~:text=The%20housing%20market%20is%20a,less%20demand%20in%20the%20market. - https://www.economicshelp.org/blog/377/housing/factors-that-affect-the-housing-market/ - https://pearsonblog.campaignserver.co.uk/supply-and-demand-the-housing-market/
housing affordability *(Dmnl)*	Auxiliary	HOUSE PRICES CHANGE RATE DUE TO REGENERATION AND POPULATION GROWTH(Time)/EARNINGS GROWTH RATE (Time)		- https://www.thesundaily.my/business/the-problem-of-measuring-housing-affordability-based-on-price-to-income-ratio-BC8730737
housing affordability class *(Dmnl)*	Auxiliary	housing affordability ([(0,0)-(10,10)] ,(1,3),(2,3),(3,3),(3.1,2),(4,2),(4.1,1),(5,1),(6,1))		- https://www.thesundaily.my/business/the-problem-of-measuring-housing-affordability-based-on-price-to-income-ratio-BC8730737
AVERAGE HOUSE AREA *(sqm)*	Constant		80	- https://www.zoopla.co.uk/for-sale/property/thamesmead/ - https://www.designingbuildings.co.uk/wiki/Minimum_space_standards
space standard class *(Dmnl)*	Auxiliary with Lookup	AVERAGE HOUSE AREA ([(0,0)-(150,10)], (37,1),(49,1),(50,2),(99,2),(100,3),(150,3))		- https://www.designingbuildings.co.uk/wiki/Minimum_space_standards

CAR PARKING SPACE CLASS *(Dmnl)*	Constant		2	• O’Keeffe et al.2022
population density class *(Dmnl)*	Auxiliary with Lookup	Density of Building Development ([(0,0)-(100,10)], (5,1),(10,1),(20,2),(30,2),(40,3),(100,3))		• Landcom, 2011
building quality class *(Dmnl)*	Auxiliary	IF THEN ELSE(buildings material class=1:AND:space standard class=1:AND:population density class=3:AND:CAR PARKING SPACE CLASS =1:AND:housing affordability class=1, 1 , buildings material class)		• Nasiri et al. 2017
SERVICES QUALITY CATEGORY *(Dmnl)*	Constant	[(0,0)-(22266,10)], (1,1),(1460,1),(3285,1),(5110,1),(6935,2),(8760,2),(10950,2),(12775,2),(14600,2),(16425,2),(18250,2),(20075,2),(21900,2),(23725,2),(25550,2),(27375,2)		• Peabody, 2021
services quality class *(Dmnl)*	Auxiliary	SERVICES QUALITY CATEGORY (Time)		
INFRASTRUCTURE QUALITY CATEGORY *(Dmnl)*	Lookup	[(0,0)-(22266,10)], (1,1),(1460,1),(3285,1),(5110,1),(6935,2),(8760,2),(10950,2),(12775,2),(14600,2),(16425,2),(18250,2),(20075,2),(21900,2),(23725,2),(25550,2),(27375,2)		• Peabody, 2021
infrastructure quality class *(Dmnl)*	Auxiliary	INFRASTRUCTURE QUALITY CATEGORY (Time)		
built environment quality class	Auxiliary	(buildings quality class+infrastructure quality class+services quality class)/3		
effect of built environment quality on flood exposure *(Dmnl)*	Auxiliary with Lookup	built environment quality class ([(0,0)-(10,10)],(1,3),(2,2),(3,1))		

BUILT ENVIRONMENT QUALITY WEIGHT *(Dmnl)*	Constant		0.4	
PROXIMITY TO FLOOD SOURCES CLASS *(Dmnl)*	Constant		2	• Kissi et al. 2015 • Ntajal et al. 2016 • Tingsanchali and Promping, 2022 • Hamidi et al. 2022
PROXIMITY TO FLOOD SOUCES WEIGHT *(Dmnl)*	Constant		0.4	
LAND USE TYPE CLASS *(Dmnl)*	Constant		2	• Tingsanchali and Promping, 2022
LAND USE TYPE WEIGHT *(Dmnl)*	Constant		0.2	
flood exposure factor *(Dmnl)*	Auxiliary	(effect of built environment quality on flood exposure*BUILT ENVIRONMENT QUALITY WEIGHT)+(PROXIMITY TO FLOOD SOURCES CLASS*PROXIMITY TO FLOOD SOURCES WEIGHT)+(LAND USE TYPE CLASS*LAND USE TYPE WEIGHT)		• Kissi et al. 2015 • Ntajal et al. 2016 • Nasiri et al. 2017 • Babanawo et al. 2022 • Hamidi et al. 2022 • Tingsanchali and Promping, 2022
FLOOD SUSCEPTIBILITY SECTION				
FAMILIES SIZE *(members)*	Constant		3	• https://www.zoopla.co.uk/for-sale/property/thamesmead/
FAMILIES SIZE WEIGHT *(Dmnl)*	Constant		0.15	

