

**TOWARDS AN INFRASTRUCTURE
ECOLOGY FRAMEWORK**
for Sustainable Urban Planning
and Water Management

Pepe Puchol-Salort

Towards an Infrastructure Ecology Framework for Sustainable Urban Planning and Water Management

by Jose Puchol-Salort

Department of Civil & Environmental Engineering
Imperial College London

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Author: Pepe Puchol-Salort

Author (as Passport): Jose Puchol-Salort

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Supervisors: Dr Ana Mijic and Prof Maarten van Reeuwijk

Co-Supervisor: Dr Stanislava Boskovic

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*This thesis was supervised by Dr Ana Mijic and Prof Maarten van Reeuwijk,
and co-supervised by Dr Stanislava Boskovic*

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Abstract

Under the increasing pressures of the climate emergency and population growth, it is crucial to address sustainable urban development and water security. Urban growth impacts environmental management in several complex ways, making it challenging to evaluate. Moreover, there is a disconnection between policy and decision-making processes in urban planning and design. To address these issues holistically, this thesis develops CityPlan, a systems-based infrastructure ecology framework for integrated urban planning.

CityPlan incorporates sustainability evaluation, simulation tools, and a portfolio of design options to enable improved assessment and decision-making for multi-stakeholder urban development projects. The framework focuses on the planning system process of the UK. It presents three proof-of-concept applications: CityPlan-Ecos, which assesses urban ecosystem services at the urban development scale; CityPlan-Water, which focuses on integrated water management and the novel concept of water neutrality at the city scale; and CityPlan-Place, which develops a data-driven approach to test potential allocation and design for water-neutral interventions.

CityPlan-Ecos confirms the need for pre-planning design to evaluate the number of urban ecosystem services provided. CityPlan-Water suggests that almost the same number of existing houses must be retrofitted with water-neutral design options to offset the negative impact of new urban developments on the water cycle. Finally, CityPlan-Place evaluates the level of water neutrality targets achieved by systemic design options across different urban scales.

This thesis has three main research contributions. First, it demonstrates the need for integrated urban planning across different scales; second, it shows the potential of multi-purpose evaluation towards improving urban sustainability and integrated water management; and third, it enables a more comprehensive decision-making process with the combination of design and evaluation inside the UK planning system. The results of this work could be essential for strategic planning of sustainable and water-neutral design in urban environments.

Statement of own work & Copyright

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Acknowledgements

Since I started this PhD thesis, numerous events happened at personal, professional, and global levels. I started this journey in a total new environment, surrounded by unknown people that will end up being great friends and remarkable colleagues. In this text, I will try to mention most of them (hopefully not forgetting anyone), as they will always occupy a space in my memory and my heart.

I would like to start by thanking the two funding bodies. This PhD 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, and without being part of the CAMELLIA research programme (Community Water Management for a Liveable London), funded by the Natural Environment Research Council (NERC) under grant NE/S003495/1.

Being part of a large research programme such as CAMELLIA enabled me to connect with many partners and collaborators. I would like to thank all of them for their support, especially from the Imperial team (Adrian, Alex, Thanos, Tom, Sharon...); from the BGS team (Darren, Carl, Chris, Swea, Tijana, Severine, Andrew...); from the UCL team (Nici, Sarah, Irene, Giuseppe, Charlotte, Ariel, Koko, Yuhong, Pouria...); from the Oxford Team (Helge, Catharina...); and from, of course, my dear friend Greta. Many of these colleagues were also part of the VENTURA project, where I collaborated more closely with the London Borough of Enfield. My special thanks go to Ish and Ian.

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Although I worked remotely during the COVID-19 pandemic, I started and finished this PhD journey physically at Office 302 of Skempton Building, Imperial College London. My heart will always belong to this office and I cannot forget to mention the people who spent hours, days, weeks, months, desk-to-desk with me: Simon, Filip, Ziyang, Chi-San, Eduardo, Fangjun, or Michael. Thanks all for your smiles and for always being supportive and approachable.

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In a similar way, Maarten's research group also started remotely and then continued in-person week after week. Although they are "proper scientists" and sometimes too technical to my knowledge, I enjoyed one and each of their sessions and appreciated all their support. Apart from their support, I especially enjoyed the meals and drinks together! I must mention here good friends like Rodrigo, Sam, Chris, Cleo, Caroline, Birgit, and Nada.

More recently I started a close cooperation with the CSEI, where I am currently preparing a very exciting work as a continuation of this PhD. In this case, all my thanks go to Tim, Jennifer, and, of course, my lovely Jeni! I would like also to thank the administrative support of Sarah, and to mention my GTA colleagues: Sunday, Mike, Andrew, Fernando, Vlad, Javier, Luke, Sam, Peter, and Emma. Additionally, I would like to thanks Ana Ruiz for her kind support.

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On a more personal side, I cannot forget my friend, colleague, sometimes therapist, sometimes taxi-driver, but always-supportive and encouraging Debora. I would like to add my friends here too. Thanks to Spaniards who did pandemic times more enjoyable and developed my loved for hiking, and to Londoners who started and finished this journey very close to me.

Ultimately, I want to mention the continuous support from my family, especially from my parents and my brother. Even if you are a bit far, I feel you very close every day of my life. And, last but not least, I would like to give the biggest thanks on Earth to my life partner, Raul. During all these years, you have been nurturing, supportive, loving, compassionate, sometimes a bit angry, but always patient and encouraging. Thanks for all your delicious meals, for spending endless days (and nights) together with our always loyal Queenie, and for giving me the balance that I need in this work-focused life.

The world is a complex, interconnected, finite, ecological-social-psychological-economic system. We treat it as it were not, as it were divisible, separable, simple, and infinite.

Our persistent, intractable global problems arise directly from this mismatch.

Donella Meadows

*To my grandmas[†],
Your respect for Nature, my inspiration.*

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List of Acronyms

BAU = Business As Usual

BGI = Blue Green Infrastructure

BGS = British Geological Survey

CSO = Combined Sewers Overflow

DE = Device Efficiency

DST = Decision-Support Tool

ESS = Ecosystem Services

GIS = Geographical Information System

GLA = Greater London Authority

HEL = House Efficiency Level

LLFA(s) = Lead Local Flooding Authority(ies)

LPA(s) = Local Planning Authority(ies)

LSOA = Lower Layer Super Output Area

MCDS = Multi-Criteria Decision Support

MCDST = Multi-Criteria Decision Support Tool

MWDP = Meridian Water Development Plan

MSOA = Middle Layer Super Output Area

NBS = Nature Based Solutions

NC = Natural Capital

NCPT = Natural Capital Planning Tool

PCC = Per Capita Consumption

QGIS = Quantum Geo-Information System

RC = Runoff Coefficient

UES = Urban Ecosystem Services

UHI = Urban Heat Island

UNC = Urban Natural Capital

UWS = Urban Water Security

TMWDP = Thamesmead Waterfront Development Plan

UPSUF = Urban Planning Sustainability Framework

VDR = Virtual Decision Room

WaNetDST = Water Neutrality Decision-Support Tool

WEC = Water Efficiency Certificate

WN = Water Neutrality

Terminology

Environmental Net Gain (ENG) = A mechanism to reverse ecosystem and biodiversity degradation in order to provide societal benefits and to ensure that infrastructure developers leave the environment in a measurably better state compared to the pre-development baseline.

Infrastructure ecology = Transdisciplinary approach that considers urban infrastructure systems as interconnected and ecological entities, and examines them as a whole integrated system using deep analogies.

Systemic design = Emerging approach that combines traditional design and systems thinking, taking a holistic and complete account of the urban form elements that constitute a complex system. The systemic design concept applied to urban planning involves a series of strategic and tactical decisions.

Systemic design conditions = A series of planning conditions that emerge from systemic design approaches after achieving a certain purpose. These conditions will ultimately inform the detailed design developed by urban planners (i.e., architects, engineers, etc.) for one or a group of future urban developments.

Systemic design options = A series of design solutions required to generate urban development scenarios that are not detailed but generic group of interventions and are studied at systems level to deliver integrated urban planning.

Strategic decisions = Based on the systemic design concept, strategic decisions are outlined by policy and governance plans, define the purpose of the design, and set the boundaries of the study (i.e., city, borough, strategic zone, or development site).

Tactical decisions = Based on the systemic design concept, tactical decisions define specific interventions that are needed to achieve a certain purpose/s and come from integrated evaluation tools/models (e.g., implement water-neutral solutions in new homes, retrofit existing infrastructure, add new blue and green space, etc.).

Urban Ecosystem Services (UES) = All benefits that citizens and human beings obtain from natural ecosystems in the urban environment (i.e., air and water quality, surface water runoff, flood mitigation, fresh water, health, wellbeing, recreation, etc.).

Urban form = Building dimensions, spacing, and envelope characteristics that influence urban microclimate and environmental balance.

Urban Water Security (UWS) = Integrated term that involves to sustainably meet the water needs of a community to an acceptable level of water quantity, quality, and flood risk to their people, environments, or economies.

Water Neutrality (WN) = Concept that aims to minimise the impacts of new development and offset the remaining environmental and social impacts based on three key urban water security indicators (i.e., water consumption, quality, and flood risk).

List of Publications and Novel Contributions

Journal articles

The following journal articles have contributed to the content of the PhD thesis:

- **Puchol-Salort, P.**; O’Keeffe, J.; Van Reeuwijk, M.; Mijic, A. (2021). An urban planning sustainability framework: Systems approach to blue green urban design. *Sustainable Cities and Society* 66: 102677.
- **Puchol-Salort, P.**; Boskovic, S.; Dobson, B.; Van Reeuwijk, M.; Mijic, A. (2022). Water neutrality framework for systemic design of new urban developments. *Water Res* 219: 118583.
- **Puchol-Salort, P.**; Rico-Carranza, E.; Beriro, D.; Boskovic, S.; Van Reeuwijk, M.; Mijic, A. (2023). Integrating water-neutral systemic design and planning decisions across different urban scales: WaNet Decision Support Tool. *Urban Sustainability*. In preparation.

In addition, during the duration of the PhD, I contributed to the following journal publications:

- O’Keeffe, J.; Pluchinotta, I.; De Stercke, S.; Hinson, C.; **Puchol-Salort, P.**; Mijic, A.; Zimmermann, N.; and Collins, A.M. (2022). Evaluating natural capital performance of urban development through system dynamics: A case study from London. *Sci Total Environ* 824: 153673.
- Mason, A.R.; **Puchol-Salort, P.**; Gathorne-Hardy, A.; Smith, B.; Myers, R. J. (2023). Local Terrestrial Biodiversity Impacts in Life Cycle Assessment: A Case Study of Sedum Roofs in London, UK. *Journal of Industrial Ecology*. Under review.
- Boskovic, S.; **Puchol-Salort, P.**; Mijic, A. (2023). Systemic Design concept applied to water-neutral urban development. *Urban Studies*. In preparation.
- Zhou, K.; **Puchol-Salort, P.**; Pluchinotta, I.; Zimmermann, N. (2023). Integrated decision-making towards urban water neutrality: a case study in Manchester. *Journal of Environmental Management*. In preparation.

- Zapata, J.; Vangipuram, B.; **Puchol-Salort, P.**; Mijic, A.; Erfani, T. (2023). Reducing the cost of Nutrient Neutrality in housing development projects through pollution trading: A cross-borough study in London. *Environmental Research Letters*. In preparation.
- Wang, Y.; **Puchol-Salort, P.**; Zimmermann, N. (2023). An activity theory-based analysis framework for micro-collaboration in participatory System Dynamics. *European Journal of Operational Research*. In preparation.

Conference papers

During the duration of the PhD, I published the following conference paper publications:

- **Puchol-Salort, P.**; Van Reeuwijk, M.; Mijic, A. (2020). *Natural Capital Impact Assessment for New Urban Developments*. PLEA 2020 Conference Paper, Planning Post Carbon Cities.
- **Puchol-Salort, P.**; Beriro, D.; Boskovic, S.; Dobson, B.; Krivtsov, V.; Marchant, A.; Mijic, A. (2022). *Integration of the CityWat model into the Urban Planning Sustainability Framework: case study for the Enfield Borough of London*. Conference paper. 39th IAHR World Congress. Granada, Spain.
- **Puchol-Salort, P.**; Boskovic, S.; Dobson, B.; Van Reeuwijk, M.; Mijic, A. (2022). *CityPlan Water Neutrality Framework for New Urban Developments*. PLEA 2022 Conference Paper, Will Cities Survive? Santiago of Chile, Chile.

Conference abstracts & posters

During the duration of the PhD, I contributed to the following conference abstracts & posters:

- **Puchol-Salort, P.** (2019). *Sustainable Architecture and Social Engagement for Flooding Resilience*. Sustainability in Our City Conference 2019. University College London, UK.
- **Puchol-Salort, P.**; O’Keeffe, J.; Van Reeuwijk, M.; Mijic, A. (2020). *An Urban Planning Sustainability Framework for Multifunctional Design Solutions*. AGU Fall Meeting 2020. Online.

- **Puchol-Salort, P.;** Van Reeuwijk, M.; Mijic, A. (2020). *Urban Planning Sustainability Framework (UPSUF) for New Urban Developments*. Rapid Cities, Responsive Architectures Conference, AMPS. Online.
- **Puchol-Salort, P.;** Boskovic, S.; Dobson, B.; Van Reeuwijk, M.; Mijic, A. (2021). *Urban Water Neutrality at City Scale: CityPlan Evaluation and Design Module*. AGU Fall Meeting 2021. Online.
- **Puchol-Salort, P.;** Lu, J.; Boskovic, S.; Dobson, B.; Van Reeuwijk, M.; Mijic, A. (2022). *Urban water neutrality at different scales: CityPlan design and evaluation framework*. EGU Conference 2022. Vienna, Austria.
- **Puchol-Salort, P.;** Boskovic, S.; Dobson, B.; Van Reeuwijk, M.; Whyte, J.; Mijic, A. (2022). *Data-Driven Design for Water Neutral Urban Development at Different Scales*. Constructing a Digital Environment, CDE Conference 2022, NERC. Birmingham, UK. Poster.
- **Puchol-Salort, P.;** Boskovic, S.; Dobson, B.; Van Reeuwijk, M.; Whyte, J.; Mijic, A. (2022). *Data-Driven Decision-Support Tool for Water-Neutral Urban Development at Different Scales*. AGU Fall Meeting 2022. Chicago, USA.
- **Puchol-Salort, P.;** Boskovic, S.; Dobson, B.; Van Reeuwijk, M.; Whyte, J.; Mijic, A. (2023). *Water neutral systemic design at different urban scales: city, borough and urban development site*. InfraCivilCon Meeting 2023. Rome, Italy.
- **Puchol-Salort, P.;** Boskovic, S.; Dobson, B.; Krivtsov, V.; Rico-Carranza, E.; Van Reeuwijk, M.; Whyte, J.; Mijic, A. (2023). *Integrated Urban Planning Decision-Making Process Towards Water Neutral Solutions*. EGU Conference 2023. Vienna, Austria.

MSc Thesis supervision

During the duration of the PhD, I contributed to the following MSc projects supervision:

- **Dehal, R.** (2020). *Development of a GIS-supported framework for urban planning evaluation of natural capital net gain*. Department of Civil and Environmental Engineering, Imperial College London.
- **Lu, J.** (2021). *Development of Water Efficiency Certificate for Urban Water Sustainability*. Department of Civil and Environmental Engineering, Imperial College London.

- **Niu, K.** (2021). *Development of Indicators to measure urban sustainability at different scales.* Department of Civil and Environmental Engineering, Imperial College London.
- **Weaber, W.** (2021). *Development of ESG assessment metrics for water infrastructure project investments.* Department of Civil and Environmental Engineering, Imperial College London.
- **Liang, Y.** (2022). *Cross-borough analysis of water management to evaluate London's housing Opportunity Areas.* Department of Civil and Environmental Engineering, Imperial College London.

PhD Outreach

External Collaborations

- Community Water for a Liveable London (CAMELLIA) research programme is one of the key funders of this PhD under grant NE/S003495/1 from the Natural Environment Research Council (NERC). CAMELLIA is a large 5-year project that involves several partners from academia, industry and policy sectors in the UK (see Figure A1, Appendices). Therefore, being part of this programme enabled me to collaborate and become colleague of a large group of internal and external stakeholders.
- Being closely related to the topic of my PhD and having one case study area in common with the CAMELLIA project, I also collaborated with all the internal and external stakeholders involved in the Virtual Decisions Rooms for Water Neutral Urban Planning (VENTURA) research programme funded by Engineering and Physical Sciences Research Council (EPSRC) under grant EP/V042084/1.
- Expert advice provision for the development of the NATURE (Nature Assessment Tool for Urban and Rural Environments, Hölzinger et al., 2021) and pre-launch testing.
- Engagement and close collaboration with LPAs (Local Planning Authorities) from the RBKC (Royal Borough of Kensington and Chelsea), who provided feedback on our UK's planning system process analysis and integration. Main contact: Ms Patricia Cuervo.
- Engagement and close collaboration with LPAs (Local Planning Authorities) from the LBE (London Borough of Enfield), who provided valuable feedback and contributed to the development of our decision-support tool WaNetDST. Main contacts: Mr Ismail Mulla & Mr Ian Russell.
- Invited speaker at: a) Water Security webinar organised by Wilo UK (online; May, 2020); b) Water Neutrality & Nutrient Neutrality webinar organised by UCL (University College London; July, 2022); c) Showcase Event organised by the CSEI (Centre for Systems Engineering and Innovation, Imperial College London; September, 2022).
- Participation in the Clean Water and Sanitation Infrastructure project in Ekumpuano, Ghana; as part of the non-profit organisation Global Brigades at Imperial College London.

- Awarded a 6-month external position as main researcher on the SAPID (Systems Approach to Data-driven Integrated Urban and Infrastructure Planning) project in collaboration with the CSEI (Centre for Systems Engineering and Innovation) at Imperial College London and the Alan Turing Institute.
- Awarded an external collaboration inside the CSEI (Centre for Systems Engineering and Innovation) at Imperial College London to write a Working Paper about systems methods and integration.

Awards

- **Best Paper Commendation** - Issued by PLEA Conference 2020, September 2020. Conference paper: *“Natural Capital Impact Assessment for New Urban Developments”*.
- **President's Award for Excellence in Societal Engagement** - Issued by Imperial College London, May 2022.
 → *This award celebrates outstanding high-quality engagement activities with the public, schools, and community groups.*
- **Best Conference Poster** - Issued by CDE Conference and NERC, July 2022.

Chapter 1

Introduction

1.1 Urbanisation pressures, environment, and water security

Under the increasing pressures of climate change and population growth at the global level, it is crucial to address water security and sustainable urban development (United Nations, 2014; Colenbrander et al., 2019; Committee on Climate Change, 2019). Urban infrastructure systems involve multiple sectors, including water, land, transport, energy, and housing, among others. These infrastructure systems interact with each other and put constant pressures on their surrounding environment and human wellbeing in the form of flood risk, water shortages, air and water pollution, and Urban Heat Island effect (Mijic and Brown, 2019). Urbanisation is a complex spatiotemporal process that influences areas beyond the urban cores, being a difficult process to control, quantify and plan (Inostroza and De la Barrera, 2019). Therefore, one of the biggest challenges of this century is to transform cities' form and function to make them more efficient and resilient (Jabareen, 2006; Oke, et al., 2017).

