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Participatory Approach to Increase Urban Flood Resilience through Blue-Green Infrastructure

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Abstract

Cities are complex and uncertain systems as they consist of mutable relations between the several dimensions and elements they are characterised by. Besides that, the level of flood risk they are experiencing is exacerbated by the changes of climatological and socio-economic factors. Decision and policy-makers cannot ignore these dynamics and should move towards an adequate approach to flood risk management. In this context, an increasing body of literature further suggests adopting resilient-based approaches, which include e.g., interactions with stakeholders and Blue-Green (BG) infrastructure implementation. Starting from these premises, this work aims at developing an innovative and participatory approach to support decision-makers in enhancing urban flood resilience through the implementation of BG infrastructure. To this aim, a System Dynamic modelling approach is adopted. The method, although replicable in different study contexts, is implemented in a one of the case studies of the CUSSH[1] and CAMELLIA[2] urban regeneration projects, namely Thamesmead (London).

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

1. INTRODUCTION

Cities are complex systems which integrate economic, social, ecological, and human dimensions that depend on and cooperate with each other. In addition, they are uncertain system as they consist of situational and changing relations between the different elements they are characterised by (Disse et al., 2020). Flooding is one of the natural disasters that all cities may encounter and that may cause 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 (Bosher, 2014). The changes of climatological 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. 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 modelling approaches and tools for flood risk management, the dynamic nature of complex urban systems is largely ignored (Perrone et al., 2020). In this regard, some studies stated that adopting resilient-based approaches could increase the system capability to deal with systems complexities and the uncertainty of future threats (Pagano et al., 2017). A central component recently recognised for building cities'

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[1] https://projectcussh.org/

[2] https://www.camelliawater.org/

resilience to flooding is stakeholder engagement. Specifically, their involvement in the entire flood risk modelling process through the adoption of participatory techniques could i) enhance researchers' knowledge on local issues; ii) support decision-makers in the identification of suitable strategies to act on the system; iii) promote awareness and motivation of those taking part in decision- or policy-making processes (Pluchinotta et al. 2021a; Giordano et al., 2020; Pagano et al., 2019; O'Donnell 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 deliver multiple co-benefits to the environment and society, while increasing urban flood resilience (Kapetas and Fenner, 2020; O'Keeffe et al., 2022).

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 relies on the integration of scientific and stakeholder knowledge and is based on System Dynamics (SD) modelling principles (see e.g., Sterman, 2000), especially applicable to water-related risk management problems.

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.

2. MATERIALS AND METHODS

The adopted methodology 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 methodological framework is based on a multi-step process of knowledge gathering and on the SD principles, i.e., a computer-aided approach for strategy and policy design (Forrester, 1961). Conceptual and numerical modelling tools are integrated with methods for the active participation of stakeholders. Firstly, available information (from reports, exiting models, etc.) and local stakeholder knowledge (collected via semi-structured interviews and workshops) on flood risk and past flooding events in the study area are integrated to build a qualitative Causal Loop Diagram (CLD) that relates the problem of flooding with the main urban dynamics of the area. It allows the understanding of the interactive relationships between different components within (and outside) a system (Coletta et al., 2021). Then, Behaviour Over Time (BOT) graphs of some key system variables under three different conditions (desired future, most likely future, feared future) are drawn by stakeholders and used for integrating CLD narrative and making preliminary hypotheses on both urban dynamics and flood risk management policies (see e.g., Elias, 2012 for further information on BOT graphs). Starting from the developed qualitative map, a quantitative SD model (i.e., Stock and Flow model) is built to assess both the urban resilience to flooding and the effect of the implementation of flood mitigation/prevention measures. To choose the most suitable strategy (i.e., bundle of actions) for enhancing the urban flood resilience, future scenarios are developed with stakeholders and compared. A sensitivity analysis of the most suitable scenario is then performed to suggest to decision-makers i) which factors or processes impact most on the 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 (Mirchi et al., 2012).

3. THE THAMESMEAD CASE STUDY

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.