CRITICAL INFRASTRUCTURE PRESENCE CLASS *(Dmnl)*	Constant		2	• EA,2012 • Salvia et al. 2022
CRITICAL INFRASTRUCTURE PRESENCE WEIGHT *(Dmnl)*	Constant		0.15	
residents' well-being class in susceptibility *(Dmnl)*	Auxiliary with Lookup	Residents’ Well-Being ([(0,0)-(10,10)], (0,3),(0.3,3),(0.4,2),(0.5,2),(0.6,2),(0.7,1),(1,1))		
RESIDENTS' WELL-BEING WEIGHT *(Dmnl)*	Constant		0.15	
community flood risk perception class in susceptibility *(Dmnl)*	Auxiliary with Lookup	Community Flood Risk Perception ([(0,0)-(10,10)],(1,3),(2,2),(3,1))		
COMMUNITY FLOOD RISK PERCEPTION WEIGHT *(Dmnl)*	Constant		0.15	
ELDERLY AND CHILDREN CLASS *(Dmnl)*	Constant		1	• Ntajal et al. 2016 • https://www.postcodearea.co.uk/postaltowns/london/se280hs/demographics/
ELDERLY AND CHILDREN WEIGHT (Dmnl)	Constant		0.15	

flood susceptibility factor *(Dmnl)*	Auxiliary	(community flood risk perception class in susceptibility*COMMUNITY FLOOD RISK PERCEPTION WEIGHT)+(CRITICAL INFRASTRUCTURE PRESENCE CLASS *CRITICAL INFRASTRUCTURE PRESENCE WEIGHT)+(ELDERLY AND CHILDREN CLASS*ELDERLY AND CHILDREN WEIGHT)+(families size class*FAMILIES SIZE WEIGHT)+(residents' well-being class in susceptibility*RESIDENTS' WELL-BEING WEIGHT)		• Kissi et al. 2015 • Ntajal et al. 2016 • Nasiri et al. 2017 • Babanawo et al. 2022 • Hamidi et al. 2022 Tingsanchali and Promping, 2022
FLOOD ADAPTIVE CAPACITY SECTION				
delayed citizens' involvement class *(Dmnl)*	Auxiliary	DELAY1(CITIZENS' INVOLVEMENT CLASS, DELAY IN CITIZENS' INVOLVEMENT)		
DRAINAGE SYSTEMS CHARACTERISTICS CLASS *(Dmnl)*	Constant		3	
DRAINAGE SYSTEMS CHARACTERISTICS WEIGHT *(Dmnl)*			0.1	
INSTITUTIONAL CAPACITY TO COPE WITH FLOODING *(Dmnl)*	Lookup	[(0,0)-(27375,10)], (1,2),(1460,2),(3285,2),(5110,2),(6935,2), (8760,2),(10950,2),(12775,2),(14600,2), (16425,2),(18250,2),(20075,2),(21900,2), (23725,2),(25550,2),(27375,2)		• Peabody, 2021
institutional capacity to cope with flooding over time *(Dmnl)*	Auxiliary	INSTITUTIONAL CAPACITY TO COPE WITH FLOODING (Time)		

HOUSEHOLDERS EDUCATION CLASS *(Dmnl)*	Constant		1	• Tingsanchali and Promping, 2022 • https://www.postcodearea.co.uk/postaltowns/london/se280hs/demographics/
WEIGHT OF FLOOD ADAPTIVE CAPACITY COMPONENTS *(Dmnl)*	Constant		0.15	
flood adaptive capacity factor *(Dmnl)*	Auxiliary	(class of preparedness towards flooding+delayed citizens' involvement class +FLOOD MONITORING AND WARNING SYSTEMS EFFECTIVENESS CLASS+HOUSEHOLDERS EDUCATION CLASS +INFORMATION SYSTEMS EFFECTIVENESS CLASS+institutional capacity to cope with flooding over time)*WEIGHT OF FLOOD ADAPTIVE CAPACITY COMPONENTS+(DRAINAGE SYSTEMS CHARACTERISTICS CLASS*DRAINAGE SYSTEMS CHARACTERISTICS WEIGHT)		• Kissi et al. 2015 • Ntajal et al. 2016 • Nasiri et al. 2017 • Babanawo et al. 2022 • Hamidi et al. 2022 • Tingsanchali and Promping, 2022
FLOOD VULNERABILITY SUB-MODEL				
EXPOSURE FACTOR WEIGHT *(Dmnl)*	Constant		0.63	• Tingsanchali and Promping, 2022
SUSCEPTIBILITY FACTOR WEIGHT *(Dmnl)*	Constant		0.26	• Tingsanchali and Promping, 2022
ADAPTIVE CAPACITY FACTOR WEIGHT *(Dmnl)*	Constant		0.11	• Tingsanchali and Promping, 2022