Currently, more than 50% of the world's population live in urban areas; a figure that will reach 66% by 2050 (United Nations, 2014). Urbanisation is often opposed to environmental protection principles due to, for example, population growth, which demands a constantly increasing urbanisation rate and housing developments (Angel et al., 2011; Batty and Spencer, 2007). Increased demand due to population increase is likely to be detrimental to natural resources and their accessibility, which are considered essential for resilience to climate change (Lawton et al., 2010; Hurlimann and Wilson, 2018; Ford et al., 2019). In

many parts of the world, urbanisation has led to unsustainable development patterns as cities are forced to cope with the rapidly growing population and increasing societal requirements such as fresh water and sanitation, clean air, good transport links, and new facilities (housing, education, recreation, etc.; Shao, 2020). To adapt change to the direction of current planning decisions, existing urban environments and new urban developments need to be transformed and (re)designed by accounting for the complexity resulting from interactions between human, built and natural systems (Williams et al., 2017; Bedinger et al., 2020; Whyte et al., 2020).

From the environment management perspective, the concept of urban ecosystem services enables the understanding of the role of natural spaces in cities (Bolund and Hunhammar, 1999; Luederitz et al., 2015). These services range from air and water quality, temperature regulation, to aesthetic and cultural values. The importance of these services has been increasingly recognised by urban planners and policy-makers as they provide essential support for human well-being and economic development in cities. For instance, a study by Kabisch et al. (2016) showed that urban green spaces play a crucial role in improving mental health and reducing stress among urban citizens. Another study by de Groot et al. (2010) demonstrated that urban green spaces provide important ecosystem services such as carbon sequestration, soil conservation, and water retention. In addition, urban trees are found to reduce the urban heat island effect, which can have significant impacts on urban energy consumption and air quality (Escobedo et al., 2011). However, urbanisation and population growth have led to the loss of many natural areas in cities, thereby reducing the provision of these valuable ecosystem services. To address this loss, planners and policy-makers need to incorporate ecosystem service values into their decision-making processes and promote the creation and conservation of urban green spaces.

One of the processes that supports the generation and delivery of ecosystem services is the water cycle, which is crucially important for urban sustainability due to reliance on water resources, the need for protection from flooding, and the impact on water quality (Hardy, Kuczera and Coombes, 2005; Dobson and Mijic, 2020). However, water security is increasingly threatened in cities worldwide (Rauch et al., 2017; Varis et al., 2017; Hoekstra et al., 2018). This is directly related to the increasing demand for housing (Nygaard, 2011; Hilber, 2015), especially in large metropolitan cities like London, UK, where Government and Local Planning Authorities are aiming to build more than half a million homes during

the next 10 years (Environment Agency, 2009; GLA, 2021). Intensive urban transformation will require a profound understanding of the water cycle as part of the urban planning process, integrating interactions between land use change, housing development, and human behaviour (Raymond et al., 2017; Jönsson et al., 2016; Figure 1.1).



Figure 1.1: Picture of new urban developments in North London surrounded by natural wetlands and green spaces accompanied by a reflecting question about how we envisage our future cities. Source: Picture taken by the author in November 2022.

An emergent term in urban and infrastructure design that brings the focus to environment management is the concept of infrastructure ecology. The concept studies the flows happening between the different components of the urban infrastructure systems and their potential synergetic effects (Pandit et al., 2017). It views the city as a complex adaptive natural ecosystem and integrates urban infrastructure as a system of systems, which is for example enabled by implementation of Nature Based Solutions (Brears, 2018; Drosou et al., 2019). The principal aim of the PhD research is to develop an integrated urban planning framework that is based on the principles of infrastructure ecology and enables addressing the complexity related to sustainable, ecosystems-focused urban development, and water-centred design across multiple urban scales. The proposed framework is focused on London's future urban development, aiming to enable coordination between stakeholders and support review of existing environmental and infrastructure policy framing to better inform urban sustainability decisions. Theoretical basis for framework development is provided by the following planning concepts and theories. Detailed review of approaches that informed framework's application is presented in Chapters 3-5.

1.2 Systemic design concept

Cities are complex systems composed by several individual sub-systems such as transport, energy, buildings, land, biodiversity, and water (Ferrer et al., 2018; Gallopin, 2020; Whyte et al., 2020). It can be argued that addressing such complexity in urban planning needs to be supported by systems-thinking to enable integrated analysis and stakeholder coordination, ultimately guiding decision makers to achieve objectives at the systems scale (Cabrera et al., 2008; Sillitto, 2012; Pandit et al., 2017). In the context of urban planning, the application of systems thinking has been discussed in the context of Nature Based Solutions (NBS, Bozovic et al., 2017), which provide multifunctional environmental, social, and economic benefits for a range of relevant stakeholders (Mijic and Brown, 2019). However, there remains a challenge in integrating sustainable urban planning with environmental management and housing design across multiple stakeholders and within a unified evaluation framework that can capture interactions between urban systems and development decisions.

Systemic design is an emerging approach that has evolved in recent decades (Jones and Kijima, 2018; Battistoni et al., 2019; Bijl-Brouwer and Malcolm, 2020), which combines traditional design and systems thinking by taking a holistic and complete account of the urban form elements that constitute a complex system (Figure 1.2a). Following systemic design principles, all physical elements within 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 different planning aspects such as urban water management as one of the layers in the design of cities (Shin et al., 2018; Moravej et al., 2021). An important aspect of systemic design as part of its holistic approach is the consideration of the surrounding areas beyond the development site and how these might influence its (micro)-climatic and environmental conditions (Givoni, 1998; Hamada, Tanaka and Ohta, 2013). While the concept provides basis for integrated planning, there is still a lack of methodology that guides the systemic design process in a structured way.

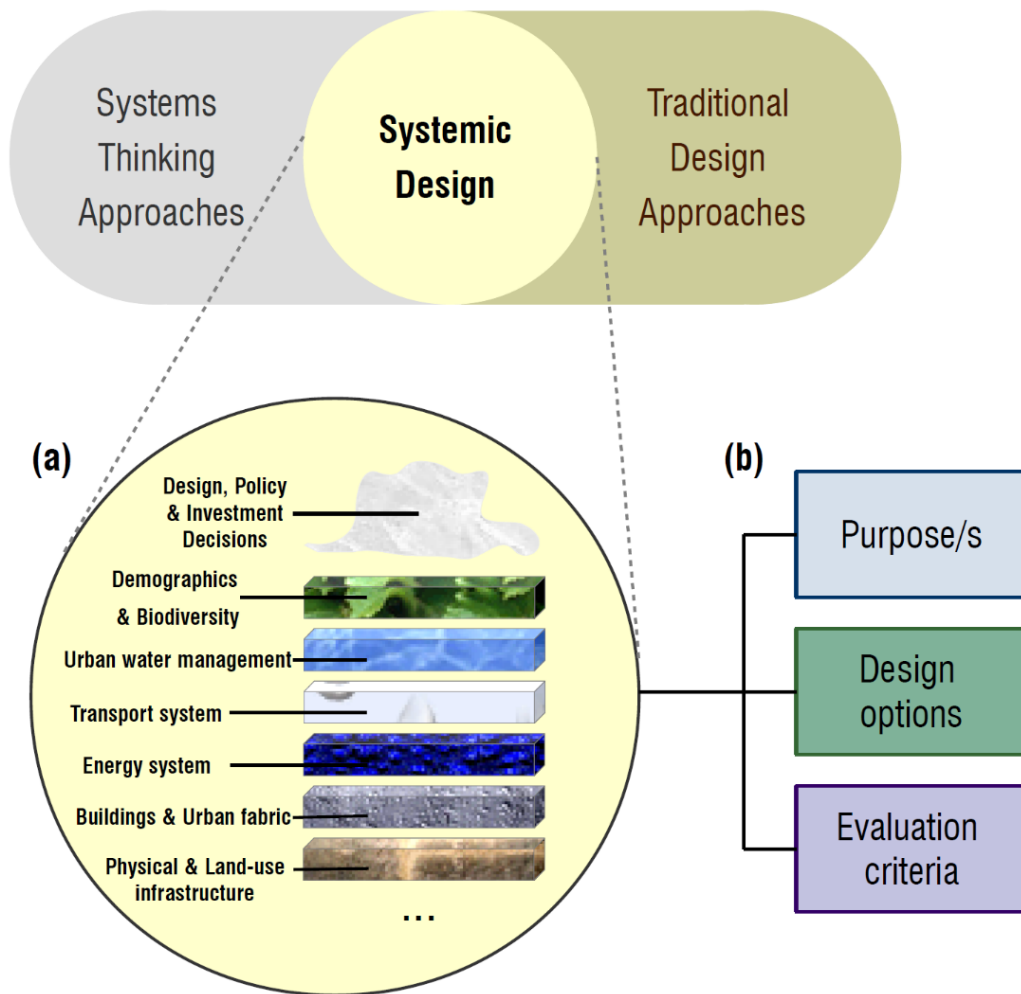


Figure 1.2: Diagram of the systemic design concept, individual urban sub-systems as layers of a holistic approach, and the application of systemic design inside the PhD thesis (i.e., purpose/s, design options, and evaluation criteria).

The systemic design concept applied to urban planning involves a series of strategic decisions outlined by policy and governance plans (Tomor et al., 2019; Jones, 2020). Those strategic decisions define the purpose of the design (which can be single or multiple) and set the boundaries of the study (i.e., city, borough, or development site). The strategic decisions are then supported by tactical decisions for future urban planning, which come from integrated evaluation and define the group of design interventions needed to achieve the urban planning purpose (Bach et al., 2014; Jones and Kijima, 2018; Miller, 2018). The combination of these two types of decisions inside the systemic design concept creates the starting point for defining a novel framework, which needs to integrate planning purpose with evaluation criteria for selection of design options (Figure 1.2b). I expand on these aspects in the following sections.

1.2.1 Systemic design purpose

In this research, I study three potential systemic design purposes: (1) design to maximise urban ecosystem services; (2) city-scale urban design for water neutrality, and (3) water-neutral spatially explicit design.

Ecosystem services are understood as all benefits that human beings obtain from natural ecosystems (Gómez-Baggethun et al., 2013). Urban areas are an interesting subject for the analysis of ecosystem services for the welfare of humans, which is where services like air quality, surface water runoff, flood mitigation, fresh water, wellbeing, or recreation are most highly valued (Derkzen et al., 2015). When applied to urban planning and design, the benefits we obtain from nature are known as Urban Ecosystem Services (UES; Bolund and Hunhammar, 1999; Luederitz et al., 2015). At the same time, in economic terms, natural ecosystems are understood as Natural Capital (NC), being all the assets that the Earth can give to us (Barbier, 2019). This might include soil, air, water and living organisms (Mace et al., 2015; Natural Capital Committee, 2018). NC can also be recognised as the economy's endowment of natural resources, being an important source of economic wealth, both for individuals and human societies (Barbier, 2019; Bright et al., 2019). However, when UES are considered key assets inside the NC concept, determining the most efficient and sustainable trade-offs between environmental conservation and development in our cities becomes very difficult (Barbier, 2019). Therefore, there is a need for a methodology that will inform systemic urban design to maximise UES.

As one of the key UES, water management has been linked with urban planning in many studies. For instance, a study by De Graaf, Van De Giesen, and Van De Ven (2007) developed the concept of the Closed City as an alternative and adaptive plan to reduce the water vulnerability in urban areas. This study connects with the previously studied approaches for sustainable urban water management and planning by Rijsberman and Van de Ven (2000), and with the City Blueprints framework developed by van Leeuwen et al. (2012). Another study by Nguyen et al. (2019) compared conventional water management approaches with the concept of the Sponge City, widely implemented in China. The authors demonstrated the ecological services of the Sponge City as well as the limitations and challenges of this concept. In addition, a comprehensive review of the context, purposes, processes and outcomes of sustainable urban water management systems was presented by Adem Esmail and Suleiman in 2020. However, there is still a need to consider

the link between planning and water management from an integrated perspective (Bozovic et al., 2017; Furlong et al., 2017; Allen et al., 2020; Rezaee et al., 2021).

In this context, the concept of Water Neutrality (WN; Kemlo and Lawson, 2009; Nel et al., 2009; Hoekstra, 2018) provides basis for integration. 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 in urban settings (Hoekstra et al., 2018; Nazemi and Madani, 2018; Van Ginkel et al., 2018; Aboelnga et al., 2019; Su et al., 2020). The concept of UWS specifically addresses water-related challenges in urban areas in contrast to the broader approach of strategic water resources management, which focuses on water resources at regional, national, or even international levels (Walmsley and Pearce, 2010; Hussain et al., 2019). Although the main objective of UWS is to ensure safe, reliable and sustainable water infrastructure systems within urban areas, so far, the water neutrality concept has not been applied in integration with UWS indicators evaluation.

With the means to assess WN in place, translating this information into the spatial allocation of urban developments is the final element in the systemic design framework. Previous studies consider allocation of urban developments as a self-contained single land use problem (Akinci et al., 2013; Liu et al., 2014). Urban planners must identify potential changes to multiple different land uses across a city and do this under the constraints of limited natural resources and conflicting societal, economic and environmental demands (Salat et al., 2010; Bodhankar et al., 2022). Ultimately, this poses sustainable urban development as a complex systems problem with multi-stakeholder requirements and interconnected uncertainties (House-Peters and Chang, 2011; Ni et al., 2014; Reid and Wood, 2023). Therefore, plausible approaches to identify optimal spatial allocation and development types that furthers water neutrality and sustainability goals are needed.

1.2.2 Design options portfolio

As part of the systemic design approach, a series of design options need to be considered to generate urban development alternatives (Battistoni et al., 2019; Pereno and Barbero, 2020). In this work, we use the term 'scenario' to refer to predicted urban development alternatives in the future under certain circumstances. Systemic design options are not detailed design solutions, but generic groups of interventions that are studied at an integrated, systems level, which enables revealing plausible mechanisms by which the intervention will have system-wide impacts and interactions with other elements of the urban environment (Bush and Doyon, 2019; Guarini et al., 2020). The selection of systemic design options is currently a main emphasis for future policies in cities and for decision-making studies in planning departments (Clark et al., 2018; Allen et al., 2020). I focus on three design options' categories, which include Blue Green Infrastructure (BGI), water systems interventions, and sustainable urban form. It is noted that proposed portfolio is far from being exhaustive and, although beyond the scope of the thesis, can be accompanied by other design options such as sustainable construction (Kilbert, 2013) or socio-ecological patterns (Erell et al., 2015; Keeler et al., 2019)

In this PhD, the term Blue Green Infrastructure is used to represent all types of NBS that can be applied to the urban environment. Nature Based Solutions (NBS) are broadly defined as solutions inspired and supported by nature that simultaneously provide environmental, social, and economic benefits to citizens (Maes and Jacobs, 2017; Raymond et al., 2017). They also have a series of co-benefits, such as improving health and quality of life, and the attractiveness of the place (Raymond et al., 2017). Examples of BGI include street trees; parks and open spaces; permeable paving; engineered stormwater controls (bioswales, rain gardens or retention ponds); green roofs; green facades; waterways and wetlands; or urban gardens (Kabisch et al. 2017; Nesshöver et al., 2017; Keeler et al., 2019). The main difference between traditional grey infrastructure and BGI is that the former is mono-functional and rigid, while the latter is self-adaptive and produces significant co-benefits or ecosystem services (e.g., air quality, flood regulation, climate adaptation, wellbeing, recreation, etc.; Keeler et al., 2019).

The role of urban infrastructure has progressively changed during the last decades and instead of only supporting human activities, now there is a growing awareness of the infrastructure role in managing natural environments to reduce unfavourable impacts

(Oke et al., 2017; Ferrer et al., 2018). Although the global focus is currently on reducing greenhouse gases emissions, systems thinking studies look beyond the carbon footprint and consider other variables such as air and water quality (Whyte et al., 2020). From the water management perspective, modern urban water systems are designed to include options such as water efficient appliances, water reuse systems (including rainwater harvesting and greywater recycling), and social awareness campaigns to reduce consumer demand (Dieu-Hang et al., 2017; Sheth, 2017; Ferrans et al.; 2018; Lu, 2019).

Urban form, generally understood as building dimensions, spacing and envelope characteristics, has a dramatic influence on urban microclimate and environmental balance (Erell and Williamson, 2015). There are different design concepts of sustainable urban form that might achieve more efficient and resilient urban lands. Some of these widely studied design concepts are compactness, density, passive solar design, sustainable transport, mixed land uses, diversity or, greening (Jabareen, 2006; Ahmadian et al., 2019). This research aims to integrate BGI, water systems interventions and urban form into a systemic design portfolio of options that maximise co-benefits between proposed solutions for future.

1.2.3 Integrated evaluation for planning decisions

Systemic design process requires analytical tools (data and models) to reveal complex spatial and temporal urban interactions and provide quantitative evidence to assess the effectiveness of the systemic design options (Ferrer et al., 2018; Gallopin, 2020). Looking at cities as complex systems implies the need for large amounts of data and information sharing (Wang et al., 2007; Osman, 2019). The process of analysing data to extract useful information and insights is considered key to enable urban sustainability (Zheng et al., 2017; Li et al., 2020). Therefore, data availability and its valuable insights play an important role to inform integrated urban planning, which needs to be addressed from a systemic design context.

There are many evaluation tools for urban infrastructure and environmental impact assessment available both in the scientific literature and engineering practice (Dunne et al., 2016). Some evaluate the benefits of BGI, while others simulate the predicted urban microclimate in a range of scales. They generally assist decision-makers to understand future

patterns of risk and provide future urbanisation maps based on planning policy scenarios (Ford et al., 2019). However, they are not always used in practice by engineers, architects, urban planners, housing developers, or Local Planning Authorities (LPAs) due to the complexity of setup and the extensive need for data and technical support (Batty and Spencer, 2007; Groot et al., 2010; Salat et al., 2010). A detailed review of a range of urban planning evaluation tools that can assess impact of new housing developments on UES provision, NC valuation, and BGI design performance is provided in Table 1.1.

Table 1.1: Summary of the selected evaluation tools informing about their name, main functions, target users, scale/s of evaluation, format, interface, licence, authors, and year of publication.

