Journal of Cleaner Production 405 (2023) 137018

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A modelling testbed to demonstrate the circular economy of water

B. Evans[a,*], M. Khoury[a], L. Vamvakeridou-Lyroudia[a,c], O. Chen[a,b], N. Mustafee[b], A.S. Chen[a], S. Djordjevic[a], D. Savic[a,c,d]

[a] Centre for Water Systems, University of Exeter, Harrison Building, North Park Road, Exeter, EX4 4QF, UK
[b] Centre for Simulation, Analytics and Modelling, Business School, University of Exeter, Xfi Building, University of Exeter, Rennes Drive, Exeter, EX4 4ST, UK
[c] KWR Water Research Institute, Groningenhaven 7, P.O. Box 1072, 3430 BB, Nieuwegein, the Netherlands
[d] University of Belgrade, Faculty of Civil Engineering, Bul. Kralja Aleksandra 73, 11120, Belgrade, Serbia

ARTICLE INFO

Handling Editor: Cecilia Maria Villas Bôas de Almeida

Keywords:
Water
Circular economy
Serious game
System dynamic modelling
Julia

ABSTRACT

Climate change poses significant challenges in terms of water scarcity, environmental crisis, and economic uncertainty. This situation drives an increasing need to pursue more sustainable futures and to conserve and maximise the use of resources whenever possible. The EU-funded *H2020 NextGen* project aimed to boost sustainability using new and novel technologies and approaches implemented within the water cycle, and to maximise the efficient use of water and water-embedded resources. To facilitate and communicate the potential benefits of such technologies, NextGen developed Serious Games (SGs), enabled by underlying System Dynamic Models (SDMs), for demonstrating how interactions between water, energy, and materials/embedded resources within the urban water cycle can be utilised in the context of the Circular Economy of water. As part of a fast-track development process, a testbed dubbed “Toy Town” was developed that encompasses a range of technologies and options that provides a demonstrable framework that can later be refined and modified accordingly for other case studies. The underlying SDM driving the SG is built using the Julia programming language. The testbed incorporates a range of components, including water-saving and water-reuse technologies, stormwater management, and wastewater treatment systems. The SDM acts fundamentally as a mass-balance model tracking over time volumetric flows of water/wastewater and the concentrations/dilution of pollutants/material within the urban water cycle. A variety of water use, water reuse and wastewater treatment components can be tested within this model to maximise the resource potential of the water and material moving through the cycle. The paper focuses on an extreme drought scenario and highlights the benefits of a modelling testbed for exploring potential technological solutions for managing the urban water cycle and how such solutions can be employed in the context of the circular economy of water. The NextGen SG thus has the potential to improve stakeholders’ understanding of the implementation of novel technologies in the water cycle and the benefits that could be accrued by such stakeholder groups.

1. Introduction

The availability of freshwater is paramount to both the human quality of life and the provision of ecosystem services. However, this resource is facing increasing pressures to the compounding effects of climate change, population growth, and changes in farming practices (Mbavarira and Grimm, 2021). The strain on water resources and the inability to meet human and ecological demands for water is referred to as “water stress” and it is estimated that 30% of the population within Europe are currently affected by water stress each year, with this value expected to increase in future due to climate change and socio-economic developments (European Environment Agency, 2021). The effect of climate change on freshwater availability is experienced at both climate extremes - droughts and floods. Intuitively, the link between long periods of droughts and water stress within a region can easily be established; however, the link between increases in the frequency and severity of extreme rainfall events seems counterintuitive when it implies an increase in rainfall volumes during these periods. Although the effect of increasing frequency and severity of extreme rainfall implies increased availability of water within a region, if this excess stormwater is not captured/managed accordingly, it can result in extreme flood events where pollutants mobilised by surface flows can lead to contamination of water resources including surface water and

* Corresponding author.
E-mail address: b.evans@exeter.ac.uk (B. Evans).

https://doi.org/10.1016/j.jclepro.2023.137018
Received 30 September 2022; Received in revised form 24 March 2023; Accepted 28 March 2023
Available online 31 March 2023

Nomenclature

β	COD Removal Efficiency Dimensionless
$bsCOD_m$	Biodegradable soluble Chemical Oxygen Demand mg
COD_c	Chemical Oxygen Demand Concentration mg/l
COD_m	Chemical Oxygen Demand Mass mg
$COD_{methane}$	Chemical Oxygen Demand that can be converted into methane gas mg
COD_{VSS}	Chemical Oxygen Demand of Volatile Suspended Solids mg
CSO	Combined Sewer Overflow
DWF	Dry Weather Flow m^3/s
EMC	Event Mean Concentration mg/l
GW	Grey Water
RWH	Rainwater Harvesting
SG	Serious Game
SDM	System Dynamic Model
SuDs	Sustainable Drainage Systems
UWOT	Urban Inundation Model
V	Volume m^3
WWTP	Wastewater Treatment Plant
ρ	Volumetric energy coefficient kWh/m^3
μ	Treatment Coefficient kWh/m^3
θ	Treatment approach coefficient Dimensionless

groundwater (Andrade et al., 2018). A circular economy approach is a model that water utilities can adopt to maintain water security (Mbavarira and Grimm, 2021) and, through novel treatment and processing technologies, supplement energy demands through the production of biogas, provide nutrient-rich resources for agriculture and other materials for reuse (Sušnik et al., 2021).

The circular economy model is based on three main principles: (a) Eliminating waste and pollution; (b) Re-cycling products and materials; and (c) Regenerating nature (Ellen Macarthur Foundation, 2010). Implementing a circular economy approach/model within a region (as a system), however, is not without its challenges; low awareness and know-how is a key barrier flagged by those surveyed by Kevin van Langen et al. (2021). One means of facilitating an understanding of complex challenges, such as those in the context of sustainability, is through the use of Serious Games (Katsaliaki and Mustafee, 2012). When designing Serious Games (SGs), it is important from a usability aspect to get the balance in terms of playability and scientific accuracy (Stanitsas et al., 2019). Extensive research has demonstrated the use of SDMs for modelling complex environmental scenarios in various contexts, including sustainability (Shen et al., 2009; Nabavi et al., 2017), water management in high-demand tourist and agricultural regions (Mereu et al., 2016), the impact of policy decisions on the water-energy-food-land-climate nexus (Sušnik et al., 2021), and at the urban household level examining the food-energy-water nexus (Du et al., 2022). The use of SDMs embedded within SGs (Evans et al., 2018; Sušnik et al., 2018) can facilitate this balance by allowing for a wealth of detailed datasets and complex interconnected models to be portrayed to a wider audience in a more accessible format that enables understanding of behaviours of such models through interaction.

The *NextGen* project (https://nextgenwater.eu/) explored the circular economy of water by investigating various strategic pathways and technological solutions for managing water and water-embedded resources across ten real-world case studies. Examples of solutions studied involve the treatment and reuse of wastewater for supplementing demands for golf courses, cleaning streets in Costa Brava (Spain); treated water-reuse, and nutrient and thermal energy recovery for tree nurseries in Athens (Greece). To facilitate the understanding of the circular economy of water to a broad audience, the NextGen project developed three SGs: one testbed/artificial case study (referred to as the *"Toy Town"*) and two real-world case studies (Athens and Costa-Brava). The case studies enable the exploration of novel technologies related to the circular economy of water; in particular, how these technologies may help manage water, energy, and material-based resources more effectively to meet the challenges that future climate scenarios may pose.

This paper focuses on the testbed model for evaluating technologies and policies for the management of an urban water cycle, which goes beyond conventional supply, treatment, and disposal that formed a template that other models were built upon. The testbed operates within the NextGen SG framework outlined by Khoury et al. (2023) and is designed to support the exploration of circular economy principles, where wastewater could be considered a valuable resource through sewer mining and treated reuse (Plevri et al., 2021), improving water security and energy security through heat recovery (Qtaishat et al., 2022) and biogas production (Kiselev et al., 2019).

2. Model design

Previous work by Bouziotas et al. (2019) using the *Urban Water Optioneering Tool (UWOT)* investigated a range of water use and reuse technologies at a neighbourhood scale for managing the urban water cycle. Fig. 1 outlines a generalised view of this cycle where the six parameters, e.g., water supply, water demand (highlighted in red), are the selected thematic areas. Under each thematic area, different technologies/components/processes can be trailed by examining circular economy potential. A testbed was developed to analyse these areas and the potential interactions between them. The main reason that a testbed was developed, rather than, for example, building the model to reflect a real-world case study, is that it allowed combining multiple options and features within a single system, acting as a paradigm. The testbed also enabled the simulation of various options, even extreme ones, which is not always possible within real systems. The testbed also served as an open benchmark for future research. The practice of using such benchmarks has long been established in water systems research, for example, the water distribution design and operation benchmarks (CWS, 2023).

Using the volumetric flows as the primary driver within the urban water cycle, a layered approach (Fig. 2) is applied to incorporate additional elements relating to material, energy, environment, and finance aspects of the circular economy, with the **first layer**, i.e., the water cycle layer, depicted in Fig. 1. The **second layer**, i.e., the materials layer, tracks the chemical composition of wastewater from various sources as it propagates through the urban water cycle where the material component can be regarded as a waste product and/or a resource. The **third layer**, i.e., the energy layer, considers energy demands and production potential, analysing the energy required for the movement and treatment of water, energy used by technologies in households that utilise water, and the potential energy recovered with respect to biogas production and material reclamation during the treatment processes. The **fourth layer** is that of the environment, whereby considerations are made in relation to variances in the environmental flows of the river system, as well as the water quality of wastewater (treated and untreated) entering water bodies as outlets, external to the system, i.e., the river network and/or the sea. The **fifth layer** (final layer) considered refers to financial estimates. The financial side considers the cost implications in technologies and connections employed within each region, the costs associated with the treatment of wastewater and the cost-benefit potential from reclaimed resources from the treated wastewater.

2.1. Water supply

The water supply to a region can come from a variety of sources, e.g., groundwater, reservoir, rainwater, desalinated water, external municipal supply. For simplicity, the testbed considers one primary source of freshwater from a nearby reservoir and a secondary source of rainfall that falls directly upon the region. In this example, the reservoir volume

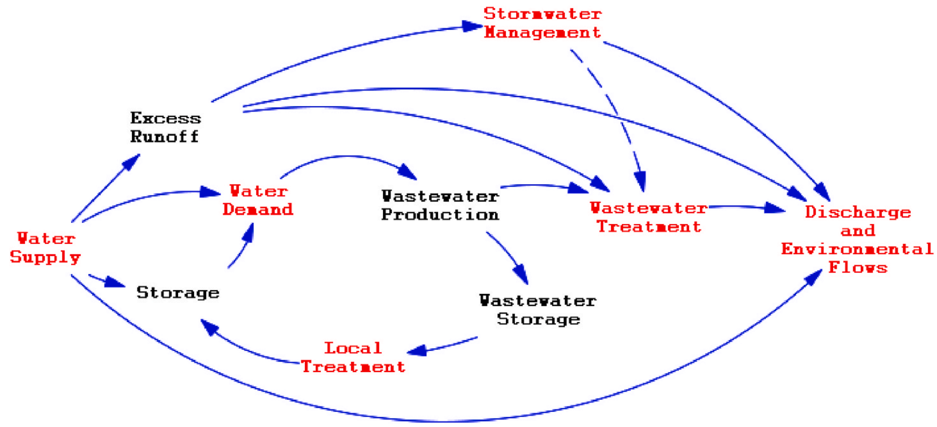

Fig. 1. A generalised view of the Urban Water Cycle and its potential use in the Circular Economy context.