flood vulnerability index *(Dmnl)*	Auxiliary	EXPOSURE FACTOR WEIGHT*flood exposure factor+SUSCEPTIBILITY FACTOR WEIGHT*flood susceptibility factor-ADAPTIVE CAPACITY FACTOR WEIGHT *flood adaptive capacity factor		• Kissi et al. 2015 • Ntajal et al. 2016 • Nasiri et al. 2017 • Babanawo et al. 2022 • Hamidi et al. 2022 • Tingsanchali and Promping, 2022
FLOOD RISK ASSESSMENT SUB-MODEL				
flood risk index *(Dmnl)*	Auxiliary	flood hazard index*flood vulnerability index		• Kissi et al. 2015 • Ntajal et al. 2016 • Nasiri et al. 2017 • Babanawo et al. 2022 • Hamidi et al. 2022 • Tingsanchali and Promping, 2022
global flood risk index *(Dmnl)*	Auxiliary with Lookup	flood risk index ([(0,0)-(25,10)], (1,1),(5,2),(10,2),(15,2),(20,3),(25,3))		
URBAN FLOOD RESILIENCE SECTION				
effect of residents' well-being on urban flood resilience *(Dmnl)*	Auxiliary with Lookup	Residents' Well-Being ([(0,0)-(10,10)],(0,1),(0.5,2),(1,3))		• Cutter et al. 2008 • Cutter et al. 2010 • Verrucci et al. 2012 • Batica et al. 2013 • Cutter et al. 2014 • Joerin et al. 2014 • Rockefeller, 2015 • Figureido et al. 2018 • Moghadas et al. 2019 • Feofilovs et al. 2020 • Satour et al. 2021 • Marasco et al. 2022

population characteristics *(Dmnl)*	Auxiliary with Lookup	ELDERLY AND CHILDREN CLASS ([(0,0)-(10,10)],(1,3),(2,2),(3,1))		• Cutter et al. 2008 • Cutter et al. 2010 • Verrucci et al. 2012 • Batica et al. 2013 • Cutter et al. 2014 • Joerin et al. 2014 • Rockefeller, 2015 • Figureido et al. 2018 • Moghadas et al. 2019 • Feofilovs et al. 2020 • Satour et al. 2021 • Marasco et al. 2022
effect of risk perception on urban resilience *(Dmnl)*	Auxiliary with Lookup	Community Flood Risk Perception ([(0,0)-(10,10)],(0,1),(0.5,2),(1,3))		• Cutter et al. 2008 • Cutter et al. 2010 • Verrucci et al. 2012 • Batica et al. 2013 • Cutter et al. 2014 • Joerin et al. 2014 • Rockefeller, 2015 • Figureido et al. 2018 • Moghadas et al. 2019 • Feofilovs et al. 2020 • Satour et al. 2021 • Marasco et al. 2022
effect of imperviousness on urban flood resilience *(Dmnl)*	Auxiliary with Lookup	imperviousness coefficient ([(0,0)-(10,10)],(0,3),(0.5,2),(1,1))		• Cutter et al. 2008 • Cutter et al. 2010 • Verrucci et al. 2012 • Batica et al. 2013 • Cutter et al. 2014 • Joerin et al. 2014 • Rockefeller, 2015 • Figureido et al. 2018 • Moghadas et al. 2019

				• Feofilovs et al. 2020 • Satour et al. 2021 • Marasco et al. 2022
effect of attractiveness on urban flood resilience *(Dmnl)*	Auxiliary with Lookup	Attractiveness for Companies ([(0,0)-(10,10)],(0,1),(0.5,2),(1,3))		• Cutter et al. 2008 • Cutter et al. 2010 • Verrucci et al. 2012 • Batica et al. 2013 • Cutter et al. 2014 • Joerin et al. 2014 • Rockefeller, 2015 • Figureido et al. 2018 • Moghadas et al. 2019 • Feofilovs et al. 2020 • Satour et al. 2021 • Marasco et al. 2022
effect of ecosystem quality state on urban flood resilience *(Dmnl)*	Auxiliary with Lookup	Ecosystem Quality State ([(0,0)-(10,10)],(0,1),(0.5,2),(1,3))		• Cutter et al. 2008 • Cutter et al. 2010 • Verrucci et al. 2012 • Batica et al. 2013 • Cutter et al. 2014 • Joerin et al. 2014 • Rockefeller, 2015 • Figureido et al. 2018 • Moghadas et al. 2019 • Feofilovs et al. 2020 • Satour et al. 2021 • Marasco et al. 2022
flood mitigation infrastructure effectiveness *(Dmnl)*	Auxiliary with Lookup	flood hazard index ([(0,0)-(10,10)],(1,3),(2,2),(3,1))		• Cutter et al. 2008 • Cutter et al. 2010 • Verrucci et al. 2012 • Batica et al. 2013 • Cutter et al. 2014 • Joerin et al. 2014

