Water Research 219 (2022) 118583

Contents lists available at ScienceDirect

Water Research

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

Water neutrality framework for systemic design of new urban developments

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ARTICLE INFO

Keywords:
Water neutrality
CityPlan-Water
Urban water security
Urban planning
Systemic design
Urban sustainability

ABSTRACT

The climate emergency and population growth threaten urban water security in cities worldwide. Growth, urbanisation, and changes to way of life have increased housing demand, requiring cities such as London to increase their housing stock by more than 15% over the next 10 years. These new urban developments will increase water demand, urban flood risk, and river water pollution levels; therefore, an integrated systems-based approach to development and water management is needed. Water Neutrality (WN) has emerged as a concept to frame the concerns about escalating water stresses in cities. We frame WN as a planning process for new urban developments that aims to minimise impacts on urban water security and offset any remaining stresses by retrofitting existing housing stock. In this work, we present a novel systemic design framework for future urban planning called CityPlan-Water, which guides how WN might be achieved to tackle current and future water pressures at a city scale. CityPlan-Water integrates spatial data with an integrated urban water management model, enabling urban design at a systems level and systematic assessment of future scenarios. We define a Water Neutrality Index that captures how successful a given urban planning scenario is in achieving WN and how multiple interventions could be combined at a city scale to improve WN. Results from CityPlan-Water suggest that it will be necessary to retrofit almost the same number of existing homes with WN design options to completely offset the impact imposed by proposed new developments. Combining options such as water efficient appliances, water reuse systems, and social awareness campaigns can offset the impact of new development on water demand by 70%, while to neutralise potential flood risk and water pollution at a city scale, interventions such as rainwater harvesting and Blue Green Infrastructure need to be added both in new urban developments and 432,000 existing London households. We see CityPlan-Water as a tool that can support the transition of urban planning towards using data-driven analysis to effectively design water neutral housing and drive sustainable development.

1. Introduction

Population growth and the climate emergency are increasing pressures on housing in cities worldwide (United Nations, 2014; Colenbrander et al., 2019; Committee on Climate Change, 2019; Cohen, 2020; Taylor, O'Brien and O'Keefe, 2020), and causing adverse effects on the urban water cycle (Rauch et al., 2017; Water UK, 2019; Zubaidi et al., 2020). One of the biggest challenges for future planning will be managing the impact of new housing developments on water sustainability (Brown et al., 2009; Jones, 2014a; Hurlimann and Wilson, 2018). Understanding the interactions between land use processes, water infrastructure and water quality will require integrated urban planning and will be essential to manage the impact of housing growth on the urban water cycle (Carmona et al., 2010; Ford et al., 2019; Medeiros and van der Zwet, 2020).

To address the complexity of the built-natural environment interdependences, a systems approach has been proposed, which integrates design and evaluation with criteria that are used to inform the level of sustainability of an urban development (Puchol-Salort et al., 2021). In the literature, there are several approaches to integrate urban planning with water management, which can address some of the aspects of the systems approach. For instance, Yang et al. (2016) present a conceptual framework for urban water sustainability that evaluate socioeconomic and environmental interactions; Furlong et al. (2017) study the benefits and opportunities of Integrated Urban Water Management plans; Ford et al. (2019) develop an Urban Integrated Assessment

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https://doi.org/10.1016/j.watres.2022.118583
Received 21 December 2021; Received in revised form 26 March 2022; Accepted 7 May 2022
Available online 12 May 2022

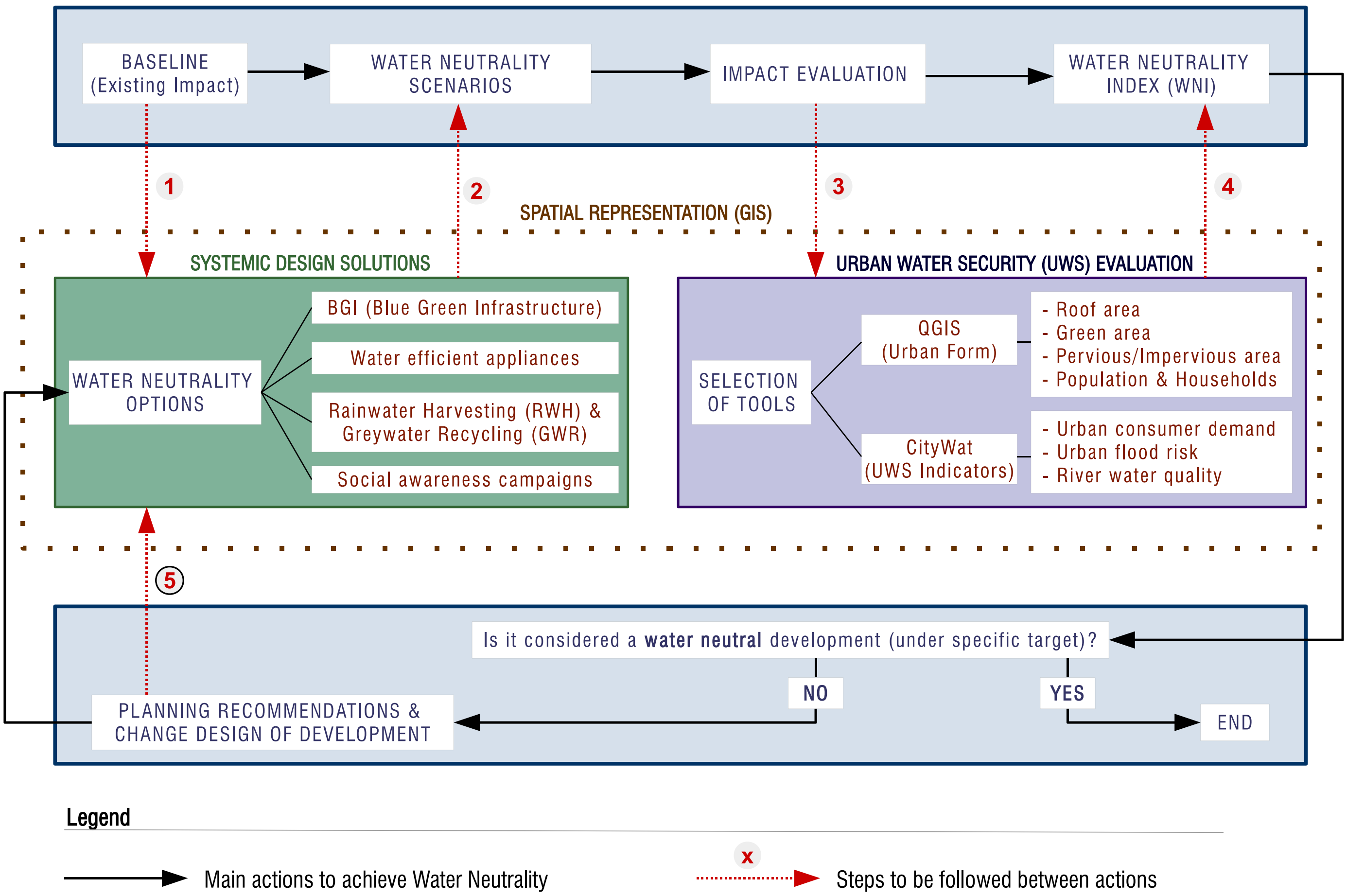

Fig. 1. Methodology diagram of the CityPlan-Water systemic design and evaluation framework. The main actions happening inside the CityPlan-Water process are indicated by black arrows, while the steps to achieve water neutrality between these actions are represented by the red numbered arrows.