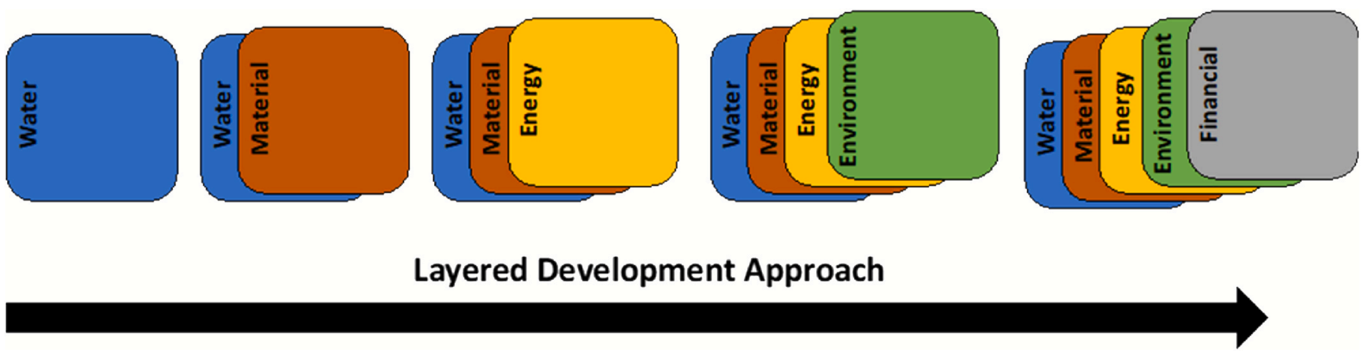

Fig. 2. The layered development approach.

is recharged solely via inflow from an upstream catchment with outflows via (i) a Compensation Release system designed to control outflows to preserve environmental flows downstream of the reservoir, (ii) water use driven by the demands of the urban environment (town/city), and (iii) a spillway, referring to instances where the reservoir capacity is exceeded (example reservoir setup shown in appendix Figure A1). Additional inflows, such as direct rainfall onto the reservoir and the outflow of evaporation of water from the reservoir, are assumed relatively small. They do not significantly affect the water balance and have thus not been considered at this stage. The storage and release of water from the reservoir to the river system are controlled via a spillway (if reservoir levels are above a threshold value) and compensation release parameters that are dependent upon the inflow and current water levels within the reservoir. Equation (1) outlines the conditional rules applied within the model for determining the outflow of the reservoir/upstream via Compensation Release:

$$\boldsymbol{IF}\left(\frac{Reservoir\ Volume}{Reservoir\ Capacity}\right) \geq Stress\ Limit\ \boldsymbol{THEN} \tag{1}$$

$$Compensation\ Release = Baseline\ Discharge\ Coeff \times Inflow$$

$$\boldsymbol{ELSE\ IF}\left(\frac{Reservoir\ Volume}{Reservoir\ Capacity}\right) \geq Severe\ Stress\ Limit\ \ \boldsymbol{THEN}$$

$$Compensation\ Release = Stress\ Discharge\ Coeff \times Inflow$$

$$\boldsymbol{ELSE}$$

$$Compensation\ Release = 0.0$$

where the ranges for the coefficients and limits can be found in appendix Table A1. This approach simplifies the management of outflows from a reservoir into a river, based on the available water storage. For example, if the water level in the reservoir exceeds a pre-defined "Stress Limit" (e.g., 50% capacity), the discharge to the environment is regulated by the "Baseline Discharge Coefficient" (e.g., 0.8). For instance, at 50% capacity, 80% of the inflow volume is released while the remaining 20% is kept in the reservoir. If the water level drops below the "Stress Limit" but stays above the "Severe Stress Limit" (e.g., 30% capacity), the outflow is reduced to a "Stress Discharge Coefficient" (e.g., 0.6), with 40% of the inflow being retained for future use.

2.2. Domestic water demands

In urban areas, the primary demand for freshwater originates from residential populations and their associated domestic water needs. Within our study, these demands are modelled by seven household component classes, whose specific per capita daily water requirements are determined by their sub-classifications. The water demands for each of the sub-classes were derived from the UWOT model (Bouziotas et al., 2019); the relative efficiency of each sub-classification with respect to water usage is depicted in appendix Table A2, where a lower ranking indicates a more water-efficient subclass. The internal water demands at the household and subsequent regional levels can be customised through the swapping of subclasses; for example, replacing standard toilets within households with vacuum toilets in this model would result in a 21% reduction in daily water use at the household level.

In addition to the water demands for houses for internal use, there is the potential of properties having external water demands relating to garden irrigation. Unlike that of the internal components, demands for the garden are dependent upon its area, the crop demand, the irrigation methods applied and whether any of the demand requirements have been met by rainfall. Additional demands, such as tourism, commercial, agricultural, and industrial use, could also be included within the water demands for regions, although they are not currently utilised in the testbed model.

Appendix Figure A2 outlines the SDM view of water management at the household level. Here the demands at the household level are driven by the population. The production of domestic wastewater is broken down into greywater and blackwater, while the "recycle demand" by the households relates to the use cases for rainwater or treated greywater at the household level.

The energy requirements for the supply of freshwater from the reservoir to the households is defined by Equation (2), where V is the volume of water requested (m^3) and ρ is a volumetric energy coefficient expressed in kWh/m^3.

$$Energy\ Water\ Supply = V \times \rho \tag{2}$$

2.3. Domestic wastewater

For the material component of the model, estimated COD mass (COD_m) inflows are used as a reference, derived from their domestic wastewater (and stormwater runoff) sources. These sources at the household level are divided into four classes, laundry, hygiene, kitchen, and toilet and expressed in terms of COD_m per person per day with values shown in Table A3 selected from ranges outlined in Meinzinger and Oldenburg (2009). Using the default water use technologies (outlined in appendix Table A2) the modelled volume of wastewater produced per person day is 168 L and the equivalent mass of COD_m present within the wastewater is 102 g deriving a COD_c (COD concentration) of domestic wastewater to be 605nullmg/l. In this study, a simplified approach was taken for modelling purposes where the COD_m production per person per day was considered constant, irrespective of the water use technology in the household. However, the volume of wastewater produced, and thus the volume in which the COD_m is diluted, was dependent on the water use technology. This means that a change in a household component, such as replacing a standard toilet with a vacuum toilet, would alter the volume of wastewater produced but not the COD_m production, leading to an increase in the COD_c in domestic wastewater. With this scenario, switching to a vacuum toilet would result in a COD_c of 770nullmg/l. In addition to domestic wastewater, combined sewer systems also receive COD inputs from stormwater runoff during rainfall events. The COD_c for stormwater, as reported by Butler et al. (2018), has an Event Mean Concentration (EMC) ranging from 20 to 365nullmg/l. In this study, a high default value of 324mg/I was selected for the testbed model, though it can be adjusted.

2.4. Energy use

Within the energy layer of the model, initial estimates in terms of energy use are derived in relation to the energy required by the water-dependent components being associated with each household based on data within the UWOT model (Bouziotas et al., 2019) with their relative rankings outlined in appendix Table A2. Households fitted with Rainwater Harvesting (RWH) or Greywater (GW) reuse will have additional energy requirements associated with the localised treatment of water.

2.5. Local treatment

There are two locally available water sources used for domestic water use within this testbed model. These are rainwater via the RWH and the GW reuse system. Based on behaviours outlined in Bouziotas et al. (2019), the localised treatment configuration can consist of a combination of up to six individual tanks (appendix Figure A3). With regard to the RWH technology, each property in that region can be fitted with rainwater harvesting storage tanks above ground and below ground. The storage capacities of these storage tanks can be customised accordingly. The option of a below-ground storage tank allows for the future inclusion of greater storage volumes for high-density conurbations such as apartment complexes. Within this model, if both rainwater reuse and greywater reuse are activated, then an additional mixing tank is included with each property. The treated greywater is mixed and stored with collected rainwater for reuse in a combined system. The control of flows into and between tanks is determined via a range of parameters relating to filtration and purification rates (appendix Figure A4). For the RWH, these include the average roof area and external non-roof areas that capture rainfall, the tank capacities, and the purification rate. The GW reuse system is dependent upon tank capacities, an initial helophyte filter rate and a secondary purification rate.

The demand for recycled water is dependent upon its defined use cases. The default use cases for rainwater and treated grey water within properties have been defined solely for toilet flushing and watering gardens. Within the model, however, users can specify whether to additionally allow for a percentage of this water to be used for laundry and showers. In that case, though, parameters for additional treatment costs need to be modified accordingly where required.

2.6. Stormwater management and wastewater treatment

The treatment of wastewater that has entered the sewer system is either carried out at the Primary Wastewater Treatment Plant (WWTP) or a Decentralised WWTP. The Primary WWTP is the main WWTP for the testbed and is designed with the entire population in mind. The capacities of the WWTPs are limited by their respective treatment rates. If the incoming flows exceed the WWTPs operational capacity, the Combined Sewer Overflow (CSO) will be activated. So, the excess stormwater mixed with domestic wastewater is diverted away from the WWTP via the CSO and is discharged as untreated effluent. (Fig. 3).

In this configuration, Sustainable Drainage systems (SuDs) are introduced, as nature-based solution that can also be utilised for stormwater management as a means of reducing stormwater inflows into the sewer systems. The SuDs are regarded as consisting of a *pervious* storage basin that captures rainfall that lands directly upon them and any overland flow from regions connected to the SuDs (Fig. 4). Overland flow, referred to as surface runoff, comes from both pervious and impervious surfaces. Pervious areas within the model are regarded as being green spaces. These areas have an infiltration rate defined for the removal of rainwater that lands upon them. For the simplified modelling approach followed in our *Toy Town* case study, it is assumed that water infiltrating the pervious area is removed from the system. If, however, the rainfall that lands on these pervious areas exceeds the infiltration rate of the soil, then the excess rainfall is directed either to the SuDs or the sewer system as stormwater runoff. The impervious area is initially pre-defined to be the largest area in the model. Rainfall landing upon impervious areas will immediately become surface runoff, again to be directed either to the SuDs or the sewer system as stormwater runoff. Not all surface runoff enters SuDs and/or sewer system as a percentage is deemed to be lost due to infiltration in pervious surface, ponding and evaporation, thus a stormwater coefficient is applied to reflect the process.

The performance of the SuDs within this model is determined by three parameters.

1. **Infiltration Rate**: This is the maximum rate at which rainfall is expected to infiltrate into the pervious areas. If the rainfall intensity is higher than the infiltration rate, then overland flow across the pervious areas and into the sewer system will occur.
2. **Storage Capacity**: This is the maximum storage volume/buffer within the SuDs based on its area and depth. Water that has infiltrated the SuDs can be temporarily stored within the SuDs whilst it infiltrates into the soil beneath. If the storage capacity of the SuDs is exceeded, then any additional inflows will become surface runoff.
3. **Soil Infiltration Rate**: This value determines the rate at which water is removed from the SuDs.

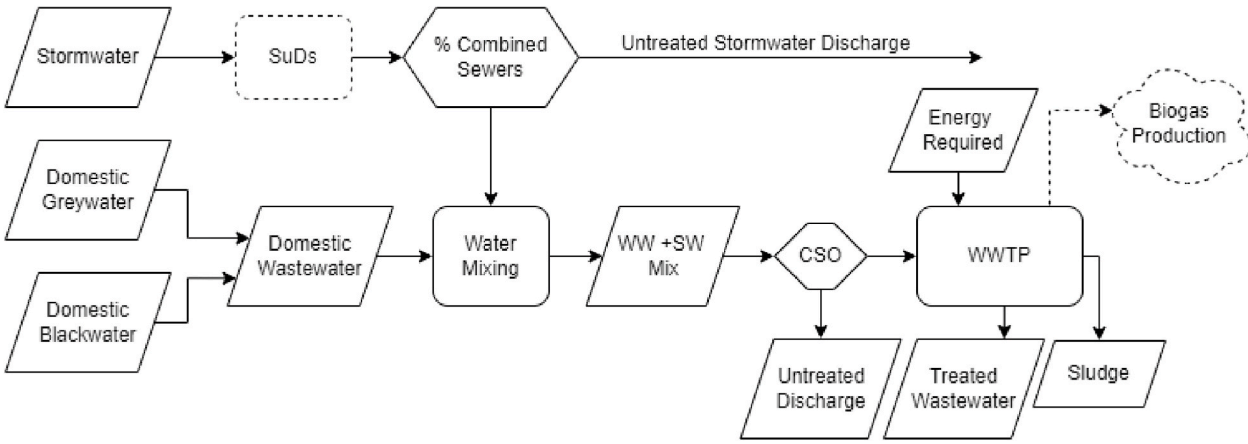

Fig. 3. Overview of stormwater and wastewater management system.