				Rockefeller, 2015 Figureido et al. 2018 Moghadas et al. 2019 Feofilovs et al. 2020 Satour et al. 2021 Marasco et al. 2022
urban performance index *(Dmnl)*	Auxiliary	(built environment quality class+ CRITICAL INFRASTRUCTURE PRESENCE CLASS+ effect of attractiveness on urban flood resilience+ effect of ecosystem quality state on urban flood resilience + population characteristics+ effect of imperviousness on urban flood resilience+ effect of residents' well-being on urban flood resilience +effect of risk perception on urban resilience+ institutional capacity to cope with flooding over time+ flood mitigation infrastructure effectiveness) *WEIGHT OF URBAN FLOOD RESILIENCE COMPONTENTS		Cutter et al. 2008 Cutter et al. 2010 Verrucci et al. 2012 Batica et al. 2013 Cutter et al. 2014 Joerin et al. 2014 Rockefeller, 2015 Figureido et al. 2018 Moghadas et al. 2019 Feofilovs et al. 2020 Satour et al. 2021 Marasco et al. 2022

10.10. Changed variables in the modelled scenarios

Stormwater system capacity *(mm/Day)*	[(0,0)-(22266,200)],(1,5),(3,104),(179,4.9),(181,103),(729,4.8),(731,97),(879,4.7),(881,95),(1094,4.6),(1096,94),(1244,4.5),(1246,92),(1460,4.4),(1462,90),(1609,4.3),(1701,89),(1824,4.2),(1826,86),(1974,4.1),(1976,85),(2189,4),(2191,83),(2339,3.9),(2341,81),(2554,3.8),(2556,79),(2704,3.7),(2706,78),(2919,3.6),(2921,76),(3069,3.5),(3071,74),(3284,3.4),(3286,72),(3434,3.3),(3436,71),(3649,3.2),(3651,68),(3799,3.1),(3801,67),(4014,3),(4016,65),(4164,2.9),(4166,63),(4379,2.8),(4381,61),(4529,2.7),(4531,60),(4744,2.6),(4746,58),(4894,2.5),(4896,56),(5110,2.4),(5112,54),(5259,2.3),(5261,53),(5474,2.1),(5476,50),(5839,2),(5841,47),(5989,1.9),(5991,45),(6204,1.8),(6206,43),(6354,1.7),(6356,41),(6569,1.6),(6571,39),(6719,1.5),(6721,37),(6935,1.4),(6937,35),(7084,1.3),(7086,33),(7299,1.2),(7301,31),(7449,1.1),(7451,29),(76	[(0,0)-(22266,200)],(1,5),(3,104),(179,4.9),(181,103),(729,4.8),(731,97),(879,4.7),(881,95),(1094,4.6),(1096,94),(1244,4.5),(1246,92),(1460,4.4),(1462,90),(1609,4.3),(1701,89),(1824,4.2),(1826,86),(1974,4.1),(1976,85),(2189,4),(2191,83),(2339,3.9),(2341,81),(2554,3.8),(2556,79),(2704,3.7),(2706,78),(2919,3.6),(2921,76),(3069,3.5),(3071,74),(3284,3.4),(3286,72),(3434,3.3),(3436,71),(3649,3.2),(3651,68),(3799,3.1),(3801,67),(4014,3),(4016,65),(4164,2.9),(4166,63),(4379,2.8),(4381,61),(4529,2.7),(4531,60),(4744,2.6),(4746,58),(4894,2.5),(4896,56),(5110,2.4),(5112,54),(5259,2.3),(5261,53),(5474,2.2),(5476,50),(5839,2.1),(5841,47),(5989,2),(5991,45),(6204,1.9),(6206,43),(6354,1.8),(6356,41),(6569,1.7),(6571,39),(6719,1.6),(6721,37),(6935,1.5),(6937,35),(7084,1.4),(7086,33),(7299,1.3),(7301,31),(7449,1.2),(7451,29),(7664,1.1),(7666,27),(7814,1),(7816,25),(8029,0.9),(8031,2	[(0,0)-(22266,200)],(1,5),(3,104),(179,4.9),(181,103),(729,4.8),(731,97),(879,4.7),(881,95),(1094,4.6),(1096,94),(1244,4.5),(1246,92),(1460,4.4),(1462,90),(1609,4.3),(1701,89),(1824,4.2),(1826,86),(1974,4.1),(1976,85),(2189,4),(2191,83),(2339,3.9),(2341,81),(2554,3.8),(2556,79),(2704,3.7),(2706,78),(2919,3.6),(2921,76),(3069,3.5),(3071,74),(3284,3.4),(3286,72),(5110,62),(6935,52),(8760,42),(10950,32),(12775,22),(14600,12),(16425,0),(18250,0),(20075,0),(21900,0),(23725,0),(25550,0),(27375,0)	[(0,0)-(22266,200)],(1,5),(3,104),(179,4.9),(181,103),(729,4.8),(731,97),(879,4.7),(881,95),(1094,4.6),(1096,94),(1244,4.5),(1246,92),(1460,4.4),(1462,90),(1609,4.3),(1701,89),(1824,4.2),(1826,86),(1974,4.1),(1976,85),(2189,4),(2191,83),(2339,3.9),(2341,81),(2554,3.8),(2556,79),(2704,3.7),(2706,78),(2919,3.6),(2921,76),(3069,3.5),(3071,74),(3284,3.4),(3286,65),(5110,56),(6935,48),(8760,38),(10950,29),(12775,20),(14600,11),(16425,0),(18250,0),(20075,0),(21900,0),(23725,0),(25550,0),(27375,0)