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.

4. MAIN RESULTS

4.1 Qualitative System Dynamics model

The final version of the CLD related to the TM study area is shown in Figure 1. 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).

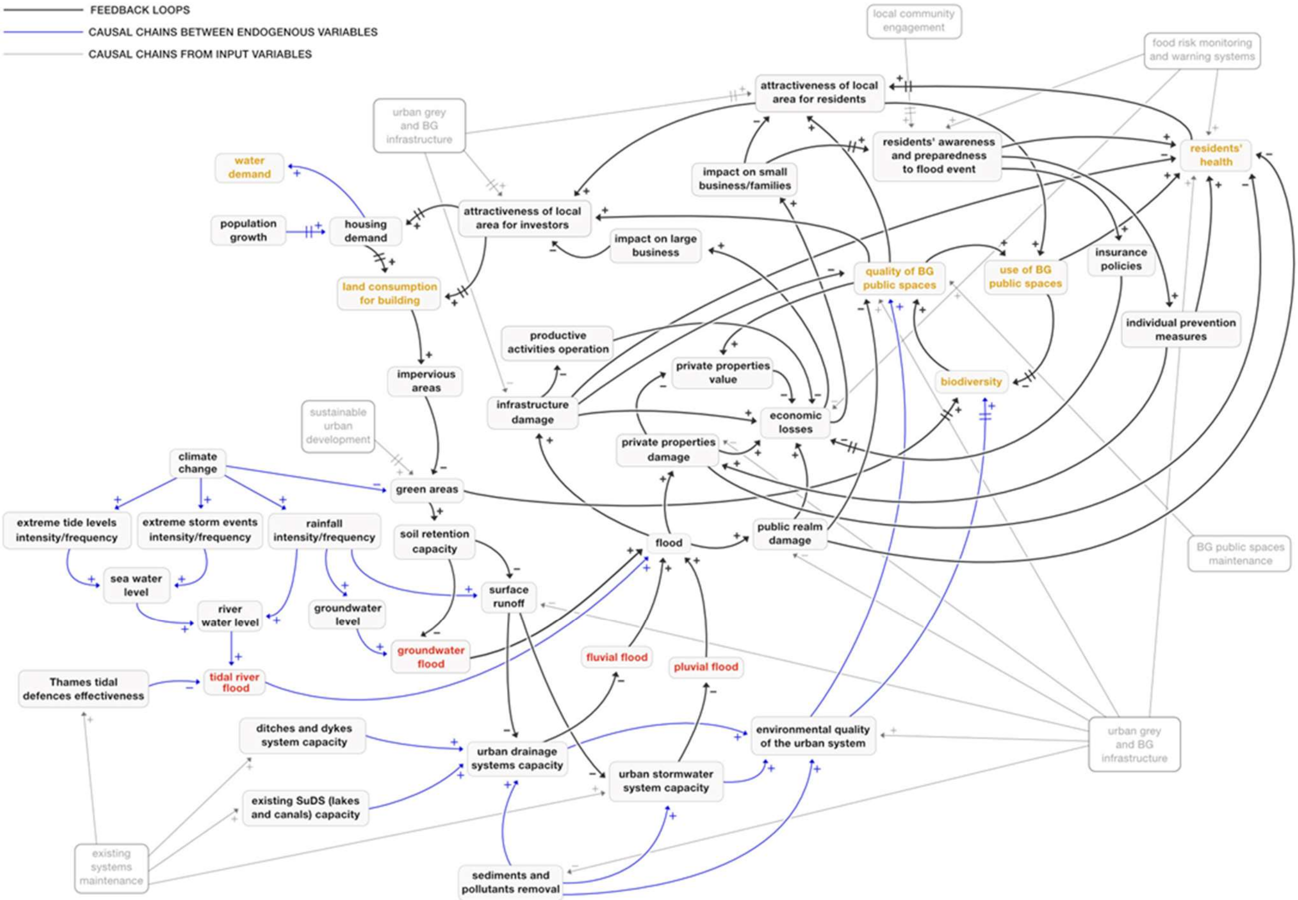

Figure 1. Thamesmead flood CLD.

