A PARTICIPATORY SYSTEM DYNAMICS MODEL TO INVESTIGATE SUSTAINABLE URBAN WATER MANAGEMENT IN EBBSFLEET GARDEN CITY

Authors

Irene Pluchinotta[1*], Alessandro Pagano[2], Tudorel Vilcan[3], Sangaralingam Ahilan[4], Leon Kapetas[5], Shaun Maskrey[6,7], Vladimir Krivtsov[8], Colin Thorne[6] and Emily O'Donnell[6].

[1*]Institute for Environmental Design and Engineering, The Bartlett Faculty of The Built Environment, University College London, UK,
Corresponding Author
i.pluchinotta@ucl.ac.uk
Central House, 14 Upper Woburn Place, London WC1H 0NN

[2]Water Research Institute, National Research Council, Italy
[3]Department for Public Leadership and Social Enterprise, The Open University, UK
[4]Centre for Water Systems, College of Engineering, Mathematics and Physical Sciences, University of Exeter, UK
[5]Department of Engineering, University of Cambridge, UK
[6]School of Geography, University of Nottingham, UK
[7] Environment Agency, King's Meadow House, Reading, RG1 8DQ, UK
[8]RBGE and Edinburgh University, Scotland, UK

Abstract: Growing urban populations, changes in rainfall patterns and ageing infrastructure represent significant challenges for urban water management (UWM). There is a critical need for research into how cities should adapt to become resilient to these impacts under uncertain futures. UWM challenges in the Ebbsfleet Garden City (UK) were investigated via a participatory process and potential sustainable solutions were explored using a System Dynamics Model (SDM). Collaborative development of the SDM by the Ebbsfleet Learning and Action Alliance developed stakeholders' understanding of future UWM options and enabled a structured exploration of interdependencies within the current UWM system. Discussion by stakeholders resulted in a focus on potable water use and the development of the SDM to investigate how residential potable water consumption in the Ebbsfleet Garden City might be reduced through a range of interventions, e.g., socio-environmental and economic policy incentives. The SDM approach supports decision-making at a strategic, system-wide level, and facilitates exploration of the long-term consequences of alternative strategies, particularly those that are difficult to include in quantitative models. While an SDM can be developed by experts alone, building it collaboratively allows the process to benefit from local knowledge, resulting in a collective learning process and increased potential for adoption.

Highlights

- Garden Cities are key for sustainable urban growth and water resource management
- Ebbsfleet stakeholders co-produced a participatory System Dynamics Model
- The model investigated different policies for sustainable Urban Water Management
- The participatory nature of the modelling supported a collective learning process
- System Dynamics modelling allowed stakeholders to explore multiple future scenarios

Keywords: System Dynamics, Ebbsfleet Garden City, Participatory Modelling, Sustainable Urban Water Management, Sustainability**,** Stakeholders

1. Introduction

Cities and societies worldwide face the challenges of delivering sustainable urban water systems that manage environmental risks (e.g. flooding, water pollution, water scarcity) and concurrently improve the quality of the environment (e.g. water quality, biodiversity), conserve and enhance natural resources, save financial resources, and improve health and wellbeing (Hellström et al., 2000; Brown et al., 2009; Butler et al., 2014). Relationships between the natural environment and urban water infrastructure are highly complex, comprised of ecological, hydrological, economic, technical, political and social elements (Bell, 2017). Furthermore, management of the urban water cycle will be impacted by increased urbanisation and population rise. By 2050, 68% of the world's population is expected to reside in cities (UN, 2018), increasing demand for clean potable systems and elevating flood risk to people, property and critical infrastructure systems that frequently operate in excess of their useful service lives (O'Donnell and Thorne, 2020). Climate change impacts are further expected to undermine the ability of existing urban water supply systems to meet the needs of future populations (Gosling and Arnell, 2016). To address these water challenges, cities and urban centres are striving to achieve Sustainable Urban Water Management, defined as "*the use of water that supports the ability of human society to endure and flourish into the indefinite future without undermining the integrity of the hydrological cycle or the ecological systems that depend on it*" (Gleick, 1998). To achieve this goal, initiatives must advocate for changes in both water supply and demand, and create systems that are functionally robust, flexible and adaptable to future conditions.

Concepts such as Water Sensitive Urban Design (WSUD) are increasingly being recognised as offering viable solutions to myriad urban water challenges. WSUD considers the coordinated planning of all water services and development of decentralised wastewater and stormwater reuse opportunities. It aims to integrate water into urban development and planning from an early stage to exploit the emerging opportunities for sensitive water cycle management (Sharma et al., 2016). This progresses from traditional approaches that manage provision of water supply, sewerage, and urban drainage through subsurface networks of piped infrastructure (Marlow et al., 2013) towards a combination of blue, green and grey infrastructure to manage water while delivering multiple co-benefits to the environment and society. Opportunities to achieve multiple objectives, such as concurrently reducing potable water demand and flood risk through rainwater harvesting initiatives, are a marked difference from traditional grey infrastructure schemes that focus on a sole objective. More integrated approaches also unlock rigid institutional frameworks and overcome the constraints of traditional technologies and non-integrated urban plans (Ahiablame et al., 2012; Coutts et al., 2012; Ashley et al., 2013).

WSUD principles are a key component of the planning and design of the Ebbsfleet Garden City, situated between Dartford and Gravesend near the River Thames, UK, and sponsored by the National Government to become a 'Garden City of the 21st Century'. A Garden City is a '*holistically planned new settlement which enhances the natural environment and offers high-quality affordable housing and locally accessible work in beautiful, healthy and sociable communities*' (TCPA, no date). Development is founded on Garden City Principles that prioritise the enhancement of the natural environment, comprehensive green infrastructure networks that deliver net biodiversity gains, and climate resilience delivered through carbon neutral and energy-positive technology (Ward, 2005). The delivery of 12,000 new homes, a new commercial centre, regional transport hub, and extensive travel networks are designed around a continuous network of blue and green space, termed the 'Garden Grid' (Ebbsfleet Development Corporation, 2017). This network of parks, open spaces and green streets include effective use of SuDS (Sustainable Drainage Systems) to attenuate, drain, infiltrate and store surface water, and deliver additional environmental and societal co-benefits (Woods Ballard et al., 2015). The 'Garden Grid' and other linked Blue-Green infrastructure will increase resilience to future flood risks associated with heavy rainfall and promotes "*a sustainable and long term response to climate change*" (Ebbsfleet Development Corporation, 2017: 36). In addition to pluvial flood risk, the Ebbsfleet Garden City is developing strategies to reduce the risk of future water scarcity. Climate change scenarios suggest that the UK will experience more frequent hot, dry summers with increased drought risk (Lowe et al., 2018) with the largest changes in precipitation occurring in the southern and eastern parts of England. In the southeast, there is a potential for short duration droughts occurring up to three times as frequently in the 2020s compared to the 1961-90 period (Wade et al 2006). Ensuring sufficient water for domestic, commercial and industrial uses, in addition to irrigating green infrastructure and maintaining a variety of habitats, are key objectives for the Ebbsfleet Garden City (Ebbsfleet Development Corporation, 2017) and require a transformative approach to Urban Water Management (UWM).

Working collaboratively with local stakeholders to co-develop strategies is a central component of transformative UWM (Ashley et al., 2012). It is premised on a move away from top-down expertise, while looking to engage with a plethora of stakeholders who are deemed legitimate participants to the identification of both problems and solutions. Not only do local stakeholders have extensive local knowledge that may not be available to researchers through literature reviews alone, the inclusion of stakeholders from different disciplines (including those not typically included in water management discussions dominated by engineers), leads to greater innovation and potential for shared action to improve UWM while delivering additional co-benefits. Learning and Action Alliances (LAA), for example, facilitate collaborative working to address local challenges and are a mechanism through which stakeholders can address complex, 'wicked' environmental problems such as those related to water and flood risk management (Ashley et al., 2012). They provide an environment where stakeholders with different viewpoints can come together to identify problems, advance solutions, and produce a collective vision for the future (Maskrey et al., 2020).

The Ebbsfleet LAA was established in 2017 as an open, collaborative forum where local stakeholders develop a joint understanding of problems and possible solutions through rational criticism, consensus-building and discussion. In late 2017, a participatory modelling process was initiated to investigate sustainable UWM challenges in the Ebbsfleet Garden City and explore potential solutions using a System Dynamics (SD) modelling approach (e.g. Sterman, 2000). The urban water system structure was modelled and its behaviour investigated over time. SD modelling is particularly useful for supporting decision-making at a strategic, system-wide level and exploring long-term consequences of alternative strategies, particularly those that are difficult to include in quantitative models (e.g. socio-institutional changes). While a System Dynamics Model (SDM) can be developed by experts alone, building it collaboratively taps into the knowledge base held by local stakeholders, resulting in a collective learning process.

Stakeholder workshops with a range of public and private organisations with interest in sustainable UWM in the Ebbsfleet Garden City initially defined five problem dimensions relating to urban water: water quality, water use optimisation (hereafter potable water use), biodiversity, flood risk management, and quality of place. Discussion and negotiation by stakeholders resulted in a focus on potable water use and the development of the SDM to investigate how residential potable water consumption in the Ebbsfleet Garden City might be reduced through a range of interventions, such as socio-environmental and economic policy incentives.

This study presents the first investigation of sustainable water management in the Ebbsfleet Garden City and highlights the importance of participatory modelling approaches in exploring solutions to water challenges that meet the strategic objectives of different stakeholder organisations. We first introduce SDMs and their application in UWM, then summarise the stages of participatory SD modelling and present the Ebbsfleet Garden City case study. Section 4 describes the co-development of the SDM, and section 5 outlines the model structure and simulation results. We close the paper with a discussion, a note on limitations and concluding remarks.

2. System Dynamics Modelling

System Dynamics (SD) modelling and simulation adopt a whole-system approach and social learning process (Bagheri, 2006; Susnik et al., 2014, 2018) which is widely regarded as an efficient methodology to address a range of dynamically complex problems including integrated water resources management (e.g. Cheng, 2010; Susnik et al., 2012; Xi and Poh, 2013),. Winz et al. (2008) systematically reviewed theoretical and practical evolution of SD in water resources management over the last 50 years and highlight the benefits of SD modelling including stakeholder participation, flexibility, ease of uptake, transparency and adaptability, foresight, and ongoing testing and learning. Beck et al. (2002) developed a concept of adaptive community learning for cultivating stakeholder-driven environmental foresight to address contemporary issues of the environment and sustainability of Lake Lanier in Georgia, USA, in the face of the rapid urbanisation of its watershed. The SD approach enabled the conceptualisation of the community's environmental concerns and associated uncertainties at the science and society interface. For community-based water resources planning, Tidwell et al. (2004) adopted SD to provide an interactive interface for engaging the public and integrating physical and social processes for watershed management in the Middle Rio Grande river basin, USA. For integrated flood management, Simonovic and Li (2003) developed a modelling framework using an SD approach to assess climate change impacts on a large-scale flood protection system for the city of Winnipeg in the Red River basin, Manitoba, Canada. More recently, SD modelling has been used to model urban water systems. Zarghami and Akbariyeh (2012) developed an SDM to consider interconnection and interdependencies amongst water supply resources (groundwater, imported freshwater and treated wastewater), demand patterns (domestic, irrigation and industry use) and management strategies (wastewater reuse and recycling, inter-basin water transfer, water price and conservation tools) for Tabriz city, Iran. They found that transfer of water from neighbouring basins is an effective strategy to meet future water demand compared to the installation of water-conserving fixtures. Chhipi-Shrestha et al., (2018) also adopted a similar SD modelling approach to explore a net-zero water community by combining various water supply sources, conservation measures and environmental potential of net-zero development in the City of Penticton (British Columbia, Canada). The SD modelling approach enabled researchers to integrate cost and energy submodules with the water-energy-carbon nexus model, allowing assessment of site-specific economic and environmental potential for net-zero water development.

Several approaches are used to model urban water systems, e.g. Urban Water Metabolism (Behzadian et al., 2015; Venkatesh et al, 2017) and Agent Based Modelling (Zhuge et al., 2020), yet the majority do not consider the dynamic evolution of phenomena (e.g. the evolution of demand and the impacts of climate change) nor the social and environmental conditions such as stakeholders' priorities and goals (Bakhtiari et al., 2020, Diaz et al., 2016). Holistic approaches to UWM are also currently missing (Renouf and Kenway, 2017). The use of a system-dynamics perspective, acknowledging the many variables, causal mechanisms and feedback processes, has been suggested to enable understanding of the complexity and time dimension of urban water security and sustainability (Hoekstra et al., 2018). This would further allow modelling of the role of both environmental and socio-economic issues.