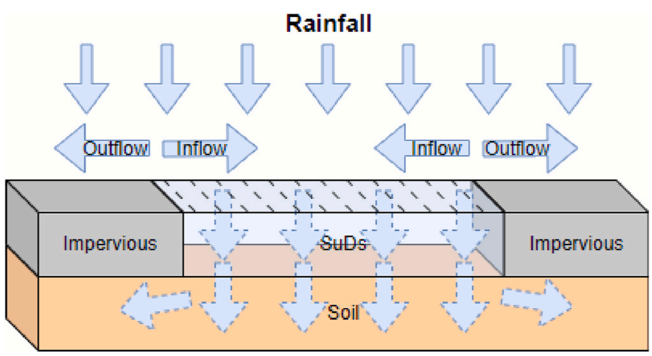

Fig. 4. SuDs implementation within Toy Town.

The first stage in the stormwater management process is to determine the volumes of direct rainfall and surface runoff into the SuDs. Appendix Figure A6 outlines a SDM modelling approach used for calculating combined inflows into a SuDs system if they have been installed in a region. Here water that lands on the pervious area may infiltrate the soil (determined by the soil infiltration rate). The SuDs activation switch represents whether a region is connected/contains SuDs and the capture/removal or surface water into the SuDs is determined by its area and infiltration rate. Once the inflows of SuDs have been determined, the removal of stormwater into a porous medium beneath can be calculated, along with any excess flows that will enter the sewer system if the SuDs capacity is exceeded (appendix Figure A5). Stormwater not captured by SuDs, either enters the combined sewer system, mixing with domestic wastewater, or enters a separate sewer system and is later discharged untreated. To capture the behaviour of CSOs more accurately, daily resolution rainfall data is re-distributed using a relative rainfall hyetograph derived from the design hyetograph presented in Ladson (2017) (Fig. 5).

The CSO design/threshold limit is set at eight times daily Dry Weather Flow (DWF) assuming 100% combined sewer value. Using this DWF threshold yields zero CSO events over the 20-year simulated timeframe when using daily rainfall values. In contrast, re-distributing rainfall, using relative rainfall hyetographs for combinations of 6-h winter storms and 3-h summer storm durations, results in an average of 180 CSO events per year (Fig. 6). Based on this analysis, the model re-distributes daily rainfall data using the provided relative design hyetographs to ensure a more accurate depiction of stormwater influence within combined sewers.

The decentralised WWTP is regarded as being at a smaller scale than that of its primary WWTP counterpart. It can be utilised in the testbed model for trial purposes to explore alternative wastewater treatment processes. The baseline configurations of both the primary and decentralised WWTP follow the same flow pathways as shown earlier in Fig. 3; however, the incoming flows, operational parameters and geographical

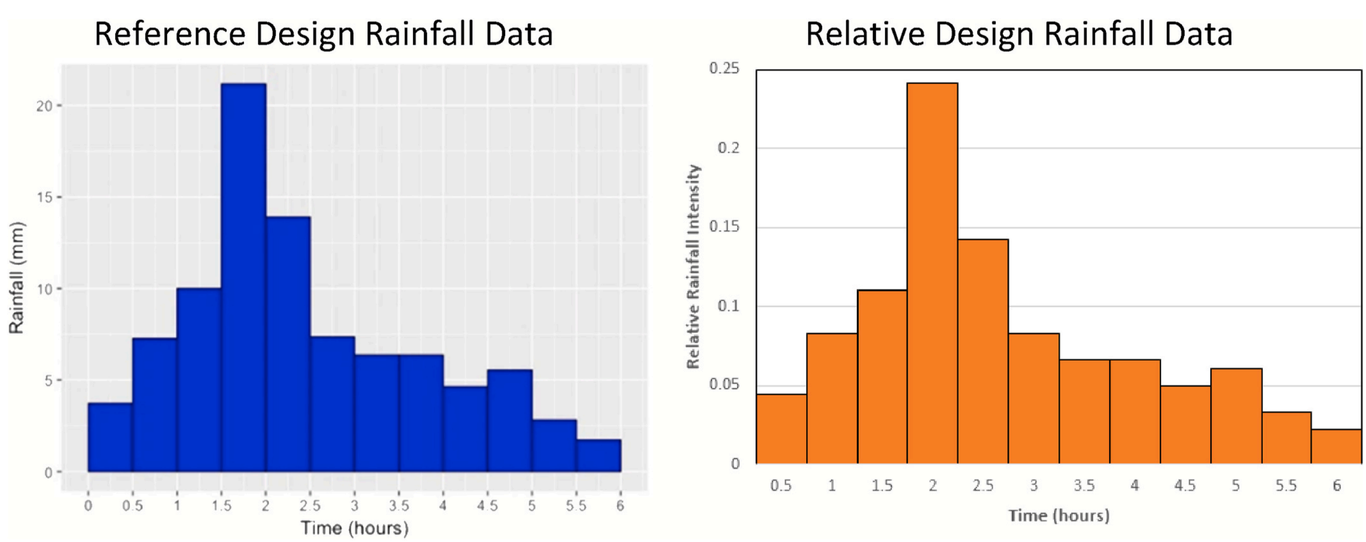

Fig. 5. Defining stormwater inflows using relative rainfall hyetographs derived from design hyetograph depicted in Ladson (2017).

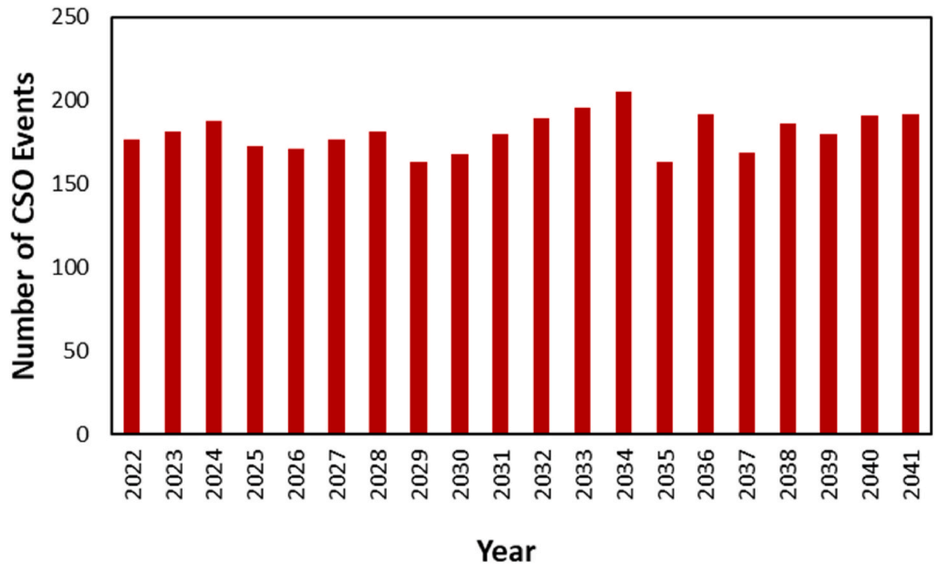

Fig. 6. Comparison of CSO events using daily rainfall data vs 6-h relative hydrographs.

locations will vary.

The COD_c of wastewater present within a combined sewer system is dependent upon the COD_c of the domestic wastewater and the volume of stormwater it is mixing with. On days where the rainfall value is below a minimum value that would trigger a CSO event, the COD calculations for wastewater influent to the respective WWTPs are calculated using daily values. When the stormwater inflow is sufficiently high to trigger a CSO event, the stormwater volume is re-distributed over the relative design hyetograph and the untreated COD_c values are derived for each sub-daily time interval to determine the volume and concentrations of uncontrolled discharge to either the river or the sea. The remaining wastewater and stormwater mix is then routed to the WWTP where sludge mass and sludge volumes are calculated along with the treated effluent COD_c values.

WWTPs within this model are designed to remove a percentage of the COD from the influent before discharging the treated effluent into the river or sea. The energy required to treat wastewater at the WWTPs is derived from a simplified equation (equation (3)) based on a treatment coefficient (μ) that determines the energy required to reduce the COD of wastewater by a fixed percentage value (e.g., reduce COD by 80%) in terms of kWh/m^3.

$$Energy = \mu \times V \tag{3}$$

On the energy production/potential side, if the player of SG specifies/enables anaerobic treatment of wastewater at the decentralised site, the model will calculate the potential biogas production. Adapting an approach outlined by Metcalf & Eddy, Inc (2013). Using influent volume and COD_m values and COD removal via anaerobic treatment, an estimate is made as the volume of methane that can be produced (equation (4)).

$$biogas\ volume = (COD_{methane} \times 0.4) / 1000 \tag{4}$$

Where: $COD_{methane} = bsCOD_m - COD_{eff} - COD_{vss}$.

$$bsCOD_m = Inflow \times bsCOD_c$$

$$bsCOD_c = 0.5 \times COD_c$$

$$COD_{eff} = (1 - \%COD\ Removal) \times bsCOD_m$$

$$COD_{vss} = 1.42 \times 0.04 \times \%COD\ Removal \times bsCOD_m$$

A by-product of the treatment process is the production of sludge. The sludge either needs to be disposed of, or it can be potentially utilised in nutrient and/or bio-recovery processes. The volume, mass and composition of sludge produced during the treatment processes are dependent upon the volume (V) of wastewater being treated, its chemical composition, and the WWTPs treatment characteristics. A simplified approach has been adopted for determining the mass of sludge produced at the primary WWTP and decentralised WWTPS outlined in equation (5), where β refers to the COD removal efficiency of the treatment facility and θ is a coefficient relating to the treatment approach e.g., aerobic, anaerobic treatments and the subtypes.

$$Sludge\ Mass = \frac{\beta \times V \times COD_c \times \theta}{1000} \tag{5}$$

2.7. Discharge and environmental flows

The large-scale primary WWTP in the model is located near the sea (Fig. 7). The smaller-scale decentralised WWTP is placed at a midstream location where it discharges into the river system (Fig. 7). Having a decentralised WWTP at a midstream point can have potential positive benefits of restoring river flows via flow augmentation within the river network. However, it is important to ensure the water quality of the effluent is not detrimental to the system (Luthy et al., 2015).

To model the potential benefits of localised improved water management by the town and discharge the midstream via a decentralised WWTP, the model assesses river flows upstream and midstream relative to the baseline river flow (appendix Figure A7). It simultaneously

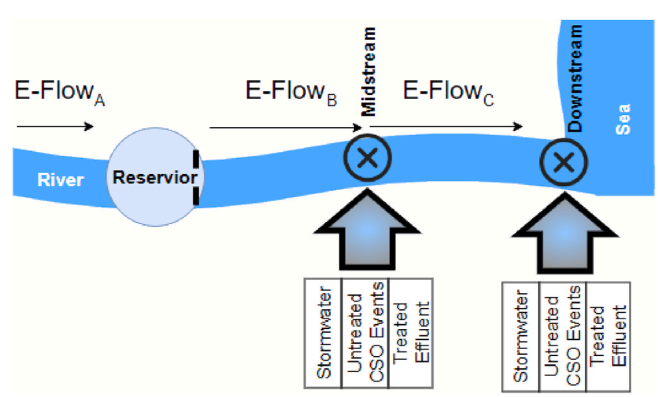

Fig. 7. River network and modelled discharge locations.

monitors the water quality of the combined discharges at the midstream location and at the downstream location as part of the overall model performance analysis.

3. Case study: Toy Town

The testbed Toy Town (Fig. 8) utilises aspects of the SUPERLOCAL model outlined in Bouziotas et al. (2019) and expands upon it by integrating additional technologies and modelled layers within rapid prototype. This Toy Town model uses a simplified representation of the urban water processes, focusing on challenges relating to the management of water resources solely for a large residential population. However, additional flows in respect to agricultural, industrial, and tourism demands can be included within future developments. Having a testbed allows for rapid model development and the flexibility to trial a range of configurations that would not be present in real-world case studies. The depicted configuration in Fig. 8 consists of the following components.