Framework that provides a multi-scale analysis of climate change impacts on cities; and, Medeiros and van der Zwet, 2020 integrate strategies for Sustainable Urban Development and evaluate them qualitatively in two European cities. However, there is still a need to integrate the entire planning process with design solutions and quantitative evaluation, which we address in this paper by adapting the Urban Planning Sustainability Framework (UPSUF, Puchol-Salort et al., 2021) to water-land system analysis. In UPSUF, systems thinking is defined as an engineering approach that integrates blue green urban design, modelling and analysis of land and building planning options to enable stakeholders' coordination and a holistic vision of the urban system.

Systemic design is an emerging approach that has evolved in recent decades. It combines traditional design and systems thinking, taking a holistic and complete account of the urban form elements that constitute a complex system (Jones and Kijima, 2018; Battistoni et al., 2019; Bijl-Brouwer and Malcolm, 2020). Following systemic design principles, all physical elements in a given space (e.g., an urban development, borough, city, etc.) define a series of layers that, together, constitute the entire urban system (Jones, 2014b; Ryan, 2014; De la Rosa and Hovanesian, 2019). Therefore, systemic design sees the planning process as a whole and considers urban water infrastructure as one of the layers in the design of cities (Shin et al., 2018; Moravej et al., 2021). In this study, we are introducing the systemic design approach to urban planning and water management guided by UPSUF.

An emerging concept in urban water management is Water Neutrality (WN; Kemlo and Lawson, 2009; Nel et al., 2009; Hoekstra, 2018). Traditionally, WN was defined as an approach to offset a predicted increase in water demand produced by a new urban development by reducing the existing demand somewhere inside the region (Environment Agency, 2009). The concept was then extended to include demand offsetting by increasing water efficiency and reducing water consumption (Hoekstra, 2008; Hoekstra et al., 2011; Makin et al., 2021). However, WN should not solely imply the need to have net zero water consumption, but also, to prioritise minimising the impacts of new development and offsetting the remaining environmental and social impacts (Wu et al., 2020; Makin et al., 2021). These impacts could be evaluated through the concept of Urban Water Security (UWS), which integrates water demand with flood risk and water quality assessments (Hoekstra et al., 2018; Nazemi and Madani, 2018; Van Ginkel et al., 2018; Aboelnga et al., 2019; Su et al., 2020). In this study, we consider that achieving WN will require not only to maintain the same post-development water demand, but also to maintain existing flood risk and water quality UWS indicators. We also allow for the WN target to be set by the decision-makers, with net zero water target (100% water neutral developments) as a default recommendation.

Finally, to maintain existing UWS indicators and efficiently implement WN at the planning phase of a new urban development, a range of WN design options will be needed, either inside or outside the development area. These design options include, for example, Blue Green Infrastructure (BGI), efficient appliances, rainwater harvesting, water reuse systems and demand management social campaigns (Dieu-Hang et al., 2017; Sheth, 2017; Ferrans et al.; 2018; Lu, 2019), amongst others. We argue that applying UPSUF to WN will support the integration of sustainable design solutions and simulation models, to achieve implementation of systemic design for urban systems planning. Although there are some valuable examples of water management evaluation models combined with spatial representation such as the DAnCE4Water model from Rauch et al. (2017) or the SUWMBA method from Morajev

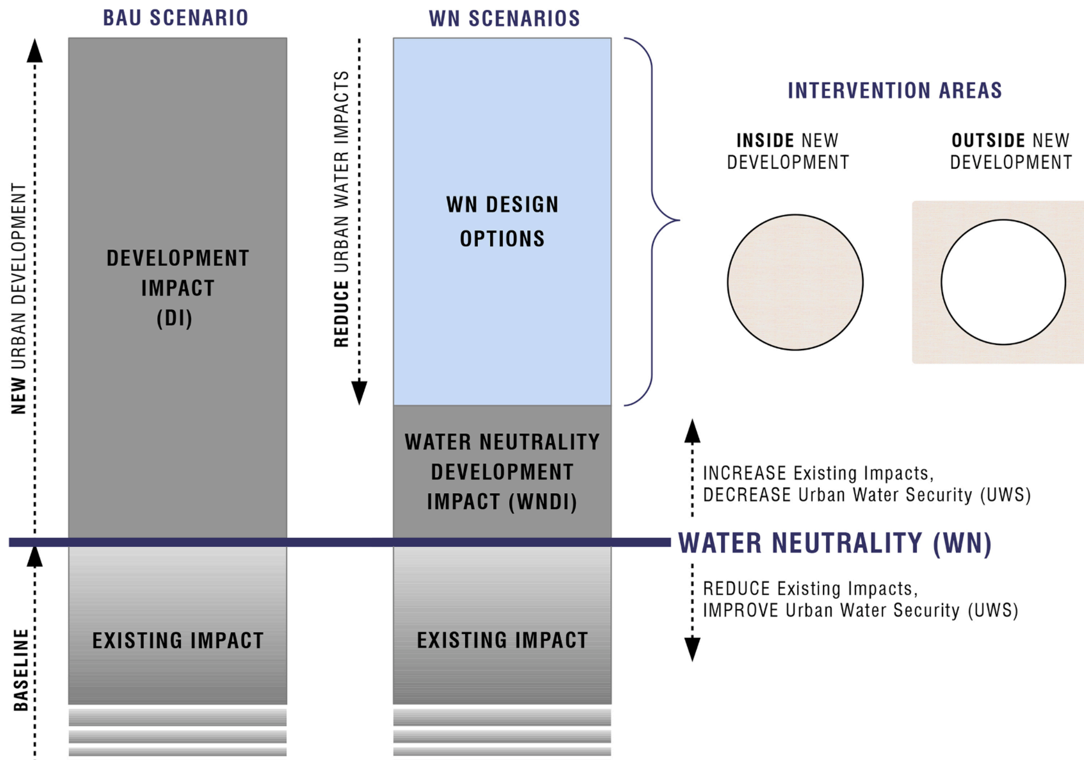

Fig. 2. Water Neutrality systemic design concept diagram. To fully achieve WN is necessary to decrease the Urban Water Security (UWS) indicators as they were at the pre-development Baseline stage (existing impact).

et al. (2021); there is no clear evidence of the WN concept being applied in urban systems and there is still a lack of an integrated method that accurately measures WN indicators combined with spatial configurations for urban planning.