TOOL		Acronym meaning	Main function	Main users	Scale/s of evaluation	Format	Interface	Licence	Authors	Year
1	EVL	Environmental Value Look-Up	Provide indicative values for environmental impacts at different stages of the policy development cycle	Government departments, non-departmental public bodies, and other organisations	Regional or area of habitat	Spread-sheet based tool	Excel	Open source	Efttec Ltd	2015
2	GREENPASS	-	Impacts of BGI and other structural urban measures based on KPIs	Urban planners, Developers and Municipalities	Individual developments and small urban interventions	Plugin inside ENVI-met	ENVI-met simulator	Licensed	Scharf and Kraus	2016
3	UIAF	Urban Integrated Assessment Framework	Spatial and temporal impact assessment of urban activity and processes based on climate change projections	Cities, Decision-makers and other Researchers	City, city-zonal and zonal-parcel scales	Modules framework	Results in UDM (GIS maps)	Open source	Ford et al.	2019
4	AST	Adaptation Support Tool	Support collaborative planning with climate change adaptation strategies for a more resilient and attractive environment (create conceptual designs based on BGI performance)	Urban planners, Landscape architects, Water managers, Civil engineers, Local stakeholders and other experts (for individual users)	City, neighbourhood and individual developments	Touch screen with panels and central satellite map	Google Earth or Open Street Map	Licensed	Van de Ven et al.	2016

5	UAST	Urban Adaptation Support Tool	Provide climate change adaptation policies based on BGI performance	Cities, Towns and other Local authorities	City, neighbourhood and individual developments	Touch screen with panels and central satellite map	Google Earth or Open Street Map	Open source	Climate ADAPT	2019
6	BEST	Benefits of SuDS Tool	Assess and monetise many of the financial, social and environmental benefits of BGI	Communities, Engineers (building, civil, drainage), Health professionals, Ecologists, Economists, Environmental managers, Flood risk managers, Landscape architects, Spatial planners and others	Various scales (from catchment to simple units)	Spread-sheet based tool	Excel	Open source	CIRIA	2019
7	InVEST	Integrated Valuation of Ecosystem Services and Trade-offs	NC and ES assessment (in biophysical and economic terms)	Decision-makers who manage lands and waters (from government agencies to non-profits to corporations)	National, regional, landscape and local	Mapping software (QGIS or ArcGIS)	Script tool + results in GIS	Open source	Sharp et al.	2018
8	NATURE	Nature Assessment Tool for Urban and Rural Environments	NC impact and environmental net-gain assessment on new developments	Local authorities, Urban Planners and Developers (Planning Context)	Individual or group of urban developments	Spread-sheet based tool	Excel	Open source	Hölzinger et al.	2021
9	NCPT	Natural Capital Planning Tool	NC impact assessment on new developments	Local authorities, Urban Planners and Developers (Planning Context)	Individual urban developments	Spread-sheet based tool	Excel	Open source	Hölzinger et al.	2019
10	ENCA	Enabling a Natural Capital Approach	Summary of selected NC or valuation tools developed by government	Anyone looking to learn more about NC and environmental valuation and need practical guidance	All scales	Databook as spread-sheet based tool	Excel	Open source	Defra (UK)	2020

1 1	NECR15 9	Natural England Commissioned Report	Literature review of the effect of land management actions on the provision of ES (Ecosystem Services Transfer Toolkit)	Natural England staff and anyone else involved in making land management decisions	Upland, freshwater, urban, lowland agriculture, coastal & marine habitats	Spreadsheet based tool	Excel	Open source	Lusardi et al. (Natural England)	2014
1 2	UMEP	Urban Multi-scale Environmental Predictor	Provide different climate simulations inside the urban environment	Researchers, Decision-makers and Practitioners	City scale	Plugin inside QGIS	QGIS	Open source	Lindberg et al.	2018
1 3	WUDAPT	Weather Urban Database and Access Portal Tools	Community-generated urban database to help better decision-making in urban design and modelling	Researchers	From national to city scale	Map based portal tool	Own website + Google Earth	Open source	Ching et al.	2018

Tools focused on environmental impacts such as EVL (Environmental Value Look-Up, Eftec Ltd, 2015), GREENPASS (Scharf and Kraus, 2019, as a plugin in ENVI_met, Simon et al., 2016), or UIAF (Urban Integrated Assessment Framework, Ford et al., 2019; rows 1-3 in Table 1.1) can be used for impact assessment from human activities and climate change towards BGI implementation. While models such as AST (Adaptation Support Tool, Van de Ven et al., 2016) or UAST (Urban Adaptation Support Tool; Climate ADAPT, 2019; rows 4-5 in Table 1.1) are primarily designed to support collaborative urban planning and to analyse BGI performance. Additionally, other tools such as B£ST (Benefits Estimation Tool; CIRIA, 2019, row 6 in Table 1.1) are focused on monetary valuation of BGI benefits. Besides, other tools such as InVest (Integrated Valuation of Ecosystem Services and Trade-offs; Sharp et al., 2018); NCPT (Natural Capital Planning Tool, Hölzinger et al., 2019) or its more recent version NATURE (Nature Assessment Tool for Urban and Rural Environments, Hölzinger et al., 2021; rows 7-9 in Table 1.1) are primarily focused on NC and ecosystem service assessment across different scales. While other tools are primarily designed to guide urban planners by a comprehensive review of the NC valuation tools from various sources such as ENCA (Enabling a Natural Capital Approach, Defra, 2020) or NECR159 (Natural England Commissioned Report, Lusardi et al., 2014; rows 10-11 in Table 1.1). Finally, there are other tools that provide simulations and guide decision-making based on climate and weather predictions such as UMEP (Urban Multi-scale Environmental Predictor; Lindberg et al., 2018, as a plugin inside QGIS, Quantum Geo-Information System, Cavallini et al., 2019) or WUDAPT (Weather Urban Database and Access Portal Tools, Ching et al., 2018; rows 12-13, Table 1.1)

In addition to the selected tools in Table 1.1, there are other urban simulation models, such as UrbanSim (Waddell et al., 2017), Delta (Simmonds et al., 2014), IRPUD (Greiving et al., 2018), MUSSA (Martinez, 2018), or TRANUS (De la Barra et al., 2018). However, none is completely focused on environmental performance, and they generally require a very detailed parameterisation; for example, information about household budgets or expenditures (Ford et al., 2019). Previous analysis show that although selected evaluation tools allow developers and engineers to evaluate the impact on the natural environment in a range of applications, they have very different ways of processing the information and providing evidence. In addition, they do not provide a consistent and interconnected insight required for the systemic design concepts, which requires integration between design options and dynamic evaluation of UES across urban scales.

1.3 Planning system and integration

The planning system process refers to the steps and procedures that are taken inside a city to achieve a particular goal (e.g., to increase the amount of social housing, to adapt to climate change and resilience, to provide more human health and wellbeing, to achieve carbon and water neutrality targets, etc.; Healey and Williams, 1993; Hassenforder et al., 2015). The steps inside the process are complex and iterative and involve many stakeholders and multidimensional information (Hamilton et al., 2001; McEvoy et al., 2018). This complexity is often causing a lack of coordination and the system not operating effectively. Therefore, good attention to the urban planning system from early stages of the design will be essential to achieve positive outcomes in future urban development.

Urban planning stakeholders currently rely on different types of information that covers a range of physical, social and economic properties and are not comparable with each other (Soma et al., 2018; Barot et al., 2019). In the context of the systemic design concept, which combines traditional design and systems-thinking approaches, all the steps inside the urban planning system process as well as stakeholders involved will be integrated. Urban planning stakeholders include urban planners, housing developers, architects, engineers, service providers (i.e., water and energy companies), policy-makers, citizens and community groups (Bingham, 2006). Among these different groups of urban planning stakeholders, the key decision-makers can be either in the public or private sector, being

mainly housing developers or Local Planning Authorities (LPAs). Their roles are explained further in the next Section 2.2. These key decision-makers are responsible for setting the systemic design purpose and criteria, which, although generally derived from consensus, can also be adaptive and flexible depending on the socio-technical, temporal and economic factors of the urban development and its surrounding context (Awasthi, Chauhan, and Goyal, 2011; Barot et al., 2019). As part of their blue green systems approach, Maksimovic et al. (2017) placed a strong emphasis on having a highly analytical pre-planning phase at the early stages of the design to enhance stakeholder coordination. However, they did not specify in detail how to make this feasible. A new framework is therefore needed to connect science-based theory with actual practice, involving all the urban stakeholders in the infrastructure design process to generate better decisions and improve the ultimate environmental performance.

The high-level overview of systemic design within the urban planning context emphasises a need for developing a process for holistic and integrated design of urban systems. Otherwise, proposed development and interventions could potentially result in a variety of unintended consequences such as decline of ecosystem services, low quality in new housing, infrastructure system failures, uneven distribution of BGI, or low sustainability design performance, among others (Keating et al., 2003; Mijic and Brown, 2019). The concept of systemic design is closely linked to a long-established foundation of Dutch water management practices that aims to prevent the shifting of problems (referred to as 'Never Shift Problems' by the Ministry of Infrastructure and the Environment and the Ministry of Economic Affairs in 2015). This principle is focused on preventing issues related to water quantity and quality from being transferred in terms of both space and time (Chen et al., 2021). The governing bodies responsible for this fundamental principle have recently emphasized that problems should not be shifted from private to public land either. Similar to systemic design, this principle operates on different layers, aiming to connect space with water and to coordinate key stakeholders as part of spatial and water planning. According to the Dutch Ministry, the implementation of 'Never Shift Problems' should follow two distinct sequences: a) retain-storage-discharge (retaining and storing water for as long as possible to prevent flooding and water scarcity); b) keep clean-separate-clean (maintaining water as clean as possible and separating contaminated water as much as possible).

In this research, I hypothesise that a framework that integrates concepts introduced in the previous sections (i.e., systemic design purpose and criteria; design options portfolio; integrated evaluation, including modelling and spatial data analysis; and the planning system process and integration) will provide scientific and practical advances in integrated infrastructure ecology for sustainable urban planning. The framework is called CityPlan and its generic components are shown in Figure 1.3.

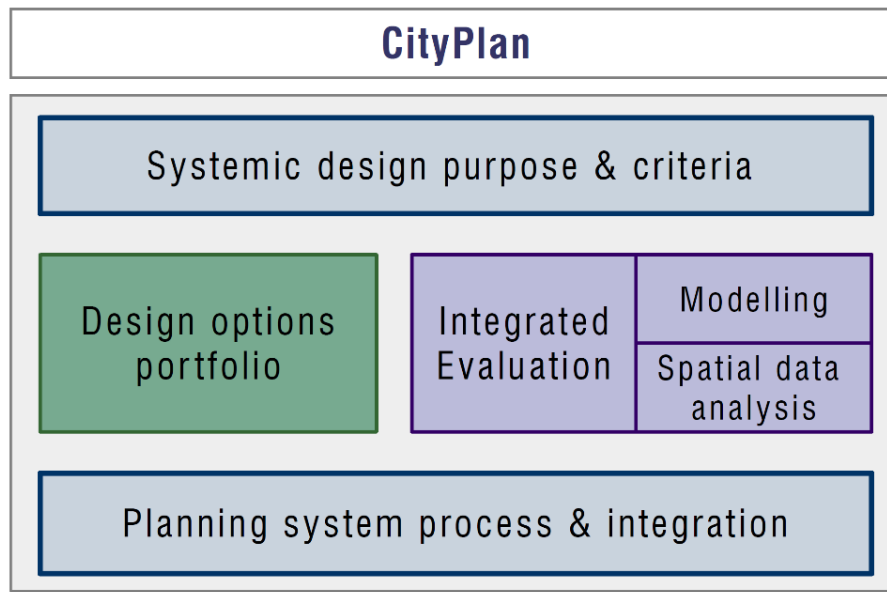


Figure 1.3: Generic components of the CityPlan infrastructure ecology framework based on systemic design principles and integrated evaluation and planning system process.

1.4 Scope of this work

The aim is to develop an integrated systems framework for implementation of the systemic design concept that supports achieving urban sustainability across different scales. The thesis focuses on the analysis of the UK's planning system process and operation, but the methodology presented is fully transferable if the local planning context is taken into consideration. This research aims to present a generic proof-of-concept for the integrated infrastructure ecology framework known as CityPlan in various applications (Figure 1.3).

Figure 1.4 provides a schematic outline of the thesis' objectives, which are:

1. To conduct analysis of the UK's planning system to understand challenges of the local and city contexts for integrated urban planning.

2. To develop an integrated urban planning framework that addresses the challenges of urban infrastructure systems based on the concept of systemic design and the UK's planning system process and operation.
3. To test the application of the framework for integration between urban planning and water management through development of:
 - a. Urban ecosystem services assessment combined with spatial representation of blue green urban scenarios.
 - b. Implementation of water-neutral systemic design options to minimise impacts of new housing on urban water security.
 - c. Spatial allocation method as part of the urban sustainability evaluation across multiple scales to support integrated water-neutral planning decisions.

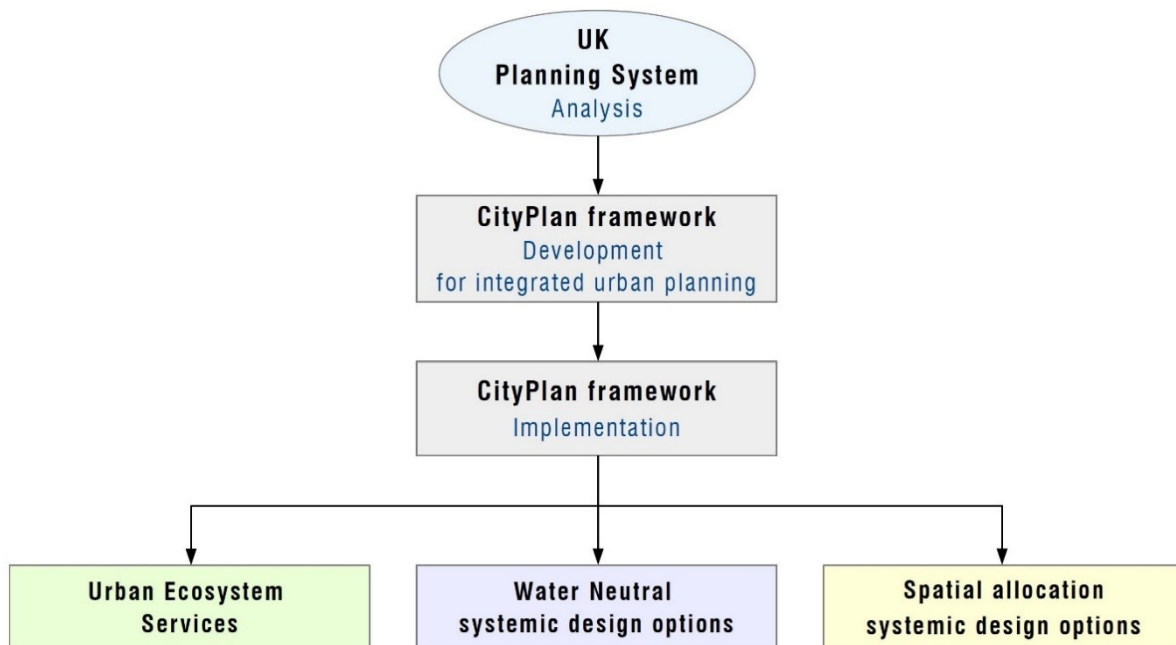


Figure 1.4: Schematic graphical outline of thesis objectives.

Achieving proposed objectives will enable me to answer the following research questions:

- a. How can systemic design concept be applied for maximising urban ecosystems services at a development scale?
- b. How can a concept of urban water neutrality be defined at the city scale in the context of systemic design?
- c. How can systemic design principles inform a spatial allocation of water-neutral design options?

1.5 Thesis outline

This thesis consists of six chapters. This chapter provides a generic context of the urban pressures and unsustainable development patterns, both in the UK and abroad. It introduces the main elements of the infrastructure ecology framework (i.e., CityPlan), those being: systemic design purpose and criteria, design options portfolio, integrated evaluation, and planning system process. Finally, it highlights the need for integrated urban planning and outlines the research objectives. The next chapters are structured as follows:

In the first part of this investigation (Chapter 2), I analyse the UK's urban planning system and identify synergies and stakeholder collaborations as part of the planning application process of a new urban development. I present London and its future urban development as the focus for assessment.

In Chapter 3, I introduce the proof-of-concept of CityPlan and its first application called CityPlan-Ecos. This version of the framework studies urban ecosystem services and aims to provide a common language for key stakeholders to design sustainable and resilient environments at the urban development scale.

In Chapter 4, I focus specifically on the water management sector to provide a more detailed case study application for CityPlan. In particular, I develop the concept of water neutrality as the second purpose and shape the second version of the framework called CityPlan-Water. In this case, a new evaluation module is introduced as part of the already developed CityWat model (Dobson and Mijic, 2020), measuring Urban Water Security (UWS) levels at the city scale.

In Chapter 5, I introduce systemic options allocation as key purpose for integrated urban planning and present the last application of the framework called CityPlan-Place. As part of its integrated evaluation, I develop a prototype of a data-driven tool to test urban water security indicators across different scales. This tool integrates spatial data with a series of rules for development impact and offset opportunity based on the current properties of the urban land.

Finally, in Chapter 6, I summarise findings of this study and key contributions to knowledge, as well as suggestions for future work and conclusions. References and Appendices are found at the end of this document.

Chapter 2

UK Planning System Integration

2.1 Introduction

One of the main priorities for the UK Government should be to protect their citizens from climate risks and to reverse the decline of natural ecosystems urgently (Clark et al., 2018). While the revised National Planning Policy Framework (NPPF) and 25 Year Environment Plan (25YEP) already provided some good suggestions to tackle climate risks and preserve the natural environment, more ambitious and specific targets are needed together with a strong and clear regulatory framework (Clark et al., 2018). These more ambitious targets will be particularly needed in urban environments, where urban housing developers aim to maximise housing growth and their businesses' profitability. However, based on the infrastructure ecology principles, housing developers should be able to maximise housing growth while having a minimum impact on the environment and while proving to regulatory bodies that they are providing Environmental Net Gain (ENG) inside their proposed developments.

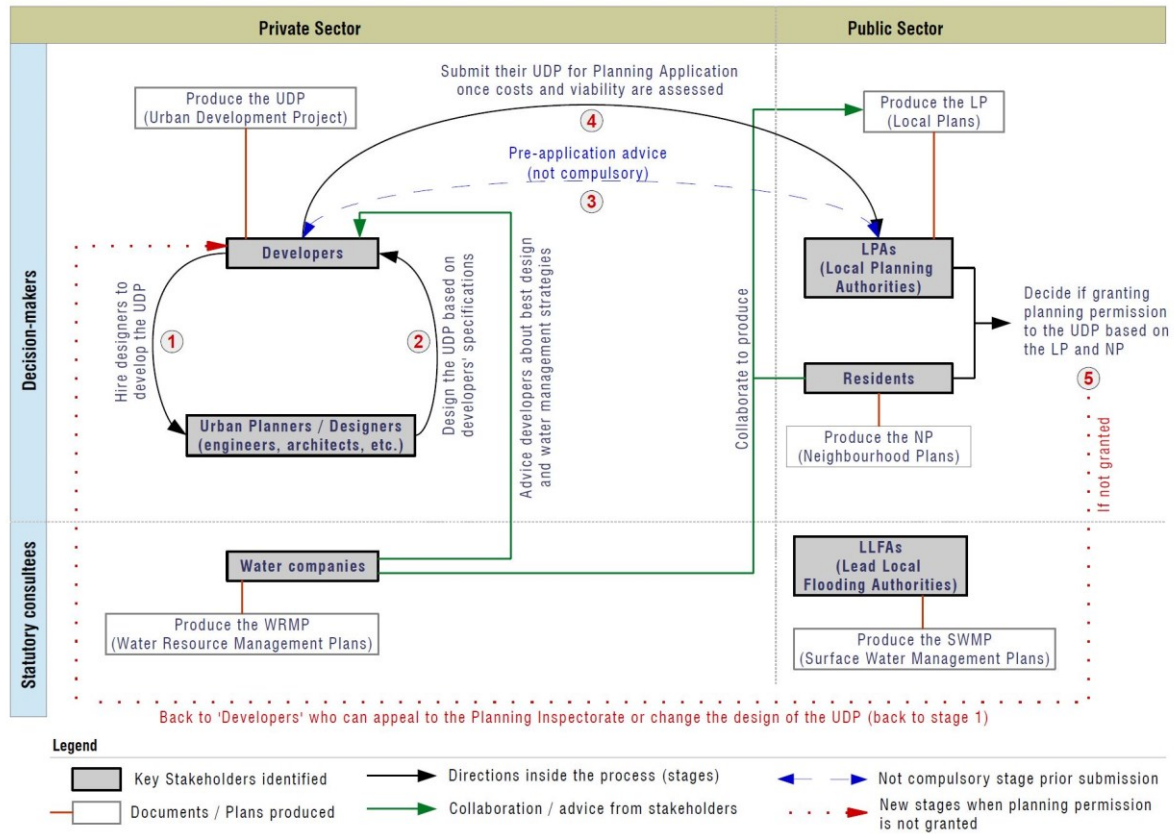
The term Environmental Net Gain (ENG) is understood as a mechanism to reverse ecosystem and biodiversity degradation to provide societal benefits (CIWEM, 2018). ENG was firstly introduced in the UK Government's 25YEP as an improvement of the increasingly well-established Biodiversity Net Gain (BNG) concept, understood as development that leaves biodiversity in a better state than it was before (Baker, Hoskin, and Butterworth, 2019). ENG is seen as a more ambitious principle that looks for widening

the net gain principles to the whole environment, being housing and urban infrastructure critical enablers of this sustainable development (CIWEM, 2018). The ENG studies are closely related to neutrality or net-zero approaches, that are included in the next chapters of this thesis (Chapters 4 and 5). At the end, the 25YEP re-commits the UK Government to its 2017 Manifesto pledge to ‘become the first generation to leave the environment in a better state than we found it’. This pledge makes the UK planning context a good setting to test environmental studies and infrastructure ecology principles at policy level.