	64,1),(7666,27),(7814,0.9),(7816,25),(8029,0.8),(8031,23),(8179,0.7),(8181,21),(8394,0.6),(8396,19),(8544,0.5),(8546,17),(8760,0),(8762,15),(8909,0),(8911,13),(9124,0),(9126,11),(9274,0),(9276,9),(9489,0),(9491,7),(9639,0),(9641,5),(9854,0),(9856,3),(10004,0),(10006,1),(10219,0),(10221,0),(10950,0),(12775,0),(14600,0),(16425,0),(18250,0),(20075,0),(21900,0),(23725,0),(25550,0),(27375,0)	3),(8179,0.8),(8181,21),(8394,0.7),(8396,19),(8544,0.6),(8546,17),(8760,144),(10031,6.5),(10033,131),(10259,6.4),(10261,129),(10585,126),(10899,6.3),(10901,123),(11122,6.2),(11124,121),(11300,6.1),(11302,119),(11519,6),(11521,117),(11657,5.9),(11659,115),(11683,5.8),(11685,115),(11694,5.7),(11696,115),(11698,5.6),(11700,115),(11736,5.5),(11738,115),(12045,5.4),(12047,112),(12225,5.3),(12227,110),(12410,5.2),(12412,108),(12590,5.1),(12592,106),(12775,5),(12777,104),(12955,4.9),(12957,103),(13505,4.8),(13507,97),(13655,4.7),(13657,95),(13870,4.6),(13872,94),(14020,4.5),(14022,92),(14235,4.4),(14237,90),(14385,4.3),(14387,89),(14600,4.2),(14602,86),(14750,4.1),(14752,85),(14965,4),(14967,83),(15115,3.9),(15117,81),(15330,3.8),(15332,79),(15480,3.7),(15482,78),(15695,3.6),(15697,76),(15845,3.5),(15847,74),(16060,3.4),(16062,72),(16210,3.3),(16212,71),(16425,3.2),(16427,68),(16575,3.1),(16577,67),(16790,3),(16792,65),(16940,2.9),(16942,63),(17155,2.8),(1715		

		7,61),(17305,2.7),(17307,60),(17520,2.6),(17522,58),(17670,2.5),(17672,56),(17885,2.4),(17887,54),(18035,2.3),(18037,53),(18250,2.1),(18252,50),(18615,2),(18617,47),(18765,1.9),(18767,45),(18980,1.8),(18982,43),(19130,1.7),(19132,41),(19345,1.6),(19347,39),(19495,1.5),(19497,37),(19710,1.4),(19712,35),(19860,1.3),(19862,33),(20075,1.2),(20077,31),(20225,1.1),(20227,29),(20440,1),(20442,27),(20590,0.9),(20592,25),(20805,0.8),(20807,23),(20955,0.7),(20957,21),(21170,0.6),(21172,19),(21320,0.5),(21322,17),(21900,144),(23171,6.5),(23173,131),(23399,6.4),(23401,129),(23725,126),(24039,6.3),(24041,123),(24262,6.2),(24264,121),(24440,6.1),(24442,119),(24659,6),(24661,117),(24987,5.9),(24989,115),(24823,5.8),(24825,115),(24834,5.7),(24836,115),(24838,5.6),(24840,115),(24876,5.5),(24877,115),(25185,5.4),(25187,112),(25365,5.3),(25367,110),(25550,5.2),(25552,108),(25730,5.1),(25732,106),(25915,5),(25917,104),(26095,4.9),(26097,103),(26645,4.8),(26647,97),(267		