In this paper, we present the novel concept of CityPlan conceived as an operational version of UPSUF. We envisage that the CityPlan can be applied to different areas of urban sustainability (i.e., water, air, biodiversity, urban microclimate, etc.); here we develop a proof-of-concept focused on WN evaluation (CityPlan-Water hereafter). There are three key contributions in this work. First, we develop the WN concept for future urban planning from a systemic design perspective. Second, we present the novel CityPlan-Water framework, where WN assessment is provided by the integrated urban water management model CityWat (Dobson and Mijic, 2020), which we combine with a spatial analysis of key urban form parameters with the focus on London, UK. CityPlan-Water could be applied at different urban scales, which is defined by the spatial extent and the resolution of the simulation model used. In this study, the WN evaluation for London is performed at a city lumped scale. CityPlan-Water provides a quantitative assessment for a series of WN design options through the novel Water Neutrality Index (WNI). Third, we demonstrate opportunities to achieve WN at a city scale depending on different scenarios and levels of offsetting the impacts of new urban development inside versus outside the development area. Finally, implications of the work, potential future scope, and overall conclusions are discussed.

2. CityPlan-Water case study: the city of London

Unavoidable pressures on water systems such as fluvial flooding, pluvial flooding, droughts, or river water quality degradation are projected to become more frequent in the UK due to climate change and increased urbanisation (Garner, Hannah & Watts, 2017; Miller and Hutchins, 2017). These pressures are very significant in London (Environment Agency, 2009; Clark et al., 2018). The city's population is projected to increase by 70,000 people per year, reaching 10.8 million citizens by 2041 (Committee on Climate Change, 2019; GLA, 2021). This will require an average increase of 66,000 new homes per year, for at least twenty years, and around 50% of these homes being affordable if Londoners' needs are to be met (GLA, 2021).

London is divided into 32 boroughs, which are sub-divided for statistical purposes into smaller zones called Lower Layer Super Output Areas (LSOAs). London's urban pattern depicts a distorted grid radiating from the city centre to the city boundaries, changing in scale and density. Central areas follow traditional Georgian planning and are generally more compact with concentrated and large green spaces, while suburbs present a more sprawl distribution surrounded by metropolitan open land and a Green Belt (GLA, 2021).

Based on the new London Plan (GLA, 2021), the 10-year predicted target for net housing completion in the city will be 522,870 new homes by 2030. Currently, the city presents a strong potential for urban regeneration, as large areas are reliant on ageing infrastructure and will benefit from redevelopment and investment opportunities. The Greater London Authority (GLA) has already identified several Opportunity Areas (OAs) in each borough, which present an effective development capacity to accommodate new housing, commercial activities and public infrastructure, and are linked to existing or potential improvements in public transport connectivity (GLA, 2021).

3. Methodology

Evaluating water neutrality at different scales, influencing planning decisions and guiding stakeholders towards water neutral developments is the key purpose of CityPlan-Water. Its functionality is based on UPSUF and integrates three key components (Fig. 1), which includes representation of the CityPlan-Water process and operation (blue cluster in Fig. 1); the systemic design solutions (green cluster); and the Urban Water Security (UWS) evaluation toolkit overview (purple cluster). In this work, UPSUF is refined to support water neutrality evaluation for

Table 1
Urban form properties selected in CityPlan-Water related to Water Neutrality, their data source, and what they inform about. Table includes the type of visualisation maps, and the land cover layers aggregated in each urban form to calculate the plan area fraction equation from Oke et al., 2017.

DATA SOURCE	WN URBAN FORM PROPERTIES			
	URBAN FORM	INFORM	VISUALISATION	
			AREA FRACTION MAPS	SUBSCRIPT x (*Eq. 2*)
Land cover raster data	Roof area	Rainwater harvesting storage capacity and urban density	Roof area density	Buildings
	Blue and green area	Amount and density of natural services (water and vegetation)	Blue & green area density	Water + tree canopy + low vegetation + tree over pervious surface
	Total pervious area	City's drainage capacity and stormwater runoff	Total pervious area density	Blue and green area + bare soil + pervious roadside + rail
	Total impervious area		Total impervious area density	Buildings + impervious surfaces + impervious roads + impervious roadside + tree over impervious surface + tree over impervious road/roadside + bridge/structure
UK Census data	Population	Water demand patterns and wastewater production	Population density	Given by UK Census
	Households		Average Household size	Given by UK Census

new urban developments, developing the proof-of-concept for CityPlan-Water.

3.1. Water Neutrality systemic design concept

The methodology of CityPlan-Water follows an iterative process that uses a defined target for Water Neutrality as a measure of the Urban Water Security through a spatial representation in GIS. The results from CityPlan-Water will determine if a new urban development with proposed WN design options can be considered water neutral under a specific target and spatial assessment scale. As with UPSUF, this iterative process provides a defined set of steps that takes the user from an initial baseline to new water neutral development scenarios, including the requirements of environment and regulatory bodies.

New developments increase the existing urban water impacts in cities and decrease UWS levels (Mekonnen and Hoekstra, 2016; Jensen and Wu, 2018). To define a new interpretation of the WN concept from a systemic design approach it is necessary to evaluate this increase under different urban design scenarios (Fig. 2). In our work, the Development Impact (DI) from new urban developments is calculated as an addition to the existing (pre-development) impacts (i.e., Baseline thereafter). To provide a comprehensive assessment of the WN concept, we consider two types of urban design scenarios: Business as Usual (BAU) scenario (left column in Fig. 2) and WN scenarios (right column in Fig. 2).

3.1.1. Water Neutrality Index

The BAU scenario represents the project that is developed and built with traditional construction and design, primarily including hard and impervious surfaces and artificial materials (Puchol-Salort et al., 2021). Under the BAU option, no WN design options are implemented, and the DI is at its maximum level. To offset the impacts, WN scenarios are developed as design options that reduce the urban water impacts. These scenarios provide different levels of impact reduction, depending on the scale and size of the intervention. The WN options can be applied inside the development area (new buildings and land) or outside (existing infrastructure retrofit). We define the remaining impact of new developments on the urban water system of the city once WN options are implemented as a Water Neutrality Development Impact (WNDI). Hence, if WNDI is zero, the proposed WN options fully offset the impacts of the new development, and WN will be fully achieved (threshold marked by the blue line in Fig. 2).

It is useful to introduce a Water Neutrality Index (WNI), which measures the relative difference between Development Impact (DI) in the BAU scenario and the Water Neutrality Development Impact (WNDI) in the WN scenarios:

$$\mathrm{WNI} = \frac{\mathrm{DI} - \mathrm{WNDI}}{\mathrm{DI}} \times 100\ (\%) \tag{1}$$

The WNI needs to be 100 to achieve full WN and to maintain UWS at the pre-development levels. In case the WNI is higher than 100, the existing UWS levels will be improved, creating an environment-positive urban development.