The CLD in Figure 1 was obtained using the Vensim® software. The information needed to build the preliminary version of the map 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. Then, an improved CLD version which includes stakeholder knowledge was obtained from the analysis of both four rounds of semi-structured interviews of approximately 1 h duration 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.

4.2 Quantitative System Dynamics model

The quantitative SD model was developed based on the CLD. The model ran over a time scale of 78 years (2023-2100), considering both the period covered by the regeneration Plan and the future time horizon considered by the flood risk management Plan. The simulation was based on a daily time step as a compromise for computing all the different flood dynamics.
The variables and causal relationships of the qualitative causal map were translated into common Stock and Flow (SF) model sets (see Sterman, 2000 for further details); mathematical equations were formulated integrating multiple information sources (i.e., scientific/grey literature, reports, databases, stakeholder consultation) to capture the interactions between different elements in the model. To handle the system complexity, specific dynamics were isolated and arranged into interconnected thematic sub-models, representing key processes and elements of an urban system exposed to flood risk. Specifically, sub-models related to flood risk assessment, tangible damage evaluation, and co-benefits analysis were developed (Figure 2). The 'flood risk assessment' sub-model provided a simplified risk evaluation, combining the flood hazard-related elements with the variables that represent the system's vulnerability to hazard. The 'tangible damage evaluation' sub-model focused on the evaluation of the effects of flooding on the built environment. The 'co-benefits analysis' sub-model investigated 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).