- **Regions**: Contain local neighbourhood information relating to populations, household water use technology, and household water reuse technology.
- **SuDs**: Sustainable Drainage Systems utilised for limiting the effects of stormwater runoff.
- **Sewer Types**: Combined and/or Separate sewer systems used for the management of domestic wastewater and stormwater.
- **Primary WWTP**: Main wastewater treatment facility, designed to handle the capacity of Toy Town wastewater inflows and stormwater.
- **Decentralised WWTP**: An optional WWTP facility with a lower treatment capacity than the primary WWTP. It can be used to take a % of wastewater and trial different treatment technologies and nutrient recovery techniques.
- **CSO**: Controls the volume of wastewater + stormwater to respective WWTPs to ensure they are not overloaded. During extreme rainfall events the wastewater stormwater mix is diverted to the river or sea untreated.
- **Reservoir**: Primary source of freshwater for Toy Town. The reservoir is recharged through rainfall in the catchment area upstream of Toy Town.
- **River**: Part of the ecosystem services within the model. Flow rates are determined by reservoir control measures and effluents that outflow midstream in the model.

The connections shown in Fig. 8 are just one of the various possible configurations within the model. Table 1 summarises the parameters that can be configured within each of the regions. Within these configurations, the water demand depends upon the water use technology selection within each of the households in a specified region. For example, the default settings within the model are 168 l/person/day; however, swapping the default “standard shower” within a household with a more water-efficient “fog shower” could reduce the demand to 122 l/person/day. Allowing for the distribution of the population over multiple regions allows for more variety within the SG and the exploration of different combinations of water-saving technologies and different connections within system. A region-based approach additionally facilitates the swapping of land uses within the model for future

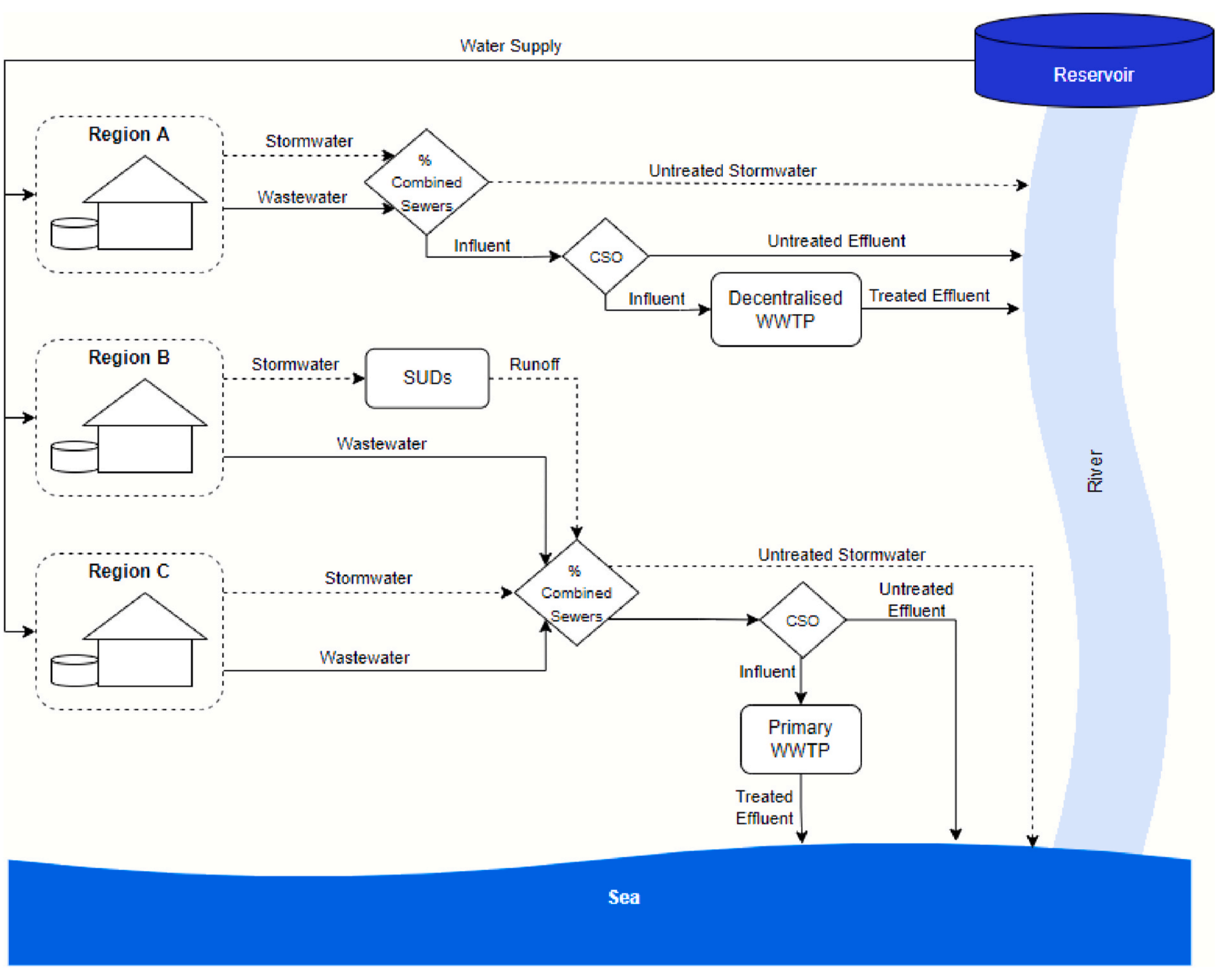

Fig. 8. Conceptual layout of the Toy Town case study.

Table 1
Region parameter options (water demands derived from UWOT model outlined in Bouziotas et al. (2019).

Parameter	Region A	Region B	Region C
% Population	0–100	0 – (100 – A)	0 – (100 – (A + B))
Bluewater Demand (l/person/day)	49.1–168.5	49.1–168.5	49.1–168.5
Rainwater Reuse	Yes/No	Yes/No	Yes/No
Greywater Reuse	Yes/No	Yes/No	Yes/No
SuDs Connection	Yes/No	Yes/No	Yes/No
% Combined Sewers	0–100	0–100	0–100
Primary WWTP Connection	Yes/No	Yes/No	Yes/No
Decentralised WWTP Connection	Yes/No	Yes/No	Yes/No

iterations, i.e., a domestic region could be replaced by an industrial or touristic region.

The Toy Town catchment area (where the residents reside) is divided up into six land-use classifications (Fig. 9). The pathways taken by rainfall that lands upon this catchment area are dependent upon the land-use type and their characteristics. The overall catchment size of Toy Town is pre-defined, with the respective area types proportioned as percentages according to the input parameters specified by the user. Therefore, within an overall catchment area defined, increasing the percentage of the pervious area would not alter the size of the catchment area, but instead, reduce the size of the impervious area accordingly.

Within the testbed model, the supply of freshwater comes from a large reservoir fed by a river system dependent upon rainfall falling on an upstream catchment located outside the bounds of the Toy Town catchment. For the modelling, synthetic rainfall at a daily resolution is applied to both the upstream and the Toy Town catchment areas. Fig. 10 shows the aggregated monthly rainfall data applied within the model over the 20-year timeframe under baseline (normal) conditions. Under this baseline rainfall scenario, the volume of rainfall landing on the upstream catchment area provides an average flow rate for the river to the reservoir of 5.3nullm^3/s.

4. Results

This section presents an analysis of the model's performance in exploring the circular economy of water and improving water security during extreme drought conditions.

4.1. Model configuration to simulate extreme drought conditions

The Toy Town model has a baseline configuration of 300 k residents residing in properties equipped with the default water use technology as described in the appendix Table A2. The model assumes 2.2 people per household, with neither RWH nor GW reuse technology enabled in the houses, and each house connected to the primary WWTP via a 100% combined sewer system.

Extreme drought conditions are simulated by reducing the incoming rainfall by 50% over the entire 20-year time frame. Figure A8 shows a bar chart comparison of the recorded reservoir levels at the end of each simulated year under normal (blue) and extreme drought (red) conditions. The dashed lines depict the E-Flow Performance (equation (5)) immediately after the reservoir (E-Flow$_B$ in Fig. 7) that corresponds to the reduction of environmental flows due to the storage and controlled discharges from the reservoir.

$$E - Flow\ Performance = \frac{E - Flow_B}{E - Flow_A} \quad (5a)$$

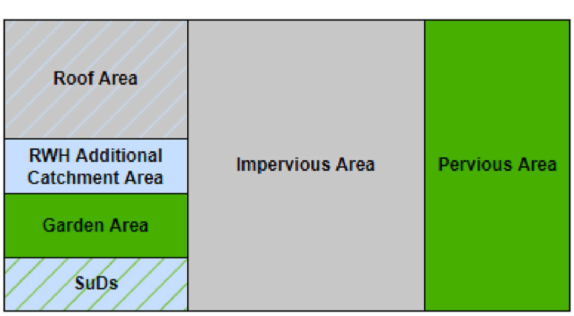

Fig. 9. Land-use classification in Toy Town catchment.

4.2. Improving water security at a localised scale

A potential means of improving water security under extreme drought conditions is to reduce the water demands at the regional/household scale. These reductions can either be achieved through modifying the internal household components to ones that are more water-efficient or via supplementing freshwater demands via RWH or/and GW reuse technologies. Table 2 outlines six local/household technology-driven scenarios trialled under drought conditions to examine their effectiveness in improving the water security of the town. For the internal household components, two components (vacuum toilet and fog shower) were selected for analysis based on their significant reductions in water demands per use. Secondary water saving measures trailed locally are the use of RWH, GW Reuse, and RWH + GW Reuse combined. Appendix Figure A9 shows the potential benefits of applying water saving technologies within households (Scenarios 1 to 3) with appendix Figure A10 showing benefits of employing RWH and GW Reuse either independently or simultaneously. These benefits are displayed in terms of enhancing water security, as indicated by analysing reservoir end of year water levels, and average e-flow performance in the river system.

4.3. Improving ecosystem services

With the vast reduction of rainfall, the river flow rate is greatly reduced both upstream and downstream of the reservoir. The inclusion of a decentralised WWTP discharging into a mid-stream location could be a potential solution for improving environmental flows. To assess the potential benefits of having a decentralised WWTP, the river flowrate at the midstream location under drought conditions is compared. Table 3 outlines 3 scenarios tested where 100% of properties in Toy Town are now connected to the decentralised WWTP that results in treated (and untreated in the event of a CSO) discharge wastewater entering the river at the midstream point depicted in Fig. 7.

Appendix Figure A11 shows the environmental flow performance after the mid-stream point (E-Flow$_C$ from Fig. 7) derived using equation (6) and the daily average COD concentrations (line graph) of wastewater (treated discharge and CSOs) being discharged the river network at the mid-stream location.

$$E - Flow = \frac{E - Flow_C}{E - Flow_A} \quad (6)$$

Scenarios 7 A–9A are analysed further with properties now being connected to a separate sewer system without SuDs (represented as Scenarios 7 B–9B in appendix Figure A12) and with the inclusion of SuDs (shown as Scenarios 7C–9C appendix Figure A13).

5. Discussion

5.1. Improving water security at a localised scale

Simulating extreme drought scenarios via a 50% reduction of rainfall increases the water stress in the region. For evaluating water stress within the model, the model is considered under stress when the reservoir level falls below 50% of its storage capacity. Under these

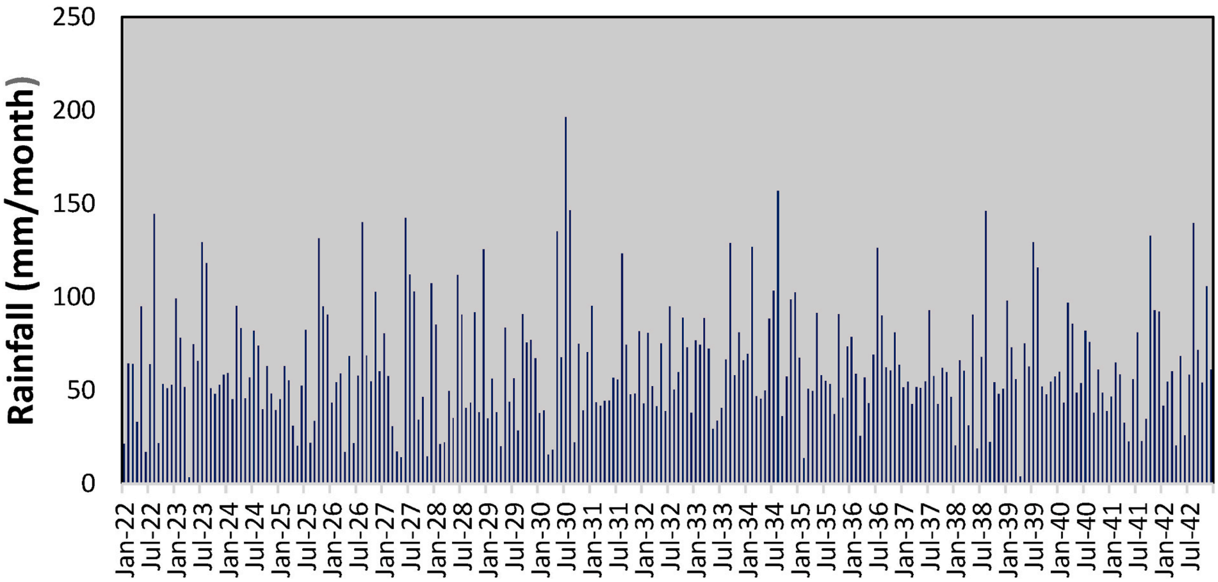

Fig. 10. Cumulative synthetic monthly rainfall under baseline conditions.