3.2. Spatial data to understand Water Neutrality urban form

Analysis of London's urban form properties is needed to understand the existing urban water system (i.e., pre-development Baseline). We have selected a series of urban form properties based on their direct relationship with the UWS indicators and the WN concept, Table 1. Roof area, blue and green area, and total pervious/impervious area are obtained from a proprietary 2m land cover raster dataset provided by the British Geological Survey (BGS); while population and size of housing are obtained from the UK Census, 2011. In this work, we study London's urban form properties and its spatial attributes following LSOA boundaries because they are publicly available from the UK census API and feature consistently sized statistical units at the highest resolution. The BGS landcover raster data is not publicly available, but a similar analysis could be performed with open-source datasets such as the Ordnance Survey OS Open Data (UK, 2019) or the London OpenStreetMap, among others.

We use the urban form data in two ways. Firstly, we introduce it in the CityWat model to ensure the accuracy of the input data. Secondly, we create a series of density maps, defined via (Oke et al., 2017):

$$\lambda_x = \frac{A_x}{A_T} \tag{2}$$

where A_x is the surface area of land cover type x in the LSOA (see last column in Table 2) and A_T is the total surface area. A summary of selected urban form properties, their total area, percentages and average area fraction indexes is in the Table A1 in Appendices.

3.3. Systemic design solutions

One of the strengths of the systemic design approach is its flexibility to be implemented at different spatial scales (Jones, 2020). An urban planner can implement systemic design solutions from an urban development to a whole city scale (Battistoni et al., 2019; Pereno and Barbero, 2020). In this work, the CityWat model assesses the urban water system of London as a whole in a lumped approach, so we perform a scenario development exercise at a city scale. The evaluation of the WN

Table 2
Water Neutrality design options definition and examples, literature references and key stakeholders involved in each intervention area.

WN DESIGN OPTIONS	DEFINITION	EXAMPLES	REFERENCES	KEY STAKEHOLDERS INVOLVED
Blue Green Infrastructure (BGI)	All types of nature-based solutions applied to the urban environment and aligned to natural water processes	Permeable paving; engineered stormwater controls; blue and green roofs; green façades; hanging gardens and vertical urban farms; parks and open spaces; ponds and waterways; and, urban gardens	Bozovic et al., 2017; Kabisch et al. 2017; Nesshöver et al., 2017; Zaid et al., 2018; Keeler et al., 2019; Ferrans et al., 2022	Developers & Central and Local Government
Water efficient appliances	Fixtures that use less water while providing a similar performance to conventional ones	Certified taps; toilets; baths; showers; and, plumbing accesories	Millock and Nauges, 2010	Developers & Citizens
Water reuse systems	Rainwater Harvesting (RWH): Collect and store rainwater in a tank, generally from building roofs or other land surfaces	Garden water butts; underground direct-pumped tanks; roof gravity or indirect-pumped tanks	Li et al., 2009	Developers, Local Government & Citizens
	Greywater Recycling (GWR): Recycle and reuse household wastewater primarily from showers and bathtubs	Direct use systems (only for watering plants); sand filter systems; and, wetlands	Campisano et al., 2017	
Social awareness campaigns	Activities that aim to educate citizens and increase their awareness in causes such as water consumption or behavioural patterns	Social media campaigns; local workshops; web-based or printed advertisement; and, public engagement events	Stavenhagen et al., 2018	Central and Local Government, Water Companies & Citizens

Note: Although some BGI design options might have a rainwater harvesting function, in this work the collection and store of water is only considered in the RWH system options.

scenarios will measure the effectiveness of the WN design options listed in Table 2, which can be implemented either inside or outside the new development area as retrofit solutions.

3.3.1. Urban Water Security indicators

Selected WN design options interact differently with UWS indicators. For instance, BGI reduces flood risk and improves water quality, but has no significant effect on consumer demand unless the water reuse functionality is introduced. Efficient appliances, however, have a positive impact on consumer demand and water quality, but do not impact flood risk. In addition to conceptually understanding the influence of each proposed intervention on UWS indicators, it is also important to highlight the different involvement from urban stakeholders in the WN design implementation (Table 2). For example, efficient appliances and social campaigns both affect consumer demand and water quality, but are responsibility of different stakeholders (i.e., efficient appliances depend on developers and citizens, while social campaigns rely on Central and Local Government, water companies and, ultimately, citizens).

To holistically assess the impacts on the urban water system for all relevant stakeholders (Puchol-Salort et al. 2021), we select three key indicators for Urban Water Security (UWS). These UWS indicators are: (a) urban consumer demand, measured by the average daily total water supplied to consumers across London in Megalitres per day, ML/day; (b) urban flood risk, measured by the average of excess stormwater runoff in Megalitres per day, ML/day; and, (c) river water quality, measured by the average daily phosphorus content in the river Thames in milligrams per litre, mg/l. Urban consumer demand is primarily relevant to water companies, urban flood risk for Local Planning Authorities, and river water quality for the England's Environment Agency (EA).

3.4. Water Neutrality evaluation

The impact of WN scenarios is evaluated in terms of UWS indicators in the third step of the CityPlan-Water process (Fig. 1). CityPlan-Water combines the CityWat urban water management integrated model (Dobson and Mijic, 2020) with QGIS (Quantum Geographical Information System, 2019). Both CityWat (see Appendix A) and QGIS are open source, which enables data to be transferable and shared with relevant stakeholders.

To accurately assess the UWS indicators within a single evaluation framework, we apply the integrated urban water management model CityWat (Dobson and Mijic, 2020). CityWat is lumped at a city level and coded in Python. CityWat facilitates holistic modelling of the urban water cycle and simulates the flow and quality of water through mass balance equations. It has been validated against historical data in London and so can provide reliable UWS projections when applied at a city or wastewater zone semi-distributed scale (Dobson and Mijic, 2020, Dobson et al., 2021).

After introducing numerical parameters from the urban form properties into CityWat such as the total number of households, total population, roof area, percent impermeable, total green area, etc. (Table A1, Appendices); the UWS indicators of the existing impacts (Baseline) are obtained via simulation. Next, looking at the predicted housing growth at the city scale and its projected population in the next 10 years from public reports and city's planning documents, different combinations of WN design options (Table 2) are implemented to obtain the WN scenarios (Fig. 2).

Once we have created the WN design options to accommodate new developments, we use CityWat simulations to verify whether the retrofitting fully offsets the new impacts of urban consumer demand and flood risk. In this simulation step, design options are modelled as changes to the urban form parameters that are used in CityWat. New urban developments will influence the rainwater harvesting capacity, increase the consumer demand based on the total projected population, decrease the percent of impermeable area, etc. (see Section 4.2). In this work, CityWat is run at a daily timestep and UWS indicators are reported as at average daily values.