SD is considered be a set of conceptual tools that enable the understanding of the structure and dynamics of complex systems; it is also a rigorous modelling method for building formal computer simulations of complex systems and using them to design more effective strategies (Sterman, 2000). SD modelling aims to capture the key variables and relationships of a system, understand their interdependencies and predict their behaviour over time. If dynamic behaviour arises from feedbacks within the system, finding effective policy interventions requires understanding the systems' structure. SDMs are widely used to analyse complex ('wicked') problems in water resources management through the integration of qualitative ('soft') and quantitative ('hard') variables (Pagano et al., 2019), that is particularly pertinent for the analysis of such multi-dimensional systems as flood risk management (Simonovic and Li, 2003) and urban water management (Zarghami and Akbariyeh, 2012; Chhipi-Shrestha et al., 2017, 2018; Araujo et al., 2019). Hard variables describe attributes or relationships in a problem regulated by physical laws or where governing rules are based on quantifiable algebraic operators. In contrast, soft variables are typically intangible, and relate to attributes of human behaviour or effects that variations in such behaviour produce. The challenge is to incorporate them in ways that are both scientifically sound and logically defendable.

SD modelling approaches facilitate collaboration among stakeholders by integrating their local knowledge and perceptions of the investigated problem, and its potential solutions (e.g. (Beck et al., 2002; Tidwell et al., 2004; Winz et al., 2008 Coletta et at., 2020). SD is well suited to the analysis of problems whose behaviour is governed by feedback relationships over a long-time horizon. The model establishes a 'business as usual' state of the system and then generates scenarios based on specific hypothetical inputs such as future policy interventions. The scenarios generated provide information about the changes in the key variables of the system based on each intervention.

SDMs describe the behaviour of complex systems over time using feedback loops, stocks, flows and modifiers. Stocks characterise the state of the system at a point in time and keep a memory of it so that its status can be described. Flows affect the stocks via inflow or outflow and interlink the stocks within a system. Flows correspond to the change per period of time that increases or decreases levels in the system. Water systems can be thus described in terms of stocks and flows within an area, exchanges with surrounding areas, external pressures, water quality and available infrastructure. Institutional actions, implementation of plans and operation and maintenance could also be included (Pagano et al., 2017; Hoekstra et al., 2018). The key aspect of SD modelling is the capability to consider the multi-dimensionality of complex problems through the integration of qualitative and quantitative variables, modelled as stocks and flows, and analysed in their dynamic evolution. Both physical laws and intangible issues (e.g. perception of a given system) are jointly considered, with specific attention to their potential interconnections and mutual influences.

3. Stages of participatory System Dynamics Modelling

According to Freeman (2000) two of the research challenges in addressing the "wickedness" of water problems are the challenge of becoming more interdisciplinary and the challenge of integrating two types of knowledge: scientific and local tacit knowledge. Within this context, participatory SD modelling is considered as a best practice methodology in several fields (e.g. Vennix, 1992; 1996; and Rouwette et al., 2002). The co-development of the SDM helps foster a feeling of ownership by the stakeholders, who will also be more likely to adopt and further recommend the model's policy solutions (Thompson et al., 2016). The model may be enriched by the stakeholders' local knowledge and the stakeholders involved will also develop a more detailed understanding of how the system works and evolves (Scott at al., 2016).

The Ebbsfleet Garden City SDM aimed to: i) elicit and structure the stakeholders' knowledge on sustainable urban water management (i.e. the five problem dimensions described in Section 4) and more specifically on potable water use; ii) build a comprehensive conceptual model, with semi-quantitative information, and; iii) define collectively and compare the expected impacts of selected strategies, with specific attention to those related to socio-institutional measures. The stages of the participatory SDM process are described in Figure 1.

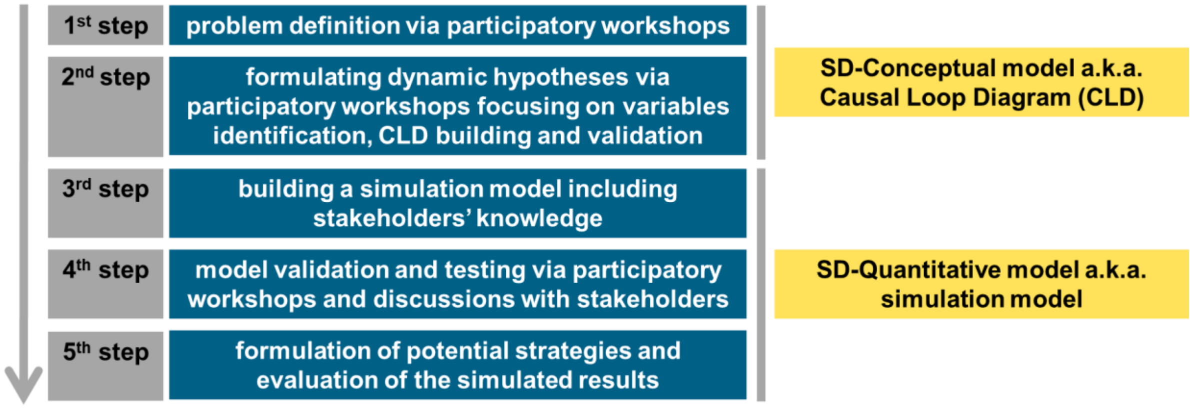


Figure 1. Modelling process using System Dynamics

The first step consists of identifying the problem through participatory workshops: it aims at collectively defining the problem to be solved and the objectives of the model. The second step, formulating a dynamic hypothesis to explain the cause(s) of the problem, leads to the development of an SD-Conceptual model or Causal Loop Diagram (CLD). A series of participatory workshops focuses on variables identification, CLD building and validation. A CLD highlights the system variables, links between these variables and polarity associated with causal links to distinguish between positive feedback loops and negative feedback loops (Sterman, 2000). A CLD thus represents a hypothesis of the feedback structure of the system (Lane et al., 2016), and also serves as a tool for the creation of a shared understanding of the system amongst members of a discussion group.

The third step is the formulation of an SD-Quantitative model or simulation model. This step includes the development of decision rules (i.e. mathematical equations), the quantification of variables, building the stock and flow diagram, and model calibration using parameters to define initial conditions. The fourth step consists of ensuring the model is appropriate for the task through model validation. Typically, this step involves a series of tests to obtain confidence in the model based on both internal and external consistency (Martis, 2006), and discussions with stakeholders involved in the modelling process. The fifth step consists of two main meetings and relates to the formulation of potential strategies and to the evaluation of the simulated results. It requires the identification of scenarios, i.e. alternative strategies, and the analysis and discussion of the simulated results generated by the model for each scenario over time (Bérard, 2006). The interactive SD model development process between experts and stakeholders through five stages enables the improvement of the SD model performance. Thus, the simulation model aims to compare different scenarios of “fictive” actions, to predict the future behaviours of the system under consideration and make recommendations (Sterman, 2000).

4. Ebbsfleet Garden City

The Ebbsfleet Garden City is the first government sponsored 'Garden City' to be built in the UK and is centred on the notions of sustainability and long-term place making. The Ebbsfleet Development Corporation (EDC) has been set up by the Government to deliver the vision of Ebbsfleet as a Garden City, which is in the process of being built with 12,000 houses scheduled for delivery over the next two decades. The area is not without its challenges, mostly owing to its industrial past (e.g. concrete production). In planning terms, this makes it a ‘brownfield’ area. Most of the sites were previously built upon and large areas are former chalk quarries which will be repurposed for development (e.g. Eastern Quarry in Figure 2). In addition, many planning applications have been approved prior to the establishment of the EDC, which makes holistic planning for sustainability and long-term place making more challenging.

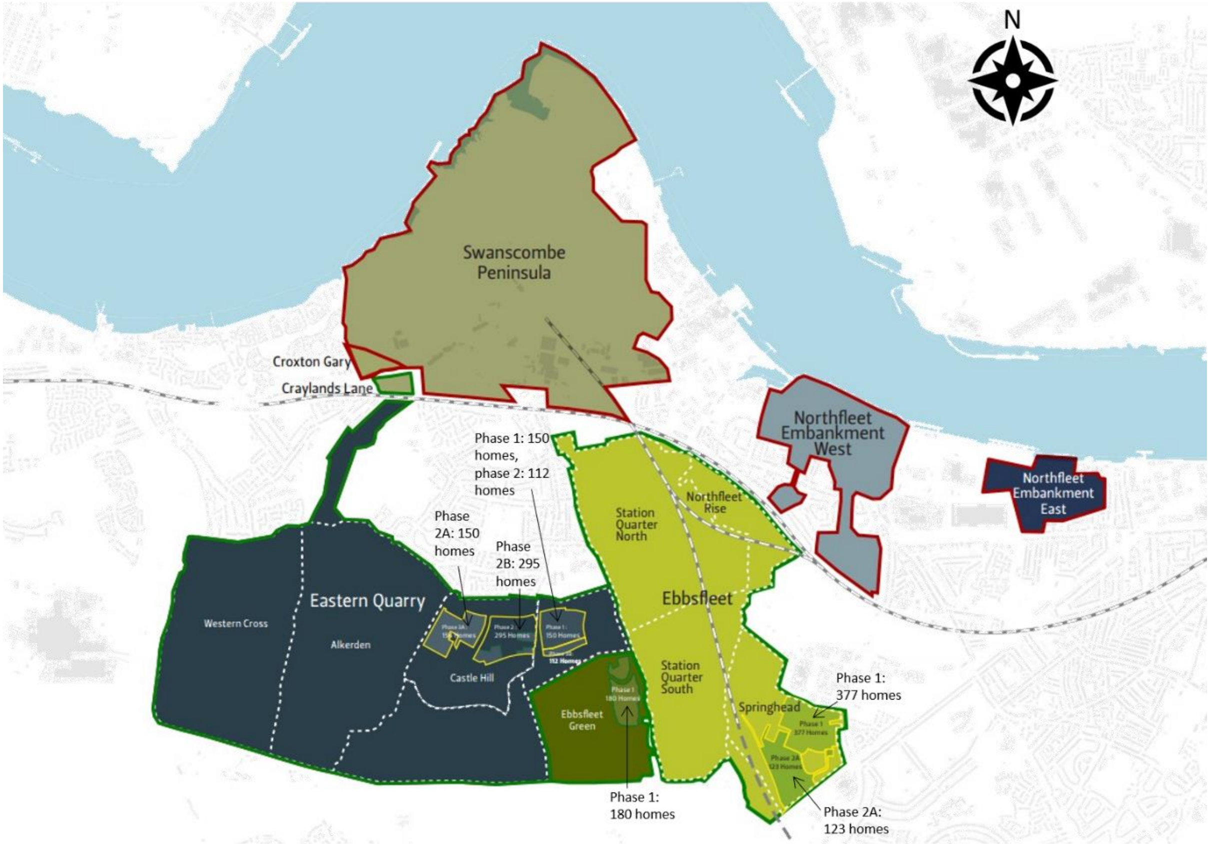


Figure 2. A map of Ebbsfleet area, showing the River Thames to the North. Red border: sites with an allocation in the Local Authority Plan but without consent; green border: outline consent boundary; yellow border: detailed/reserved matters boundary and dashed black and white border: area masterplan boundary. Adapted from Ebbsfleet Development Corporation (2017)

Ebbsfleet is governed at the intersection of nested administrative layers. Within the boundaries of the Garden City, where the EDC has statutory powers, resides Kent County Council, Gravesham Borough Council, Dartford Borough Council and Swanscombe & Greenhithe Town Council. The Ebbsfleet Garden City has two different water and wastewater companies (Southern and Thames Water). The LAA played a pivotal role in bringing together these, and other, stakeholders on a regular basis, as no common vision can be established in their absence.

Table 1. The main stakeholder organisations in the Ebbsfleet LAA and their core functions in the Ebbsfleet Garden City (from a water management perspective).