As introduced in Section 1.4, the planning system is a complex and iterative process that should be integrated and understood in a holistic way to achieve the required sustainability expectations from the UK Government. Therefore, in this Chapter 2, I analyse in depth the planning application process in the UK’s system as well as the urban stakeholders involved, both in private and public sectors. This analysis is a key element to develop and understand the functionality of the infrastructure ecology framework CityPlan, presented in more detail in the next Chapter 3.

2.2 UK’s planning system

Early engagement with the planning system and local stakeholders is crucial to deliver sustainable urban development (UNISDR, 2017; Clark et al., 2019). In some cases, engagement may take place prior to land purchase; allowing developers to assess the costs (profitability) and viability of the development project. It also provides an opportunity to demonstrate the sustainability credentials of the development proposal to LPAs. Typically, there are several urban stakeholder groups involved in the planning application process. These include private and public sector actors, although there is often overlap between the two groups. For instance, housing developers can either be a private company or the Council Authorities of a city or borough. In that last instance, both developers and LPAs will be in the same group (i.e., public sector). Understanding the different relationships and collaborations between urban stakeholders will be essential for a practical integration in a systemic design framework. A graphical representation of the UK’s planning process and the five stages explained below is shown in Figure 2.1.



Note: In some cases, the 'Developers' can be the LAs (Local Authorities) as most councils in the UK have land to develop. Although in this context the 'Developers' figure will be in the Public Sector too, it should be a differentiation of functions between LAs and LPAs to ensure transparency.

Figure 2.1: Detailed analysis of the urban planning application process in the UK's context. Urban planning stakeholders are divided between private and public sectors; and between two decision groups: decision-makers and statutory consultees. The compulsory stages for planning application are represented with black arrows and red numbering; while pre-application advice is not compulsory, and it is represented with blue dotted double arrowed line. In case planning application is not granted, developers can appeal the decision or move back to stage 1 (red dotted arrow).

Urban stakeholders can be divided into 'decision-makers' (those who are responsible for decisions) and 'statutory consultees' (who advise other stakeholders and collaborate to produce Local Plans). Decision-makers may include developers, urban planners and designers, LPAs, and neighbours; while statutory consultees include water companies, and Lead Local Flooding Authorities (LLFAs). Developers typically produce and submit urban development projects using the expertise of designers and urban planners, as well as a team of engineers and architects specialised in urban systems design and infrastructure (Clark et al., 2018). Development plans (stage 1) are based on developers' specifications while also soliciting advice from statutory consultees such as water companies, who produce the Water Resource Management Plans (Bide and Coleman, 2019). Their advice is generally focused on best water management strategies and viability for BGI. In addition, LLFAs and risk management authorities periodically organise public

consultations to gather relevant information about flood risk at both national and local levels. This information is thoroughly reviewed by technical staff and then compiled to create the Flood Risk Management Plans (FRMPs). The plans provide guidance for urban developers and communities to collaborate in flood management (HM Government, 2022). FRMPs are typically employed during stages 1 and 2 of the planning application process.

Following draft production of the urban development project (stage 2), developers have the option to obtain pre-application advice from LPAs (stage 3). While this stage is not compulsory, it provides a cost-effective way of assessing the viability of the development prior to the planning application submission (HM Government, 2019).

Once all relevant sustainability and economic variables have been assessed and addressed by developers, the planning application can be submitted to the LPAs (stage 4). LPAs produce the Local Plans incorporating advice, where necessary from statutory consultees such as water companies, who produce the Water Resource Management Plans, and from residents, who contribute to the Neighbourhood Plans (HM Government, 2015, 2019).

Developers and urban planners can then move to more detailed design and building specifications if planning is granted (stage 5). If planning permission is not granted, developers are able to appeal to the Planning Inspectorate or change the design of the Urban Development Project, effectively returning to stage 1. These different stages inside the UK planning application process will be integrated and reproduced as part of the infrastructure ecology framework presented in the next Chapter 3.

Many councils in the UK own strategically important land, which they may wish to develop, for example, as affordable housing or publicly accessible space (Bide and Coleman, 2019). To ensure full transparency under such circumstances there should be a differentiation of functions between Local Authorities and LPAs, where LPAs in conjunction with residents decide if planning permission should be granted.

It is not uncommon that sustainability becomes a secondary goal to project viability and profitability for developers (Clark et al., 2018; HM Government, 2019; Bide and Coleman, 2019). One of the main objectives of the infrastructure ecology framework presented in this thesis is to express the real benefits of sustainable design solutions using evaluation tools and sustainability criteria. Therefore, based on the analysis presented in this section,

both private and public sectors will benefit from guidance at early stages of the design process, both in terms of the proposal viability and provision of potential design options. All findings from the analysis conducted in this Chapter 2 will be integrated and carefully considered in the development of the infrastructure ecology framework.

2.3 London as main case study area

In the UK, the level of urban growth will be particularly critical in London where population is projected to increase by 70,000 people every year, reaching 10.8 million citizens in 2041 (Committee on Climate Change, 2019; GLA, 2019). This will require an increase of 66,000 new homes per year, for at least twenty years, and around 50% of these homes should be affordable if Londoners needs are to be met (GLA, 2020). This unprecedented urban growth and housing demand is putting pressure on the capital's land, housing, infrastructure and natural environment. In addition, London is one of the most at-risk urban areas to climate change, facing water supply challenges (i.e., a rapidly increasing supply-demand gap), heat waves, flooding and air pollution (Environment Agency, 2009; Clark et al., 2018; Ford et al., 2019; GLA, 2019). This is particularly evident in the water management field, where unavoidable pressures such as fluvial and pluvial flooding, droughts, or river water quality degradation are projected to become more frequent due to climate change and increased urbanisation (Environment Agency, 2009; Garner, Hannah & Watts, 2017; Miller and Hutchins, 2017). For all the reasons stated above, I selected London as the main case study area in this PhD. Using different applications of the infrastructure ecology framework, the studies in next chapters will move across scales (from the city as a whole to the borough and urban development scale).

London is divided into 32 boroughs, which are sub-divided for statistical purposes into smaller zones called Lower Layer Super Output Areas (LSOAs; Figure 2.2). There are 4,835 LSOA units inside London boundaries, ranging from 1.70 ha to 1,580 ha in total area. 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). See Figure B.1 in Appendices for a detailed land-use map of London.

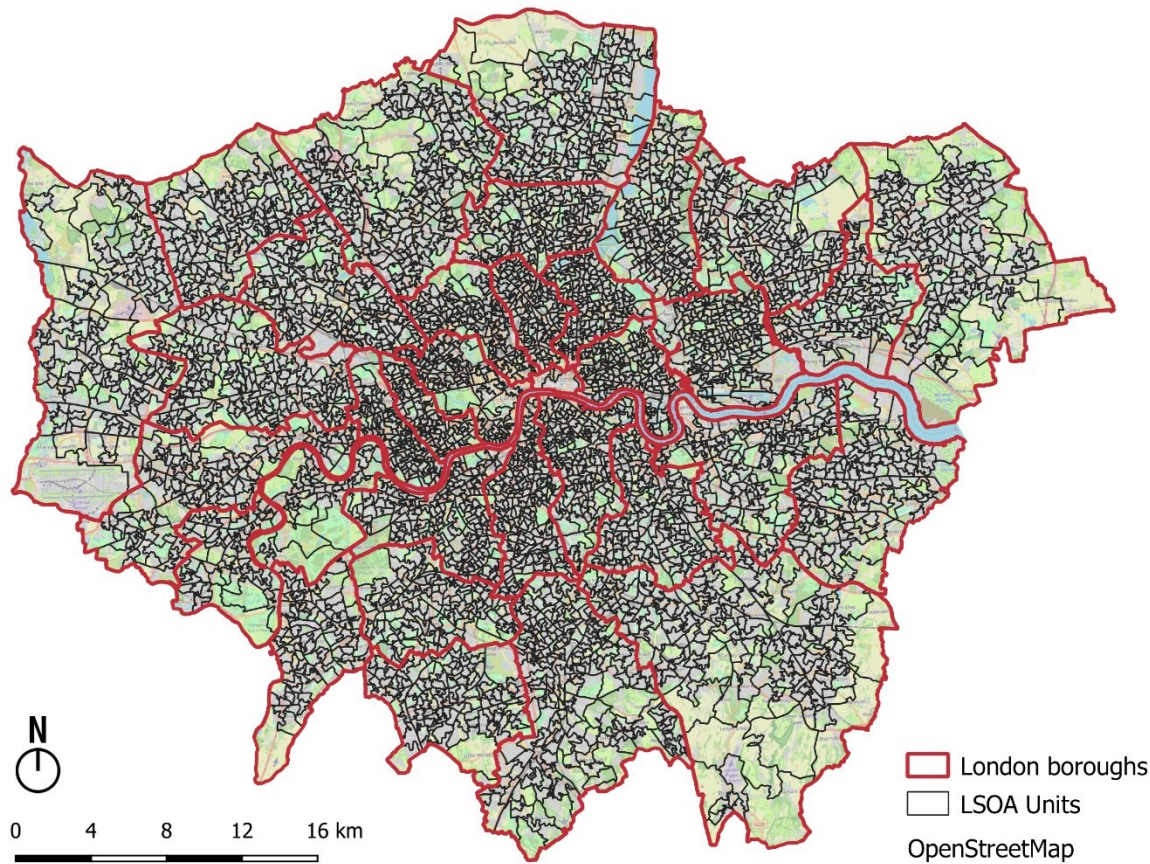


Figure 2.2: London map with boundaries of 32 boroughs (marked in red) and 4,835 Lower Layer Super Output Areas (LSOAs; marked in black) above OpenStreetMap.

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). Two of the largest urban developments projected in the city are Thamesmead Waterfront Development Plan (TMWP) and Meridian Water Development Plan (MWDP). These two developments will be the case study areas of Chapter 3 and Chapter 5, respectively, in which more details about their physical properties and housing targets will be provided.

Chapter 3

A Systemic Design Framework to Enhance Urban Sustainability

Note: This chapter is based on the published journal article Puchol-Salort, P.; O’Keeffe, J.; Van Reeuwijk, M.; Mijic, A. (2021). An urban planning sustainability framework: Systems approach to blue green urban design. *Sustainable Cities and Society* 66: 102677.

I was the main author of this paper and contributed towards the great majority of the work; my co-authors Dr Mijic and Dr Reeuwijk are my main supervisors, and Dr O’Keeffe was a post-doctoral researcher in my research group. They supervised the work published in the article and guided me through the writing and publication process.

3.1 Introduction

Human activities linked to urbanisation have significant impacts on the natural environmental. Stresses such as the climate emergency and other unpredictable events (e.g., COVID-19 pandemic) are threatening how cities operate and perform (Rice, 2020; Sharifi & Khavarian-Garmsir, 2020). Under these circumstances the role of built-natural infrastructure is more important than ever yet our understanding of how it responds to extreme events is lacking (Salama, 2020; Ugolini et al., 2020). While managing the effects of urban growth and urbanisation represents a significant challenge, it also provides an

opportunity to rethink how we plan and design our urban spaces to support sustainability, both in terms of new urban development projects and in retrofitting existing urban spaces.

An urban development project includes the design of built grey infrastructure (i.e., buildings and supporting civil infrastructure such as roads, pavements, etc.) along with associated green and blue space around it, including vegetation, blue spaces (i.e., rivers and lakes), and other types of natural surfaces (Erell et al., 2015; Wu et al., 2019). Both grey and natural spaces are essential for providing Urban Ecosystem Services (UES). Therefore, design options that integrate grey with blue-green infrastructure need to be included as part of urban sustainability evaluation processes (Guarini et al., 2020; Kapetas and Fenner, 2020). While definitions of urban sustainability vary (see Oke and Stewart, 2012; Erell et al., 2015), overarching principles include offsetting increasing pressures on the natural environment or infrastructure systems, while providing the same opportunities that we currently have to future generations (Brundtland, 1987; Riera Pérez et al., 2018; Barbier, 2019). Blue green urban design integrates sustainable construction and sustainable urban form concepts in the design of buildings; and where possible, the use of BGI in the open space areas (Kilbert, 2013; Bozovic et al., 2017; Davoudi and Sturzaker, 2017; Opoku, 2019).

Despite its importance, quantifying or measuring sustainable urban development with suitable indicators within an urban planning policy and decision-making context is difficult, both in research and in the professional practice fields. This is largely due to the complex interactions between many different types of systems in urban settings (Batty, 2008; Pandit et al., 2017; Boeing, 2018; Yeo and Lee, 2018). These include social, built, and natural systems which intersect and interact in numerous complex ways that result in urban pressures (land use change, air and soil contamination, green space reduction, etc.) and critical challenges (social equity, wellbeing, administrative cooperation, etc.; McPhearson et al., 2016). Therefore, developing a whole-system understanding is central to: 1) integrating multiple aspects of sustainable development for blue green urban design (Oke and Stewart, 2012; Russo and Cirella, 2020); 2) evaluating and justifying design sustainability for multiple stakeholders (Pandit et al., 2017; Bide and Coleman, 2019); and, 3) utilising the multiple benefits provided by the natural environment through ESS evaluation (Ossa-Moreno et al., 2017; Mijic and Brown, 2019).

In the context of decision-making, investment in natural ecosystems versus traditional engineering solutions is under-researched and there is little evidence to prove their key

role for urban sustainability (Nesshöver, 2017). Achieving urban sustainability, therefore, requires an appropriate methodology with shared evaluation metrics to link planning, ecological, and engineering design perspectives within urban environments. These perspectives can be linked using a systems thinking approach, employed by engineers and researchers to develop quantitative models and new forms of integration to understand urban complexities (Whyte et al., 2020).

In this chapter, I present the CityPlan infrastructure ecology framework (i.e., Urban Planning Sustainability Framework, UPSUF, Puchol-Salort et al., 2021); which, guided by the systemic design concept, combines evaluation methods with the UK planning system process to facilitate a common understanding of the opportunities for sustainable urban developments. An important feature of CityPlan is the spatial representation of the urban development within a GIS tool, linking the systemic design options and its integrated evaluation toolkit in a more comprehensive way. Visualisation makes the process for sustainable design more effective and reliable, leading to better planning decisions (Mellino et al., 2014).

The chapter is organised as follows: firstly, a general description of CityPlan is provided; followed by a detailed explanation of its three main components: a) Systemic design purpose and criteria linked to the planning system process and integration; b) Design options portfolio; and c) Integrated evaluation including modelling and spatial data analysis. In this case, the integrated sustainability evaluation is based on UES assessment and develops the first application of the framework called CityPlan-Ecos. This version of the framework combines benefits provided from natural spaces within the urban boundaries (Tan et al., 2020) and is aligned with the concept of Urban Natural Capital (UNC; Barbier, 2019; Bright et al., 2019; Bateman and Mace, 2020). Secondly, the main case study area applied to CityPlan-Ecos is presented, where the framework is conceptualised and tested. Thirdly, results comparing four urban design scenarios are presented and discussed. Finally, potential future work is discussed, followed by the closing remarks.

3.2 CityPlan framework

3.2.1 Methodology

To achieve sustainable urban design, it is necessary to look at a city holistically (Pandit et al., 2017); building an understanding of many interdependencies and operational risks inherent within urban built, natural and social systems. Viewing a city as a ‘system of systems’ (Kotov, 1999; Little et al., 2019) presents a significant challenge, but one which can be addressed through systemic design (see Keating et al., 2003; Williams et al., 2017).

In this part of the work, I apply systemic design as an engineering approach for integrated analysis of land and building systems that require stakeholders’ coordination and can help decision-makers achieve objectives of the system as a whole (Pandit et al., 2017; Whyte et al., 2020). Sustainable urban development requires a balance of several objectives and opportunities such as affordable housing, good transport links, clean air and water, biodiversity, or community services (education, recreation, etc.); although these are sometimes in disagreement and present serious challenges (Keeler et al., 2019). Additionally, systemic design is the best way to reliably compare Blue Green versus grey approaches to address urban sustainability challenges, evidencing their real value from a long-term perspective (Keeler et al., 2019). For all these reasons, systemic design lies at the core of the CityPlan framework, which is defined by two key elements: 1) improved urban development design and evaluation process through integration of the built and natural system components; and 2) improved system understanding and decision-making through integration of multiple stakeholder perspectives in the planning and co-development process. The CityPlan framework aims to coordinate the urban planning process at different stages and across various applications, integrating the work of several stakeholders and preventing them from working in silos.

CityPlan (Figure 3.1) is based on the UK’s planning system integration explained in Chapter 2 and addresses the ambition of city councils to grant more planning applications to urban development projects that are considered ‘sustainable’ (HM Government, 2015; Clark et al., 2019). Hence, this framework is primarily aimed at two stakeholder groups: 1) those involved in development and construction (housing developers, urban planners, and designers, i.e., engineers, architects, etc.); and 2) those involved in planning and use (LPAs or City Planners, and residents; Figure 2.1, Chapter 2). This is in addition to

statutory consultees which include water companies, as part of the private sector, and the LLFAs, as part of the public sector (Figure 2.1, Chapter 2). While all stakeholders have specific objectives and look at urban planning through a different lens, all share a common challenge: an incapacity to collectively determine whether an urban development project can be considered ‘sustainable’ or not (HM Government, 2018).

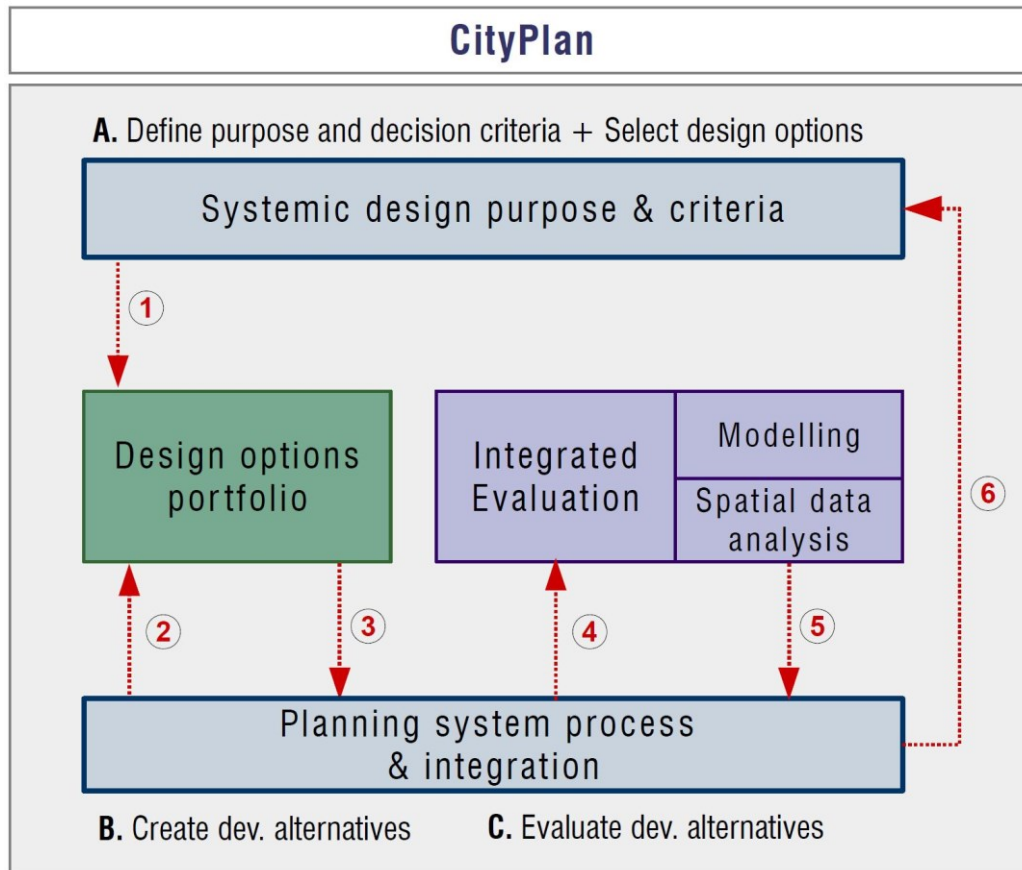


Figure 3.1: General diagram of the CityPlan framework. Its three components are: 1) Systemic design purpose and evaluation criterion inside the UK’s planning system process (in blue), considering not only the development site but also its surrounding areas to achieve a holistic approach; 2) Design options portfolio (in green); and 3) Integrated Evaluation Toolkit (in purple). The governance and decision-making actions inside the UK’s planning system process are represented by the three letters (A, B, C), while the six steps inside the framework are represented by numbered red arrows. Adapted from the Urban Planning Sustainability Framework, UPSUF, Puchol-Salort et al., 2021.