		95,4.7),(26797,95),(27010,4.6),(27012,94),(27160,4.5),(27162,92),(27375,4.4)		
Canals capacity (mm/Day)	[(0,0)-(22266,20000)],(1,760),(1460,685),(3285,548),(5110,411),(6935,274),(8760,137),(10950,0),(12775,0),(14600,0),(16425,0),(18250,0),(20075,0),(21900,0),(23725,0),(25550,0),(27375,0)	[(0,0)-(22266,20000)],(1,760),(1460,685),(3285,548),(5110,411),(6935,274),(8760,137),(10950,760),(12775,760),(14600,760),(16425,685),(18250,548),(20075,411),(21900,274),(23725,137),(25550,0),(27375,760)	[(0,0)-(22266,20000)],(1,760),(1460,685),(3285,548),(5110,457),(6935,366),(8760,275),(10950,184),(12775,93),(14600,2),(16425,0),(18250,0),(20075,0),(21900,0),(23725,0),(25550,0),(27375,0)	[(0,0)-(22266,20000)],(1,760),(1460,685),(3285,541),(5110,450),(6935,359),(8760,268),(10950,177),(12775,86),(14600,0),(16425,0),(18250,0),(20075,0),(21900,0),(23725,0),(25550,0),(27375,0)
Pumps capacity *(mm/Day)*	[(0,0)-(22266,5000)],(1,4450),(1460,4005),(3285,3560),(5110,3115),(6935,2670),(8760,2225),(10950,1780),(12775,1335),(14600,890),(16425,445),(18250,0),(20075,0),(21900,0),(23725,0),(25550,0),(27375,0)	[(0,0)-(22266,5000)],(1,4450),(1460,4005),(3285,3560),(5110,3115),(6935,2670),(8760,2225),(10950,1780),(12775,1335),(14600,890),(16425,445),(18250,4450),(20075,4005),(21900,3560),(23725,3115),(25550,2670),(27375,2225)	[(0,0)-(22266,5000)],(1,4450),(1460,4005),(3285,3560),(5110,3204),(6935,2848),(8760,2492),(10950,2136),(12775,1780),(14600,1424),(16425,1068),(18250,712),(20075,356),(21900,0),(23725,0),(25550,0),(27375,0)	[(0,0)-(22266,5000)],(1,4450),(1460,4005),(3285,3553),(5110,3197),(6935,2841),(8760,2485),(10950,2129),(12775,1773),(14600,1417),(16425,1061),(18250,705),(20075,349),(21900,0),(23725,0),(25550,0),(27375,0)
Community sense of safety (Dmnl)	1 (low class)	[(0,0)-(22266,10)],(1,1),(1460,1),(3285,1),(5110,1),(6935,1),(8760,2),(10950,2),(12775,3),(14600,3),(16425,3),(18250,3),(20075,3),(21900,3),(23725,3),(25550,3),(27375,3)	[(0,0)-(22266,10)],(1,1),(1460,1),(3285,2),(5110,2),(6935,2),(8760,2),(10950,2),(12775,1),(14600,1),(16425,1),(18250,1),(20075,1),(21900,1),(23725,1),(25550,1),(27375,1)	[(0,0)-(22266,10)],(1,1),(1460,1),(3285,2),(5110,2),(6935,2),(8760,2),(10950,2),(12775,2),(14600,2),(16425,2),(18250,2),(20075,2),(21900,2),(23725,2),(25550,2),(27375,2)
Citizens' involvement (Dmnl)	1 (low class)	1 (low class)	1 (low class)	[(0,0)-(22266,10)],(1,1),(1460,2),(3285,3),(5110,3),(6935,3),(8760,3),(10950,3),(12775,3),(14600,2),(16425,2),(18250,2),(20075,2),(21900,2),(23725,

				2),(25550,2),(27375,2)
Wetlands area *(sqkm)*	—	—	—	[(0,0)-(22266,10)],(1,0),(1460,0),(3285,0.31),(5110,0.31),(6935,0.31),(8760,0.31),(10950,0.31),(12775,0.31),(14600,0.31),(16425,0.31),(18250,0.31),(20075,0.31),(21900,0.31),(23725,0.31),(25550,0.31),(27375,0.31)
Wetlands hydrological performance *(mm/Day)*	—	—	—	[(0,0)-(22266,10)],(1,0),(1460,0),(3285,0.9),(5110,0.9),(6935,0.9),(8760,0.9),(10950,0.9),(12775,0.9),(14600,0.9),(16425,0.9),(18250,0.9),(20075,0.9),(21900,0.9),(23725,0.9),(25550,0.9),(27375,0.9)
Urban green avenue /woodland area *(sqkm)*	—	—	—	[(0,0)-(22266,10)],(1,0),(1460,0),(3285,0.15),(5110,0.2),(6935,0.25),(8760,0.3),(10950,0.35),(12775,0.36),(14600,0.36),(16425,0.36),(18250,0.36),(20075,0.36),(21900,0.36),(23725,0.36),(25550,0.36),(27375,0.36)
Urban green avenue /woodland hydrological performance *(mm/Day)*	—	—	—	[(0,0)-(22266,10)],(1,0),(1460,0),(3285,0.62),(5110,0.62),(6935,0.62),(8760,0.62),(10950,0.62),(12775,0.62),(14600,0.62),(16425,0.62),(18250,0.62),(20075,0.62),(21900,0.62),(237