<table>
<tr><th>Stakeholder</th><th>Statutory responsibilities in the Ebbsfleet Garden City</th></tr>
<tr><td>Ebbsfleet Development Corporation</td><td>Quasi-Autonomous Non-Governmental Organisation (QUANGO) set up by Government to speed up delivery of up to 12,000 homes and create a 21st century Garden City. Has planning and operational functions in Ebbsfleet.</td></tr>
<tr><td>Kent County Council</td><td>Drainage and flood risk management policies and guidance in Kent.</td></tr>
<tr><td>Gravesham Borough Council</td><td rowspan="3">Local government function for drainage and flood risk management in Ebbsfleet.</td></tr>
<tr><td>Dartford Borough Council</td></tr>
<tr><td>Swanscombe & Greenhithe Town Council</td></tr>
<tr><td>Southern Water</td><td rowspan="2">Water company responsible for water and wastewater services.</td></tr>
<tr><td>Thames Water</td></tr>
<tr><td>Environment Agency</td><td>Flood risk management function for main rivers.</td></tr>
<tr><td>Kent Wildlife Trust</td><td>UK leading conservation charity, attends to wildlife protection and biodiversity.</td></tr>
</table>

4.1. Ambitions of the Ebbsfleet SDM

The development of an SDM for the Ebbsfleet Garden City allowed the exploration of sustainable urban water management in a structured way, facilitating stakeholders' understanding of where future policy interventions might be best focused in relation to urban water consumption in the Ebbsfleet Garden City (see Section 5.3). In collaboration with local stakeholders, sustainable urban water management was subdivided into five different components, or problem dimensions (see Figure 3), and one (potable water use) was later selected for further study and became the basis of the SDM. The primary modelling research question, and an early outcome of the study, became: 'How might residential potable water consumption in the Ebbsfleet Garden City be reduced through a range of interventions, such as socio-environmental and economic policy incentives or physical interventions?' (see Section 4.2, Workshop 4). The co-development of the SDM took place over five stakeholder workshops (described below).

4.2. Collaborative modelling of the Ebbsfleet water system

Workshop 1 - Problem definition

In the first workshop, stakeholders were asked to identify key challenges related to sustainable urban water management in the Ebbsfleet Garden City. Five problem dimensions were selected by the group to take forward into initial discussions (see ovals in Figure 3). Using each of these key challenges as a discussion point, the stakeholders went on to identify metrics that might be used to measure change in them (see boxes in Figure 3).

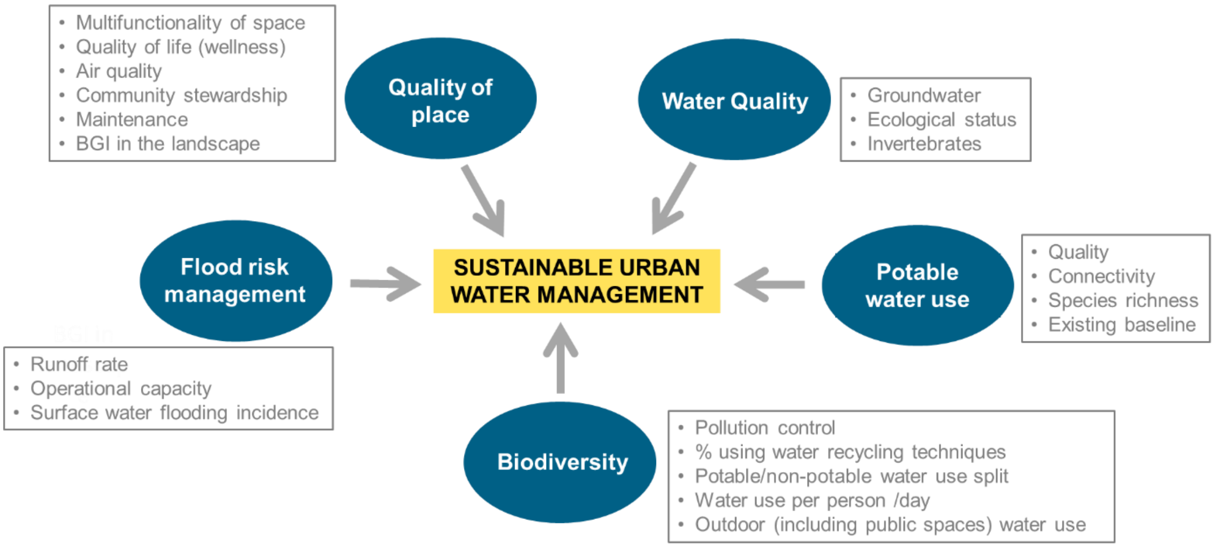


Figure 3. Problem dimensions (ovals) and metrics (boxes) associated with sustainable urban water management, as identified by stakeholders during Workshop 1

Workshop 2 – Exploring the problem dimensions

In the second workshop, stakeholders explored the system further by defining an initial list of variables whose behaviour over time determines each of the problem dimensions. These early discussions around variables and the direct causal relationships between them represent the building blocks of the next stage of the model, the CLD.

Workshop 3 – Towards a preliminary CLD

Stakeholders refined the list of variables and metrics to more fully define each problem dimension. The variables were organised in terms of their effect on the metric (i.e. whether it causes it to increase or decrease). This was an iterative process during the workshop session. For example, variables were selected for removal if they were found to be repeated, tangential to the key issues, or ambiguous. The stakeholders ensured variable names were clear and concise, providing variable definitions and exploring potential data sources that would help generate the equations used in the subsequent SDM. The original five problem dimensions were reduced to four as consensus could not be reached between stakeholders with regards to mapping the variables and metrics associated with the ‘Biodiversity’ problem dimension. The output was a co-produced glossary of variables (Appendix I Table A).

Following workshop 3, the research team created a preliminary CLD (Figure 4a). This consisted of three elements: variables, the links between them, and signs on the links (which define the nature of the causal relationship). This drew on the problem dimensions and metrics identified by the Ebbsfleet stakeholders and constituted the backbone of the SDM. While the preliminary CLD was developed by the research team alone, the knowledge it represents was originally sourced from local stakeholders and, therefore, it could not have been developed without their involvement and expertise. Using input from the stakeholders during Workshop 3, the research team also changed each problem dimension into measurable quantities as required for the SDM. For example, while the problem dimension ‘Quality of Place’ is commonly used in policy and practice related to sustainable new developments (e.g. Ebbsfleet Development Corporation, 2017), it is not associated with a specific metric. Stakeholders agreed that high quality Blue-Green infrastructure creates high quality places, hence ‘Blue-Green space’ became the measurable variable to represent ‘Quality of Place’. Similarly, ‘Flood Risk Management’ became ‘Runoff rate’, and ‘Water Quality’ became ‘Ecological Status’. The research team then reproduced the CLD in Vensim® Software (by Ventana Systems) for presentation to the Ebbsfleet stakeholders at the next workshop (Figure 4b).

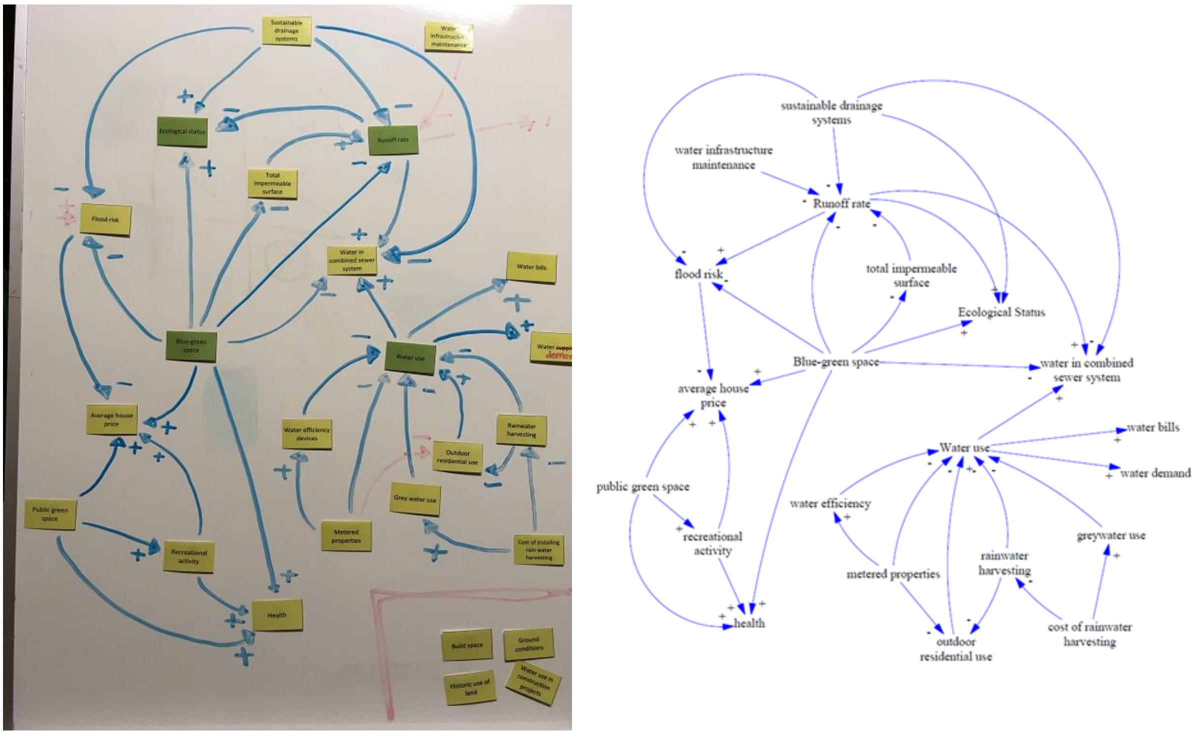


Figure 4. Preliminary Causal Loop Diagram (CLD) (a) photograph (b) reproduction in Vensim® Software (by Ventana Systems). Originally part of a blog series on the Ebbsfleet system dynamics participatory workshops (Blue-Green Cities blog, 2018)

Workshop 4 - Validating the CLD

The preliminary CLD in Figure 4 was presented to the Ebbsfleet stakeholders during the fourth workshop. The objective was for the stakeholders to assess the validity of the relationships represented in the CLD and make changes accordingly. A section of the CLD focusing on the potable water use problem dimension was then selected by the Ebbsfleet stakeholders for more detailed analysis and conversion into the SDM, based on discussion of their key strategic objectives and current focus with regards to sustainable water management. The problem dimension is hereafter termed ‘potable water use’ (Figure 5).

While reducing potable water consumption is of interest to all stakeholder groups, particularly as all new residential developments in the Ebbsfleet Garden City will be metered, the development of the modelling research question, and indeed the decision to focus on the potable water use problem, was led by Southern Water representatives as this aligns with their current Target 100 initiative: a commitment to support customers to reduce personal consumption to an average of 100 litres per day by 2040 (Southern Water, 2020). Such a reduction in water usage (and positive impact on the water balance) would further reduce the pressure on current infrastructure and water resources and the potential need for additional water supply infrastructure in the future. A key objective for the Ebbsfleet Development Corporation is to ensure enough water for domestic, commercial and industrial uses within the Garden City (Ebbsfleet Development Corporation, 2017) and water scarcity is a significant, and increasing risk for Kent County Council according to a recent climate change risk and impact assessment (Kent County Council, 2020). Discussions led to the modelling focus: 'How might residential potable water consumption in the Ebbsfleet Garden City be reduced through a range of interventions, such as socio-environmental and economic policy incentives or physical interventions?'

Following the decision to focus on potable water use, workshop participants were asked to add and remove variables, alter causal relationships and polarities, add variable definitions, and define units of measurements. The research team then refined the CLD based on the stakeholders' input, with several iterations between the team prior to the final CLD (Figure 5). Links in green represent variables and connections added by the research team to help the transition to the SDM, which required subsequent validation from the stakeholders.

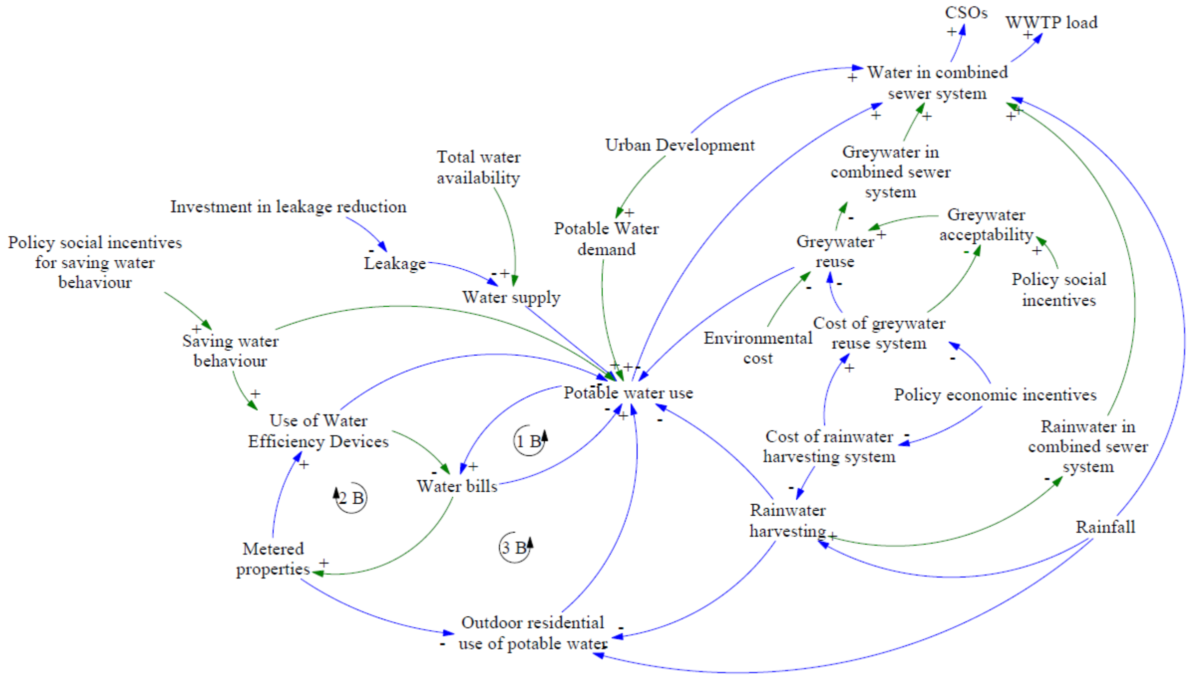


Figure 5. Final Causal Loop Diagram (CLD) for the Ebbsfleet Potable Water Use problem dimension. CSOs = combined sewer overflows, WWTP = wastewater treatment plant load, using Vensim® Software (by Ventana Systems)

Workshops 5 – Validating the SDM and scenario building

The final workshop focused on further developing the SDM and validating the variables, links and equations. The SD-Quantitative model created by the research team after workshop 4 was discussed with Ebbsfleet stakeholders with expertise in UWM. System boundaries and inputs were defined, data required to run the model were discussed in detail, and possible data sources were identified. Additionally, different scenarios under which to run the model were developed, focusing on how socio-environmental and economic incentives may affect the outcomes of the SDM (see Section 5 for further details on the SDM structure and scenario analysis).