Table 2
Configuration list for comparison of water saving and reuse technologies.

Scenario	Internal Water Use Components	Water Reuse Technology
Drought	Default (see appendix A1)	None
1	Vacuum Toilet	None
2	Fog Shower	None
3	Vacuum Toilet + Fog Shower	None
4	Default (see appendix A1)	RWH
5	Default (see appendix A1)	GW Reuse
6	Default (see appendix A1)	RWH + GW Reuse

Table 3
Testing the addition of decentralised WWTP.

Scenario	% Properties Connected to Decentralised WWTP	Water Saving Approach
Scenario 7 A	100	None
Scenario 8 A	100	Vacuum Toilet + Fog Shower
Scenario 9 A	100	RWH + GW Reuse

circumstances, the only means of managing water supply within the reservoir is by controlling the volume of discharge to the environment via a compensation release mechanism, as described previously in equation (1).

Without any additional interventions, the percentage of days where the reservoir is regarded as being under stress (volume of the reservoir is <50% of its storage capacity) or empty is outlined in Table 4. Here we observe that under the severe drought conditions, and over the simulated 20-year timeframe, there are days of the year when the reservoir cannot meet the water demands of the town. As appendix Figure A8 shows, under normal conditions, with the water demands of the population, the e-flow performance downstream of the reservoir is between 70% and 80%. Under extreme drought conditions, however, this e-flow performance drops significantly to around 30%. Even with the large reductions in the volume of water now being discharged to the river, the water levels within the reservoir remain relatively low resulting in long periods of water stress for the regions and even periods where the levels are insufficient to meet the demands of the town (Table 4).

Table 4
Examining reservoir stress and severe stress outputs.

Scenario	% Days reservoir under stress (<50% capacity)	% Days reservoir is empty
Normal Rainfall	12.95	0.0
Extreme Drought	66.59	1.80

Analysing the performance of water saving technologies individually and in combination (Table 5) shows that the reduction of demands at the households reduces the duration the reservoir is under stressed conditions, as well as the average number of days per year the reservoir is deemed to be empty (to be less than one day per year). Appendix Figure A9 shows that the combination of vacuum toilet and fog shower in all properties (Scenario 3) additionally improves environmental flows to 35%

The application of RWH technology at the household level does show some benefits; however, out of the six localised measures trialled to mitigate against extreme drought, it showed the lowest benefits. This underperformance can arguably be attributed to the fact that RWH requires rainfall as its water source, and with the 50% reduction of rainfall under extreme drought conditions, there is a limited resource available. In contrast, GW reuse shows more significant benefits (Table 6).

5.2. Improving ecosystem services

Here we see that the combined outflows from the decentralised WWTP result in a substantial improvement in the e-flow performance, bringing the flowrate within the river network back to its pre-drought conditions; however, the combined (treated discharge + untreated CSO discharge) COD concentrations entering the network are significantly high. For Scenario 7, the range of average daily concentration of

Table 5
Water saving technology scenarios.

Scenario	% Days reservoir under stress (<50% capacity)	% Days reservoir is empty
Extreme Drought	66.59	1.80
1	56.19	0.77
2	53.35	0.53
3	39.58	0.14

Table 6
Water reuse scenarios.

Scenario	% Days reservoir under stress (<50% capacity)	% Days reservoir is empty
Extreme Drought	66.59	1.80
4	57.26	1.48
5	33.74	0.05
6	20.04	0.0

COD entering the river via the combination of treated and untreated discharges is between 210 and 246nullmg/l, which approaches the maximum compliance limit in the UK of 250nullmg/l and above the standard EA compliance limit of 125nullmg/l (Environment Agency, 2019). Whilst the implementation of water saving technologies improves the water security, the change in the influent concentrations results in increases in COD discharge concentrations that exceed the maximum compliance limits with the maximum average COD value of 440nullmg/l being recorded.

With the capacity of the decentralised WWTP being less than the primary WWTP, the combination of rainfall and domestic wastewater from a population of 300 k leads to a large number of uncontrolled discharges via the CSO (shown in Table 7).

A means of preventing these uncontrolled CSO event discharges is to move from a combined sewer system approach to a separate sewer system. By switching from 100% combined to 100% separate sewer system we see a large reduction in average COD concentrations being discharged into the river (appendix Figure A12). With this separate sewer system, the range in COD concentrations with no water saving technology is now between 124nullmg/l to 140nullmg/l with an average of 131nullmg/l, which is still higher than the compliance limit. Both scenarios that utilise water saving technology still have high average COD outflows though they are now kept below the 250nullmg/l maximum compliance limit set within the UK. A final means of bringing down this COD further is by including SuDs to reduce the volume of surface runoff entering the river network. By including SuDs the COD being carried directly from the storm sewer into the river network is reduced (appendix Figure A13). This reduction brings the COD discharge values for RWH + GW reuse combined down to an average of 121nullmg/l, which is below the standard EA compliance limit, though the compromise of this reduction is the reduction of e-flow performance.

5.3. Material and energy recovery

By utilising decentralised WWTP with anaerobic digestion, there is a reduction in sludge mass produced and the production of biogas that can be utilised to supplement energy demands. Under the initial conditions of treating combined wastewater inflows with no water saving or reuse technology under drought conditions, the primary WWTP produces 9380 tonnes of dry sludge mass per year. In comparison, the transition to Scenario 9 with the anaerobic treatment of domestic wastewater only (no stormwater mixing) results in just 763 tonnes of dry sludge mass to dispose of per year. Additionally, the volume of biogas produced via the anaerobic treatment of domestic wastewater is 2.88 million Nm^3 per year. With ~2kwh of electrical energy per cubic meter of biogas, the energy potential of the biogas produced is 5.75Gwh annually.

Table 7
Average No. CSO events per year.

Scenario	Average no. CSO events per year
Scenario 7	233.7
Scenario 8	233.7
Scenario 9	215.14

5.4. Integration of model into a Serious Game

As outlined in Khoury et al. (2023), the testbed model provides insight into how the players' choices in the SG will influence their "Circular Economy Score". This score is driven by five primary key performance indicators: *Water Health*, *Energy Health*, *Material Reuse Health*, *Environmental Health*, and *Financial Health*. Fig. 11 shows an example of the testbed model within the online NextGen SG.

The testbed model, developed using the high-performance Julia programming language, simulated 20 years of sub-daily resolution data on a desktop PC equipped with 32GB of RAM and an i7 processor. The median runtime for the 20-year simulation was found to be less than 0.4 seconds (Fig. 12). This modelling performance facilitates its use within an SG environment where players can interact with the model efficiently in an online environment receiving almost instant feedback from their decisions. The testbed model has been integrated into SG and is available at the following link: http://nextgen-serious-game.s3-website.eu-central-1.amazonaws.com/# . The NextGen SG allows players to either find solutions to pre-defined scenarios or undertake an interactive exploration of the model by creating new scenarios.

5.5. Expanding testbed into real-world case studies

Recent work has investigated adapting the testbed model to approximations of real-world case studies to demonstrate and enhance engagement within those regions. Within the use case of Athens, the river and reservoir system were replaced with an aquifer and a decentralised WWTP for a specialised sewer mining unit for supplementing water and nutrient demands for a tree nursery in Athens (Fig. 13). For the Costa Brava case study (Fig. 14), the three regions (A, B, and C) were reduced to two distinct regions (Residential and Tourist) to enable the depiction of seasonal water demands within the region. Further to this, the decentralised WWTP was replaced with a water reclamation plant that treats wastewater to reuse it for cleaning streets and watering golf courses. Additionally, like that of the Athens case model, the Costa Brava model obtains freshwater primarily via an aquifer, though there is the additional inclusion of a desalinisation plant that can be used in periods when the aquifer is regarded as being under stress.

6. Conclusions and policy implications

As one of the responses to the future challenges posed by climate change, the European Green Deal has formulated a Circular Economy Action Plan. Within this plan they highlight how the implementation of circular economy principles can substantially mitigate the adverse environmental effects associated with resource extraction and utilization, while concurrently supporting the restoration of natural capital and biodiversity in Europe (European Commission & Directorate-General for Communication, 2020). Migrating to circular economy approach, however, is not without its challenges. In a survey carried out by Kevin van Langen et al. (2021) they found that the most relevant barriers to adopting a circular economy approach were "Resistance to change", the "Low awareness and know how", "Lack of policies/regulations", and "current linear design of products; with Afghani et al. (2022) highlighting four barrier classes relating to the assessment of the legitimacy of circular water technologies as.

1. Regulative barriers concerning legal frameworks and regulations;
2. Normative barriers concerning norms and values;
3. Cognitive barriers concerning knowledge and capabilities;
4. Pragmatic barriers concerning social, economic, and environmental benefits.

To address the cognitive and pragmatic barriers that hinder adoption of circular economy practices, this study proposed the use of a testbed model coupled with a SG to represent key aspects of circular economy

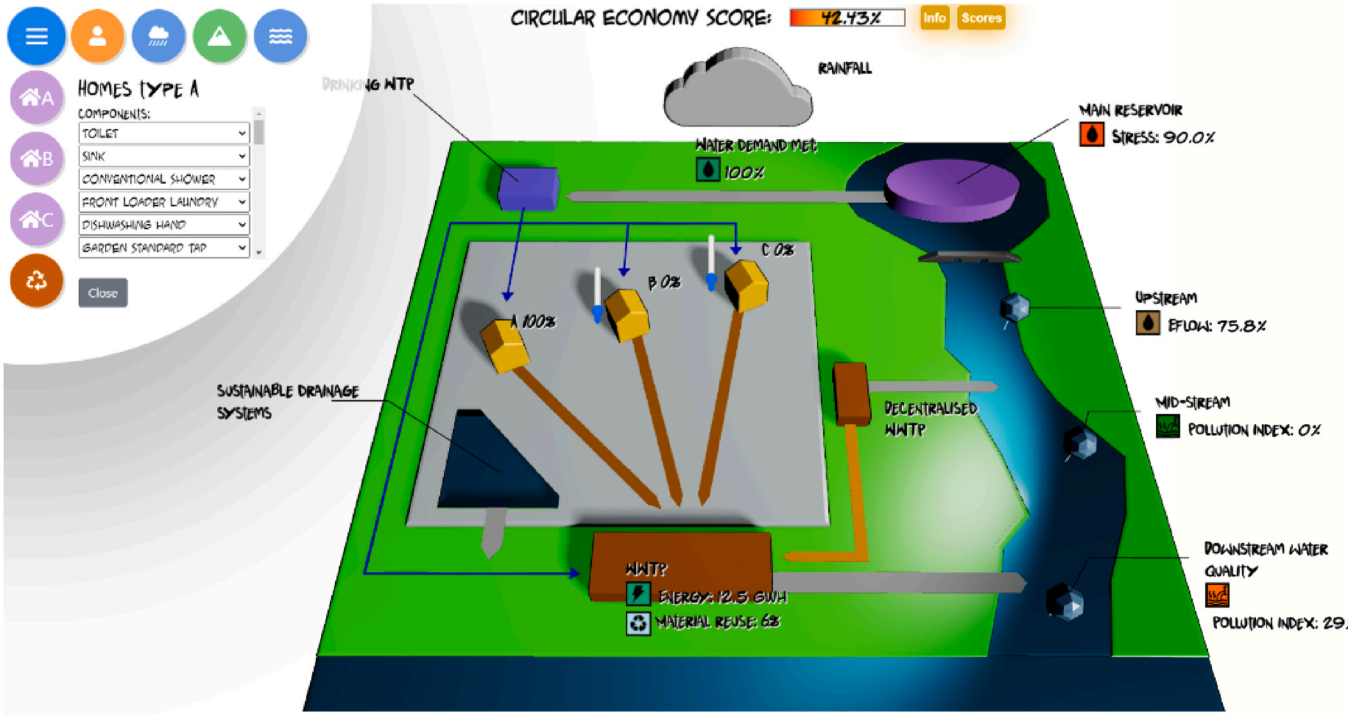

Fig. 11. Example of Toy Town model within the Serious Game.