CityPlan is comprised of six steps (red arrows in Figure 3.1) based on the UK’s planning system’s process (three lettered actions in Figure 3.1). These six steps guide the user from an existing urban development baseline to a new validated and sustainable development project and operate across the three framework components: 1) Systemic design purpose

and criteria inside the integrated planning system process; 2) Design options portfolio; and 3) Integrated evaluation toolkit (blue, green, and purple clusters in Figure 3.1, respectively). CityPlan generates and assesses various urban development alternatives referred to as 'scenarios'. This term is used in this and the following chapters to describe predicted urban development alternatives under specific future circumstances.

The application of CityPlan is an iterative process, linking the systemic design options with an evolving integrated evaluation toolkit, which are all spatially represented in a GIS tool to achieve more reliable and accurate results. This process is designed to reflect current planning phases, mirroring the different design-cycle actions that an urban development project undergoes at governance and decision-making level until the planning application is granted.

3.2.2 Application

CityPlan's operation consists of six distinct steps (see Figure 3.1). The first step looks at the systemic design purpose and the decision criteria to be followed in a certain area (action A in Figure 3.1). Establishing the baseline conditions of this area (i.e., the pre-development scenario) is an essential step prior to any new urban development design. The type of information required is dependent on the type of development but may involve surveys of site ecology, current infrastructure, land use and hydrology (Jabareen, 2006). Once the baseline conditions are identified, the second step is to implement a selection of systemic design options to the existing pre-development scenario in order to obtain a new urban development scenario (action B in Figure 3.1). The action of traditional design lies in the implementation of these design options (e.g., by adding BGI to existing infrastructure, by integrating water efficiency solutions, or by considering sustainable urban form options).

The third step brings the new urban development scenario to the urban planning process to select the evaluation criteria for the fourth step, where the integrated evaluation toolkit assesses the proposed new urban development under these criteria. In step 5, the evaluation process combines a visual representation of the urban development using a GIS tool before returning to the planning system process (action C in Figure 3.1).

Finally, the sixth step of the framework involves a comparison of the evaluation outputs with the initial systemic purpose and the decision criteria under planning guidelines. If results indicate that the proposed development achieves the purpose, this may be the final stage of the systemic design process inside CityPlan. However, if the obtained metrics suggest that the proposed development does not achieve the purpose, or does not achieve it to an acceptable target, the process continues by modifying the design options based on the initial criteria (back to step 2).

The iterative process of CityPlan's application provides a standardised sequence which take the user from an initial baseline scenario to a new urban development plan, incorporating the requirements of governance and regulatory bodies, as well as those of the end-users – predominantly the residents. This approach also facilitates the exploration and quantitative evaluation of scenarios and testing different design options, all of which can then be compared to the baseline and the decision criteria. A clear alignment between the CityPlan's actions (Figure 3.1) and the planning system process (Figure 2.1, Chapter 2) is evident at this stage.

3.3 CityPlan-Ecos

Evaluating urban sustainability using the concept of Urban Ecosystem Services and guiding planning decisions towards blue green urban design is the key purpose of CityPlan-Ecos. In this first application of CityPlan, the first component (blue cluster in Figure 3.2) includes the systemic design purpose (i.e., UES), the decision criterion (i.e., a comparison of the sustainability performance difference between before and after new development, also measured with NC impact scores), and the planning system and operation stages (i.e., development of scenarios and evaluation metrics).

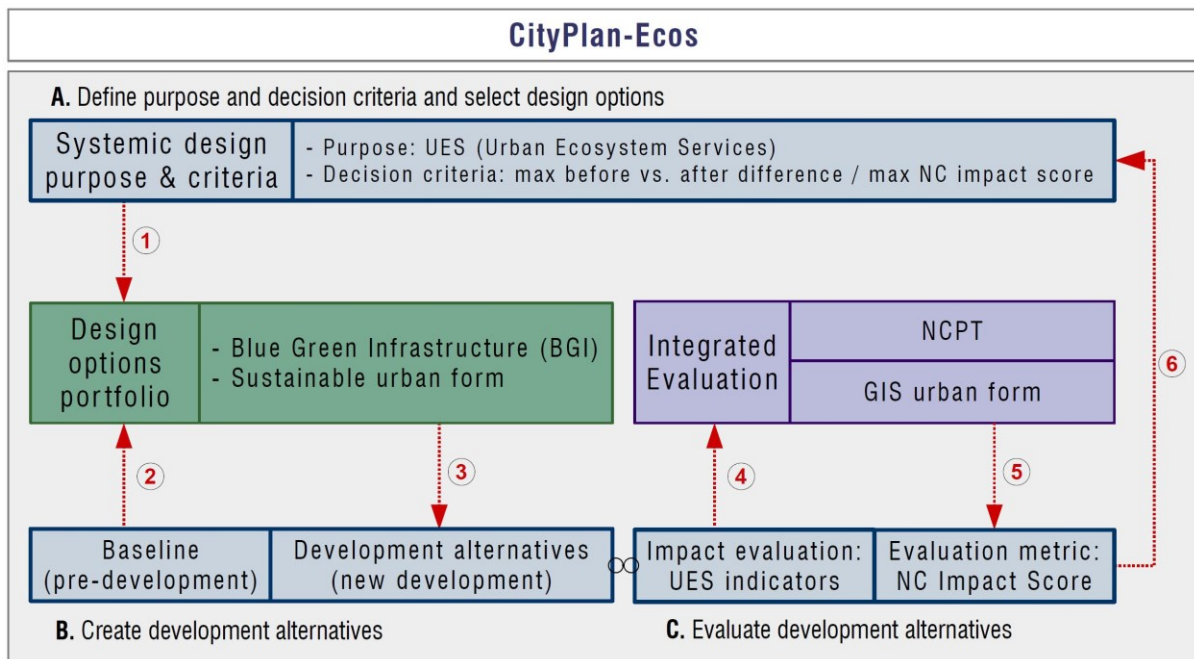


Figure 3.2: Methodology diagram of the CityPlan-Ecos systemic design and evaluation framework. The governance and decision-making actions are represented by the three letters (A, B, C), while the six steps inside the framework are represented by numbered red arrows.

The second component (green cluster in Figure 3.2) includes the design options portfolio (i.e., a combination of BGI, sustainable urban form and sustainable construction methods; Kilbert, 2013; Erell et al., 2015; Oke et al., 2017). Urban form includes building dimensions, shape, orientation, and spacing, as well as the characteristics of artificial surfaces and the amount of green space. Urban form associated with infrastructure influences climate adaptation and is crucial to achieve sustainability (Ford et al., 2019). Whereas sustainable construction makes an efficient use of local materials and natural resources (water, energy, etc.) during the construction process and the lifetime of the building.

The third component (purple cluster in Figure 3.2) includes the integrated evaluation cluster formed by the NCPT (Natural Capital Planning Tool; Hölzinger et al., 2019) and GIS urban form data. These tools enable an UES assessment method with BGI implementation. If results indicate that the proposed development is sustainable, this may be the final stage of the design process. However, if the metrics suggest the proposed development is unsustainable, or not sustainable enough, the process will continue, coming back to step 2 and modifying the design options of the new development until the metrics are positive (iterative process in Figure 3.2). While the systemic design purpose and criteria as well as the UK's planning system process and integration have been already explained in the previous Chapters 1 and 2, in the next sections 3.3.1 and 3.3.2 I explain in more detail the design options portfolio and the integrated evaluation cluster applied to CityPlan-Ecos.

3.3.1 Sustainable urban design options

Systemic design options are necessary to develop new urban development scenarios from the pre-development baseline (step 2 in Figure 3.2) and involve a mixture of built grey and BGI. In the long term, the benefits provided by BGI can outweigh those of traditional grey infrastructure (Bozovic et al., 2017), but achieving urban sustainability requires facilitating the flow of UES while including sufficient grey infrastructure to achieve the goals of the development in terms of housing, transport, water infrastructure, etc. (Kapetas and Fenner, 2020; Newton and Rogers, 2020). As a result, it is necessary to determine what the optimal combination of BGI vs grey interventions should be and how different uses of BGI can be linked to UES.

In this section, I explore this link by integrating BGI with urban form and construction concepts. From sustainable urban form concepts, I specifically focus on: i) building dimensions and spacing, avoiding overly compact or sprawled urbanisation; ii) building density and use, supporting mixed-use buildings and a healthy number of habitants/m² of the building; iii) surface properties, avoiding impervious and paved areas; and, iv) the amount of green space around the buildings, placing as much green space as possible in the open spaces. While from the sustainable construction perspective, I include the use of local and natural materials, and an efficient use of resources during construction and life

cycle of the building (water, energy, etc.). Table 3.1 compares sustainable with more traditional design options supported by CityPlan-Ecos' portfolio. The selected portfolio of design options will interact in the urban environment ultimately resulting in an associated set of UES (constituting different services and in differing amounts).

Table 3.1: Sustainable design options used in the CityPlan-Ecos, divided in three areas of study: i) BGI (Blue Green Infrastructure), ii) Urban form and, iii) Construction. Comparison of sustainable design options against traditional (grey) solutions.

CityPlan-Ecos Design Options			
Area	Group	Sustainable Design Option	Traditional Options
OPEN SPACE	Blue Green Infrastructure (BGI)	Street trees	Sterile corridors with hard and non-permeable roads/pavements
		Permeable paving	Non-permeable paving
		Engineered stormwater controls (bioswales, rain gardens and retention ponds)	Non-permeable surfaces directly connected to sewage system
		(Blue) Green roofs	Hard surface roofs
		Green façades/walls	Hard surface walls
		Parks and open spaces	Non-shaded and non-permeable communal spaces
		Rainwater harvesting systems	Large impermeable surfaces directly connected to sewage systems
		Ponds, waterways and wetlands	Heavy underground water infrastructure disallowing water for placemaking
		Urban gardens	Large impermeable surfaces with no vegetation
BUILDINGS	Urban Form	Building dimensions and spacing (compactness)	Too compact or too sprawl urbanisation
		Building density and use	Single use development (instead of mixed use) and lots of dwellings/habitants per m ² built
		Surface properties (cover)	Impervious and artificial surfaces (horizontal and vertical)
		Amount of green space around buildings	No green around buildings, with mostly impervious and paved areas
	Construction	Use of sustainable materials (fabric)	Non-local and non-natural materials
		Efficient use of resources during construction and life-time of the building (water, energy, etc.)	Waste of water and energy during construction and building life-time (low efficiency)

In addition, a comparison based on several sources of literature (Keeler et al., 2019; Bozovic et al., 2019) guided the selections of ten UES to be included in CityPlan-Ecos integrated evaluation (Table 3.2): air quality; Urban Heat Island effect mitigation; water quality; water supply; stormwater management; recreation and well-being; urban agriculture; biodiversity; aesthetics; and, resources efficiency.

Table 3.2: Comparison of the most widely assessed UES based on two acknowledged sources of literature. UES in green are those identified in both sources, while those in orange are only identified in one of the sources, but considered critical for the CityPlan-Ecos' aim. There are also some UES in white that are not included in this study and some extra comments that justify this selection (ticks are UES found in both sources without any comments, and crosses are UES that has not been selected). Last column presents the ten UES included and studied by CityPlan-Ecos.

URBAN ECOSYSTEM SERVICES (UES) COMPARISON			
Most common UES (based on Keeler et al. 2019)	NBS-related ES (based on Bozovic et al. 2017)	Comments	CityPlan-Ecos UES
Urban air quality	Air quality	✓	Urban Air quality
Carbon sequestration		X	
Coastal protection		X	
UHI and heat extremes mitigation	UHI mitigation	✓	UHI mitigation
	Water quality	Water quality is important for urban environments (both in landscapes and buildings)	Urban Water quality
Urban water supply		An important UES to be considered when designing buildings and public spaces	Urban water supply
Stormwater and wastewater management	Flood mitigation	Water management can be included with flood mitigation	Flood mitigation and stormwater management
Riverine flood impact reduction		✓	
Recreation opportunities	Well-being	Well-being' might include 'recreation' and 'mental health'	Recreation and well-being
Mental Health			
Urban agriculture		Very important UES in an urban context	Urban agriculture
	Biodiversity	Very important for nature conservation	Biodiversity
	Aesthetics	Very important when designing an urban development project	Aesthetics
	Noise reduction	X	
	Resources efficiency	Very important UES for energy consumption	Resources efficiency
TOTAL N. OF UES	10	9	10

While this study selected the ten UES for CityPlan-Ecos based on two acknowledged sources of literature (Table 3.2), it is important to note that in a real planning application process, key decision-makers and urban stakeholders such as housing developers and LPAs would influence the selection of these UES too (Jato-Espino et al., 2014; GLA, 2021). Depending on the context and specific conditions of the urban development site, decision-makers might also assign varying weights to each UES. For instance, an area more susceptible to flooding might assign higher importance to "Flood mitigation and stormwater management," while another facing water scarcity issues might give greater weight to "Urban water supply," and so on.

Blue green urban design options are generally assessed individually and a holistic approach that studies the UES provided by integrated design solutions is still lacking (Carmona et al., 2010). Hence, one of the innovations of CityPlan-Ecos is the ability to quantify the impact of a combination of blue-green urban design solutions, increasing the number of UES provided. The UES provided by combinations of blue-green urban design options are described in Table 3.3 (for instance, street trees combined with sustainable urban form and sustainable construction provide seven UES, that are: 1) aesthetics, 2) UHI mitigation, 3) flood mitigation and stormwater management, 4) urban air quality, 5) recreation and well-being, 6) resources efficiency and, 7) urban water supply; while permeable paving combined with sustainable urban form and sustainable construction provide three UES, that are: 1) flood mitigation and stormwater management, 2) resources efficiency and, 3) urban water supply; and so on). Those UES will be crucial to offset the negative impacts of the new urban development in the form of housing, pollution, urban heat island effect, or climate change, among others (Mijic and Brown, 2019).

Before moving to the integrated evaluation stage, a series of design scenarios need to be developed. The comparison between these design scenarios forms an essential part of UES assessment (Mace et al., 2011); while it does not try to predict the future, it helps to recognise a range of future possibilities under different assumptions. This aligns with the CityPlan's approach because the framework has the capacity to explore a series of potential urban developments which are then compared to the existing baseline's conditions. The results can highlight potential scenarios where urban development projects can more appropriately fit existing or future sustainability policies.

Table 3.3: UES provided by the combination of the CityPlan-Ecos urban design options. BGI solutions are combined with sustainable urban form and sustainable construction principles.

UES PROVIDED BY SUSTAINABLE DESIGN OPTIONS IN CITYPLAN-ECOS									
Area	Group	BUILDINGS							
		Sustainable Urban Form				Sustainable Construction			
	Design solution	Building dimensions and spacing (compactness)	Building density and use	Surface properties (cover)	Amount of green space around buildings	Use of sustainable materials (fabric)	Efficient use of resources during construction and life-time of the building (water, energy, etc.)	TOTAL N. of UES	
OPEN SPACE	Street trees	Aesthetics	UHI mitigation	Flood mitigation and stormwater management	Urban Air quality Recreation and well-being		Resources efficiency Urban water supply	7	
	Permeable paving			Flood mitigation and stormwater management		Resources efficiency	Urban water supply	3	
	Engineered stormwater controls (bioswales, rain gardens and retention ponds)	Urban Water quality UHI mitigation		Flood mitigation and stormwater management Aesthetics	Urban Water quality Urban water supply		Resources efficiency	7	
	(Blue) Green roofs	Aesthetics	UHI mitigation	Flood mitigation and stormwater management	Biodiversity Urban Air quality	Resources efficiency		6	
	Green façades/walls	Aesthetics	UHI mitigation		Biodiversity Urban Air quality		Resources efficiency	5	
	Parks and open spaces	Aesthetics	UHI mitigation Urban Water quality	Flood mitigation and stormwater management Urban agriculture	Biodiversity Urban Air quality Recreation and well-being		Resources efficiency Urban water supply	10	
	Rainwater harvesting systems			Flood mitigation and stormwater management		Resources efficiency	Urban water supply	3	
	Ponds, waterways and wetlands	Aesthetics		Flood mitigation and stormwater management	Recreation and well-being Biodiversity		Resources efficiency Urban water supply	6	
	Urban gardens	Recreation and well-being	Urban agriculture		Biodiversity		Resources efficiency	4	

3.3.2 Integrated Evaluation

The third component of the CityPlan framework is an integrated evaluation toolkit - a flexible and evolving cluster that has the capacity to select different evaluation tools and models depending on the specific case study. In the case of CityPlan-Ecos, various combinations of blue-green urban design options (Table 3.3) can be analysed and assessed using computational tools. There are a number of different tools that can be used for UES assessment. Some of the most commonly used are: B£ST (Benefits Estimation Tool; Ciria, 2019); InVest (Integrated Valuation of Ecosystem Services and Trade-offs; Sharp et al., 2018); and NCPT (Natural Capital Planning Tool; Hölzinger et al., 2019). Among them, NCPT is one of the most commonly used in the urban planning context in the UK. This tool is primarily aimed at the urban development scale and provides numerical (but qualitative) scores for several UES, covering most of the ten UES classified in CityPlan-Ecos (Table 3.2). The only two UES missing in the NCPT compared to CityPlan-Ecos (Table 3.2) are: a) urban water supply, and b) resources efficiency. However, NCPT lacks a graphical representation of land use, reducing the capacity of the evaluation to generate useful evidence or fully engage with stakeholders.

In order to support planning policies that describe the spatial and temporal interactions of an urban development project together with its socio-economic factors, new analytical tools are required (Ford et al., 2018, 2019). Therefore, CityPlan-Ecos upgrades NCPT's functionality through the spatial representation of both pre- and post-development land-use areas of the urban development site using GIS software. This improves the accuracy of results and allows more flexibility in terms of considering other architectural design parameters, such as orientation or urban form of buildings, which directly affect the environmental and thermal performance of the urban development (Jabareen, 2006; Erell et al. 2015; Ahmadian et al., 2019). The framework uses QGIS (Cavallini et al., 2019) for this purpose as it is a free and open-source tool, and can be easily shared with all relevant stakeholders. While quantification of benefits provided by sustainable design solutions can be achieved through various metrics, the inclusion of computational tools with the capacity for a spatial representation has the potential to provide significant increased benefit (Mijic and Brown, 2019). Including GIS capabilities in CityPlan-Ecos improves its capacity to demonstrate the implications of change, generating evidence on the benefits of the proposed urban developments to stakeholders and delivering solutions that achieve maximum sustainability values.