				25,0.62),(25550,0.62),(27375,0.62)
Intensive Blue/Green roofs area *(sqkm)*	—	—	—	[(0,0)-(22266,10)],(1,0),(1460,0),(3285,0.02),(5110,0.025),(6935,0.03),(8760,0.035),(10950,0.04),(12775,0.04),(14600,0.04),(16425,0.04),(18250,0.04),(20075,0.04),(21900,0.04),(23725,0.04),(25550,0.04),(27375,0.04)
Intensive Blue/Green roofs hydrological performance *(mm/Day)*	—	—	—	[(0,0)-(22266,10)],(1,0),(1460,0),(3285,0.75),(5110,0.75),(6935,0.75),(8760,0.75),(10950,0.75),(12775,0.75),(14600,0.75),(16425,0.75),(18250,0.75),(20075,0.75),(21900,0.75),(23725,0.75),(25550,0.75),(27375,0.75)
Parks area *(sqkm)*	—	—	—	[(0,0)-(22266,10)],(1,0),(1460,0),(3285,0.62),(5110,0.62),(6935,0.62),(8760,0.62),(10950,0.62),(12775,0.62),(14600,0.62),(16425,0.62),(18250,0.62),(20075,0.62),(21900,0.62),(23725,0.62),(25550,0.62),(27375,0.62)
Parks hydrological performance *(mm/Day)*	—	—	—	[(0,0)-(22266,10)],(1,0),(1460,0),(3285,1),(5110,1),(6935,1),(8760,1),(10950,1),(12775,1),(14600,1),(16425,1),(18250,1),

				(20075,1),(21900,1),(23725,1),(25550,1),(27375,1)
Lakes and canals naturalization *(Dmnl)*	—	—	—	[(0,0)-(27375,10)],(1,0),(1460,0),(3285,0.05),(5110,0.05),(6935,0.05),(8760,0.05),(10950,0.05),(12775,0.05),(14600,0.05),(16425,0.05),(18250,0.05),(20075,0.05),(21900,0.05),(23725,0.05),(25550,0.05),(27375,0.05)
Proximity to natural spaces *(Dmnl)*	0.5 (medium level)	0.5 (medium level)	0.5 (medium level)	[(0,0)-(22266,10)],(1,0.5),(1460,0.5),(3285,0.52),(5110,0.54),(6935,0.56),(8760,0.58),(10950,0.6),(12775,0.62),(14600,0.64),(16425,0.66),(18250,0.68),(20075,0.7),(21900,0.72),(23725,0.74),(25550,0.76),(27375,0.78)
Wetlands biodiversity performance *(Dmnl/Day)*				[(0,0)-(22266,10)],(1,0),(1460,0),(3285,1.5e06),(5110,1.5e06),(6935,1.5e-06),(8760,1.5e-06),(10950,1.5e-06),(12775,1.5e-06),(14600,1.5e-06),(16425,1.5e-06),(18250,1.5e-06),(20075,1.5e-06),(21900,1.5e-06),(23725,1.5e-06),(25550,1.5e-06),(27375,1.5e-06)

Urban green avenue /woodland biodiversity performance *(Dmnl/Day)*	—	—	—	[(0,0)-(22266,10)],(1,0),(1460,0),(3285,1.5e06),(5110,1.5e06),(6935,1.5e-06),(8760,1.5e-06),(10950,1.5e-06),(12775,1.5e-06),(14600,1.5e-06),(16425,1.5e-06),(18250,1.5e-06),(20075,1.5e-06),(21900,1.5e-06),(23725,1.5e-06),(25550,1.5e-06),(27375,1.5e-06)
Intensive Blue/Green roofs biodiversity performance *(Dmnl/Day)*	—	—	—	[(0,0)-(22266,10)],(1,0),(1460,0),(3285,1.5e06),(5110,1.5e06),(6935,1.5e-06),(8760,1.5e-06),(10950,1.5e-06),(12775,1.5e-06),(14600,1.5e-06),(16425,1.5e-06),(18250,1.5e-06),(20075,1.5e-06),(21900,1.5e-06),(23725,1.5e-06),(25550,1.5e-06),(27375,1.5e-06)
Parks biodiversity performance *(Dmnl/Day)*	—	—	—	[(0,0)-(22266,10)],(1,0),(1460,0),(3285,1.5e06),(5110,1.5e06),(6935,1.5e-06),(8760,1.5e-06),(10950,1.5e-06),(12775,1.5e-06),

				(14600,1.5e-06), (16425,1.5e-06), (18250,1.5e-06), (20075,1.5e-06), (21900,1.5e-06), (23725,1.5e-06), (25550,1.5e-06), (27375,1.5e-06)

11. CURRICULUM

VIRGINIA ROSA COLETTA

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RESEARCH EXPERIENCE

Collaboration with the Water Research Institute, National Research Council (IRSA-CNR, Bari, Italy) on some activities related to the EU Horizon 2020 Projects RESET (Restarting Economy in Support of Environment, through Technology) and REXUS (Managing Resilient Nexus Systems Through Participatory Systems Dynamics Modelling)
11/06/2021-ongoing

- Development of an innovative methodology for integrating monitoring and modelling systems to support urban climate change adaptation processes
- Analysis of the Water-Energy-Food Nexus through integrated modelling, aimed at identification of measures to reduce sectoral conflicts

Collaboration with University College London (London, England) on some activities related to the Projects CUSSH (Complex Urban Systems for Sustainability and Health) e CAMELLIA (Community Water Management for a Liveable London)
30/11/2020-ongoing
Development of a System Dynamics model to explore different urban flood risk management scenarios