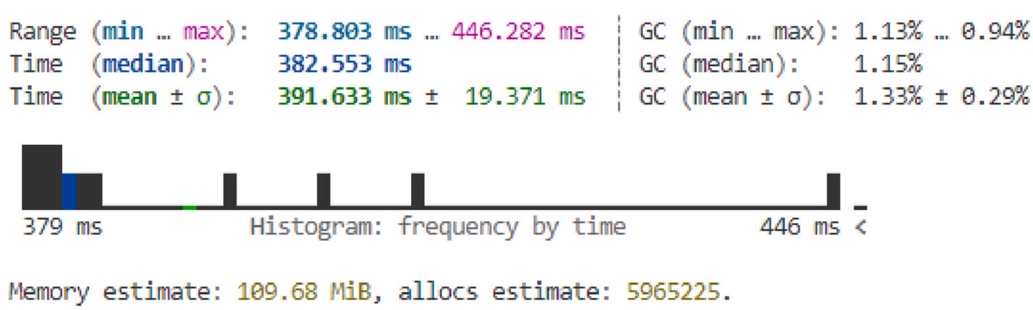

Fig. 12. Toy Town Model Performance of a 20-year simulation at daily/sub-daily adaptive time intervals.

concepts for urban water in an interactive and tangible way. By demonstrating the potential benefits of circular economy models, this approach can help to overcome cognitive and pragmatic barriers and pave the way for addressing normative and regulative barriers to adoption.

The flexibility of the testbed modelling approach allows for the creation of bespoke models and SG interfaces for the demonstration of new technologies. Within the Athens tree nursery case study, Plevri et al. (2020) demonstrated the use of a modular sewer mining unit that can be utilised for urban green irrigation at point of demand that can be used for water reuse, nutrient recovery to supplement demands for production of fertilizer, and thermal recovery for use in heating buildings on site. Through adaptation of the testbed model the potential benefits of this sewer mining technology is demonstrated within a SG (Fig. 13). For Costa Brava the testbed model was reconfigured (Fig. 14) to demonstrate the resource potential of a wastewater treated within a localised water reclamation plant as a means for use within the city to supplement local demands for municipal use and within the tourism sector.

The development of a testbed modelling platform centred on the urban water cycle enables testing and the demonstration of a broad range of scenarios to assess various elements of the water circular economy. The testbed model coupled within a SG therefore allows users to evaluate the effects of various modifications, from small-scale changes such as replacing household water use devices to larger-scale improvements such as adopting sustainable drainage systems and decentralised wastewater treatment. Moreover, the modular nature of the testbed model allows for future customisation, enabling the substitution of components present to produce bespoke scenarios to trial a range of technologies within different geographical regions.

CRediT authorship contribution statement

B. Evans: is the main author. He designed the testbed model and developed the Julia code for integration into the Serious Game. **M. Khoury:** is the second author, he contributed ideas relating to modelling, programmed the Serious Game and organised playing sessions to test the model and gather feedback. **L. Vamvakeridou-Lyroudia:** Writing – original draft. **O. Chen:** Writing – original draft. **N. Mustafee:** contributed ideas, helped with writing. **A.S. Chen:** Writing – original draft. **S. Djordjevic:** Writing – original draft. **D. Savic:** Writing – original draft.

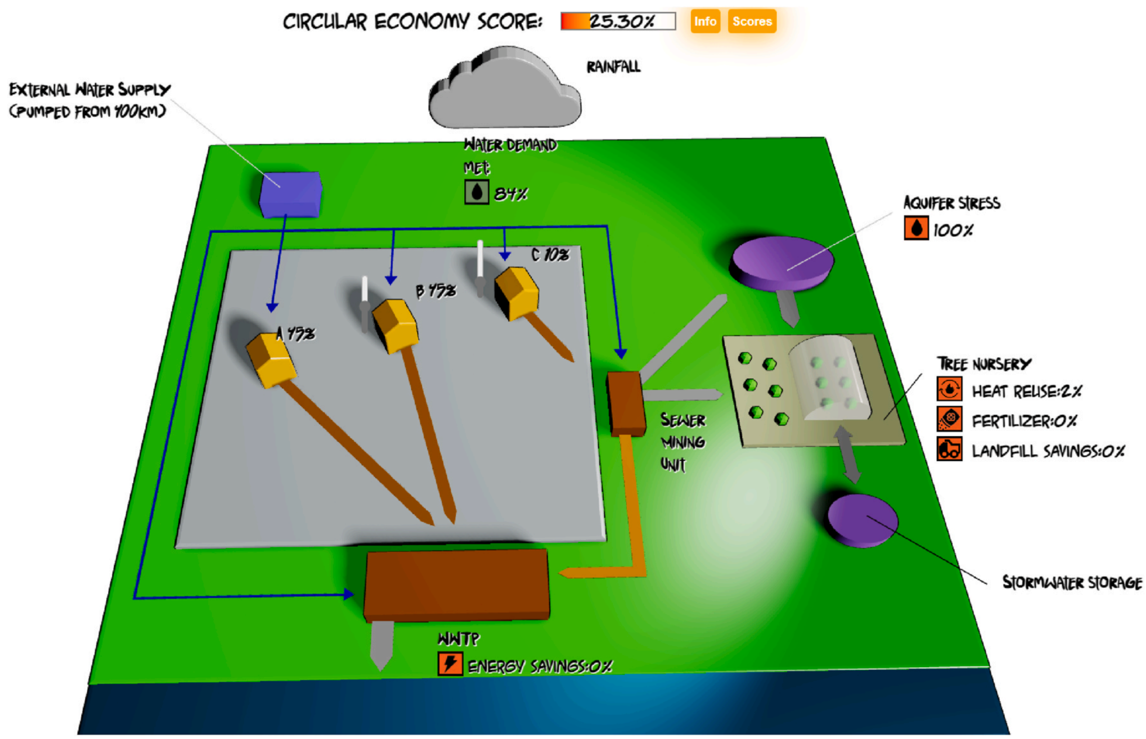

Fig. 13. Example SG for modelling potential of sewer mining units for tree nurseries in Athens.

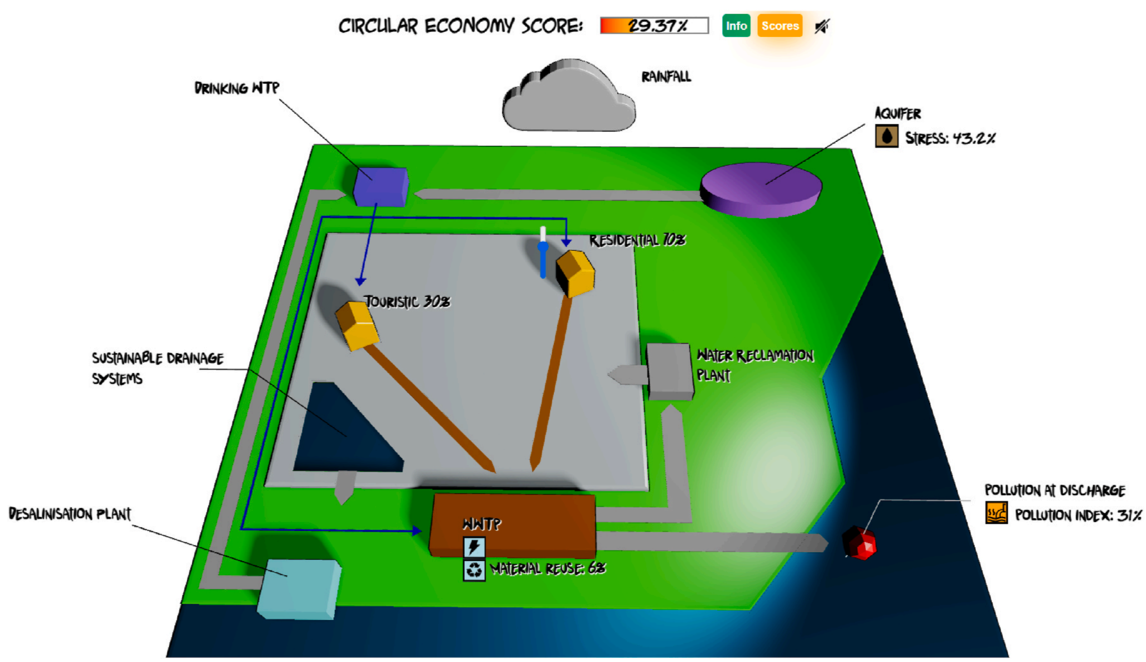

Fig. 14. Example SG for modelling water reclamation for touristic uses in Costa Brava.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The work presented in this paper was funded by the H2020 EU project NextGen “Towards a next generation of water systems and services for the circular economy”, GA 776541 (2018–2022).

Appendices.

Table A1
Parameters used for determining controlled reservoir discharge for environmental flow

Parameter	Range	
	Min	Max
Baseline Discharge Coefficient	0.0	1.0
Stress Discharge Coefficient	0.0	Baseline Discharge Coefficient
Stress Limit	0.0	1.0
Severe Stress Limit	0.0	Stress Limit

Table A2
Household water demands/internal water consumption and energy use rankings where the lower the number the less water/energy are used (derived from UWOT model outlined in Bouziotas et al., 2019).

Household Component Class	Household Component Sub Class	Water Demand Ranking	Energy Use Ranking
Washing Machine	Front Loader Eco	1	1
	Front Loader*	2	2
	Top Loader	3	3
Sink	Water Saving	1	2
	Recirculation Pump	2	1
	Standard*	3	3
Shower	Fog	1	1
	Recirculation	2	2
	Water Saving	3	3
	WTW	3	3
	Standard*	4	4
Dishwasher	Energy Certified	1	1
	Conventional	2	2
	Hand*	3	3
Cooking	–	–	–
Food Grinder	–	–	–
Toilet	Dry Flush	1	1
	Compost	2	1
	Vacuum	3	2
	High Pressure	4	1
	Water Saving	5	1
	Dual Flush	6	1
	Standard*	7	1

* Default selected technology for region.