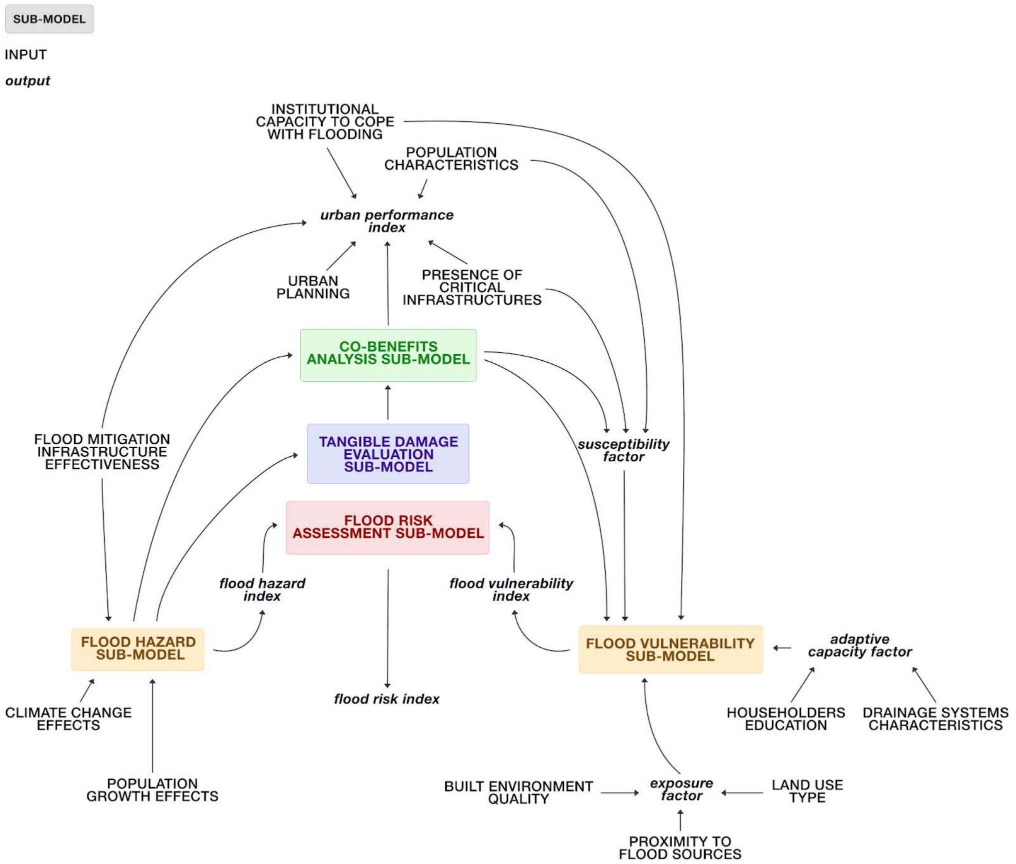

Figure 2. Interactions between the different SD sub-models proposed for the analysis of urban flood resilience. The sub-models are in coloured rectangles, while the main inputs/outputs of the sub-models are respectively in capital letters and italics.

The information obtained from the sub-model was then synthesised for planning and strategic purposes through the construction of indices that aggregate representative variables of the behaviour of the system, i.e., the flood hazard index, flood vulnerability index, flood risk index and urban performance index (see e.g., Tingsanchali and Promping, 2022). The flood risk index was computed as the product of the flood hazard index (FHI) and the flood vulnerability index (FVI) and classified into three ranges from very low/low to high/very high. FHI was calculated associating a hazard class to the flood depths generated by the different flood sources; while FVI through the exposure factor, the susceptibility factor, and the adaptive capacity factor using an additive function with weights. The urban performance index provided a comprehensive overview of the urban resilience to flooding. System characteristics related to five resilience dimensions (social, economic, institutional, infrastructural, and environmental) were selected and assigned to three different classes for this purpose.

4.3 Future scenarios building and comparison

The quantitative model was used with the aim of identifying, through scenario analysis, the impact that different actions would have on the model's outputs. Different scenarios were proposed and co-designed with stakeholders during an online workshop (approximate duration 1 h) held on 27 October 2022, namely 'replacing infrastructure at lifecycle end', 'planned ordinary maintenance', and 'BG infrastructure implementation'. The behaviour of the key variables of the model (e.g., flood risk index and urban performance index) were compared using the baseline scenario as a reference. The scenarios analysis confirmed both i) the positive effect of grey drainage systems on flood hazard and ii) the ability of BG infrastructure to provide hydrological and social/environmental benefits which contribute to the enhance urban flood resilience. However, the scenarios showed that the BG infrastructure implementation would not be sufficient on its own to both reduce flood risk and enhance urban flood resilience when the service life of the Grey systems is over. Hence, Hybrid systems (Grey and BG) should be provided for. A sensitivity analysis was then performed for investigating the influence of single variables of the model on the urban performance index. 'Population characteristics', 'critical infrastructure presence', and 'institutional capacity to cope with flooding' seem to be the aspects that influence most the resilience of the urban system.

5. DISCUSSION AND CONCLUSIONS

Cities are complex and uncertain, and their 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. Compared to traditional hydrological models for flood risk management, this work adopted 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 processes were integrated with others. For this purpose, SD was used and the full potentialities of both System Thinking and Dynamic Simulation were exploited. Specifically, using CLD as a tool for qualitative modelling allowed to: i) integrate hydrologic 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. The development of a Stock and Flow model provided a deeper understanding of complex systems behaviour and supported the identification of suitable actions in view of managing flood risk and improving urban flood resilience. Specifically, the effectiveness of the implementation of BG infrastructure (under different scenarios that include coupling with Grey infrastructures) was evaluated. The 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 fact, the iterative integration of scientific and stakeholder knowledge allowed the peculiarities of the case study to be accounted for. In addition, stakeholders supported the modeller in selecting actions and strategies to be implemented. In addition, the ability of BG infrastructure to provide hydrological, social, and environmental benefits, if combined with well-functioning Grey infrastructure, was confirmed. Through a sensitivity analysis, the SD model provided also 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.

Specific reference was made to the Thamesmead case study (London, UK). However, the developed methodological approach is suitable for replication in other contexts.

6. ACKNOWLEDGMENTS

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