Workshops 6 – Scenario analysis presentation

Lastly, the scenario analysis was presented to the stakeholders in a final meeting. The simulated results were collectively discussed, and stakeholders briefly explored how the model could be useful to them.

5. Outcomes of the participatory SDM process

5.1. The model structure

The model focuses on a systematic analysis of the urban water supply system in the Ebbsfleet Garden City (the full list of equations is included in Appendix II). The model is built upon the principle of water balance, performing a comparison between water demand and water supply and considering the potential impact of strategies such as Rainwater Harvesting (RWH) and Greywater Reuse (GWR). It runs over a time scale of 30 years, accounting for the evolution of the city from 2019 to 2049. This timescale considers both the time needed to complete the development of the area and the time needed for some variables to become fully effective. The simulation is based on a yearly time step (i.e. the water balance is computed annually) and it is focused on future residential development (i.e. it does not consider the existing buildings). Individual stakeholders' behaviours are aggregated for this analysis.

The overall structure of the SDM is presented in Figure 6. The variables in green identify input variables previously identified in the CLD and validated by the stakeholders. The variables in red identify input variables that have been added during workshop 5 and mainly represent measures/policies identified to modify the state of the system and its dynamic evolution. Based on the conceptual structure of the CLD, the model includes the components described in Table 2. The conceptual structure was developed through knowledge obtained from the expert judgement of the research team and Ebbsfleet stakeholders with expertise in UWM, in addition to existing reports and other public material. It thus represents one possible set up of an SDM.

Variables such as 'Command and control regulatory policy instruments', 'Social-Environmental Incentivising Policy Instruments' and 'Economic Incentivising Policy

Instruments' represent the possible macro areas of intervention for strategies and measures suggested by the stakeholders during the last participative workshop.

Table 2. Description of the SDM conceptual structure.

Variable	Description
Water supply	The water supply mainly depends on the 'availability' related to two main systems; 'Thames Water Utilities Limited' and 'Southern Water'. Thames Water systems are older and the effect of leakages is taken into account through a 'Leakages ratio', depending both on 'Ageing' and on the 'Investment in leakage reduction'. For simplicity, both 'Ageing' and 'Investment in leakage reduction' are constant for this analysis. The 'yearly water availability' represents a limit/target value that could be supplied by the water utilities (currently per capita water consumption is approximately 120 l/day). Additionally, the supply side includes the potential contribution of 'Infiltration-storage-recharge volume'.
Water bills	Water bills (stock) is computed from the identification of a baseline unit value (in current conditions, the price of water for residential use is 0.8073 £/l)[1] and potential causes for its increase. The dynamics of this stock is described by the following differential equation (see also definition 45 in Appendix II which gives the notations in the Vensim format): $Water\_bills_{t+1} = Water\_bills_t + WB\_change\_rate * dt$ Here *WB_change_rate* is the rate of water bill increase. One assumption is that water bills can increase until a maximum value of £1.2 per l (an increase of approx. 50%). The increase in 'water bills' is activated if the 'Potable water use' exceeds 70% of the water supply and the increase is limited by the 'Use of water efficiency devices'. Strategies and policy instruments can contribute to changes in this variable, as discussed during the stakeholder workshop.
Rainwater harvesting (RWH)	The effectiveness of RWH systems starts from a base value (i.e. 0), and increases according to the change in two variables; 'RWH properties #' (i.e. the total number of households with such systems installed, compared to the total number of properties (12,000)) and 'Rainfall'. According to the information provided by experts during the stakeholder workshop, the volume of RWH is assumed to be almost 60% of the volume needed for toilet flushing (i.e. 1/3 of the water demand).
Greywater reuse (GWR)	This variable describes the volume of Grey Water (GW) reused on a yearly basis for residential purposes only. It increases in a way that is proportional to potable water use until a certain threshold is reached (depending on the effectiveness of the treatment and on the amount of potable water use that cannot be reused, globally ~30%). Additionally, the increase in GWR is affected by the level of 'GWR acceptability' by the potential end-users, and by the 'Cost of GWR systems'. The 'GWR acceptability' is affected both by economics, i.e. the 'Cost of GWR systems', and by levels of 'Environmental Awareness'. Strategies and ad hoc policy instruments can modify these variables.

[1] https://www.thameswater.co.uk

Grey Water (GW)	This variable defines the volume of GW that flows yearly in combined sewer systems. It mainly depends on 'Potable water use' and on 'Greywater reuse'. It relates to 'CSOs' (Combined Sewer Overflows) and to the 'WWTP load' (Wastewater Treatment Plant load). The latter could be reduced by 'Investments in WWTP'. The wastewater contribution is a fraction of the potable water (0.7, see Appendix II).
Population	This stock defines the evolution of the population in the area, and there is an 'increase rate' related to the progress of 'urban development' (i.e. the number of houses built). The dynamics of this stock is described by the following differential equation (see also definition 26 in Appendix II which gives the notations in the Vensim format): $Population_{t+1} = Population_t + Increase\_rate*dt$ The key assumption is that the population increases with time, as the number of buildings increase. An average of 3 persons per household is assumed, and the total number of 12,000 houses to be built before the project is completed. 'Population' also directly affects the evolution of other variables, primarily the water demand.
Potable Water Balance	The dynamics of this stock is described by the following differential equation (see also definition 27 in Appendix II which gives the notations in the Vensim format): $Potable\_water\_balance_{t+1} = Potable\_water\_balance_t + (Inflow-Outflow)*dt$ The rate of change in this stock is the net result of its increase (i.e. inflow to the stock from 'RWH' and 'Yearly water supply') and decrease (i.e. outflow from the stock due to 'Potable water demand' and 'Outdoor residential use of potable water', and adjusted to consider the use of water efficiency devices). Negative values of the potable water identify a potential water supply deficit. Positive values instead represent the potential volume of water that can be saved in different scenarios (which could be either accumulated or just not withdrawn/supplied).
(Water) Balance	This component depends primarily on the difference between the 'Potable water demand' (which is conditioned by the 'water bills') and the 'Yearly water supply'. It is directly affected by the 'Outdoor residential use of potable water', as well as by the 'Greywater reuse' and 'Rainwater harvesting'. It represents one of the key elements of the model.
Use of water efficiency devices	This variable depends on the number of 'Metered properties', 'Environmental awareness' (related to 'Social-Environmental incentivising policy instruments') and 'Command and control authoritative policy instruments'. 'Metered properties' (current value 0.8) is a dimensionless input variable, changing from 0 (no properties with metering systems) to 1 (all properties with metering systems). All new properties in the Ebbsfleet Garden City will have a water meter installed.
Environmental awareness	The dynamics of this stock is described by the following differential equation (see also definition 9 in Appendix II which gives the notations in the Vensim format): $Environmental\_awareness_{t+1} = Environmental\_awareness_t + Inflow\_EA*dt$ Here *Inflow_EA* is the rate of change in this stock and is calculated as 10% of the product between 'Environmental awareness' and 'Socio-Environmental incentivising policy instruments'. The maximum value of

	the ‘Environmental awareness’ stock is capped at 0.8; once the maximum value is achieved no further increase takes place.

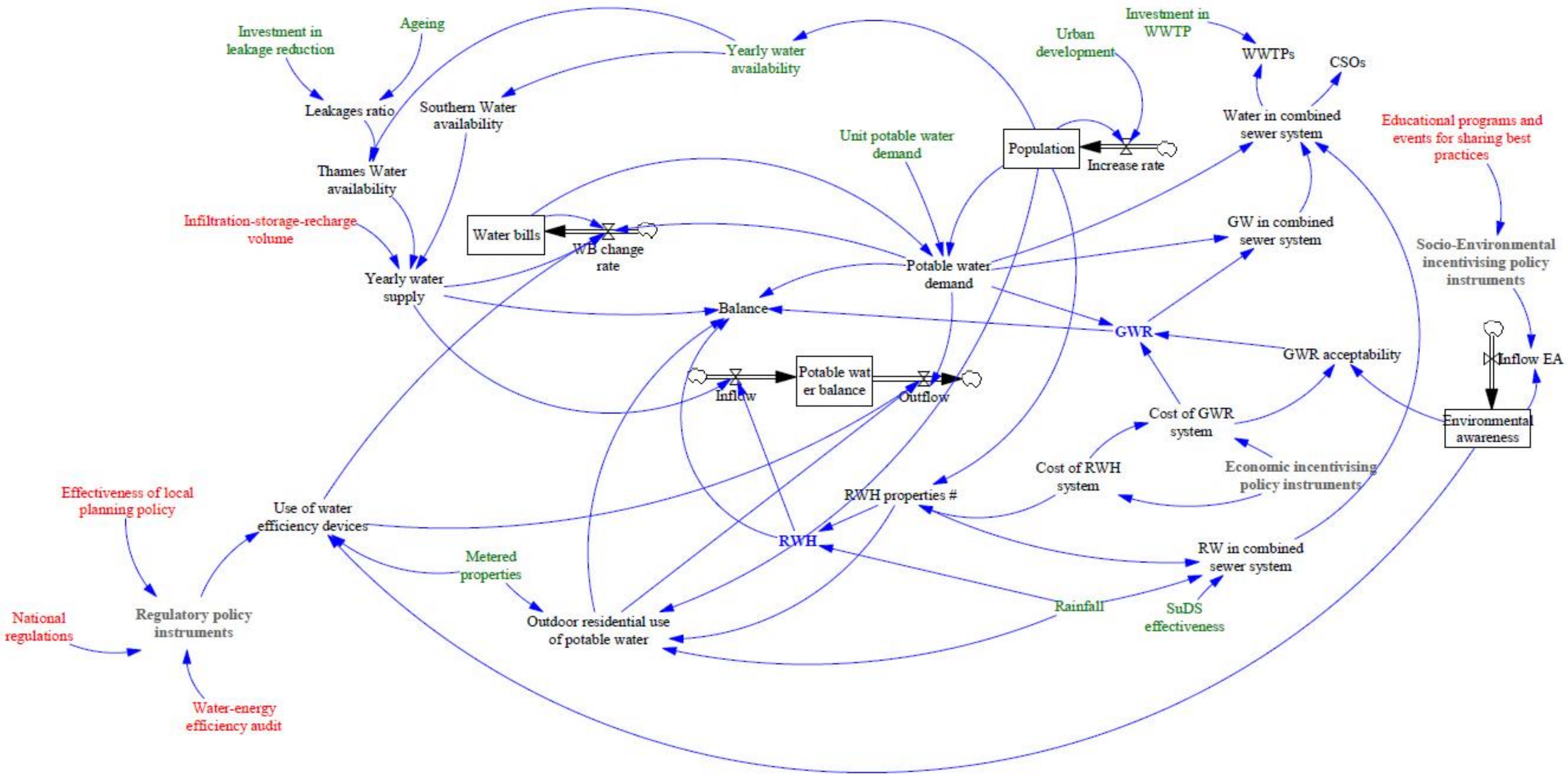


Figure 6. System Dynamics Model (SDM) for the Potable Water Use problem dimension. Variables in green = input variables already identified in the CLD and validated by the stakeholders; red = input variables that were added during workshop 5; WWTP = wastewater treatment plant load, CSOs = combined sewer overflows, GW = greywater, GWR = greywater reuse, BAU = business-as-usual, WB = water bills, RWH = rainwater harvesting, EA = environmental awareness, SuDS = sustainable drainage systems.