Finally, UWS values are processed to obtain the novel Water Neutrality Index (WNI) as explained in Section 3.1.1 and obtain WNI

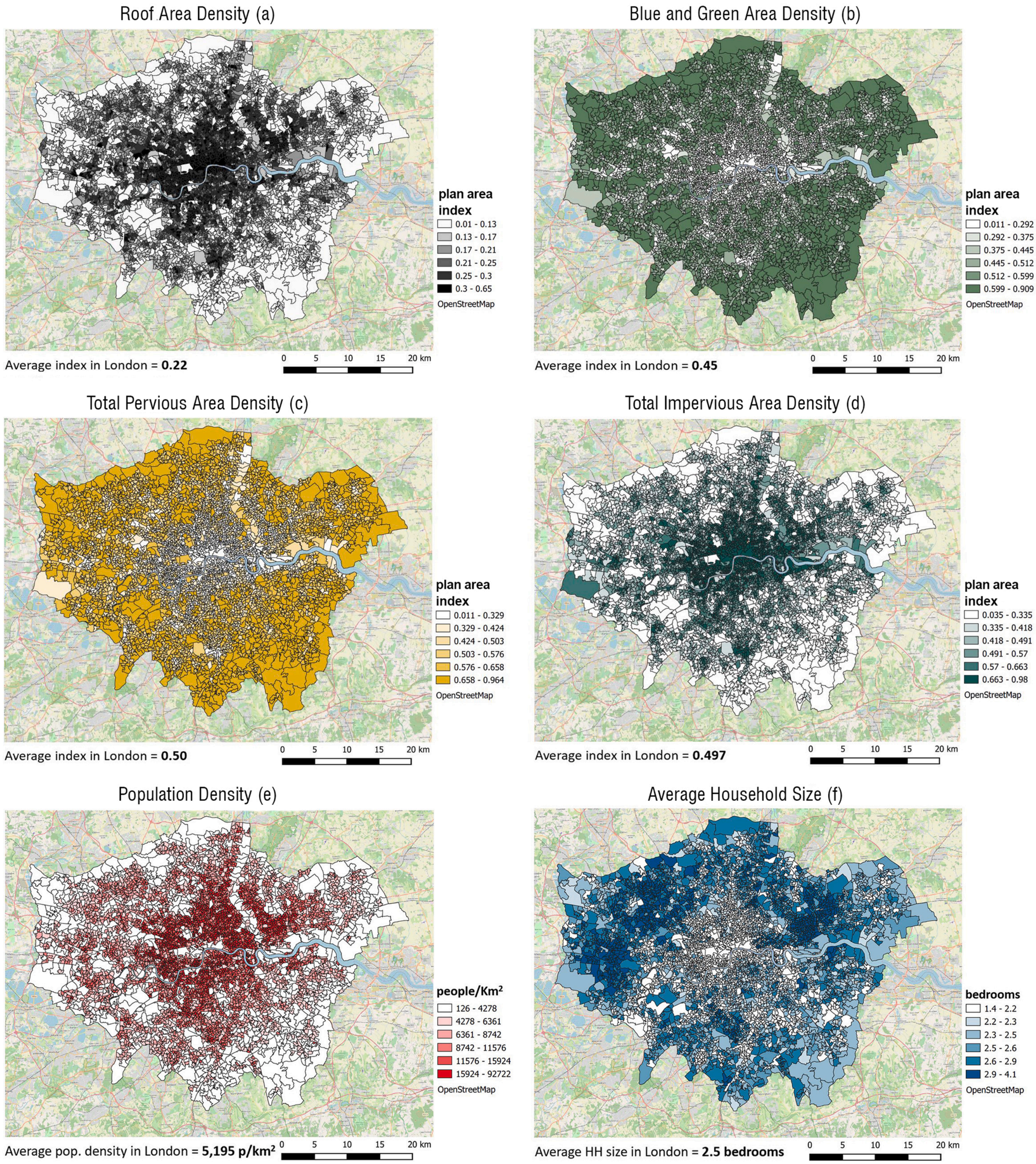

Fig. 3. Key London's Water Neutrality (WN) urban form properties represented in plan area fraction maps and divided by LSOA boundaries. Data sources: British Geological Survey landcover dataset and UK Census 2011.

metrics in percentages. Ultimately, if results from the WNI indicate that the proposed development achieves a specific WN target, this will be the final stage of the process. But, if metrics suggest that the new development is far from the target, it will be necessary to either provide a series of planning recommendations or move back to the systemic design solutions stage and implement new WN options until water neutrality is achieved (step five in Fig. 1).

4. Results

Systemic design for water neutrality is developed at a city scale and is based on the future predicted housing growth in London, where 522,870 new households are aimed to be built during the next 10 years (GLA, 2021). As the CityWat model is lumped at a city scale, we cannot specify spatially where these new households will be located. However, the

Table 3
Water Neutrality scenarios developed in CityPlan-Water for London's case study, including the number of homes with WN design options and the type of WN design options implemented, both in new and existing housing.

WN Scenarios for CityPlan-Water in London				
WN SCENARIOS	**Number of homes with WN design options**		**WN design options implemented**	
	New housing	**Existing housing**	**New housing**	**Existing housing**
Baseline (London Existing)	-		-	
BAU (10-year housing projection)	-		-	
WN DESIGN OPTIONS APPLIED TO NEW URBAN DEVELOPMENTS ONLY				
(A) Efficient appliances in new homes	522,870	-	Water efficient appliances	-
(B) 80% green roofs in new homes	522,870	-	BGI (Green roofs)	-
(C) Citizens concerned with water	522,870	-	Social campaigns	-
(D) RWH in new homes	522,870	-	RWH	-
(E) GWR systems in new homes	522,870	-	GWR	-
(F) (A + B + C + D + E)	522,870	-	Water efficient appliances, BGI (Green roofs), Social campaigns, RWH & GWR	-
WN DESIGN OPTIONS APPLIED TO EXISTING BUILDINGS ONLY (RETROFIT)				
(G) Retrofit homes with efficient appl.	-	432,500	-	Water efficient appliances
(H) Retrofit homes with RWH	-	432,500	-	RWH
(I) Add BGI to the existing London land	-	(19 km^2 of land)	-	BGI (Green spaces, urban gardens & Permeable paving)
WN DESIGN OPTIONS APPLIED TO NEW URBAN DEVELOPMENTS AND EXISTING BUILDINGS (RETROFIT STAGES)				
(J) RETROFIT Stage 1 (F+ G)	522,870	432,500	Efficient appliances, BGI (Green roofs), Social campaigns, RWH & GWR	Water efficient appliances
(K) RETROFIT Stage 2 (H + J)	522,870	432,500	Water efficient appliances, BGI (Green roofs), Social campaigns, RWH & GWR	Water efficient appliances & RWH
(L) RETROFIT Stage 3 (I + K)	522,870	432500 homes & 19 km^2 of land	Water efficient appliances, BGI (Green roofs), Social campaigns, RWH & GWR	Water Efficient appliances, RWH & BGI (Green spaces, urban gardens & Permeable paving)

results show the aggregated effect of the impact of new development and the scale of interventions needed for impact mitigation.

4.1. Analysis and visualisation of London's urban form properties

The area fraction equation (equation 2; Oke et al., 2017) is used in this work to visualise London's urban form properties objectively. The density maps (Fig. 3) inform about the heterogeneity of each urban form in London and will help decision-makers to perceive which parts of the city are in more need of certain WN design options.