3.4 Results at urban development site scale

3.4.1 Case study area: Thamesmead Waterfront Development Plan

Community Water for a Liveable London (CAMELLIA) is a major five-year NERC research programme that started in October 2018 and is focused on sustainable water management inside the capital. Thamesmead is one of the main case study areas inside CAMELLIA, from which this PhD thesis is a key contributor among other partners and organisations (see Figure A.1, Appendices).

Thamesmead is a 750-ha area in Southeast London currently undergoing a large regeneration programme that will last for the next 30 years. Located between two London boroughs (Figure A.2, Appendices): Greenwich (Thamesmead Moorings) and Bexley (Thamesmead East), the area contains a significant number of social housings, originally built by the now-disbanded Greater London Council (GLC) as part of their 1967 Masterplan (Cherry and Pevsner, 1964). GLC was the highest administrative body for Greater London at local level from 1965 to 1986, being now inoperative.

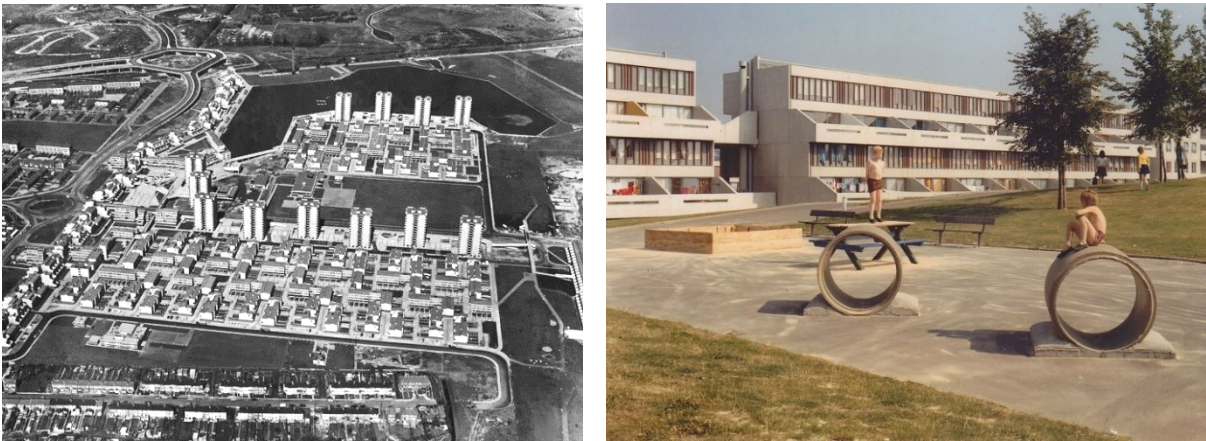


Figure 3.3: Aerial photograph taken during the 1970s that shows the brutalist architecture of Thamesmead Southmere Estate (left) and one promotional picture of the Estate with children playing on the new green parks (right). Source: © Bexley Local Studies and Archive Centre.

At that time, Thamesmead was named “Town of the 21st Century” and tried to reflect futuristic design ideas to create a utopia of affordable housing and provide an effective solution to London’s post-war housing shortage. One of the main GLC’s division architects, Robert Rigg, believed that lakes and canals reduced vandalism and other types of crime, so he designed most of the estates with plenty of green spaces and artificial lakes,

such as the Southmere Estate (Figure 3.3). However, this and other infrastructure ideas that were part of the Brutalism movement, such as overhead walkways and tunnels, were proven insufficient to achieve this sense of safety. Most of these features fell into disrepair shortly after the estates were opened and were soon considered unsafe places to walk, later becoming a symbol of urban decay (see pictures of Figure A.3, Appendices).

Currently Thamesmead neighbourhood is home to over 45,000 people in approximately 16,000 households, 5,200 of which are owned by the Peabody Housing Association (Ford and Baikie, 2016). Peabody also owns a significant portion of currently unused land, accounting for 65% of the Thamesmead area (Askew, 2018) of which approximately 150 ha are blue or green-space. This includes 32 ha of water comprising five lakes and 7 km of canals, five neighbourhood parks and 14 Sites of Nature Conservation Interest (SNCI). The total estimated Natural Capital potential value provided by Thamesmead's blue and green-space is estimated to be at least £306 million or £257 per person per year (Askew, 2018; Vivid Economics, 2018). Despite this, most of the blue and green space remains underutilised with significant portions of the area currently inaccessible.

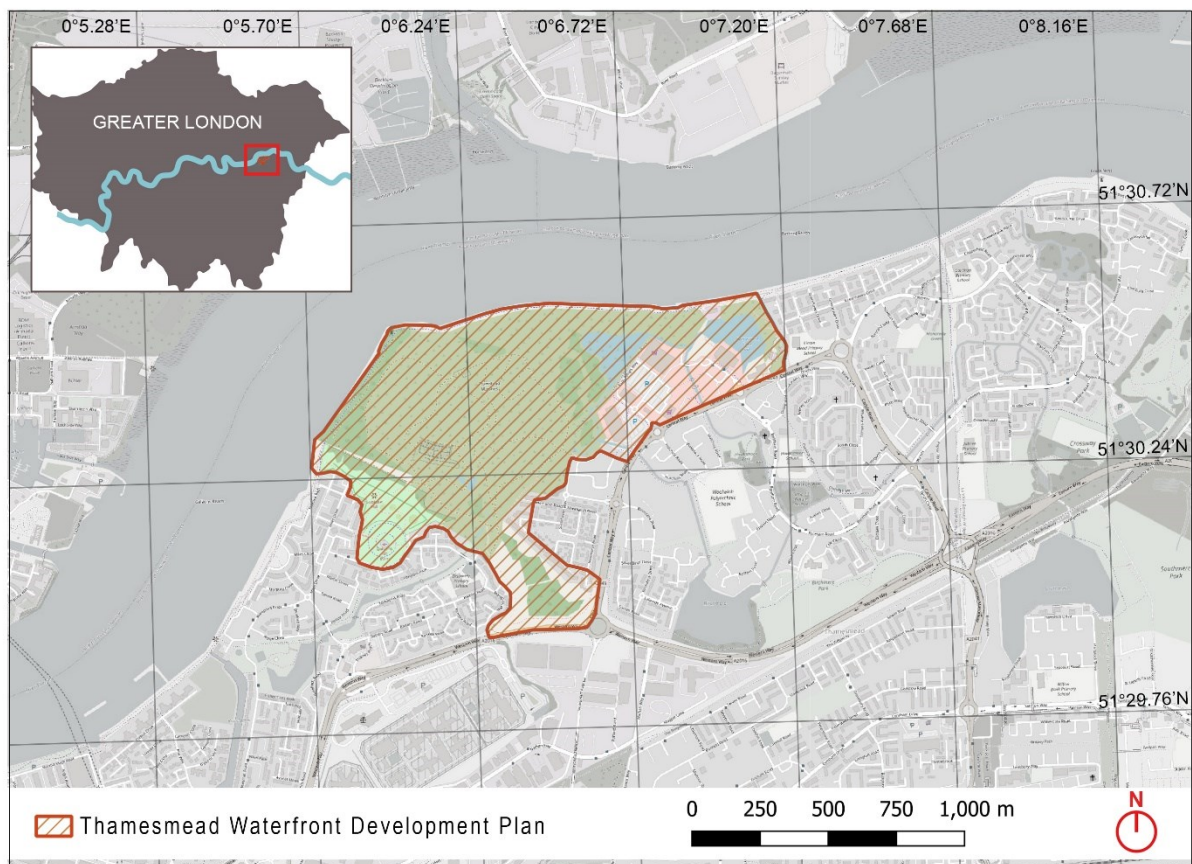


Figure 3.4: Thamesmead Waterfront Development Plan (circled in red) inside the Greater London area. Figure developed by the author and published in O'Keeffe et al., 2022.

Current plans involve developing the area to accommodate significant increase in population: it is expected that by 2050 more than 100,000 people will call Thamesmead their home. This will be complemented by a new railway station and a new tram station, which will connect this neighbourhood with Central London in less than 20 min. Peabody's goal is to design all new houses intelligently, with sustainable principles and to recover the old ones, making them again safe and secure (Askew, 2018). This will involve improving its environmental and community qualities, turning Thamesmead into a centre of culture, arts and heritage.

The Thamesmead Waterfront Development Plan (circled in red in Figure 3.4 and in blue in Figure A.2, Appendices) forms one of the most important aspects of this neighbourhood's redevelopment. The scheme will include more than 11,500 new homes within a 100-ha site, utilising almost 3 km of undeveloped river waterfront (see aerial views for current development site and developer's future vision in Figure A.4, Appendices). Almost 80 ha of these 100 ha are brown, blue and green space managed solely by Peabody (Royal Borough of Greenwich, 2014), most of which is currently inaccessible (Figure 3.5). This generates a unique development opportunity to provide a diverse range of UES. This £8bn new urban development will be one of the largest projects of its type in Europe and will be based around a range of new transport connections, including a new underground station connected to the Elizabeth Line (GLA, 2018). See rendered images of future TMWP in Figure A.5, Appendices.



Figure 3.5: Pictures of the Thamesmead Waterfront Development Plan (TMWDP) site before any development works have started. Abundant green and blue spaces that are inaccessible to the public are visible from the outside boundaries. Pictures taken by the author in 2021.

3.4.2 Systemic design urban scenarios

Thamesmead Waterfront Development Plan (TMWDP) is used to evaluate the sustainability levels of several systemic design options for new urban developments at this proof-of-concept of CityPlan-Ecos. As part of its integrated evaluation cluster, UES accounting will be the starting point to understand the environmental impact created by new housing developments. I develop four urban design scenarios for TMWDP in order to compare different levels of environmental impact. However, before presenting these four systemic design urban scenarios, it is necessary to understand the pre-development land-use map, which will act as the initial baseline (step 1 in Figure 3.2). This pre-development map is represented based on research data previously collected and supplemented by OpenStreetMap and Google satellite maps.



Figure 3.6: Pre-development land-use map or ‘baseline’ for Thamesmead Waterfront Development Plan (TMWDP).

Approximately 50% of the development site is currently developable brownfield land and hazardous-waste land-fill (Figure 3.6). Hazardous landfill cannot be used for building, but it has other potential uses, including a nature reserve. Under current planning conditions from the Royal Borough of Greenwich, blue space (lakes and canals), part of the amenity

grassland and the protected wetland inside TMWDP must be preserved as Sites of Nature Conservation Importance (SNCI). With the exception of the water-pump station, all existing buildings inside the development site, predominantly supermarkets, department stores or leisure centres, will be removed and redesigned in all four design options. Paved areas (including car parks, and play areas) will be also redesigned, with the exception of the Thames path pedestrian and cycling trail, which is also protected by Greenwich planning policies.

Based on the aforementioned constraints, a realistic but unfavourable scenario is developed (Figure 3.7). This is considered the Business As Usual (BAU) scenario, which represents traditional building approaches: relying heavily on grey infrastructure and building solutions with minimal consideration of sustainable urban form (e.g. appropriate building orientation, shape, density and natural surfaces, such as green roofs or green walls; see Table 3.1). The built-up areas with different types of densities (high, medium and low) are built with traditional ways of construction. As aforementioned, blue space, protected wetland and intertidal mud-sand are preserved and have not changed. Other land-uses, such as mixed woodland and amenity grassland, have been diminished in some parts and then augmented elsewhere, especially where there is hazardous waste land fill at the moment. A spatial representation of the land-use distribution and two street canyons sections with selected design options of Scenario 1 are represented in Figure 3.7.

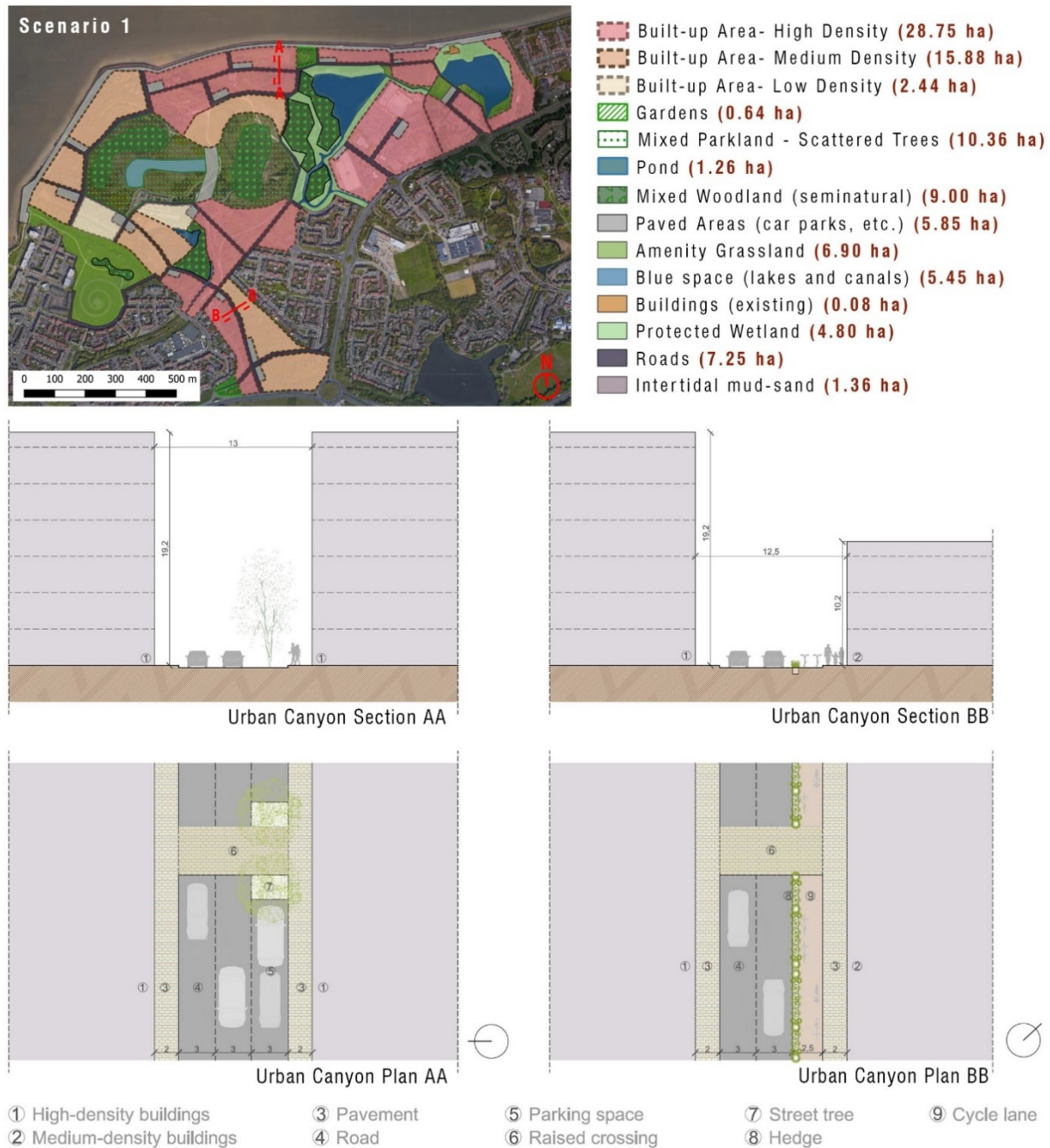


Figure 3.7: Scenario 1 land-use map (i.e., Business As Usual, BAU, scenario) for Thamesmead Waterfront Development Plan (TMWDP; above) and street canyons with systemic design options for Scenario 1 based on two sections: AA (cutting through high-density buildings on both sides of the street; below left) and BB (cutting through high-density and medium density buildings on each side of the street; below right).

Scenario 2 represents the same number of built-up hectares of Scenario 1, but instead of being high-, medium-, or low-density built-up areas; those are exchanged for ‘buildings covered with green roofs’ or ‘buildings with green walls’ land uses (Figure 3.8). In the same way, the previous ‘roads’ have been replaced by ‘local green roads’; while ‘paved areas (car parks, etc.)’ are transformed into ‘gardens’ (including the Thames path). A

spatial representation of the land-use distribution and two street canyons sections with selected design options of Scenario 2 is represented in Figure 3.8.

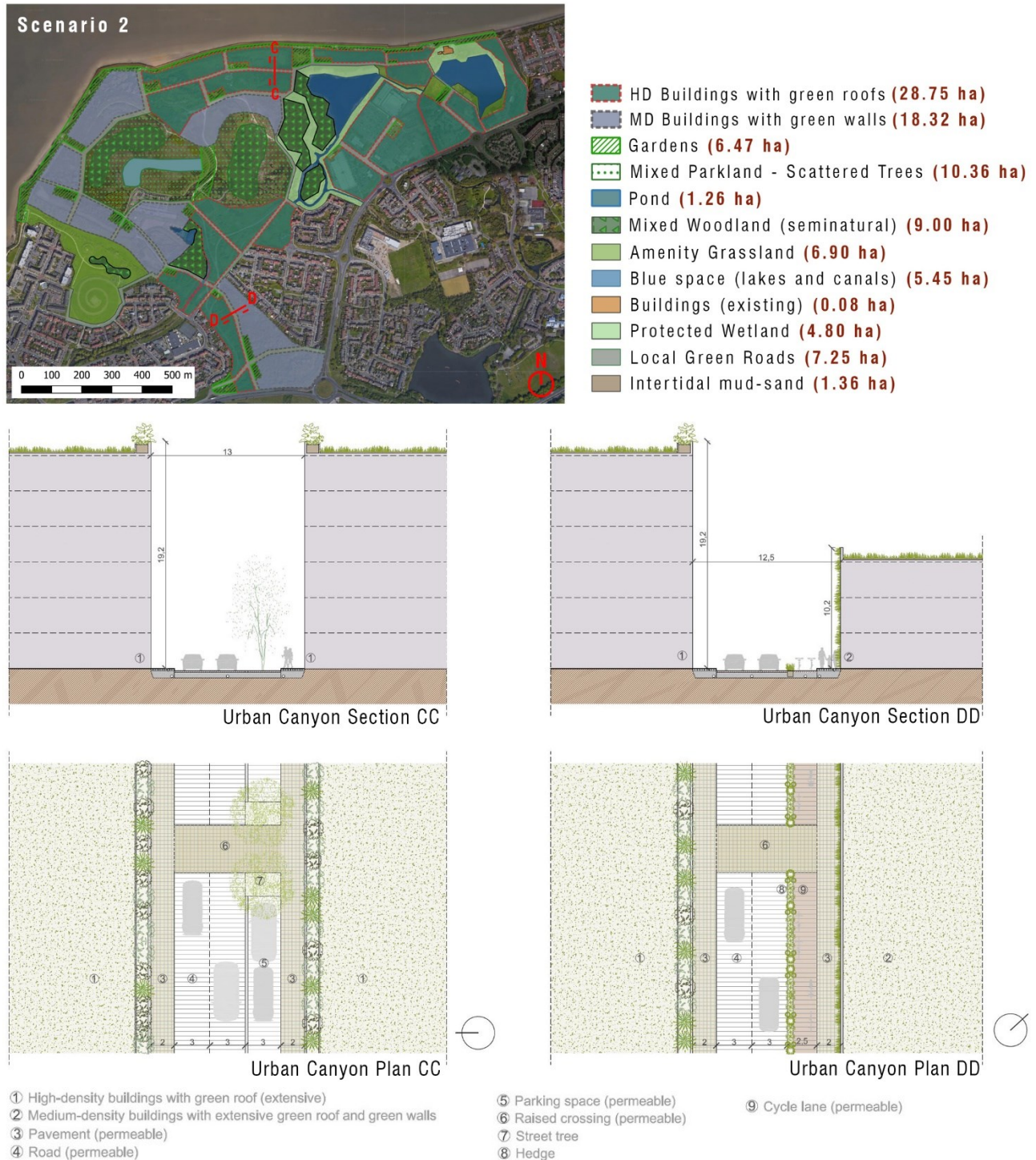


Figure 3.8: Scenario 2 land-use map for Thamesmead Waterfront Development Plan (TMWDP; above) and street canyons with systemic design options for Scenario 2 based on two sections: CC (cutting through high-density buildings on both sides of the street; below left) and DD (cutting through high-density and medium density buildings on each side of the street; below right).