5.2. Scenarios

Different strategies were proposed and co-designed through a participatory exercise during the fifth stakeholder workshop and separated into different policy instruments. The scenario analysis aimed to semi-quantitatively assess the impact of the different strategies on the model output variables in order to: i) identify suitable combinations of strategies, ii) understand their effectiveness, potential consequences, side effects and synergistic impacts, and iii) discuss the feasibility and the relevance of the selected strategies, in view of the main objective (improving the sustainability of water management in the Ebbsfleet Garden City). The scenario analysis does not aim to quantify the exact changes in the state of model variables, rather it compares the trends, under multiple different conditions, of the key variables (i.e. environmental awareness, greywater reuse, rainwater harvesting, outdoor residential use of potable water, water balance). For this reason, most of the input variables used in the scenario analysis have been replaced by a dimensionless scale (0-1). As an example, values close to 0 represent a variable which is ‘low’, ‘limited’, ‘not available’, or ‘not effective’. Values close to 1 represent ‘high’, ‘relevant’, ‘present’, or ‘effective’ characteristics of the same variable. The comparison is performed using the Business-As-Usual (BAU) condition as a reference. More specifically, BAU describes the potential evolution of the system if the main variables and drivers keep their current state. Although several different scenarios were collectively built and tested, only a small subset determined the most relevant by the stakeholders is discussed in full detail.

Scenario A ‘Actions on the supply side’. This scenario analyses the implementation of ‘technical’ actions on the infrastructural system, i.e. orientated to improve the state of the network (through leakage reduction) and to increase the available volume of water (assuming that an additional volume is made available using infiltration-storage-recharge systems). The additional volume is calculated as a fraction (5-10%) of the volume to be supplied in 2049 (the end of the model run) (Table 3).

Table 3. Scenario A ‘Actions on the supply side’

VARIABLE	BAU (Business-As-Usual)	SCENARIO A
Investment in leakage reduction [-]	0.5	0.9
Infiltration-storage recharge volume [m^3]	0	7.665e+007

Scenario B ‘Policy Instruments’. This scenario is based on the combination of different policy instruments, i.e. socio-environmental and/or economic policy instruments that are implemented together with ad hoc regulatory policy instruments (Table 4).

Table 4. Scenario B ‘Policy Instruments’

VARIABLE	BAU (Business-As-Usual)	SCENARIO B
Socio-environmental incentivising policy instruments [-]	0.2	0.9
Economic incentivising policy instruments [-]	0.2	0.9
Effectiveness of local planning policy [-]	0.5	0.9
National regulations [-]	0.3	0.9
Water-energy efficiency audit [-]	0.3	0.9

Scenario C ‘Mixed strategy’. This scenario is based on the combination of both the investments on the ‘supply side’ (scenario A) and policy instruments (scenario B) and aims to highlight the beneficial role of synergistic implementation of multiple measures acting on different dimensions of the problem (Table 5).

Table 5. Scenario C

VARIABLE	BAU (Business-As-Usual)	SCENARIO C
Socio-environmental incentivising policy instruments [-]	0.2	0.9
Economic incentivising policy instruments [-]	0.2	0.9
Effectiveness of local planning policy [-]	0.5	0.9
National regulations [-]	0.3	0.9

Water-energy efficiency audit [-]	0.3	0.9
Investment in leakage reduction [-]	0.5	0.9
Infiltration-storage recharge volume [m^3]	0	7.665e+007

- **Scenario D 'Rainwater harvesting'.** This scenario explores the effect of installing RWH systems in an increasing number of properties over the whole area. Given current low levels of acceptability of RWH systems, this scenario explicitly considers the impact of socio-institutional measures, particularly assuming an increase in both 'Educational programmes and events for sharing best practices' (0.9) and 'Economic incentivising policy instruments' (0.9). Three following 'sub-scenarios' were investigated, considering a different number of houses equipped with RWH systems: Scenario D1: 10% of houses with RWH systems
- Scenario D2: 30% of houses with RWH systems
- Scenario D3: 70% of houses with RWH systems

5.3. Scenario Analysis

The results of the scenario analysis are shown in Figures 7 and 8, and compare the effectiveness of different measures/strategies. Specifically, the actions on the supply side (Scenario A) show both an immediate and a long-term positive effect directly on the potable water balance as additional volume is made available to the users (Figure 8). However, this does not have any relevant impact in terms of behaviours orientated to water saving and sustainable use of water resources, i.e. there is no influence on environmental awareness or on the use of alternative water sources such as RWH or GWR (Figures 7b and 7c). Scenario B shows that a similar impact can be achieved by activating policy instruments with both socio-institutional actions and strategies on the economic side. This directly increases 'environmental awareness' (Figure

7a), which should have a cascading positive impact on the use of RWH and GWR, reducing water consumption and consequentially improving the water balance (Figures 7d and 8). Although the expected benefit to the water balance is lower in Scenario A than in Scenario B, this result can be achieved with a combination of actions that are not related to the infrastructure system. Scenario C shows that a synergistic combination of actions on the supply side and on the policy side can have a reinforcing effect, and produce a much higher increase in water balance (Figure 8), due to both an increased water availability and an improved use of alternative water sources (GWR and RWH). The specific contribution of RWH has been explicitly investigated in Scenarios D1-D2-D3, which incorporate the role of 'soft' measures ('Educational programmes and events for sharing best practices' and 'Economic incentivising policy instruments') aiming to increase the adoption of RWH systems. Even a moderate change in the area equipped with RWH systems may have a meaningful impact on the water balance of the whole area.

The model in its current form assumes that actions start at the beginning of the simulation, which does not allow for corrective actions depending on system evolution. Negative water balance (Figure 8) represents potentially unsustainable system conditions which impact the quality of the water supply and would require corrective actions. Similarly, positive water balance defines a system fully capable of guaranteeing water supply, and define the potential volume of water that can be saved in different scenarios (which could be either accumulated or just not withdrawn). In such conditions additional actions should be implemented (e.g. a reduction of supply). These features will be further improved in future model developments.

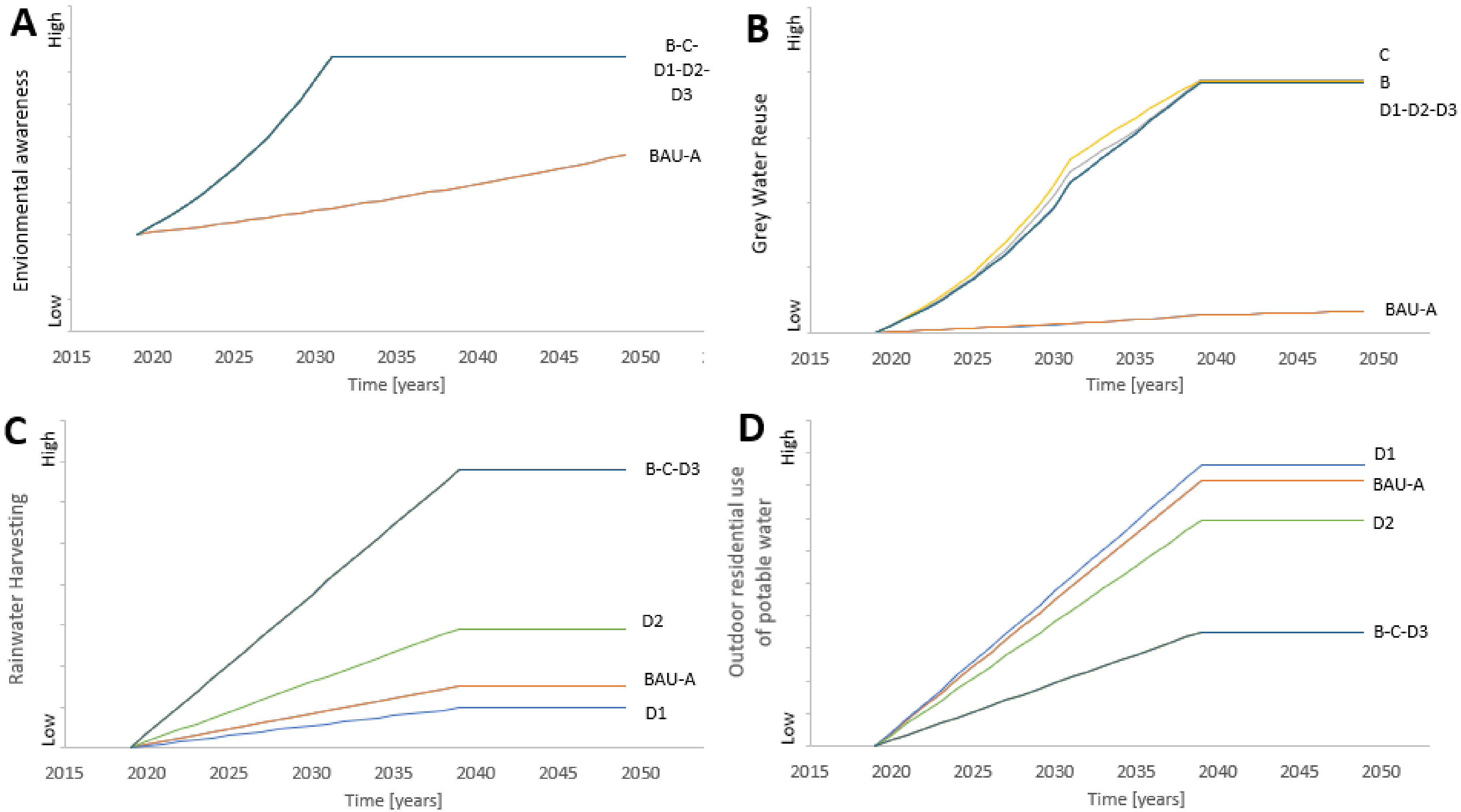


Figure 7. Evolution of the variables a) Environmental Awareness, b) Grey Water Reuse (GWR), c) Rainwater Harvesting (RWH) and d) Outdoor Residential Use of Potable Water under different scenarios. Where scenarios plot on the same line, their labels are separated by a hyphen. For example, where Business as Usual and Scenario A overlap, the label 'BAU – A' is used.

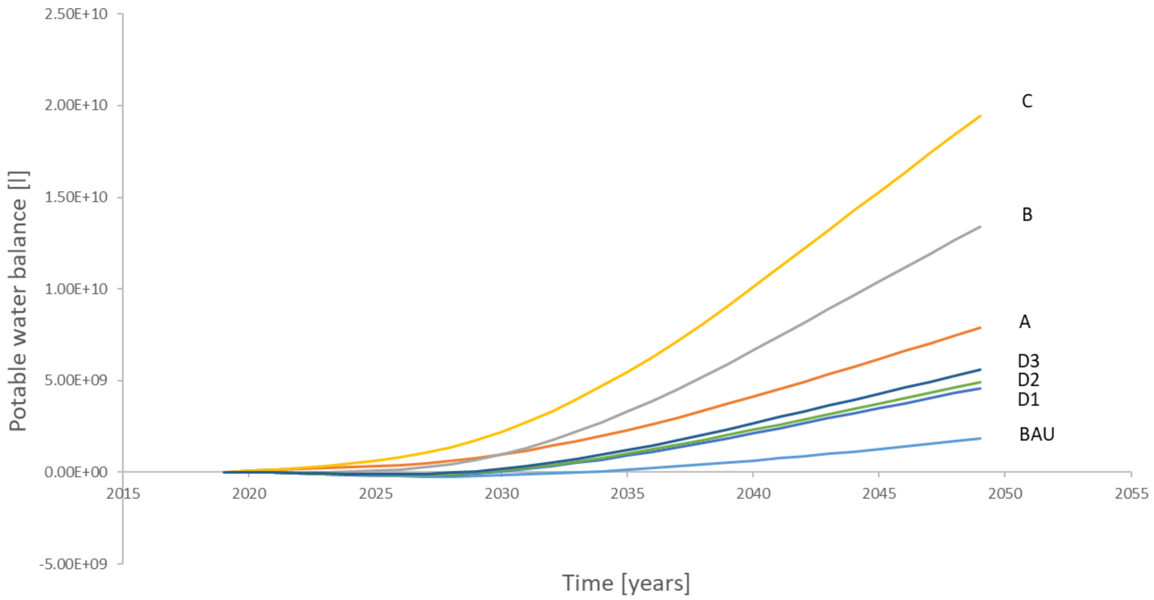


Figure 8. Evolution of the variable ‘Potable water balance’ in the different scenarios. BAU refers to Business-As-Usual scenario

6. Discussion

The collaborative development of an SDM in Ebbsfleet Garden City enabled numerous stakeholders to contribute their own knowledge and insights into the model, and ensure that local knowledge of the system fed into its dynamics. Throughout the model-building process, the participatory nature of SDM supported a collective learning process, giving the stakeholders a more holistic understanding of the urban water system, its interdependencies and complexities. The stakeholders explored how different variables impacted upon the system dynamics, and through these observations were able to identify different strategies that might be employed to reduce potable water use in the Ebbsfleet Garden City.