The plan area fraction indices in each LSOA unit vary considerably from one urban form property to other. While roof area maximum value is 0.61 and minimum 0.01, with an average across London of 0.22 (Fig. 3a); the blue and green area ranges from 0.011 to 0.909, with an average across London of 0.45 (Fig. 3b). While the total impervious area percentage is around 37% of the city (Table A1, Appendices), the average plan area indexes of the pervious and impervious areas are almost equivalent (around 0.5 each). In addition, some LSOA units show a maximum of 0.98 of impervious area fraction, which reveals that there are London areas which are dramatically impervious, while others are very permeable, especially in the outskirts of the city (area density down to 0.035, Fig. 3d). Finally, London's average population is 5,195 people per km^2, although this can go up from 15,924 p/km^2 to 92,722 p/km^2 in the most densely populated LSOA zones (Fig. 3e). Regarding household size, the average in London is at 2.5 bedrooms per household although most of the central LSOA areas present between 1.4 and 2.2 bedroom per household, and houses in residential outskirts go up to 4.1 bedrooms in average per household (Fig. 3f).

The urban form area fraction maps indicate that most of the building and impervious surfaces are concentrated in the central London, presenting major risks for flooding and the most significant challenges for urban WN. Although London is considered a green city, there are still some areas in the city centre that suffer from a lack of green space and a large percentage of impermeable surfaces. In parallel to this, a larger number of citizens are concentrated in the city centre, where also the average household size is smaller than in the city boundaries. This might produce highly localised water demand patterns and severe issues of wastewater production and sewage overflow. Although these localised issues cannot be captured with the CityWat model, they could be evaluated in more detail with semi-distributed water management models (Dobson et al., 2021) or other finer resolution evaluation tools.

4.2. Water Neutrality scenarios and systemic design options

The scenario development process starts with the Baseline and the BAU simulations, which do not include any WN design option. The Baseline includes the impact from 3,266,170 existing households and a total population of 8,961,989 people (UK Census, 2011), while the 10-year housing projection for the London BAU scenario adds up to 3,789,040 homes and 9,800,000 people (GLA, 2021). Other input

Table 4
Water Neutrality Index scores based on the 10-year housing target in London. It follows a colour code from red being WNI=0 (worst WN outcome) to green WNI=100 (WN fully achieved) and having grades of yellow and orange for intermediate values.

WATER NEUTRALITY (WN) SCENARIOS	Urban Water Security (UWS) Indicators		
	Urban consumer demand (Consumer supplied, ML/day)	Urban flood risk (Excess stormwater runoff, ML/day)	River water quality (Phosphorus content, mg/l)
	Water Neutrality Index (WNI, %)		
WN DESIGN OPTIONS APPLIED TO NEW URBAN DEVELOPMENTS ONLY			
(A) Efficient appliances in new homes	35	4	25
(B) 80% green roofs in new homes	0	35	8
(C) Citizens concerned with water	5	1	3
(D) RWH in new homes	18	8	10
(E) GWR systems in new homes	14	2	8
(F) (A + B + C + D + E)	71	48	63
WN DESIGN OPTIONS APPLIED TO EXISTING BUILDINGS ONLY (RETROFIT)			
(G) Retrofit homes with efficient appliances	29	3	20
(H) Retrofit homes with RWH	16	7	9
(I) Add BGI to the existing London land	0	45	11
WN DESIGN OPTIONS APPLIED TO NEW URBAN DEVELOPMENTS AND EXISTING BUILDINGS (RETROFIT STAGES)			
(J) RETROFIT Stage 1 (F + G)	100	51	84
(K) RETROFIT Stage 2 (H + J)	105	57	88
(L) RETROFIT Stage 3 (I+K)	105	100	99

variables, such as building, green and impervious area in each scenario, are summarised in the Table A2 in Appendices. Next, to develop the WN scenarios, the design options explained in the Section 2.2 (Table 1) are implemented.

To introduce water efficiency (Millock and Nauges, 2010), we consider installing appliances with an average of 35% water use reduction (Jorge and Covas, 2017; Callejas-Moncaleano et al., 2021) in all new 522,870 households (Scenario A). Next, we implement BGI solutions to the new building infrastructure (Bozovic et al., 2017; Kabisch et al. 2017; Nesshöver et al., 2017; Zaid et al., 2018; Keeler et al., 2019; Ferrans et al., 2022). All new homes are equipped with 80% of green roof area in Scenario B (Liu et al., 2022). Finally, social awareness campaigns are assumed to affect the behaviour of all citizens living in new homes and reduce their demand by 4% (Mortazavi-Naeini et al., 2019), which defines Scenario C. The total number of citizens in new homes is calculated by the average number of people per household in London, estimated at 2.5 (UK Census, 2011) and multiplied by the number of new predicted homes (GLA, 2021). This is different to the expected population growth of the city as some citizens are expected to be relocated from existing areas.

Rainwater harvesting design (Li et al., 2009) assumes a 400-litre tank installed in each new household. This volume is calculated by averaging the 1,000-litre tanks commonly used for individual households and considering a smaller capacity for flat buildings per household (Scenario D). To enhance the water reuse capacity, a GWR reuse system (Campisano et al., 2017) that assumes a 50% greywater recycle is installed in all new 522,870 new homes in Scenario E. Finally, Scenario F is set by aggregating all the WN design options from Scenarios A to E. All the scenarios developed in this systemic design process are summarised in the Table 3.

Once the options for new homes are defined, scenarios for retrofitting existing homes and urban infrastructure are developed by implementing the WN design options outside the development area. It is predicted with CityWat simulations that 432,500 existing homes is the minimum amount to fully offset the impacts in urban consumer demand. Hence, the Scenario G will implement efficient appliances of 35% consumer reduction in all these 432,500 existing homes. The first retrofit stage (Scenario J) will aggregate all the WN options in new homes (Scenario F) with the Scenario G. As Scenario J does not offset flooding risk or river quality, in Scenario H we install RWH systems of 400-litre tanks in all retrofit households. Next, the second retrofit stage (Scenario K) aggregates Scenario H with Scenario J.

The CityWat simulations also showed that 19 km^2 of impermeable land needs to be made permeable in the existing London's surface to completely offset the impacts in urban flood risk by new projected development. Hence, in Scenario I several solutions of BGI, all of them being permeable, are added to the city to reduce the total existing impervious area. In the end, all scenarios, both in new and existing retrofit solutions, are aggregated in the third and final retrofit stage (Scenario L), in which the impacts on the urban water system by new developments are aimed to be offset.

4.3. Urban Water Neutrality of London

After following the systemic design process explained above, the Urban Water Security (UWS) evaluation step is developed with the CityWat model. The simulations from the CityWat model provide raw values for each UWS indicator and each scenario (Table A3, Appendices). These raw values may be useful for water companies and environmental regulators such as the UK Environment Agency but might be hard to interpret by other stakeholders. The percentage increase in UWS indicators with the BAU Scenario compared to the Baseline is 12% for the consumer urban demand, 56% for the urban flood risk, and 10% for the river water quality.