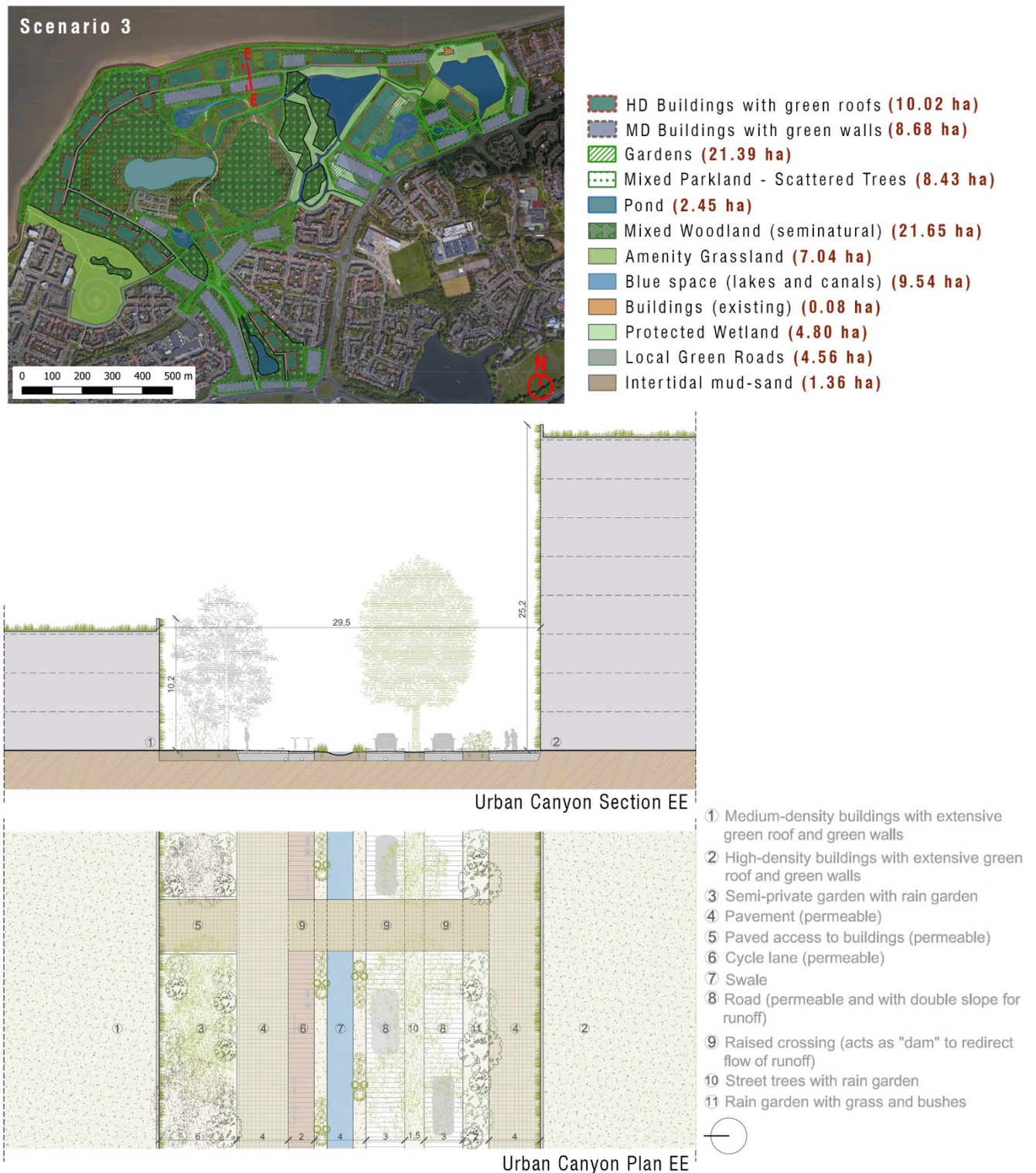


Figure 3.9: Scenario 3 land-use map for Thamesmead Waterfront Development Plan (TMWDP; above) and street canyon with systemic design options for Scenario 3 based on one representative Section EE (cutting through high-rise and medium-rise buildings on each side of the street; below).

Scenario 3 is based on a completely new urban layout design (Figure 3.9). In this case, more green, blue and recreation spaces are arranged around the built-up areas to increase the UES received. This scenario is based on compact densities (i.e., combination of high-rise and medium-rise buildings) and BGI around them (e.g., rain gardens, permeable paving, street trees, etc.), which is regarded to be a more sustainable option for future cities than low-density layouts (Ahmadian et al., 2019).

In addition to the BGI solutions implemented in Scenario 3, other design aspects are considered such as: i) most existing woodland is preserved; ii) more woodland and pond areas are added inside the parkland; iii) gardens (which represent BGI) are placed around most of the building blocks; iv) blue space is considerably increased with new lakes and a new canal network. A spatial representation of the land-use distribution and one representative street canyon section with selected design options of Scenario 3 is represented in Figure 3.9, where buildings with roofs are linked to tall buildings between eight and twelve floors tall and buildings with green walls are linked to medium-density buildings between three and six floors tall.

Finally, Scenario 4 has a similar ethos to Scenario 3, but represents an option that preserves most of the existing natural environment, especially mixed woodland area, and leaves more space for BGI, represented as ‘gardens’ (see Figure 3.10). Additionally, buildings facing the river are envisioned as tall buildings with green roofs, while buildings with green walls are placed inland and pictured as medium-density buildings of between three and six floors tall. A spatial representation of the land-use distribution and one representative street canyon section with selected design options of Scenario 4 is represented in Figure 3.10.

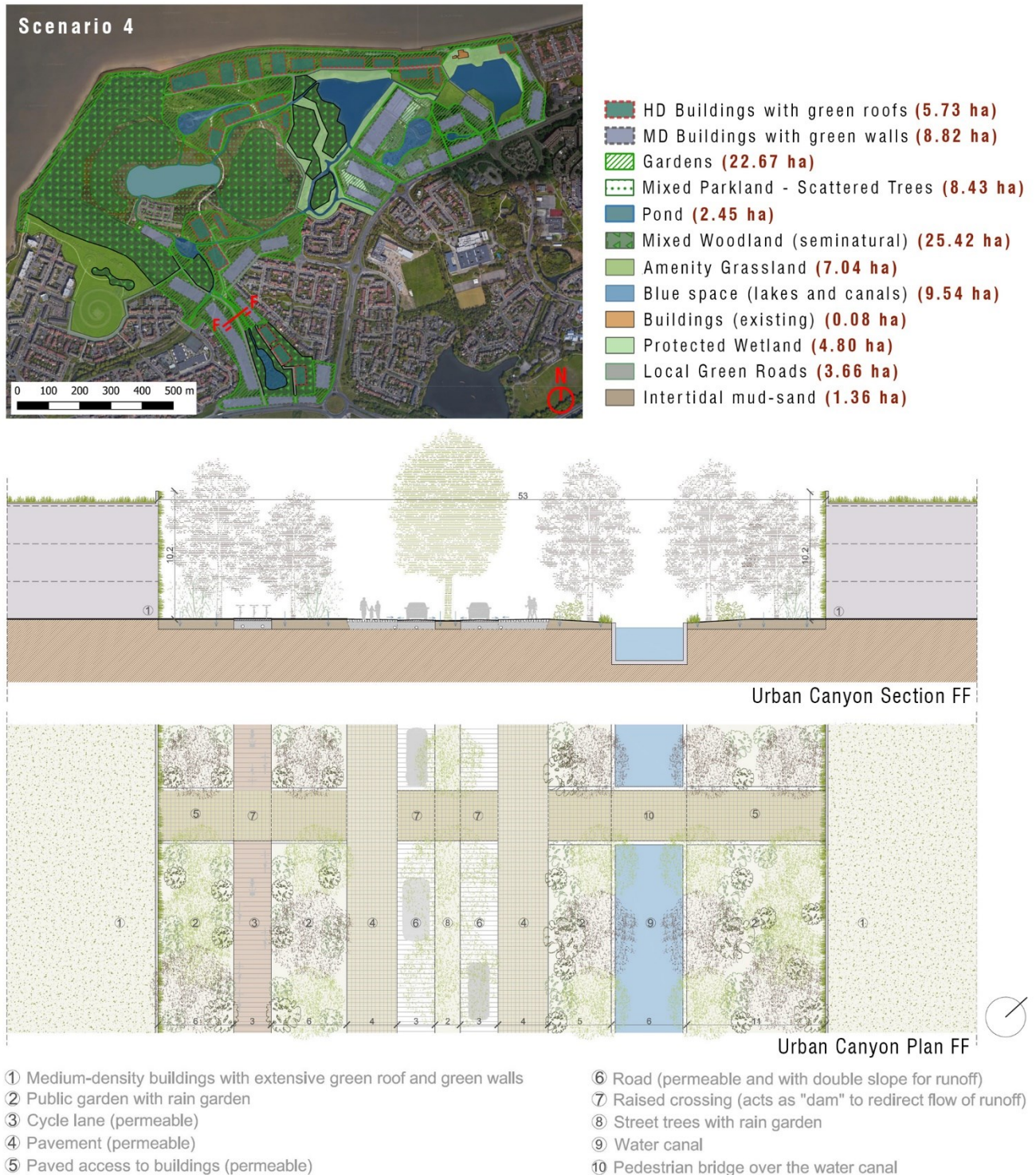


Figure 3.10: Scenario 4 land-use map for Thamesmead Waterfront Development Plan (TMWDP; above), and street canyon with systemic design options for Scenario 4 based on one representative Section FF (cutting through medium-rise buildings on both sides of the street; below).

In terms of number of houses, Peabody has a target of 11,500 new homes for this large urban development plan. It is demonstrated in the literature that the concept of density, understood as the ratio of people or dwelling units to land area, is quite critical and is based on specific thresholds (Jabareen, 2006). Therefore, the values for high-, medium- or low-density can be defined differently depending on the designer and always will depend on the particular context of the development and its surroundings (Ahmadian et al., 2019). In London, for instance, there are areas where 6- or 8-floor buildings might be considered as a high-density intervention (outskirts suburban areas), while in other areas the same number of floors will be considered a low-density intervention (central areas, e.g., Westminster).

Hence, the number of dwellings per hectare (ha) inside these built-up areas has been estimated in order to achieve Peabody's target for each urban design scenario previously presented (see Table A.1, Appendices). These estimated densities provide a general idea of the housing typologies that might be included in each systemic design scenario.

3.4.3 Impact Evaluation Results

In this section the numerical results obtained from the four spatially represented systemic urban scenarios are discussed and compared. These results are in the form of positive or negative scores for each UES analysed, which are summarised in Table 3.4.

Table 3.4: Ecosystem Services and Natural Capital Net-Gains scores obtained from the Natural Capital Planning Tool (NCPT) for the Thamesmead Waterfront Development Plan (TMWDP) in the four systemic design urban scenarios studied.

Natural Capital Impact Assessment of Thamesmead Waterfront Development Plan								
	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
								
Ecosystem Services (ES)	NC Impact Score	NC Net-Gains	NC Impact Score	NC Net-Gains	NC Impact Score	NC Net-Gains	NC Impact Score	NC Net-Gains
1. Harvested Products	-75	NO	-121	NO	-85	NO	-10	NO
2. Biodiversity	-32	NO	-12	NO	-6	NO	(+)9	NO
3. Aesthetic Values	-225	NO	(+)36	YES	(+)79	YES	(+)213	YES
4. Recreation	(+)139	YES	(+)170	YES	(+)228	YES	(+)388	YES
5. Water Quality Regulation	-202	NO	-5	NO	(+)72	YES	(+)132	YES
6. Flood Risk Regulation	-39	NO	-1	NO	(+)19	YES	(+)32	YES
7. Air Quality Regulation	-37	NO	(+)8	YES	(+)46	YES	(+)72	YES
8. Local Climate Regulation	-105	NO	(+)133	YES	(+)176	YES	(+)224	YES
9. Global Climate Regulation	(+)25	YES	(+)48	YES	(+)60	YES	(+)65	YES
10. Soil Contamination	0	NO	0	NO	0	NO	0	NO
Natural Capital Net-Gains (number of services achieving net-gain)		2 / 10		5 / 10		7 / 10		8 / 10

As seen in the first column of Table 3.4, the Scenario 1 (BAU) results in only two positive ES, which are recreation (+139) and global climate regulation (+25). The positive recreation score is easily explained because the current land is not accessible to the public and as soon as new green space is open, it directly provides new leisure and outdoor activity space to citizens. All the other scores are negative, and the aesthetic values in particular (-225), which can be explained due to the traditional way of building and lots of grey infrastructure systems, such as roads and paved areas.

Regarding Scenario 2, Table 3.4 reveals that five ES achieve UNC net-gain, which indicates a significant improvement compared to Scenario 1. However, there are still some important UES in negative values, e.g. harvested products (-121) or water quality regulation (-5); which means that built-up areas are predominant and more BGI is still needed.

In Scenario 3 most UES are positive and achieve NC net-gains, but still harvested products (-85) and biodiversity (-6) are negative. Having no harvested activity in the post-development design should not mean a decline in harvested products because no agriculture activities are present in the pre-development site either. This is interpreted as another limitation of the NCPT. In addition, biodiversity is negative because the tool sees “gardens” as a decline compared to the current “poor grassland”, but the tool does not include any other land use options that could increase the sustainability score. In contrast, Recreation (+228) is still the biggest positive score. This is explained firstly because the space is currently inaccessible and, secondly because there is a considerable increase in blue and green space as part of this urban design. Finally, in Scenario 4, all UES scoring values are positive, with the exception of harvested products (-10), for same reasons as in Scenario 3. All the other scores are soundly positive, which means that preserving the natural environment and creating a compact distribution with large amount of BGI around the buildings will be the most sustainable option to select.

The results collected in Table 4.3 provide a general idea of the TMWDP level of sustainability based on different systemic design approaches; however, the scores are only an indication of the UES net-gain and the tool presents a large number of limitations. As mentioned in Section 3.3.1, each of these UES evaluated by NCPT might carry different weights depending on the context and specific conditions of the urban development site (e.g., a development located in a congested traffic area might assign extra weight to “Air Quality Regulation,” while another placed in an area with frequent CSO spills might give additional importance to “Water Quality Regulation”). It is important to highlight that the NC Impact Scores in Table 4.3 only indicate the relative differences between the Baseline conditions and a series of systemic design scenarios, representing trends resulting from various land-use changes. They are not intended to be one hundred percent reliable. For instance, buildings covered with green roofs and buildings with green walls are the only two sustainable building options given by the NCPT as part of its land-use portfolio. This is therefore seen as an important limitation and new land uses and sustainable building typologies should be added as part of a new tool, e.g., ‘buildings with rainwater harvesting systems’, ‘swales’, differentiate between ‘intensive’ vs. ‘extensive’ green roofs; among others. This demonstrates the necessity to create a new integrated modelling tool that improves these limitations and enables a more streamlined planning and development process, leading to a better quality and design for new urban developments.

3.5 Discussion

In this Chapter 3, I presented a new theoretical framework that combines systemic design options with a series of evaluation metrics applied to the UK's urban planning system. The framework is called CityPlan and aligns the design options with the actions occurring at the decision-making and governance level. It aims to facilitate urban stakeholder partnership at these two levels (design and decision-making) and to increase engagement at the early stages of the urban design process. In future stages of the work, the stakeholder engagement could be achieved by participatory activities, such as planners or community group workshops. Collaborative workshops and social engagement events are proved to be very effective in raising general public awareness and government support towards sustainable architecture and new urban design solutions (see Puchol-Salort et al., 2018; Bell and Johnson, 2020).

In its first application, CityPlan looks at Urban Ecosystem Services (UES) evaluation as proxy for urban sustainability (i.e., CityPlan-Ecos). The results from CityPlan-Ecos demonstrated the importance of systemic design at early stages of the urban development project and showed a great potential to achieve sustainability depending on the buildings layout and urban form selected. Although the NCPT presented several limitations, the functionality of CityPlan has considerable potential in systems modelling. Despite the fact that CityPlan-Ecos only includes a static evaluation of the urban development project based on a 'before-after' evaluation, new models that include a more dynamic approach are considered in the next stages of the work (Chapter 4 and Chapter 5). Additionally, these new models could include new and more detailed typologies as part of the systemic design process to represent three-dimensional BGI in buildings such as hanging gardens or inter-floor gardens at multiple levels, which will increase the ecosystem services provided and influence their scoring values.

CityPlan is designed as an adaptable and extensible tool allowing continual improvement during its application on real case studies, where approved certifications such as BREEAM Communities (Building Research Establishment Environmental Assessment Method; BRE Global, 2017), LEED-ND (Leadership in Energy and Environmental Design; USGBC, 2012), CASBEE-UD (Comprehensive Assessment System for Built Environment Efficiency; IBEC, 2014) and PASSIVEHAUS (Passive House Institute, 2020) could be added. Facing future

work and aiming to increase the usability of CityPlan-Ecos, one of the potential directions of this work will be to add approved certifications into the integrated evaluation toolkit to complement the results from modelling simulations. However, these certifications sometimes present a series of limitations and need a comprehensive revision too (see Kaur and Garg, 2019). Although I conducted a preliminary review of these certifications in Appendix E.1, there are already some sources in the literature that looked for a revised method, with the Comprehensive Assessment Method for Sustainable Urban Development (CAMSUD; Ali-Toudert et al., 2020) being one of the most attractive ones. CAMSUD reports a detailed study for five of the most widely-used urban rating systems around the world, comparing their weaknesses and strengths. There are forty urban sustainability criteria presented in CAMSUD based on these well-established rating systems and one of the future objectives in CityPlan-Ecos could be to include these criteria in its integrated evaluation toolkit and examine to what extent the designed urban development project achieves each criterion.

Finally, including dynamic models in CityPlan will provide evidence of urban sustainability to urban stakeholders and decision-makers in the UK's planning context. Decision-makers have a huge responsibility to incentivise private developers towards more investment on urban development projects that combine private and public value. Furthermore, it is important to clarify that, at this stage, the cost of each design option and its future maintenance has not been taken into account in the UES assessment and scoring. In real-life applications, the actual cost of the proposed design can significantly influence its success and effective implementation. As Bateman and Mace (2020) suggest, public decision-makers can either create positive incentives, such as subsidies or Payment Ecosystem Services (PES) schemes or, negative disincentives, such as taxes or deterrent regulations. Hence, CityPlan-Ecos has the potential to provide new insights towards these incentives and help policy-makers to change the existing obsolete urban policies.

3.6 Conclusions

In this chapter, a new framework for sustainability evaluation in the UK's urban planning context has been defined. CityPlan's application shows potential for better urban planning decisions and therefore for essential benefits to the society.

Findings from this chapter applied to Thamesmead Waterfront Development Plan (TMWDP) confirmed that a more compact building distribution with larger areas of Blue Green Infrastructure (BGI) will increase the level of Urban Ecosystem Services (UES) provided, these being understood as the number of benefits that citizens obtain from the natural environment and also representing a good measure for urban sustainability. Conventional design solutions, however, are in alignment with the traditional urban planning standards, which generally provide sprawl urbanisation with extensive impervious concrete-based infrastructure areas. One of the key factors for housing developers are the profitability opportunities of the urban development, not considering the long-term environmental performance of the project. Hence, the systemic design process inside CityPlan will inform housing developers and other decision-makers about this long-term environmental performance from early stages of the project.