By investigating several potential future scenarios, the stakeholders were able to explore how different strategies might play out in the longer term, and how different strategies might be combined to achieve optimum urban water consumption. Some of these strategies, particularly socio-institutional measures, are traditionally difficult to model, however SDM provides a methodology where the effects of these can be seen alongside their quantitative counterparts. Scenario analysis is especially useful in this regard.

Some suggestions are relatively broad, for instance developing some form of socio-environmental and economic policy incentives that may appeal to local residents and businesses and help reduce their water consumption, but they do help to highlight relevant issues. Approaches on the 'supply side', such as investing in projects to reduce leakage, or increasing the available volume of water through infiltration-storage-recharge systems, support meeting future water supply and improving the water balance over both the short and long term. However, an improved efficiency (more water savings and an increase in water balance) can be achieved if socio-environmental and economic policy incentives are activated as well. Furthermore, these incentives directly support the implementation of RWH and GWR systems through an increase of the environmental awareness.

The key contribution of this paper relates to the participatory modelling process, in which invaluable local knowledge of the Ebbsfleet Garden City was utilised to co-develop an SDM that addressed a problem that is important to a wide range of stakeholders. Previously the solution to this 'wicked' problem, namely reducing potable water use, hinged on whether changes in societal behaviour or regulations/price increases would have the greatest impact. The SDM allowed the stakeholders to explore multiple potential future scenarios that both combined these changes and looked at them in isolation, thus giving them an insight into how different strategies interact. It is beyond the scope of this SDM to identify what specific policy strategies need to be selected or how they should be structured in detail. The objective of the SDM is to provide evidence of the impacts of these broad strategies on the system as a whole, and highlight future discussion topics that local stakeholders must address in order to achieve sustainable UWM. The general interventions that are covered in the scenario analysis presented here should be further explored in order to design more specific actions, such as possible interventions for increasing the environmental awareness (e.g. engagement campaigns) or other ‘socio-environmental’ incentives or competitions based on different sustainability criteria, e.g. which households/streets can reduce their water consumption the most over a defined period (Pluchinotta et al. 2019). Further work is needed to focus on the details of these strategies and their practical implementation. For instance, the identification of which stakeholders need to be involved in the actual decision-making process should be further discussed, in light of shared responsibilities and current regulations and legislation.

Stakeholders were generally supportive of the SD modelling process and, during the last meeting, stakeholders positively reaffirmed the usefulness of the model. They referenced some future work where they see the SD model as being useful. The stakeholders mentioned that the findings of this study could be useful in supporting the formulation of the Southern Water “Target 100” agenda (this being also the focus of the SD model) and other strategies, e.g. the Ebbsfleet development corporation Sustainable homes agenda and the “Code for Sustainable Homes, Ebbsfleet Garden City”. Furthermore, stakeholders emphasised the need for a joined approach to develop integrated water management in Ebbsfleet Garden City and discussed the leakage reduction as priority issue, as a significant proportion of the water gets lost during the transmission.

6.1. Limitations

All models represent a simplification of reality and model definition is influenced by, among other factors, the modelling objective, data availability and limitations imposed by time and logistical constraints. The limitations of the participatory SDM presented in this paper include an oversimplification of processes such as population growth (more realistically represented by considering migration, birth and death rates), the absence of a feedback mechanism for adapting the supply to the demand with time (more realistically the supply would be reduced following a potentially lower demand thanks to the wider use of RWH and GWR), the lack of attention to the rebound effect and limited detail regarding changes in environmental awareness. The latter is complex yet in the current model structure it is set to increase proportionally to the application of the socio-environmental policy instruments. While the current model structure is adequate for the analysis presented in this paper, future developments should explore potential links between environmental awareness and other variables, e.g. water tariffs.

The main limitations of SDMs are related to the limited capability of explicitly representing spatial processes and micro-scale dynamics. SDMs are not intuitive and have a low direct reusability (their replicability is strictly related to the specificities of the case study under consideration), and only provide a partial view of the problem (depending on the number and knowledge of the stakeholders involved). SDM does not allow a thorough analysis and comparison of strategies in terms of benefits and costs, for which we refer to specific methodologies (e.g. Cost-Benefit Analysis, Multiple-Criteria Decision Analysis).

From a collaborative perspective, the main limitation is a lack of regular participation in workshops by the stakeholder group. Stakeholders in Ebbsfleet underlined the strain of their daily workload which made their participation in the workshops inconsistent. Furthermore, there is competition for airtime with similar participatory initiatives, which further decreases the amount of time and interest that stakeholders could give to developing the SDM, often not seen as a 'necessity' when compared with other aspects of their work. One of the biggest challenges is thus encouraging stakeholders to attend workshops and ensure continuity between workshops. Despite this, there was an abundance of positive feedback from stakeholders about the content of the workshops, where they reported that in the process of developing the SDM they learned new aspects about their practice, had a chance to reflecting on communal topics and were informed of the perspectives of other stakeholders.

7. Conclusions

This study presents the first investigation of sustainable water management in the Ebbsfleet Garden City and highlights the importance of participatory modelling approaches in exploring solutions to water challenges that meet the strategic objectives of different stakeholder organisations, in this case, reducing potable water use to tackle the increasing risk of water scarcity in south east England. The development of the Ebbsfleet Garden City SDM allowed exploration of sustainable UWM in a structured way, facilitating stakeholders' understanding of where future interventions for reducing urban water consumption in the Ebbsfleet Garden City might be best focused. The participatory nature of the model-building process supported a collective learning process, beginning with the analysis of the complexity of the whole system and enhancing comprehension of the myriad interdependencies and complexities. The outcomes from the SDM and the scenario analysis suggest a range of paths that could be followed to reduce potable water use in the Ebbsfleet Garden City. The SDM approach is thus an effective way to support decision-making at a strategic, system-wide level through collaborative discussion, to ultimately enable the exploration of long-term consequences of alternative UWM strategies, particularly those that are difficult to include in quantitative models (e.g. socio-institutional changes). Improved integration of the SDM with more quantitative tools (e.g. Urban Water Metabolism modelling) is a future objective to provide more detailed evidence of the impacts of different actions and strategies on UWM.

Acknowledgements

This research was performed as part of an interdisciplinary project undertaken by the Urban Flood Resilience Research Consortium (www.urbanfloodresilience.ac.uk). This work was supported by the UK Engineering and Physical Sciences Research Council (grant numbers EP/P004180/1, EP/P003982/1, EP/P004210/1, EP/P004318/1, EP/P004431/1 and **EP/R511699/1**). The associated data and metadata are available at https://doi.org/10.17639/nott.7042. We would like to thank Ebbsfleet Water Forum stakeholders (formally the Ebbsfleet Learning and Action Alliance) for their contributions and support of this work.

References

Ahiablame, L., Engel, B., Chaubey, I., (2012). Effectiveness of low impact development practices: Literature review and suggestions for future research. Water Air Soil Pollut. 223, 4253-4273.

Ashley, R., Blanskby, J., Newman, R., Gersonius, B., Poole, A., Lindley, G., Smith, S., Ogden, S., Nowell, R., (2012). Learning and Action Alliances to build capacity for flood resilience. J. Flood Risk Manage. 5, 14–22.

Ashley, R., Lundy, L., Ward, S., Shaffer, P., Walker, L., Morgan, C., Saul, A., Wong, T., Moore, S., (2013). Water-sensitive urban design: opportunities for the UK. Municipal Engineer, 166(ME2), 65-76.

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

Beck, M.B., Fath, B.D., Parker, A.K., Osidele, O.O., Cowie, G.M., Rasmussen, T.C., Patten, B.C., Norton, B.G., Steinemann, A., Borrett, S.R., Cox, D., Mayhew, M.C., Zeng, X.Q., 2002. Developing a concept of adaptive community learning: Case study of a rapidly urbanising watershed. Integrated Assessment, 3(4), 299-307.

Bell S (2017) Urban Water Sustainability. Routledge.186p

Behzadian, K., Kapelan, Z. (2015). Modelling metabolism based performance of an urban water system using WaterMet2. Resources, Conservation and Recycling 99 84–99

Bakhtiari, P. H., Nikoo, M. R., Izady, A., & Talebbeydokhti, N. (2020). A coupled agent-based risk-based optimization model for integrated urban water management.

Sustainable Cities and Society, 53 (November 2019), 101922. https://doi.org/10.1016/j.scs.2019.101922

Bérard, C. (2010). Group model building using system dynamics: An analysis of methodological frameworks, Electronic Journal of Business Research Methods, 8 (1), pp. 35-45.

Blue-Green Cities blog (2018). Using System Dynamics for Sustainable Water Management in Ebbsfleet: Part 3. https://blogs.nottingham.ac.uk/blue-greencities/2018/10/02/using-system-dynamics-for-sustainable-water-management-in-ebbsfleet-part-3/ accessed 17.08.20.

Brown, R.R., Keath, N. and Wong, T.H. (2009) Urban water management in cities: historical, current and future regimes. Water science and technology 59, 847-855.

Butler, D., Farmani, R., Fu, G., Ward, S., Diao, K. and Astaraie-Imani, M. (2014) A New Approach to Urban Water Management: Safe and Sure. Procedia Engineering 89, 347-354.

Cheng, L., 2010. System dynamics model of Suzhou water resources carrying capacity and its application. Water Science and Engineering, 3(2), 144-155.

Chhipi-Shrestha, G., Hewage, K., Sadiq, R., 2017. Water-Energy-Carbon nexus modeling for urban water systems: system dynamics approach. J. Water Resour. Plann. Manage., 143(6),

Chhipi-Shrestha, G., Hewage, K., 2018. Economic and energy efficiency of net-zero water communities: system dynamics analysis. J. Sustainable Water Built Environ, 4(3), 1-14.

Coutts, A., Tapper, N., Beringer, J., Loughnan, M., Demuzere, M. (2012). Watering our cities: The capacity for Water Sensitive Urban Design to support urban cooling and improve human thermal comfort in the Australian context. Progress in Physical Geography, 1-27, doi: 10.1177/0309133312461032.

Coletta V.R., Pagano A., Pluchinotta I., Fratino U., Scrieciu A., Nanu F., Giordano R; (2020). 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

Díaz, P., Stanek, P., Frantzeskaki, N., Yeh, D.H. (2016). Shifting paradigms, changing waters: Transitioning to integrated urban water management in the coastal city of Dunedin, USA, Sustainable Cities and Society, Volume 26, Pages 555-567, https://doi.org/10.1016/j.scs.2016.03.016

Ebbsfleet Development Corporation (2017) Ebbsfleet Implementation Framework. https://ebbsfleetdc.org.uk/wp-content/uploads/2017/04/Ebbsfleet-Implementation-Framework.pdf accessed 13.01.20.

Freeman, David M. (2000) Wicked water problems: Sociology and local water organizations in 726 addressing water resources policy. J Am Water Res Assoc. 36:483-491.

Giordano, R., Brugnach, M., Pluchinotta, I., 2017. Ambiguity in problem framing as a barrier to collective actions: some hints from groundwater protection policy in the Apulia region. Group Decis. Negot. 26 (5), 911–932.

Gleick, P.H. (1998) Water in crisis: paths to sustainable water use. Ecological applications 8, 571-579.

Gosling, S.N. and Arnell, N.W. (2016) A global assessment of the impact of climate change on water scarcity. Climatic Change 134, 371-385.

Hellström, D., Jeppsson, U. and Kärrman, E. (2000) A framework for systems analysis of sustainable urban water management. Environmental impact assessment review 20, 311-321.

Hoekstra, A.Y. Buurman, J., van Ginkel, K.C.H. (2018). Urban water security: A review Environ. Res. Lett.13 053002

Jeong, S., Park, J. (2020). Evaluating urban water management using a water metabolism framework: A comparative analysis of three regions in Korea, Resources, Conservation and Recycling, Volume 155, https://doi.org/10.1016/j.resconrec.2019.104597

Kent County Council (2020). Climate Change Risk and Impact Assessment for Kent and Medway. Part 1: Methodology and Summary of Findings. https://www.kent.gov.uk/__data/assets/pdf_file/0015/111381/CCRIA-for-Kent-and-Medway-part-one-methodology-and-summary-findings.pdf accessed 17.08.20.