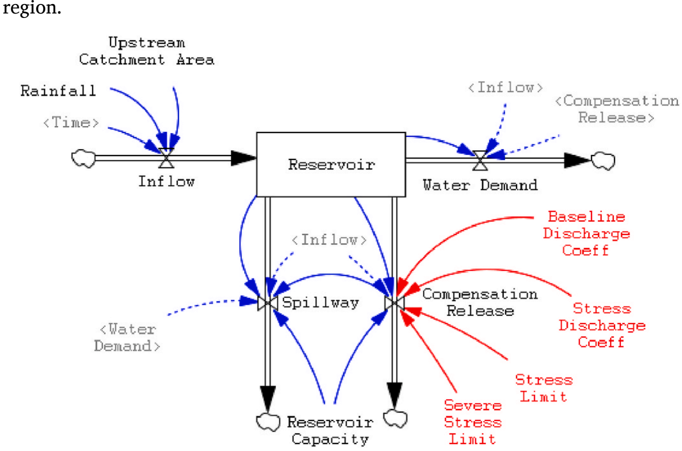

Fig. A1. Simplified Reservoir Setup

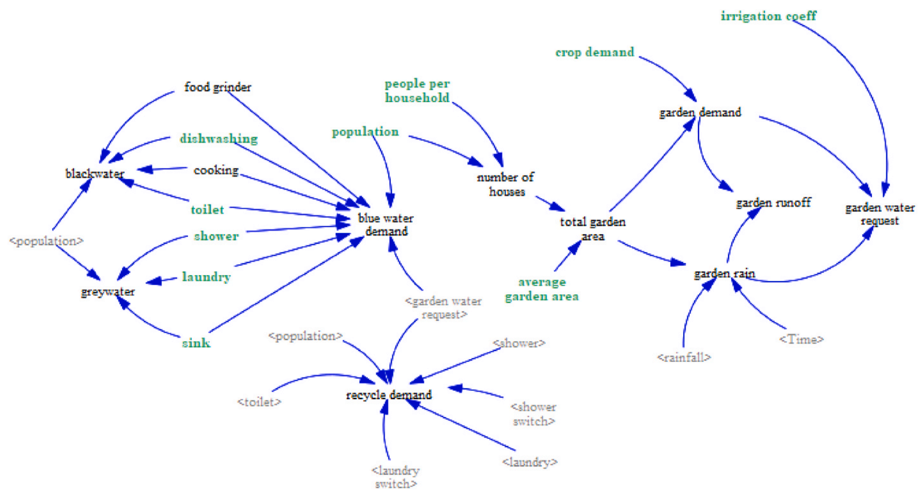

Fig. A2. Defining Household Bluewater Demands

Table A3
COD sources within Household Wastewater (COD values derived from ranges in Meinzinger and Oldenburg, 2009)

House Wastewater Classification	Source	COD (g/person/day)	Household Component Class
Greywater	Laundry	24.4	Washing Machine
	Hygiene	5.25	Sink
			Shower
Blackwater	Kitchen	17.0	Cooking
			Dishwasher
			Food Grinder
	Toilet	55.7	Toilet
Combined	**Total**	**102.35**	**All**

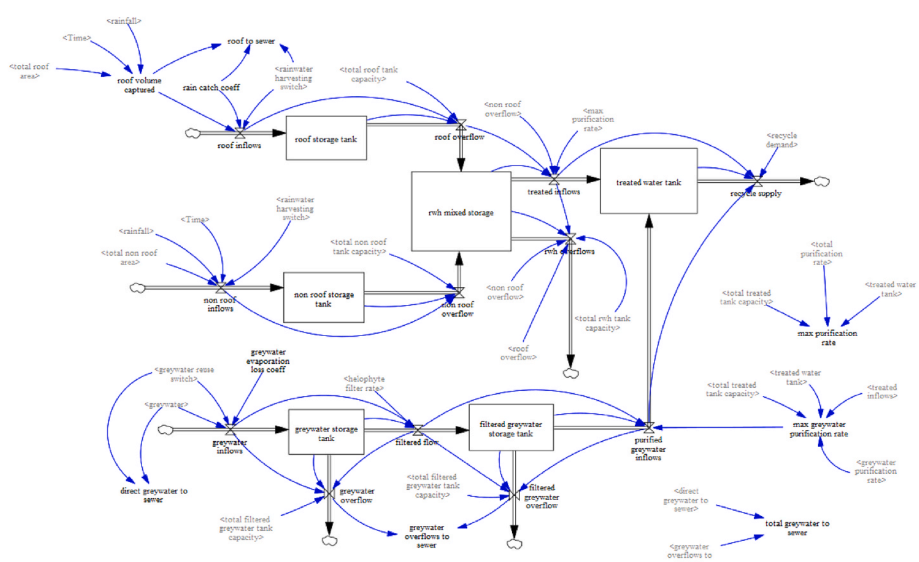

Fig. A3. SDM representation of localised water treatment processes

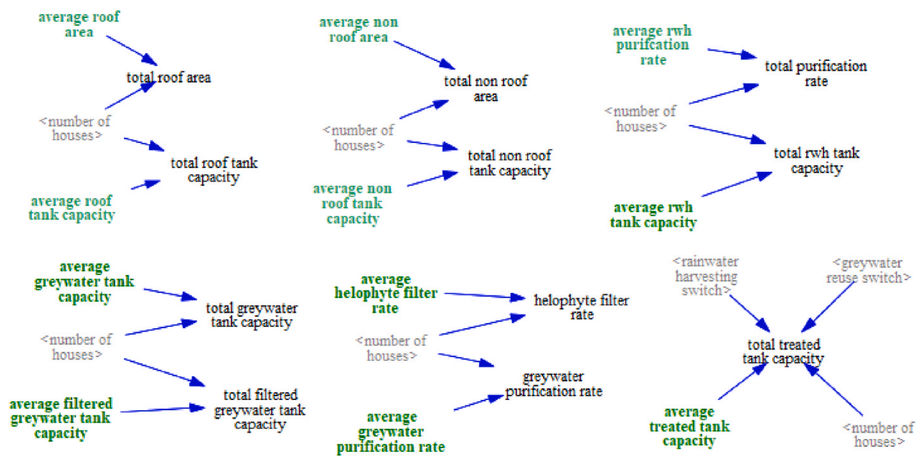

Fig. A4. RWH and GW Reuse parameters

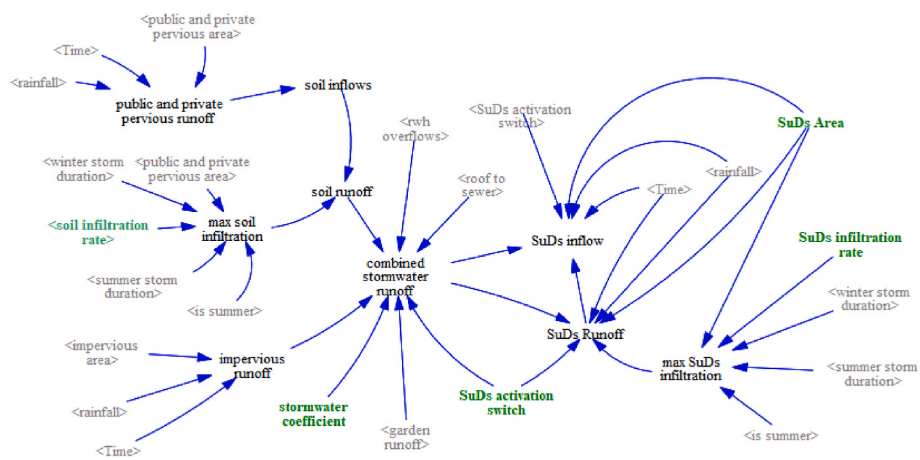

Fig. A5. Stormwater runoff modelling

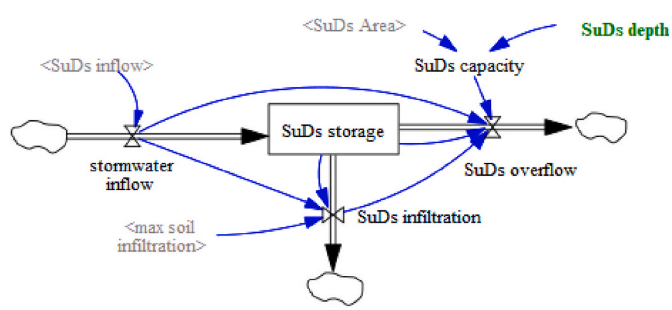

Fig. A6. SuDs storage diagram

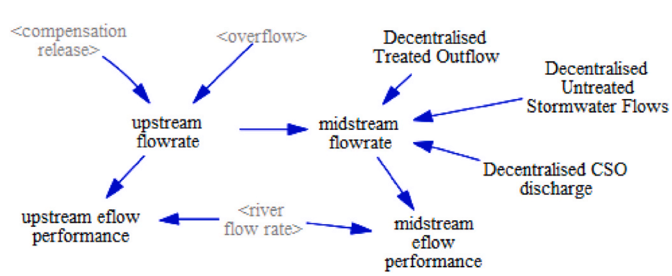

Fig. A7. Monitoring river flow rates

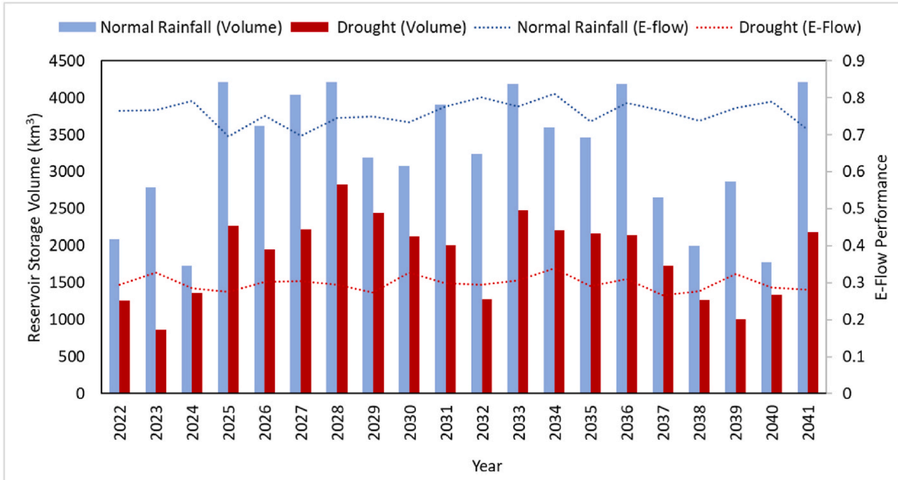

Fig. A8. Reservoir end-of-year storage volumes and environmental flows for baseline configuration under normal and extreme drought conditions

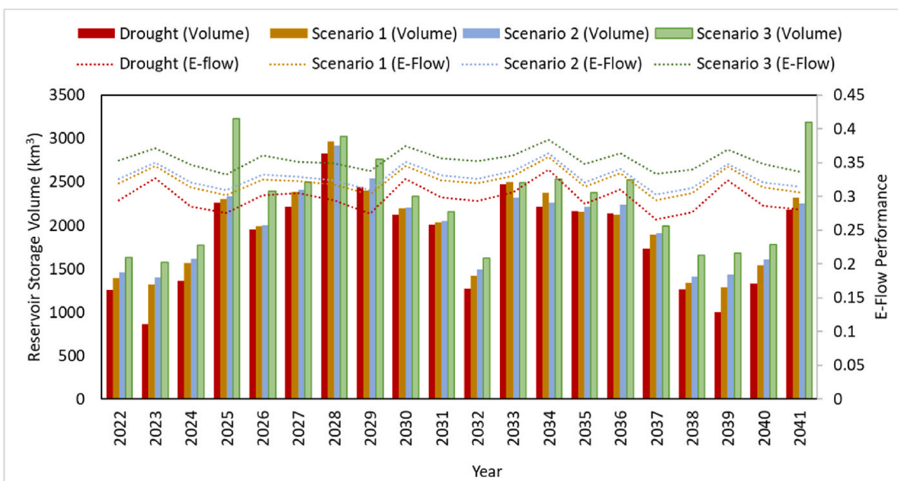

Fig. A9. Influence of water-saving technology on reservoir volumes and environmental flow

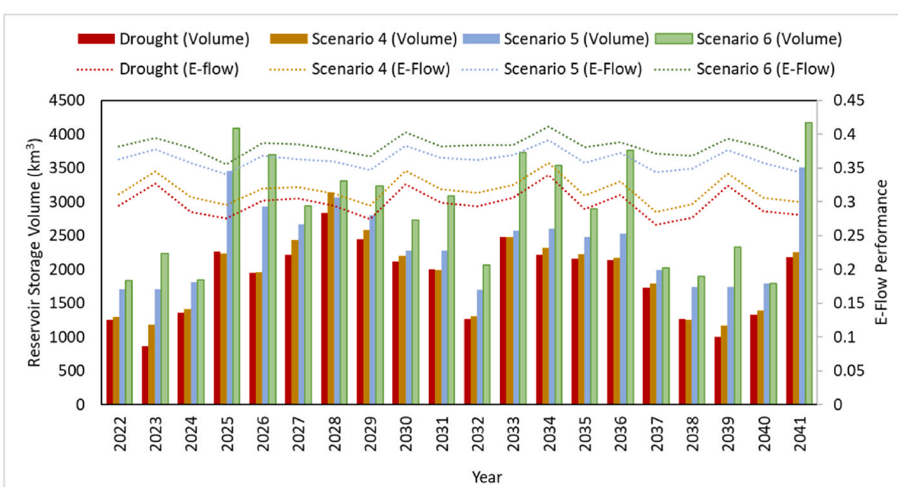

Fig. A10. Influence of water reuse technology on reservoir levels and environmental flow