Collaboration with the Water Research Institute, National Research Council (IRSA-CNR, Bari, Italy) and the National Institute for Research and Development of Marine Geology and Geoecology (GEoEcoMar, Romania) on some activities related to the EU Horizon 2020 Projects NAIAD
2018 – 2019
Nature-Based Solutions co-design for the reduction of hydraulic risks and risks related to climate change

EDUCATION

University College London, research period abroad to carry out part of the doctoral research activity
1/10/2021-17/12/2021

Politecnico di Bari, Ph.D in the Risk and environmental, territorial and building development Ph.D course, Politecnico di Bari jointly with the Water Research Institute, National Research Council (IRSA-CNR, Bari)
01/11/2019 – ongoing

Politecnico di Bari, Master's Degree in Environmental and Land Planning Engineering
09/2016 – 03/2019
Thesis in Management of the Hydrographic Basins, entitled "Development of drought local impact indicators and NBS co-design: stakeholder involvement in the Lower Danube", Prof.Ing.U.Fratino, Ing.R.Giordano, Ing.A.Pagano

Politecnico di Bari, Bachelor's Degree in Building Engineering
09/2013 – 10/2016
Thesis in Technical Hydraulics, entitled "The treatment of rainwater related to an industrial factory", Prof.Ing.V.Amoruso

FURTHER INFORMATION

Representative of Ph.D students of the Department of Civil, Environmental, Land, Building Engineering and Chemistry (DICATECh) of Politecnico di Bari
05/02/2021-ongoing

International English Language Testing System (IELTS) Academic Version – B2 level

Registered Engineer of the Province of Bari, Section A, Civil and Environmental Sector (ID number: 11619)

MAIN SCIENTIFIC PUBLICATIONS

Paper for journal

- **Coletta** V.R., Pagano A., Pluchinotta I., Zimmermann N., Davies M., Butler A., Fratino U., Giordano R. Participatory Causal Loop Diagram Building for Supporting Decision-Makers Integrating Flood Risk Management in an Urban Regeneration Process. Earth's Future. Submitted
- Scrieciu A., Pagano A, **Coletta** V.R., Fratino U., Giordano R., 2021. Bayesian Belief Networks for Integrating Scientific and Stakeholders' Knowledge to Support Nature-Based Solution Implementation. Frontiers in Earth Science. https://doi.org/10.3389/feart.2021.674618
- **Coletta** V.R., Pagano A., Pluchinotta I., Fratino U., Scrieciu A., Nanu F., Giordano R, 2021. Causal Loop Diagrams for supporting Nature Based Solutions participatory design and performance assessment. Journal of Environmental Management. https://doi.org/10.1016/j.jenvman.2020.111668

Paper/Abstract for conference proceedings

- **Coletta** V.R., Imbò A., Pagano A., Giordano R., Fratino U. Water resources management in an international watershed: the Isonzo-Soca case study. 43rd ICIRBM, November 25-26, 2022, Rende, Italy. ISBN 9788897181866
- **Coletta** V.R., Pagano A., Pluchinotta I., Zimmermann N., Fratino U., Giordano R. Developing an adaptive strategy for urban flood risk management using a participatory exploratory modelling approach. 7th IAHR Europe Congress, September 7-9, 2022, Athens, Greece. ISBN 9786188567535
- Pagano A., **Coletta** V.R., Scrieciu A., Giordano R. Integrating knowledge using Bayesian Networks to support NBS modelling and implementation. 39th IAHR World Congress. 19-24 June 2022, Granada (Spain). ISBN/EAN 9789083261218

Abstract

Several modelling tools commonly used for supporting flood risk assessment and management are highly effective in representing physical (hydrological) phenomena but provide a rather limited understanding of the multiple implications that flood risk and flood risk reduction measures have on highly complex systems such as urban areas. In fact, the dynamic and unstable evolution – characterised also by significant uncertainty – of flood risk in urban systems is typically neglected. A limited understanding of the complex set of interactions between flood risk and urban areas may result in an ineffective flood risk management. In this context, some studies highlighted the relevance of resilience-based approaches to increase the capability of urban systems to deal with complex and uncertain future threats.

The present work proposes an innovative modelling approach to support decision-makers, at a planning or strategic level, in managing urban flood risk while defining strategies for enhancing the resilience of the system. To this aim, the multi-dimensional implications of flood risk and of different flood risk management strategies are analysed and simulated. The adopted modelling approach is based on System Dynamics (SD) modelling principles and relies on the integration of scientific and stakeholder knowledge. Reference is made to one of the case studies of the CUSSH and CAMELLIA projects, namely Thamesmead (London), a formerly inhospitable marshland currently undergoing a process of urban regeneration and increasingly vulnerable to flooding. It represents an interesting opportunity for building a replicable approach to integrate urban development dynamics with flood risk, ultimately supporting decision-makers in identifying mitigation/prevention measures and understanding how they could help achieve multi-dimensional benefits.