Lane, D.C, Munro, E. Husemann, E. (2016). Blending systems thinking approaches for organisational analysis: Reviewing child protection in England, European Journal of Operational Research, Volume 251, Issue 2, Pages 613-623, https://doi.org/10.1016/j.ejor.2015.10.041

Lowe, J., Bernie, D., Bett, P., Bricheno, L., Brown, S., Calvert, D., Clark, R., Eagle, K., Edwards, T., Fosser, G., Howard, T., Kaye, N., Kendon, E., Krijnen, J., Maisey, P., McDonald, R., McInnes, R., McSweeney, C., Mitchell, J., Murphy, J., Palmer, M., Roberts, C., Rostron, J., Sexton, D., Thronton, H., Tinker, J., Tucker, S. and Yamazaki, K. (2018) UKCP18 Science Overview report. Met Office Hadley Centre, Exeter (2018).

Marlow, D.R., Moglia, M., Cook, S. and Beale, D.J. (2013) Towards sustainable urban water management: A critical reassessment. Water research 47, 7150-7161.

Martis, M. S. (2006). Validation of simulation based models: A theoretical outlook. Electronic Journal of Business Research Methods, 4(1), 39–46.

Maskrey S, Vilcan T, O’Donnell E and Lamond J. (2020) Using Learning and Action Alliances to build capacity for local flood risk management. Environmental Science and Policy, 107, 198-205.

O'Donnell, E. and Thorne, C. (2020) Drivers of Future Urban Flood Risk. Phil. Trans. R. Soc. A 378, 20190216. http://dx.doi.org/10.1098/rsta.2019.0216

Özerol, G., Dolman, N., Bormann, H., Bressers, H., Lulofs, K., & Böge, M. (2020). Urban water management and climate change adaptation: A self-assessment study by seven midsize cities in the North Sea Region. Sustainable Cities and Society, 55(January), 102066. https://doi.org/10.1016/j.scs.2020.102066

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, Science of the Total Environment, 690 543–555. https://doi.org/10.1016/j.scitotenv.2019.07.059

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., Kazakçi, A.O., Giordano, R., Tsoukiàs, A., 2019b. Design theory for generating alternatives in public decision making processes. Gr. Decis. Negot. 28, 341–375. https://doi.org/10.1007/s10726-018-09610-5

Renouf, M.A. and Kenway, S.J. (2017), Evaluation Approaches for Advancing Urban Water Goals. Journal of Industrial Ecology, 21: 995-1009. doi:10.1111/jiec.12456

Rouwette, E.A.J.A., Vennix, J.A.M. and Mullekom, T.v. (2002), Group model building effectiveness: a review of assessment studies. Syst. Dyn. Rev., 18: 5-45. doi:10.1002/sdr.229

Scott, R.J., Cavana, R.Y., Cameron, D. (2016) Recent evidence on the effectiveness of group model building, European Journal of Operational Research, Volume 249, Issue 3, 2016, 908-918

Sharma, A., Pezzaniti, D., Myers, B., Cook, S., Tjandraatmadja, G., Chacko, P., Chavoshi, S., Kemp, D., Leonard, R. and Koth, B. (2016) Water sensitive urban design: An investigation of current systems, implementation drivers, community perceptions and potential to supplement urban water services. Water 8, 272.

Simonovic, S.P., Li, L., 2003. Methodology for assessment of climate change impacts on large-scale flood protection system. Journal of Water Resources Planning and Management, 129(5), 361-371.

Southern Water (2020). Target 100. https://www.southernwater.co.uk/water-for-life/target-100 accessed 24.07.20.

Sterman, J., (2000). Business Dynamics: Systems Thinking and Modelling for a Complex World. McGraw-Hill Higher Education.

Sušnik, J., Vamvakeridou-Lyroudia, L.S., Savić, D.A., Kapelan, Z., 2012. Integrated System Dynamics Modelling for water scarcity assessment: Case study of the Kairouanregion. Science of the Total Environment, 440, 290-306. DOI: 10.1016/j.scitotenv.2012.050.085.

Sušnik, J., Vamvakeridou-Lyroudia, L.S., Baumert, N., Kloos, J., Renaud, F., La Jeunesse, I., Mabrouk, B., Savić, D.A., Kapelan, Z., Ludwig, R., Fischer, G., Roson, R., Zografos, C., 2014. Interdisciplinary assessment of sea-level rise and climate change impacts on the lower Nile delta, Egypt, Journal Science of the Total Environment, 503-504, 279-288.

Sušnik, J.; Chew, C.; Domingo, X.; Mereu, S.; Trabucco, A.; Evans, B.; Vamvakeridou-Lyroudia, L.; Savić, D.; Laspidou, C.; Brouwer, F., 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.

TCPA (no date) Garden City Principles. Town and Country Planning Association (TCPA). https://www.tcpa.org.uk/garden-city-principles accessed 13.0120.

Thompson J.P., Howick, S., Belton, V. (2016) Critical Learning Incidents in system dynamics modelling engagements, European Journal of Operational Research, Volume 249, Issue 3, Pages 945-958, https://doi.org/10.1016/j.ejor.2015.09.048

Tidwell, V.C., Passell, H.D., Conrad, S.H., Thomas, R.P., 2004. System dynamics modeling for community-based water planning: Application to the Middle Rio Grande. Aquat. Sci., 66, 357-372.

UN (2018) World urbanisation prospects: The 2018 revision [key facts]. https://esa.un.org/unpd/wup/Publications/Files/WUP2018-KeyFacts.pdf accessed 18.03.19.

Venkatesh, G., Helge Brattebø, Sveinung Sægrov, Kourosh Behzadian & Zoran Kapelan (2017) Metabolism-modelling approaches to long-term sustainability assessment of urban water services, Urban Water Journal, 14:1, 11-22, DOI: 10.1080/1573062X.2015.1057184

Vennix, J. A. M., Andersen, D. F., Richardson, G. P., & Rohrbaugh, J. (1992). Model-building for group decision support: Issues and alternatives in knowledge elicitation. European Journal of Operational Research 59(1): 28–41

Vennix, J.A.M., 1996. GroupModel Building: Facilitating Team Learning Using System Dynamics. Wiley.

Wade, S. Barnett, C. and Fenn, T. (2006). Climate change and water resources. DEFRA Cross Regional Climate Change Impacts and Adaptation Research Programme: Topic C –Water. SR 664. HR Wallingford.

Ward (2005), The garden city: Past, present and future. Routledge, Oxford.

Woods Ballard, B., Wilson, S., Udale-Clarke, H., Illman, S., Scott, T., Ashley, R. and Kellagher, R. (2015) CIRIA report C753 The SuDS Manual.

Xi, X., Poh, K.L., 2013. Using system dynamics for sustainable water resources management in Singapore. Procedia Computer Science, 16, 157-166.

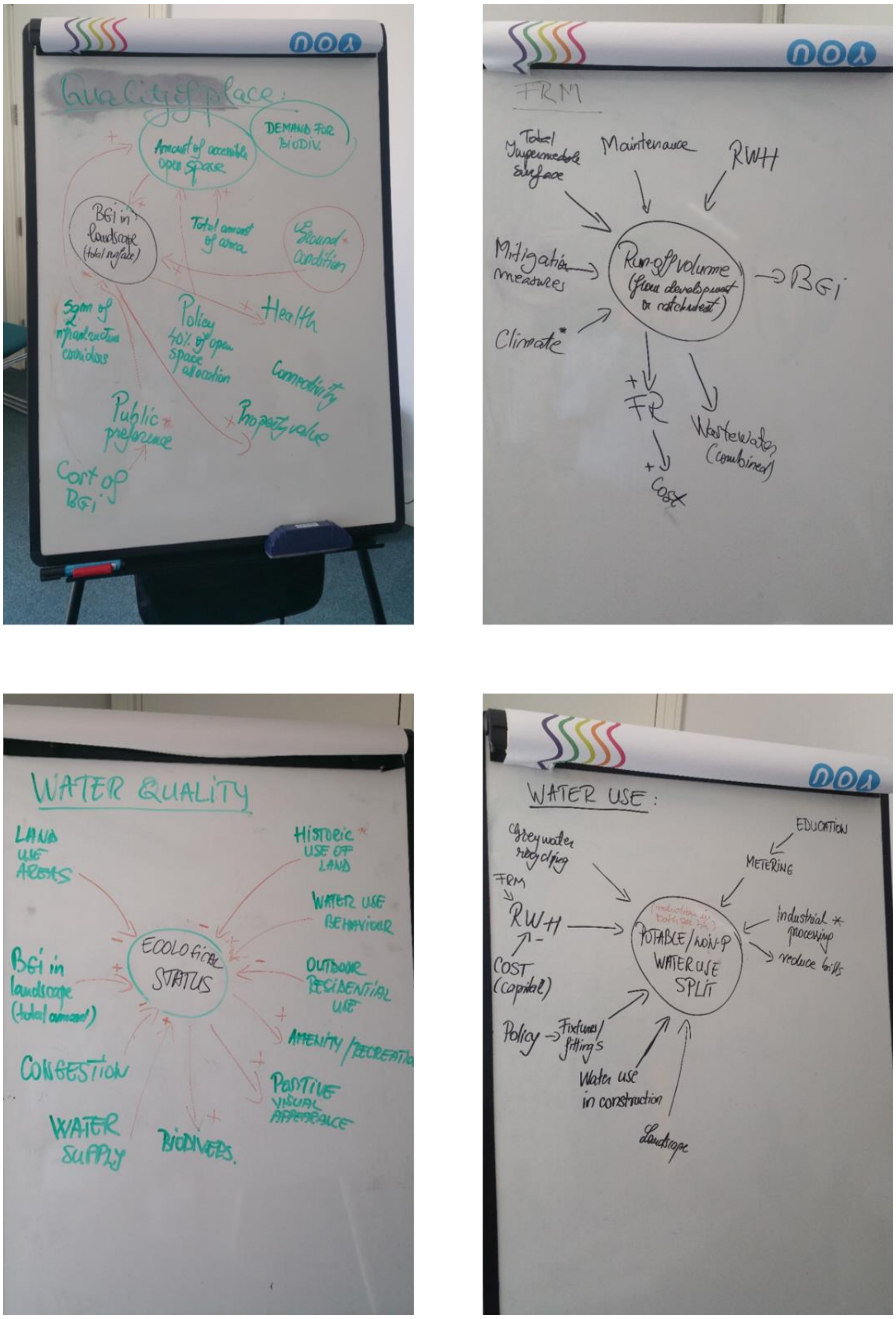
Winz, I., Brierley, G., Trowsdale, S., 2009. The use of system dynamics simulation in water resources management. Water Resour Manage, 23, 1301-1323.

Zarghami, M., Akbariyeh, S., 2012. System dynamics modeling for complex urban water systems: Application to the city of Tabriz, Iran. Resources, Conservation and Recycling, 60, 99-106.

Zhuge, C., Yu, M., Wang, C., Cui, Y., & Liu, Y. (2020). An agent-based spatiotemporal integrated approach to simulating in-home water and related energy use behaviour: A test case of Beijing, China. Science of the Total Environment, 708, 135086. https://doi.org/10.1016/j.scitotenv.2019.135086

Appendix I

This section includes additional details related to the CLDs developed during the qualitative modelling process described in section 4.2 of the manuscript.



Appendix I Figure A. Variables identified by Ebbsfleet stakeholders at a modelling workshop to describe the four main problem dimensions related to the sustainable water management. Originally published as part of a blog series (Blue-Green Cities blog, 2018a).

Appendix I Table A. Output from Workshop 3: a table detailing the variables included in the preliminary Causal Loop Aiagram, their meaning and potential sources of data. Adapted from Blue-Green Cities blog (2018b).