Based on the raw values and following equation (1), we calculate the scores for the Water Neutrality Index (WNI) for each UWS indicators. Table 4 demonstrates that urban consumer demand is not completely neutralised (WNI=100) until scenario J, which implies to fully implement all the WN design solutions inside development area and retrofit 432,500 existing homes with water efficient appliances outside the development. Urban flood risk is more difficult to be neutralised and does not achieve a score of WNI=100 until scenario L, which means to implement all the previous WN options and add 19 km^2 of BGI to the existing London's land. Finally, water quality achieves a maximum score of WNI=99 with scenario L too. Other intermediate scores for the WNI for each WN scenario are found in Table 4.

5. Discussion

In this study, we focus on three key contributions to WN urban design; we first developed a WN concept for systemic design of new urban developments and then proposed a CityPlan-Water framework and the Water Neutrality Index. From the results in Table 4, we observe that some WN design options are multi-functional and have a significant effect on all the UWS indicators (i.e., RWH systems), while others only affect one or two indicators (e.g., green roofs or GWR systems). Based on the results obtained from the WNI in London, for the level of options implemented we note that it will be necessary to retrofit a considerable number of existing households outside the development area to achieve WN of new urban developments at a city scale in London. These results of WN concept are based on the WNI value of 100, but this target could be scale-specific (e.g., water neutrality at a borough or wastewater zone level) or set at a different WN level (e.g., 80% water neutral developments). Although the value of water in London urban developments might be similar for being part of the same city, this might not always be the case and some trade-offs between the costs and the benefits of the WN solution per unit of water could emerge too. Finally, the selection of UWS indicators and target value for each indicator may vary depending on the urban context and the decision-makers involved. The targets for each Urban Water Security indicator might change depending on the urban area studied and its own properties (e.g., an area more prone to urban flooding could have a higher target for the urban flood risk indicator compared to consumer demand or river water quality in order to be considered 'water neutral'). In this study we have examined three, often competing, objectives (water supply, quality, and flooding). However, there may be cases where the value of a unit of water supply is different in different locations. If these locations can be made commensurate by a weighting determined by the decision maker, then the CityPlan-Water framework can proceed as presented in this study; if they cannot, then additional metrics for different locations can instead be introduced, allowing the decision maker to contextualise the trade-offs between locations alongside the trade-offs between quality/supply/flooding."

The work also contributes to the analysis of achieving the water neutrality at a city scale. Although incorporating WN design options in new urban developments is cost-effective and cheaper than retrofitting at a later stage (Allen et al., 2020), the total number of new homes represent a small share of the total housing stock in London (UK Census, 2011). Offsetting outside the development area will be often necessary to achieve WN, but this might present a series of challenges and opportunities. Two clear challenges are the current climate crisis and the dependency of the WN success on the change of the water demand patterns. To address this, proposed WN design options must be adaptable not only to climate change mitigation and resilience, but also to cultural and societal needs. Therefore, future stages of the work should introduce climate change scenarios and predicted population patterns as input data for the model evaluation. In addition to this, there are also physical and economic challenges such as retrofitting ageing infrastructure, which is always more costly and complicated to execute than a new construction (Simpson et al., 2021).

Retrofitting existing infrastructure, however, presents great opportunities as well. London planning authorities might need regional cross-borough plans to develop integrated water management strategies and the systemic design process inside CityPlan-Water could be key to succeed on future water neutrality implementation. Next steps of the work could study London's Opportunity Areas in more detail to analyse potential locations and how the retrofit options might be practically implemented. Systemic design is aimed to connect all the multi-scale boundaries inside the city and facilitate new models for collaborative water management and decision making.

The systemic design process could be enhanced by analysing the city's urban form through a more detailed mapping exercise, which would identify additional features of the urban system in relation to the defined purpose. To achieve water neutral developments, features that might provide new scenario configurations include information on city's developable land availability; compactness of the city's urban pattern around the development area; predicted future climate conditions; historical citizens' willingness to change their behaviour towards environmental causes; availability of public funds towards retrofitting options; relationship between the Local Planning Authorities and urban developers in a particular Council; etc. These additional features combined with a refined information of the new urban developments' distribution will increase the accuracy of the WNI results. Moreover, a participatory involvement from different types of urban stakeholders will provide a valuable input to validate further the CityPlan-Water framework.

Another potential direction for future work could be to develop a digital tool that can process and map the data automatically, linking the GIS datasets with the integrated urban water management model (i.e., CityWat). This pre-processing tool could be in the form of a plugin inside the QGIS software or formalised as a Python package. In addition, specifically defining the type of BGI in terms of water management function (infiltration, storage, or treatment) to the WN design options will increase the accuracy of the UWS results. Future studies could evaluate the existing efficiency levels of each zone inside the city based on the buildings' age and population patterns. This could be used to support water consumption predictions and develop a generic water performance certificate at a city or national scale.

Finally, the findings from the WNI are based on city-scale targets following the CityWat model's scope, but other case studies and scales might be considered in future stages. In this work, we presented the proof-of-concept of CityPlan-Water and the use of spatial data is taken from the BGS dataset in large resolution and divided by the LSOA boundaries, but next stages might include more publicly available datasets or different boundaries (i.e., London boroughs or wards). Large urban developments in London are scheduled for the next 20-30 years (e.g., Thamesmead Waterfront Development Plan in Greenwich or Meridian Water Development in Enfield), which will create an important impact into the overall water system of the city and could be studied individually or in conjunction inside CityPlan-Water. As previously mentioned, the future studies on water neutral developments could be done in collaboration with the Local Planning Authorities of each borough and public/private housing developers in a participatory way.

6. Conclusion

This paper introduced a novel approach for the Water Neutrality concept for new urban developments. It applied the WN concept to the Urban Planning Sustainability Framework (UPSUF) and developed a new operational framework called CityPlan-Water. The framework combines WN options from a systemic design perspective and evaluates urban water security at a city scale, all being spatially represented in a GIS dataset. Using the proposed Water Neutrality Index, a series of urban design scenarios could be explored and different levels of WN based on the 10-year housing projection in London can be developed, providing a valuable information on the scale of implementation needed to minimise impacts of new developments on urban water security.

The knowledge from this work and the application of the CityPlan-Water to the WN concept points to valuable potential to change how we design our cities to achieve urban water security. CityPlan-Water is aligned with the United Nations Sustainable Development Goal 6 (SDG 6) that advocates for clean water and sanitation for all, but future versions of CityPlan might be relevant to other SDGs too (e.g., Affordable and Clean Energy, Sustainable Cities and Communities, or Climate Action, among others).

The framework has a strong potential for digitally enhanced decision making at different scales. Combining design and evaluation will guide different groups of stakeholders, some of those being housing developers, Local Planning Authorities or water companies, among others. In the end, the results from CityPlan-Water show a great potential of the framework to guide urban planners and policymakers from early stages of the planning process towards sustainability and urban resilience in cities' design.

Authorship contribution statement

PPS: Conceptualisation, Methodology, Visualisation, Data curation, Coding, Simulations, Validation, Writing – original draft. **SB:** Conceptualisation, Visualisation, Writing – review & editing. **BD:** Methodology, Computational Modelling, Coding, Writing – review & editing. **MvR:** Conceptualisation, Writing – review & editing. **AM:** Conceptualisation, Methodology, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare no known competing interests or personal relationships to influence the work reported in this paper.