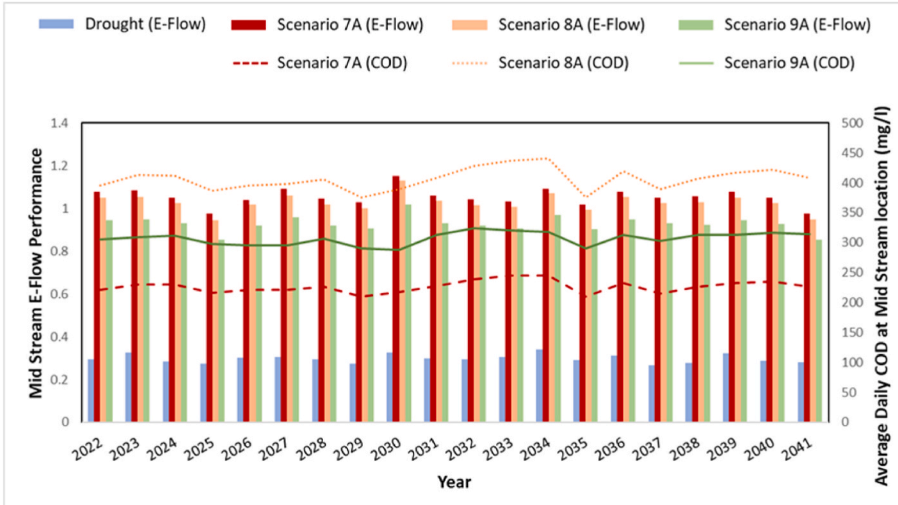

Fig. A11. E-Flow performance and average daily COD at the midstream location

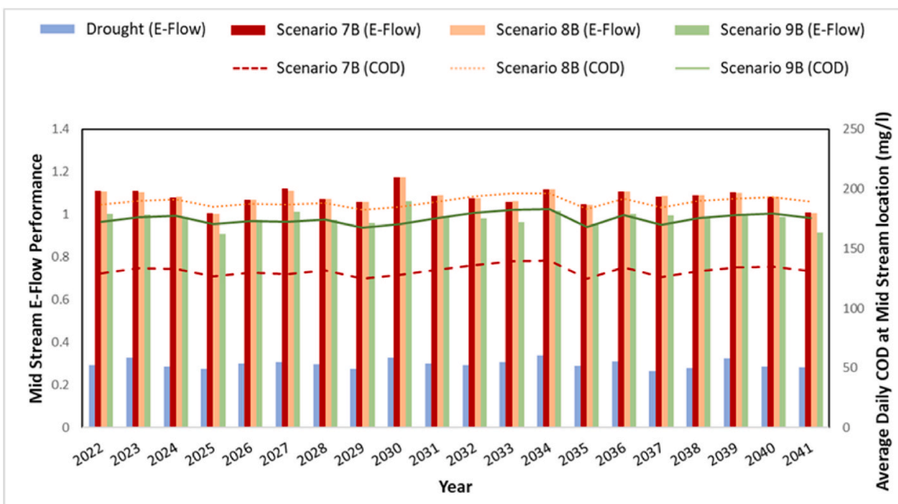

Fig. A12. E-Flow performance and average daily COD at the midstream location (Separate Sewers)

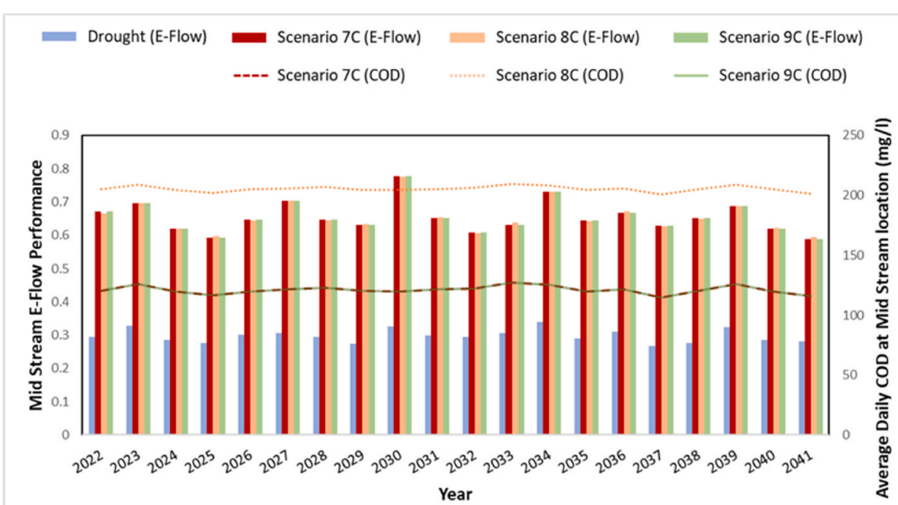

Fig. A13. E-Flow performance and average daily COD at the midstream location (Separate Sewers + SuDs)

References

Afghani, N., Hamhaber, J., Frijns, J., 2022. An integrated assessment framework for transition to water circularity. Sustainability 14 (14). https://doi.org/10.3390/su14148533.

Andrade, L., O'Dwyer, J., O'Neill, E., Hynds, P., 2018. Surface water flooding, groundwater contamination, and enteric disease in developed countries: a scoping review of connections and consequences. Environ. Pollut. 236, 540–549. https://doi.org/10.1016/j.envpol.2018.01.104.

Bouziotas, D., van Duuren, D., van Alphen, H.-J., Frijns, J., Nikolopoulos, D., Makropoulos, C., 2019. Towards circular water neighborhoods: simulation-based decision support for integrated decentralized urban water systems. Water 11 (6). https://doi.org/10.3390/w11061227.

Butler, D., James Digman, C., Makropoulos, C., Davies, J.W., 2018. Urban Drainage. CRC Press LLC. http://ebookcentral.proquest.com/lib/exeter/detail.action?docID=5303411.

Du, S., Liu, G., Li, H., Zhang, W., Santagata, R., 2022. System dynamic analysis of urban household food-energy-water nexus in Melbourne (Australia). J. Clean. Prod. 379, 134675 https://doi.org/10.1016/j.jclepro.2022.134675.

Ellen Macarthur Foundation, 2010. Circular economy introduction. https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview.

Environment Agency, 2019. Waste Water Treatment Works: T*reatment Monitoring and Compliance Limits*. Https://Www.Gov.Uk/Government/Publications/Waste-Water-Treatment-Works-Treatment-Monitoring-and-Compliance-Limits/Waste-Water-Treatment-Works-Treatment-Monitoring-and-Compliance-Limits#lut-for-Bod-and-Cod.

European Commission, & Directorate-General for Communication, 2020. Circular Economy Action Plan : for a Cleaner and More Competitive Europe. Publications Office of the European Union. https://doi.org/10.2779/05068.

European Environment Agency, 2021. Water Resources across Europe — Confronting Water Stress: an Updated Assessment.

Evans, B., Vamvakeridou-Lyroudia, L., Susnik, J., Trabucco, A., Mereu, S., Albin, X.D., Chew, C., Savic, D., 2018. SIM4NEXUS – coupling a system dynamic model with serious gaming for policy analysis. In: la Loggia, G., Freni, G., Puleo, V., de Marchis, M. (Eds.), HIC 2018. 13th International Conference on Hydroinformatics, vol. 3, pp. 676–683. https://doi.org/10.29007/w5vl. EasyChair.

Katsaliaki, K., Mustafee, N., 2012. A survey of serious games on sustainable development. Proceedings of the 2012 Winter Simulation Conference (WSC) 1–13. https://doi.org/10.1109/WSC.2012.6465182.

Kevin van Langen, S., Vassillo, C., Ghisellini, P., Restaino, D., Passaro, R., Ulgiati, S., 2021. Promoting circular economy transition: a study about perceptions and awareness by different stakeholders groups. J. Clean. Prod. 316, 128166 https://doi.org/10.1016/j.jclepro.2021.128166.

Khoury, M., Evans, B., Chen, O., Chen, A.S., Vamvakeridou-Lyroudia, L., Savic, D.A., Djordjevic, S., Bouziotas, D., Makropoulos, C., Mustafee, N., 2023. NEXTGEN: a serious game showcasing circular economy in the urban water cycle. J. Clean. Prod. 391, 136000 https://doi.org/10.1016/j.jclepro.2023.136000.

Kiselev, A., Magaril, E., Magaril, R., Panepinto, D., Ravina, M., Zanetti, M.C., 2019. Towards circular economy: evaluation of sewage sludge biogas solutions. Resources 8 (2). https://doi.org/10.3390/resources8020091.

Ladson, Tony, 2017. Rainfall excess hydrograph. Hydrology, Natural Resources and R. https://tonyladson.wordpress.com/2017/03/23/rainfall-excess-hydrograph/.

Luthy, R.G., Sedlak, D.L., Plumlee, M.H., Austin, D., Resh, V.H., 2015. Wastewater-effluent-dominated streams as ecosystem-management tools in a drier climate. Front. Ecol. Environ. 13 (9), 477–485. https://doi.org/10.1890/150038.

Mbavarira, T.M., Grimm, C., 2021. A systemic view on circular economy in the water industry: learnings from a Belgian and Dutch case. Sustainability 13 (6). https://doi.org/10.3390/su13063313.

Meinzinger, F., Oldenburg, M., 2009. Characteristics of source-separated household wastewater flows: a statistical assessment. Water Sci. Technol. 59 (9), 1785–1791. https://doi.org/10.2166/wst.2009.185.

Mereu, S., Sušnik, J., Trabucco, A., Daccache, A., Vamvakeridou-Lyroudia, L., Renoldi, S., Virdis, A., Savić, D., Assimacopoulos, D., 2016. Operational resilience of reservoirs to climate change, agricultural demand, and tourism: a case study from Sardinia. Sci. Total Environ. 543, 1028–1038. https://doi.org/10.1016/j.scitotenv.2015.04.066.

Metcalf & Eddy Metcalf & Eddy Inc., 2013. Wastewater Engineering: Treatment and Resource Recovery : Treatment and Resource Recovery. McGraw-Hill Higher Education. http://ebookcentral.proquest.com/lib/exeter/detail.action?docID=5662641.

Nabavi, E., Daniell, K.A., Najafi, H., 2017. Boundary matters: the potential of system dynamics to support sustainability? J. Clean. Prod. 140, 312–323. https://doi.org/10.1016/j.jclepro.2016.03.032.

Plevri, A., Lytras, E., Samios, S., Lioumis, C., Monokrousou, K., Makropoulos, C., 2020. Sewer mining as A basis for technological, business and governance solutions for water in the circular economy: the NextGen Athens demo. Environmental Sciences Proceedings 2 (1). https://doi.org/10.3390/environsciproc2020002054.

Plevri, A., Monokrousou, K., Makropoulos, C., Lioumis, C., Tazes, N., Lytras, E., Samios, S., Katsouras, G., Tsalas, N., 2021. Sewer mining as a distributed intervention for water-energy-materials in the circular economy suitable for dense urban environments: a real world demonstration in the city of Athens. Water 13 (19). https://doi.org/10.3390/w13192764.

Qtaishat, Y., Hofman, J., Adeyeye, K., 2022. Circular water economy in the EU: findings from demonstrator projects. Cleanroom Technol. 4 (3), 865–892. https://doi.org/10.3390/cleantechnol4030054.

Shen, Q., Chen, Q., Tang, B., Yeung, S., Hu, Y., Cheung, G., 2009. A system dynamics model for the sustainable land use planning and development. Habitat Int. 33 (1), 15–25. https://doi.org/10.1016/j.habitatint.2008.02.004.

Stanitsas, M., Kirytopoulos, K., Vareilles, E., 2019. Facilitating sustainability transition through serious games: a systematic literature review. J. Clean. Prod. 208, 924–936. https://doi.org/10.1016/j.jclepro.2018.10.157.

Sušnik, J., Chew, C., Domingo, X., Mereu, S., Trabucco, A., Evans, B., Vamvakeridou-Lyroudia, L., Savić, D.A., 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). https://doi.org/10.3390/w10020139.

Sušnik, J., Masia, S., Indriksone, D., Brēmere, I., Vamvakeridou-Lydroudia, L., 2021. System dynamics modelling to explore the impacts of policies on the water-energy-food-land-climate nexus in Latvia. Sci. Total Environ. 775, 145827 https://doi.org/10.1016/j.scitotenv.2021.145827.