Variable name	New variable name	Meaning	Potential data sources
Potable/non-potable water use split	Water use	Potable water use per residential property	Southern/Thames Water
Ecological status	Biodiversity	Variety of plant/animal life in a specific area	Local authorities, Kent Wildlife Trust
BGI in landscape	Blue-green space	Area of Blue-Green space	Local authorities, Kent Wildlife Trust
Reduction in runoff	Runoff rate	Average surface water runoff rate for a specific rainfall event	Local authorities, Southern/Thames Water
Reduced bills	Water bills	Average annual residential water bill	Southern/Thames Water
Metering	Metered properties	Residential metered properties (as a % of total properties)	Southern/Thames Water
Fixtures/fitings	Water efficiency devices	Reduction in potable water use due to use of water efficiency devices	Southern/Thames Water
Greywater harvesting	Greywater reuse	Greywater use by residential property (as a % of total properties)	Southern/Thames Water, project research
Water use in construction	Water use in construction projects	Amount of water (L) used annually in construction projects	Project research
Water supply	Water supply	Annual potable water available in the Ebbsfleet Garden City	Project research
Cost (capital)	Cost of installing rainwater harvesting systems	Cost per rainwater harvesting installation	Southern/Thames Water, project research
FRM	Flood risk	Number of buildings currently in area of flood risk (e.g. EA's flood zone 3)	Environment Agency (EA)
RWH	Rainwater harvesting	Residential properties with RWH systems (as a % of total properties)	Southern/Thames Water, project research
Maintenance	Water infrastructure maintenance	Frequency of water infrastructure maintenance	Southern/Thames Water, project research
Mitigation measures	Sustainable Drainage Systems	Surface water reduction offered by existing Sustainable Drainage Systems	Project research
Total impermeable surface	Total impermeable surface	Total area of impermeable surfaces	Project research
Amount of accessible open space	Public green space	Total area of public green space	Local authorities, Ebbsfleet Development Corporation
Total amount of area	Build space	Area of development land	Local authorities, Ebbsfleet Development Corporation
Wastewater (combined)	Water in combined sewer system	Annual volume of water in combined sewer system that goes to wastewater treatment plant	Southern/Thames Water
Ground conditions	Geology	Underlying geology	Ebbsfleet Development Corporation, project research
Health	Mortality rates	Annual mortality rates	Local authorities
Property value	Average house price	Annual average house price	Project research
Outdoor residential water use	Outdoor residential water use	Average annual outdoor use of potable water	Southern/Thames Water, project research
Historic use of land	Historic use of land	Historic use of land, e.g. industry (linking with contamination potential)	Local authorities, Ebbsfleet Development Corporation
Amenity/recreation	Recreational activity	Annual visits to key parks/open space	Local authorities, project research

References Appendix I

Blue-Green Cities blog (2018a). Using System Dynamics for Sustainable Water Management in Ebbsfleet: Part 2. https://blogs.nottingham.ac.uk/blue-greencities/2018/09/12/using-system-dynamics-for-sustainable-water-management-in-ebbsfleet-part-2/ accessed 17.08.20.

Blue-Green Cities blog (2018b). Using System Dynamics for Sustainable Water Management in Ebbsfleet: Part 3. https://blogs.nottingham.ac.uk/blue-greencities/2018/10/02/using-system-dynamics-for-sustainable-water-management-in-ebbsfleet-part-3/ accessed 17.08.20.

Appendix II

This section includes additional details related to the Ebbsfleet Garden City SDM, including the key variables and full list of the equations used in the model. The source file (.mdl format, Vensim® Software by Ventana Systems) is available upon request (please contact the corresponding author). The simulation is based on a yearly time step (i.e. the water balance is computed annually).

The Ebbsfleet Water Use SDM currently contains 51 definitions documented below; the diagram of the model is given in the main text (Figure 6). The model definitions include a number of constants and algebraic equations, and four ordinary differential equations. Specifically, the differential equations have been used to describe the dynamics of 'Population', 'Potable water balance', 'Water bills' and 'Environmental Awareness'. These differential equations are solved using the Euler method (which is ideal for simpler 'well-behaved' problems and is suitable for the current version of the model), but optionally can also be solved using the Fourth Order Runge-Kutta method (which may be of value for future more complex modifications). The documentation entries follow the standard Vensim format: name of variable, followed by the details of its calculation (including initial values where applicable), followed by its units, and then optionally by a comment. Further information is also available in Table 2 of the manuscript, where the representation of differential equations has been adapted for enhanced readability. Unless otherwise specified, the model structure is based on expert knowledge of the Ebbsfleet stakeholders and UWM researchers.

Model definitions:

(01) Ageing=
0.2
Units: [Dimensionless, range 0-1]

(02) Balance=

Yearly water supply+RWH+GWR-(Potable water demand+Outdoor residential use of potable water)
Units: [litres/Year]

(03) Cost of GWR system=
3(1-Economic incentivising policy instruments)*Cost of RWH system*
Units: [£/Year]

(04) Cost of RWH system=
5000(1-Economic incentivising policy instruments)*
Units: [£/Year]
Comment: The constant 5000 has units [£/Year]

(05) CSOs=
*0.5*Water in combined sewer system*
Units: [litres/Year]

(06) Economic incentivising policy instruments=
0.2
Units:[Dimensionless, range 0-1]

(07) Educational programmes and events for sharing best practices=
0.2
Units: [Dimensionless, range 0-1]

(08) Effectiveness of local planning policy=
0.5
Units: [Dimensionless, range 0-1]

(09) Environmental awareness= INTEG (Inflow EA, 0.3)
Initial value=0.3
Units: [Dimensionless, range 0-1]
Comment: the behaviour over time of the variable "Inflow_EA" was defined during the modelling activities with the experts and stakeholders.

(10) FINAL TIME = 2049
Units: Year
The final time for the simulation.

(11) GW in combined sewer system=
*0.85*0.7*Potable water demand-GWR*
Units: [litres/Year]
Comment: 0.85 is an efficiency factor of the sewer system, while 0.7 is the ratio of drinking water becoming GW. Both constants were defined during the modelling activities with the experts, and are coherent with reference values (e.g. "Greywater recycling and reuse" by the Association for Rainwater Harvesting and Water Utilisation).

(12) GWR=
*0.2*Potable water demand*GWR acceptability*(1-Cost of GWR system/15000)*
Units: [litres/Year]

Comment: The constant 15000 has units of [£/Year] - the level at which the cost becomes prohibitive - too high for the reuse to be economical. The values were defined during the modelling activities with the experts. Reference values of GWR cost can be found e.g. at https://greywateraction.org/, https://www.gwig.org/ and in the scientific literature (e.g. Yi-Kai et al. 2016).

(13) GWR acceptability=
Environmental awareness*(1-Cost of GWR system/15000)
Units: [Dimensionless, range 0-1]
Comment: see eq. (12)

(14) Increase rate=
IF THEN ELSE(Population<=35000, Urban development*0.15 , 0)
Units: [persons/year]
Comment: 0.15 here has units [person/(household*Year)]; it restricts the Urban Development transfer into the Population numbers

(15) "Infiltration-storage-recharge volume"=
0
Units: [litres/Year]
Comment: this variable depends on the future developments of the water supply system, where it would reflect the processes influencing the dynamics of the local reservoirs. For the purpose of the simulation presented in the current paper the value of this variable is set to zero in the BAU scenario due to uncertainty and the lack of data, but activated for a scenario analysis.

(16) Inflow=
Yearly water supply+RWH
Units: [litres/Year]

(17) Inflow EA=
IF THEN ELSE(Environmental awareness<0.8, 0.1*Environmental awareness*"Socio-Environmental incentivising policy instruments", 0)
Units: [1/Year]
Comment: The constant 0.1 is the rate of transfer (i.e. fraction per year to which the transfer is restricted). The behaviour over time of the variable was defined during the modelling activities with the experts and stakeholders.

(18) INITIAL TIME = 2019
Units: Year
The initial time for the simulation.

(19) Investment in leakage reduction=
0.5
Units: [Dimensionless, range 0-1]

(20) Investment in WWTP=
0.5
Units: [Dimensionless, range 0-1]

(21) Leakages ratio=

(Ageing+(1-Investment in leakage reduction))/2
Units: [Dimensionless, range 0-1]

(22) Metered properties=
0.8
Units: [Dimensionless, range 0-1], Ratio Metered properties/Total properties

(23) National regulations=
0.3
Units: [Dimensionless, range 0-1]

(24) Outdoor residential use of potable water=
0.5(6*365-Rainfall)*50*(Population/3-"RWH properties #")*(1-Metered properties)*
Units: [litres/Year]
Comment:
0.5 --> 1/2 of new houses with garden 50 [m^2/household] = average garden size
6 [litres/(m^2 day)] = average daily water requirement (1mm rain = 1 l/m^2)
365 [days/Year], 3 [person/household]

(25) Outflow=
(Potable water demand+Outdoor residential use of potable water)(1-Use of water efficiency devices)*
Units: [litres/Year]

(26) Population= INTEG (Increase rate, 5)
Initial value = 5
Units: Person, Range [0,50000]
Comment: Initial value set to 5 to avoid division by 0.
Source: adapted from https://ebbsfleetdc.org.uk/ *according to expert judgement*

(27) Potable water balance= INTEG (Inflow-Outflow, 0)
Initial value=0
Units: [litres]

(28) Potable water demand=
(0.8073/Water bills)(Unit potable water demand*365*Population)*
Units: [litres/Year]
Comment: 0.8073 [£/litre] is the initial BAU water price for residential use; 365 days per year.
Source: online, water utility companies' websites (i.e. Southern Water www.southernwater.co.uk *and Thames Water and* https://www.thameswater.co.uk/ *)*

(29) Rainfall=
609
Units: [mm/Year]
Source: https://en.climate-data.org/europe/united-kingdom/england/dartford-8840/

(30) Regulatory policy instruments=
(Effectiveness of local planning policy+National regulations+"Water-energy efficiency audit")/3
Units: Dimensionless

(31) RW in combined sewer system=
*Rainfall*1e+06*0.5*(1-SuDS effectiveness)*("RWH properties #"/12000)*
Units: [litres/Year]
Comment: 12000 is the total number of households, 0.5 [-] is the runoff coefficient, 1e+06 [m^2] approx. urbanized area under investigation
609 [mm/Year] is a typical rainfall value

(32) RWH=
"RWH properties #"(0.6*1000*3)*(Rainfall/609)*
Units: [litres/Year]
*Comment: 0.6 [-] is a runoff coefficient, 3 people per household, 1000 expected water harvested per year [l/(person*year)].*

(33) "RWH properties #"=
0.7(Population/3)*(1-Cost of RWH system/5000)*
Units: households
Comment: 0.7 fraction of houses equipped with RWH systems, 3 people per household, [person/household], 5000 is the levels of cost [£/Year] at which RWH becomes uneconomic. Reference information e.g. at https://www.renewableenergyhub.co.uk/rainwater-harvesting-information/rainwater-collection-cost.html

(34) SAVEPER =
TIME STEP
Units: Year [0,?]
The frequency with which output is stored.

(35) "Socio-Environmental incentivising policy instruments"=
DELAY1(Educational programmes and events for sharing best practices, 5)
Units: [Dimensionless, range 0-1]

(36) Southern Water availability=
Yearly water availability/3
Units: [litres/Year]
Comment: 1/3 is the fraction of total supply provided by this company

(37) SuDS effectiveness=
0.4
Units: [Dimensionless, range 0-1]

(38) "Tariff/Tariff BAU"=
1.2
Units: Dimensionless

(39) Thames Water availability=
*Yearly water availability*2/3*((1-Leakages ratio))*
Units: [litres/Year]
Comment: 2/3 is the fraction of total water supplied by this company

(40) TIME STEP = 1
Units: Year [0,?]
The time step for the simulation.

(41) Unit potable water demand=
140
*Units: [litres/(person*day)]*

(42) Unit potable water supply=
*Potable water demand/(365*Population)*
*Units: [litres/(person*day)]*
Comment: 365 days per year

(43) Urban development=
12000
Units: households
Source: adapted from https://ebbsfleetdc.org.uk/ according to expert judgement

(44) Use of water efficiency devices=
*Metered properties*Environmental awareness*Regulatory policy instruments*
Units: [Dimensionless, range 0-1]

(45) Water bills= INTEG (WB change rate, 0.8073"Tariff/Tariff BAU")*
Initial value=0.8073"Tariff/Tariff BAU"*
Units: [£/litre]
Comment: 0.8073 [£/litre] is the current (BAU) price
Source: online, water utility companies' websites (i.e. Southern Water www.southernwater.co.uk and Thames Water and https://www.thameswater.co.uk/)

(46) Water in combined sewer system=
*RW in combined sewer system+0.85*0.3*Potable water demand+GW in combined sewer system*
Units: [litres/Year]

(47) "Water-energy efficiency audit"=
0.3
Units: [Dimensionless, range 0-1]

(48) WB change rate=
*IF THEN ELSE((Potable water demand>0.7*Yearly water supply):AND:Water bills <1.25, "Tariff/Tariff BAU"*0.05*(1-Use of water efficiency devices) , 0)*
*Units: [£/(litre*year)]*
*Comment: the constant 0.05 has units [£/(litre*year)] and represents a 5% yearly increase*

(49) WWTPs=
*0.5*Water in combined sewer system*(1-Investment in WWTP)*
Units: [litres/Year]

(50) Yearly water availability=
*365*Population*120*

Units: [litres/Year]
*Comment: 120[l/(person*day)] is the per capita water consumption; 365 days per year*

(51) Yearly water supply=
Southern Water availability+Thames Water availability+"Infiltration-storage-recharge volume"
Units: [litres/Year]

References Appendix II

Yi-Kai, J. Chen, Y.; Lin, J.-M. Greywater Reuse System Design and Economic Analysis for Residential Buildings in Taiwan. Water 2016, 8, 546.