Acknowledgements

This research is part of the CAMELLIA project (Community Water Management for a Liveable London), funded by the Natural Environment Research Council (NERC) under grant NE/S003495/1; and, part of the euPOLIS project, funded by the European Union's Horizon 2020 program H2020-EU.3.5.2., under grant agreement No. 869448. It would not have been possible without funding from the Engineering and Physical Sciences Research Council (EPSRC) Centre for Doctoral Training (CDT) in Sustainable Civil Engineering under grant EP/L016826/1. The authors acknowledge the valuable collaboration from the British Geological Survey, especially Dr Tijana Jovanovic and Dr Christopher Jackson.

Appendix A.1. Supporting material

The code for the integrated model CityWat and all its supporting material can be found in a data repository at: https://github.com/barneydobson/citywat.

Table A1
Summary table of London's urban form properties, divided in raster and UK Census datasets. These values are introduced in the CityWat model to evaluate the UWS indicators of the existing impacts (Baseline) of the city. Data sources: British Geological Survey landcover dataset and UK Census 2011.

London's Urban Form Properties Summary Table			
Raster Urban Form Properties	Total area (m²)	Percentage (%)	Average Plan Area Index
Buildings / Roofs	232,986,000	14.81	0.220
Impervious surfaces / Roads / Bridges	284,280,000	18.07	0.227
Trees over impervious surfaces	57,406,700	3.64	0.050
Total Impervious Area	574,672,700	36.52	0.497
Water	11,388,900	0.72	0.0014
Trees / Low vegetation	883,864,000	56.17	0.450
Blue and green area	895,252,900	56.89	0.4514
Soil/Pervious roadside	75,036,900	4.77	0.038
Rail	16,248,900	1.03	0.012
Total Pervious Area	986,538,700	62.69	0.5014
Others	12,298,600	0.79	0.0016
LONDON	1,573,510,000	100	1
Census Urban Form Properties	Total	Density / Average	Average Size
Population	8,173,940	5,195 p/km^2	Ø
Households	3,266,170	Ø	2.5 beds

Table A2
Systemic design scenario development for CityPlan-Water and their variables. This data is introduced in the CityWat evaluation model. Data sources: British Geological Survey landcover dataset and Census 2011.

Systemic Desing Scenario Development for CityPlan-Water in London															
	Variables	Baseline (London Existing)	10-year housing projection (London BAU)	(A) Efficient appliances in new homes	(B) 80% green roofs in new homes	(C) Citizens concerned with water	(D) RWH in new homes	(E) GWR systems in new homes	(F) (A + B + C + D + E)	(G) Retrofit homes with efficient appl.	(H) Retrofit homes with RWH	(I) Add BGI to the existing London land	(J) RETROFIT Stage 1 (F + G)	(K) RETROFIT Stage 2 (H + I)	(L) RETROFIT Stage 3 (J + K)
Fixed variables	London area (km^2)	1,572.12	1,572.12	1572.12	1572.12	1572.12	1572.12	1572.12	1572.12	1572.12	1572.12	1572.12	1572.12	1572.12	1572.12
	Population (km^2)	8,961,989	9,800,000	9,800,000	9,800,000	9,800,000	9,800,000	9,800,000	9,800,000	9,800,000	9,800,000	9,800,000	9,800,000	9,800,000	9,800,000
	N. of Households (n.)	3,266,170	3,789,040	3,789,040	3,789,040	3,789,040	3,789,040	3,789,040	3,789,040	3,789,040	3,789,040	3,789,040	3,789,040	3,789,040	3,789,040
	Building area (km^2)	232.980	270.282	270.282	270.282	270.282	270.282	270.282	270.282	270.282	270.282	270.282	270.282	270.282	270.282
	Green area (km^2)	883.864	846.562	846.562	846.562	846.562	846.562	846.562	846.562	846.562	846.562	865.562	846.562	846.562	865.562
	Total impervious area (km^2)	574.672	611.974	611.974	611.974	611.974	611.974	611.974	611.974	611.974	611.974	592.974	611.974	611.974	592.974
UWN Design options	Total n. of homes with efficient appliances (n.)	0	0	522,870	0	0	0	0	522,870	432,500	0	0	955,370	955,370	955,370
	People concerned with water	0	0	0	0	1,307,175	0	0	1,307,175	0	0	0	1,307,175	1,307,175	1,307,175
	Green roof area (km^2)	0	0	0	29.842	0	0	3	29.842	0	0	0	29.842	29.842	29.842
	Total RWH volume (ML)	0	0	0	0	0	209.148	0	209.148	0	173	0	209.148	382.148	382.148
	Total n. of homes with GWR systems (n.)	0	0	0	0	0	0	522,870	522,870	0	0	0	522,870	522,870	522,870
	New BGI area (km^2)	0	0	0	0	0	0	0	0	0	0	19	0	0	19

Table A3
UWS indicators in absolute numbers: urban consumer demand in ML/day; urban stormwater runoff in ML/day; and phosphorus content in mg/l).

SCENARIOS	Urban Water Security (UWS) Indicators		
	Urban consumer demand (Consumer supplied, ML/day)	Urban flood risk (Excess stormwater runoff, ML/day)	River water quality (Phosphorus content, mg/l)
ABSOLUTE NUMBERS			
London Baseline (Existing Impact, 3,266,170 existing homes)	1,489.7	14.8	1.66
London BAU Scenario in a 10-year housing projection (522,870 new homes, Total = 3,789,040 homes)	1,670.6	23.1	1.82
New impact added to London's urban water system	180.9	8.3	0.16
WATER NEUTRALITY (WN) SCENARIO DEVELOPMENT			
A) All new homes in London (522,870) with **efficient appliances** of **35% reduction**	1,607.8	22.8	1.78
B) All new homes in London (522,870) with **80% green roofs**	1,670.6	20.2	1.81
C) All London citizens living in these new homes (1,307,175) **concerned with water** (4% reduction)	1,661.8	23.0	1.82
D) All new homes in London (522,870) with **400 l/h RWH** water tank	1,638.0	22.4	1.80
E) All new homes in London (522,870) with a **50% GWR system**	1,645.6	22.9	1.81
F) (A + B + C + D + E)	1,541.5	19.1	1.72
How much does it need to be OFFSET to achieve full WN?	51.9	4.3	0.06
G) **Retrofitting 432.500 existing homes** in London with **efficient appliances of 35% reduction**	1,618.7	22.8	1.79
H) **Retrofitting 432.500 existing homes** in London with **400 l/h RWH water tank**	1,641.0	22.5	1.81
I) Adding **19 km^2** (19,000,000 m^2) **of green space (BGI)** to London's land (reducing it from the existing impervious area)	1,670.6	19.4	1.80
RETROFIT STAGES			
J) **RETROFIT Stage 1** (F + G)	1,489.5	18.9	1.68
K) **RETROFIT Stage 2** (H + J)	1,480.2	18.4	1.68
L) **RETROFIT Stage 3** (I + K)	1,480.2	14.8	1.66

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