Finally, this part of the work is focused on a particular urban development project (TMWDP) where the UNC value is higher than the average in other similar urban areas. This points to important directions for future research, such as including new case studies facing different challenges. A new urban development project called Meridian Water Development Plan (MWDP) in North London is presented in Chapter 5, enabling more robust data analysis as well as more diverse and collaborative research with different types of stakeholders. Ultimately, the work in this Chapter 3 will support the urban sustainability field's advancement towards a more integrated and multifaceted methodology, where built and ecological systems are widely seen as an interconnected entity.

Chapter 4

Systemic Design Towards Urban Water Neutrality

Note: This chapter is based on the published journal article Puchol-Salort, P.; Boskovic, S.; Dobson, B.; Van Reeuwijk, M.; Mijic, A. (2022). Water neutrality framework for systemic design of new urban developments. *Water Res* 219: 118583.

I was the main author of this paper and contributed towards the great majority of the work; my co-authors Dr Mijic and Dr Reeuwijk are my main supervisors followed by Dr Boskovic and Dr Dobson acting as co-supervisors. They supervised the work published in this paper and guided me through the writing and publication process.

The code for the integrated model CityWat and all its supporting material used in this Chapter 4 can be found in a data repository at: <https://github.com/barneydobson/citywat>.

4.1 Introduction

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 systemic design approach has been proposed in previous chapters, which integrates design and evaluation with criteria that are used to inform the level of sustainability of an urban development.

In the literature, there are several approaches to integrate urban planning with water management, which can address some of the aspects of the systemic design 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 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 system process with design options and quantitative evaluation, which I address in this chapter by adapting the CityPlan framework to water-land system analysis.

Systemic urban designers see the planning process as a whole and study how different parts influence each other, making more comprehensible its complexity. Therefore, systemic design will consider urban water infrastructure as one of the layers in the design of cities (Shin et al., 2018; Moravej et al., 2021) and can evaluate the impacts on water security guided by the Water Neutrality (WN) concept. In this chapter, I implement the systemic design concept to urban planning and water management driven by CityPlan and 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 Urban Water Security (UWS) indicators. The new framework will enable WN targets to be set by the decision-makers, with net zero water target (100% water-neutral developments) as a default recommendation.

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 included in this case are, 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. I argue that applying CityPlan to WN will support the integration of sustainable design options 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 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 UWS indicators combined with spatial configurations for urban planning.

In this chapter, I present the second application of CityPlan (i.e., CityPlan-Water) as a proof-of-concept focused on WN evaluation. There are three key contributions in this part of the work. First, I develop the WN concept for future urban planning from a systemic design perspective. Second, I present the novel CityPlan-Water framework, where WN assessment is provided by the integrated urban water management model CityWat (Dobson and Mijic, 2020), which I combine with a spatial analysis of key urban form properties 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, I demonstrate opportunities to achieve WN at the 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.

4.2 CityPlan-Water

Evaluating water neutrality across different scales, influencing planning decisions, and guiding stakeholders towards water-neutral developments is the key purpose of CityPlan-Water. Its functionality is based on CityPlan and integrates three key components (Figure 4.1), which includes representation of the CityPlan-Water process and operation; the design options portfolio; and the integrated evaluation toolkit. The first one (blue cluster in Figure 4.1) includes the systemic design purpose (i.e., urban Water Neutrality, WN), the decision criterion (i.e., to offset the UWS impacts and to obtain the maximum value of the Water Neutrality Index, WNI), and the planning system and operation stages (i.e.,

development scenarios and evaluation metrics). The second component (green cluster in Figure 4.1) includes the design options portfolio (i.e., a combination of BGI and WN design options). The third component (purple cluster in Figure 4.1) includes the integrated evaluation cluster formed by the CityWat integrated water management model and GIS urban form data.

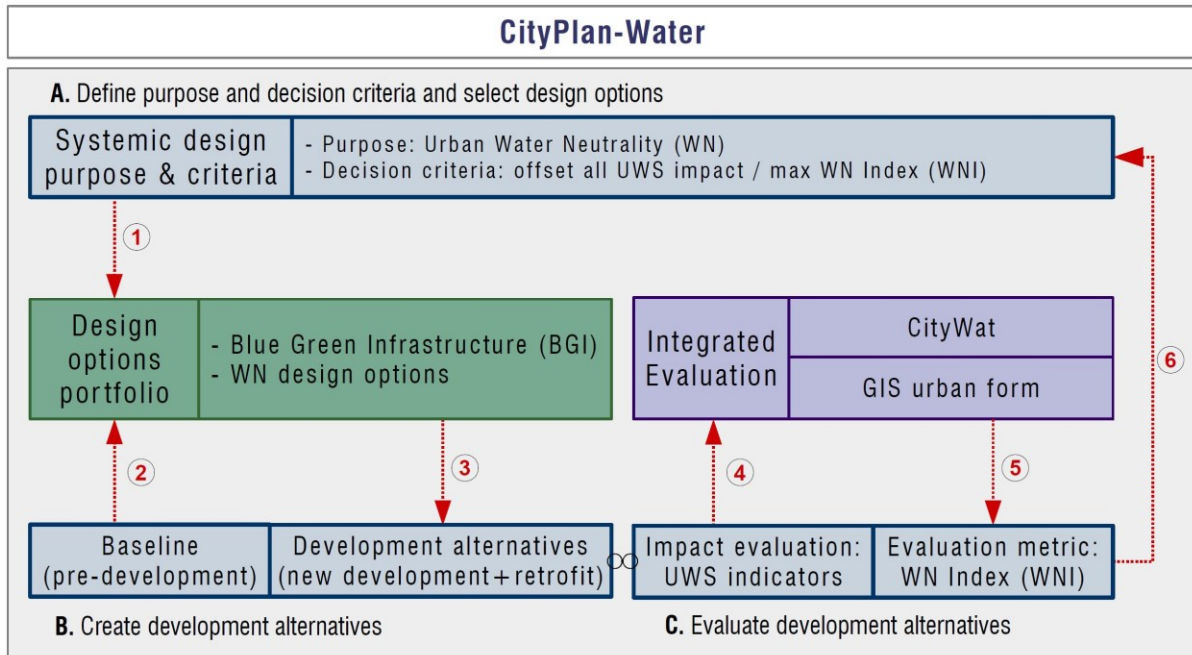


Figure 4.1: Methodology diagram of the CityPlan-Water systemic design and evaluation framework. The governance and decision-making actions are represented by the three letters (A, B, C), while the six steps inside the framework are represented by numbered red arrows.

4.3 Water Neutrality systemic design concept

The methodology of CityPlan-Water follows an iterative process that uses a defined target for WN as a measure of UWS 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 a certain spatial assessment scale. As with CityPlan-Ecos, 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 (Figure 4.2). In this part of the 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 and similarly to the scenario development presented in Chapter 3, I consider two types of urban design scenarios: Business as Usual (BAU) scenario (left column in Figure 4.2) and WN scenarios (right column in Figure 4.2).

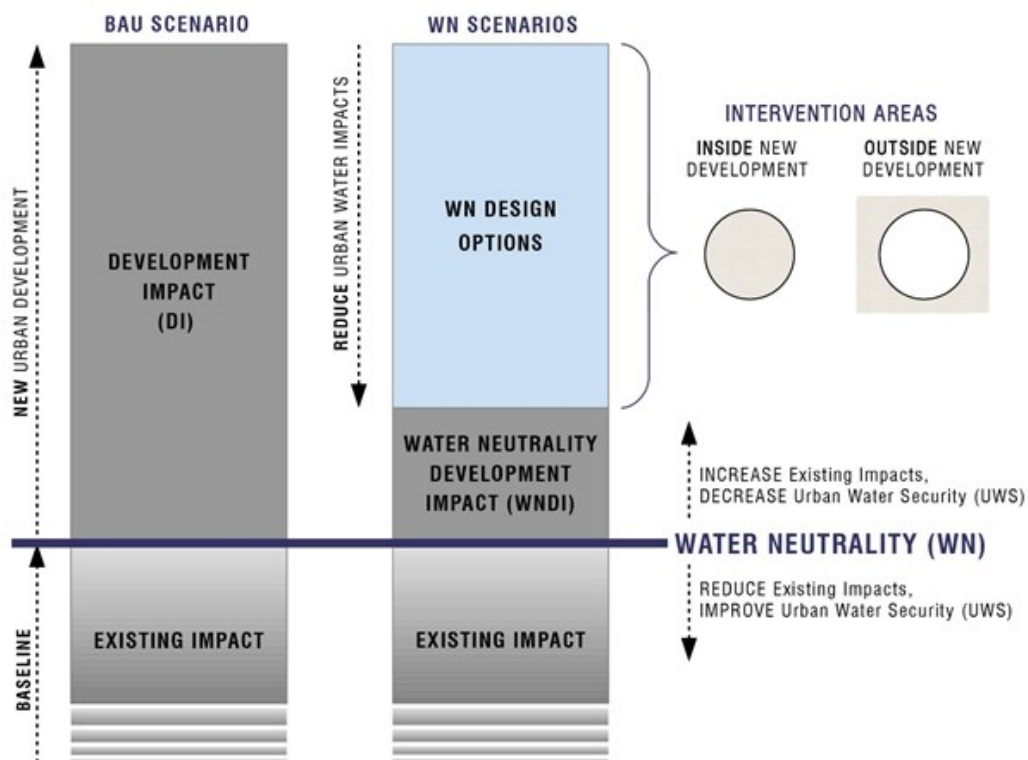


Figure 4.2: Water Neutrality (WN) systemic design concept diagram. To fully achieve WN is necessary to decrease the Urban Water Security (UWS) indicators as they were at the pre-development Baseline stage (existing impact).

4.3.1 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 (see Table 3.1). 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). I 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 Figure 4.2).

At this stage, it is useful to introduce the 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:

$$\text{WNI} = (\text{DI} - \text{WNDI}) / \text{DI} \times 100 (\%) \quad (1)$$

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 (i.e., regenerative design).

4.4 Water Neutrality urban form properties

Analysis of London's urban form properties is needed to understand the existing urban water system (i.e., pre-development Baseline). I have selected a series of urban form properties based on their direct relationship with the UWS indicators and the WN concept, Table 4.1. 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; Figure B.1, Appendices); while population and size of housing are obtained from the UK Census, 2011. In this work, I study London's urban form properties and its spatial attributes following LSOA boundaries (spatial units marked in black in Figure 2.2) as 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.

Table 4.1: Water Neutrality urban form properties selected in CityPlan-Water, their data source, and what they inform about. The 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.

WN URBAN FORM PROPERTIES				
DATA SOURCE	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 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

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

$$\lambda_x = A_x / A_T \quad (2)$$

where A_x is the surface area of land cover type x in the LSOA (see last column in Table 4.1) 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 4.2.

Table 4.2: Summary table of London’s Water Neutrality 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 (Figure B.1) and UK Census 2011.

London's Urban Form Properties Summary Table			
Raster Urban Form Properties	Total area (m ²)	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

4.5 Systemic design options

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 options from an urban development to a whole city scale (Battistoni et al., 2019; Pereno and Barbero, 2020). In this part of the 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 the city scale. The evaluation of the WN scenarios will measure the effectiveness of the WN design options listed in Table 4.3, which can be implemented either inside or outside the new development area as retrofit solutions.

Table 4.3: 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 accessories	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.

4.5.1 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 4.3). 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 (Figure 2.1, Chapter 2), I select three key indicators for Urban Water Security (UWS). This selection is based on acknowledged sources of literature that combine consumer 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). Therefore, the UWS

indicators considered in this work 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).

4.6 Water Neutrality evaluation

The impact of WN scenarios is evaluated in terms of UWS indicators in the fourth step of the CityPlan-Water process (Figure 4.1). CityPlan-Water combines the CityWat urban water management integrated model (Dobson and Mijic, 2020) with QGIS (Quantum Geographical Information System, 2019). Both CityWat (see note in title page) 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 the 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 the 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 4.2); 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 4.3) are implemented to obtain the WN scenarios (Figure 4.2).

Once I have created the WN design options to accommodate new developments, I 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 4.7.3). 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 4.3.1 and obtain WNI 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 options stage (step 2 in Figure 4.1) and implement new WN design options until water neutrality is achieved (step six in Figure 1).

4.7 Water-neutral systemic design at the city scale

Systemic design for water neutrality is developed at the 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 results show the aggregated effect of the impact of new development and the scale of interventions needed for impact mitigation.

4.7.1 Analysis and visualisation of London's urban form properties

The area fraction equation (equation 2; Oke et al., 2017) is used in this part of the work to visualise London's urban form properties objectively. The density maps (Figure 4.3) 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 (Figure 4.3a); the blue and green area ranges from 0.011 to 0.909, with an average across London of 0.45 (Figure 4.3b). While the total impervious area percentage is around 37% of the city (Table 4.2), 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, Figure 4.3d).

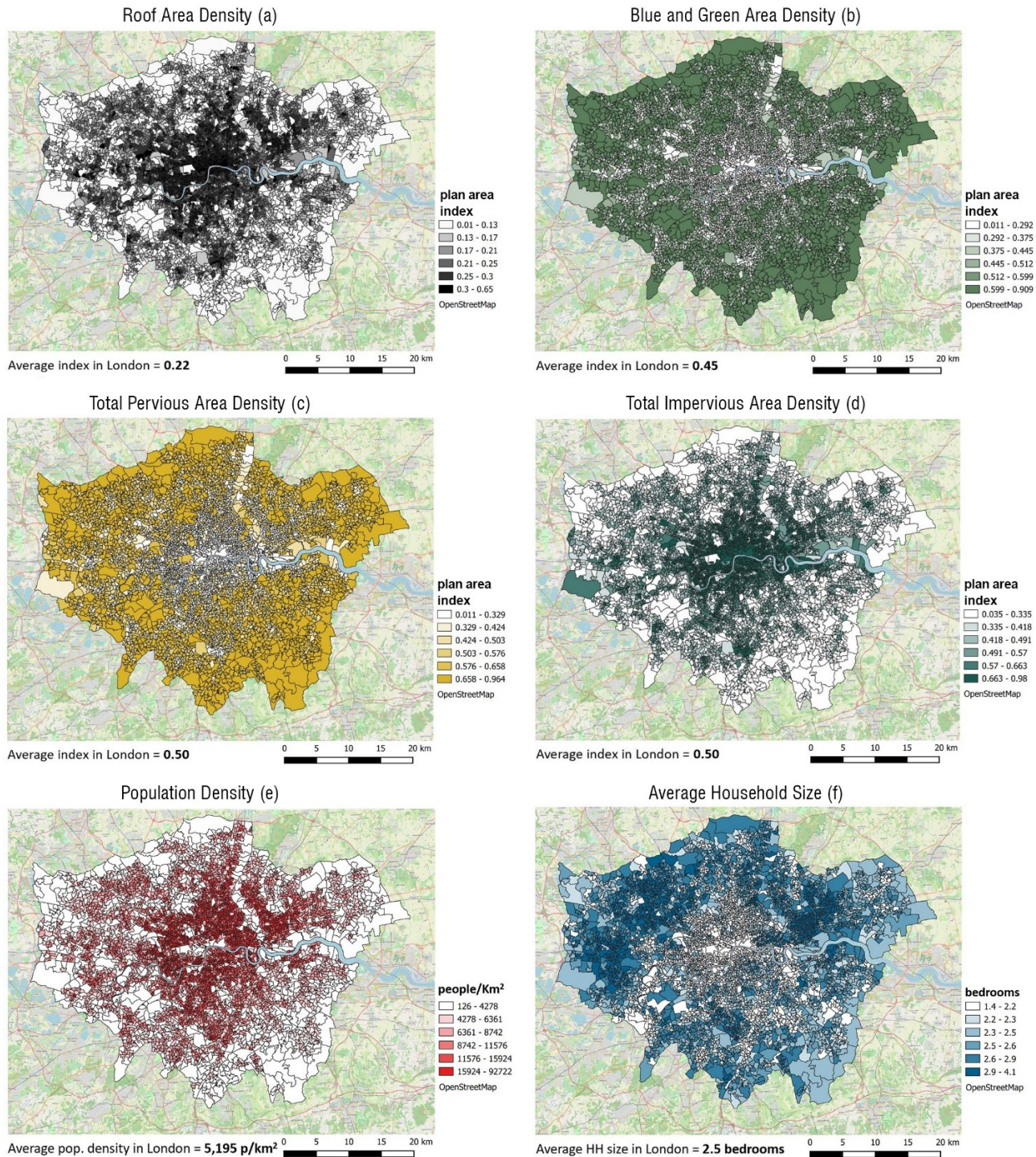


Figure 4.3: Key London's Water Neutrality (WN) urban form properties represented in plan area fraction maps and divided by LSOA boundaries. Data sources: British Geological Survey landcover dataset (Figure B.1) and UK Census 2011.

Finally, London's average population is 5,195 people per km², although this can go up from 15,924 p/km² to 92,722 p/km² in the most densely populated LSOA zones (Figure 4.3e). 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 (Figure 4.3f).

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 data-driven evaluation tools.

4.7.2 Scenario development at the city scale

The scenario development process starts with the Baseline and the BAU simulations, which do not include any WN design option (similarly to Section 3.4.2 in CityPlan-Ecos, Chapter 3). 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 variables, such as building, green and impervious area in each scenario, are summarised in the Table B1 in Appendices. Next, to develop the WN scenarios, the design options explained in the Section 4.5 (Table 4.3) are implemented.

To introduce water efficiency (Millock and Nauges, 2010), I consider installing appliances with an average of 35% water use reduction (Vieira, Jorge and Covas, 2017; Callejas-Moncaleano et al., 2021) in all new 522,870 households (Scenario A). Next, I 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.

Table 4.4: 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)

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 4.4.

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 km² 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.

4.7.3 Results and recommendations at the city scale

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 B2, 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 (Figure 4.4).

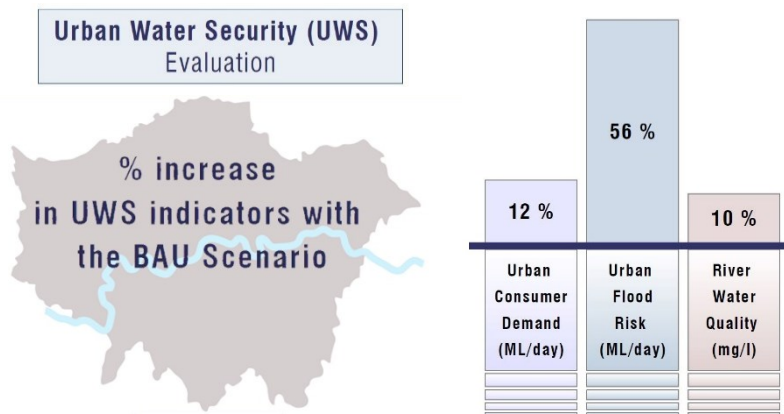


Figure 4.4: Percentage increase in each Urban Water Security indicator in a Business As Usual scenario based on London's 10-year housing target of 522,870 new households.

Based on the raw values and following equation (1), I calculate the scores for the Water Neutrality Index (WNI) for each UWS indicators. Table 4.5 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 km² 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.

Table 4.5: Water Neutrality Index (WNI) 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

4.8 Discussion

In this chapter, I focused on three key contributions to WN systemic urban design. I developed a WN concept for systemic design of new urban developments and then proposed a CityPlan-Water framework and the Water Neutrality Index, WNI. From the results in Table 4.5, I 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 I 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 the 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 the 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 I have examined three, often competing, indicators (i.e., 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.

This part of the work also contributes to the analysis of achieving water neutrality at the city scale. The results obtained from the WNI and its application to real case studies constitute a series of tactical decisions for decision-makers (i.e., GLA, Natural England, or the Environment Agency). In this case the tactical decisions from systemic design to

achieve a water-neutral London would be to implement WN design options to all 522,870 new homes, retrofit 432,500 existing homes, and add 19 km² of new BG space to the city's land (transform grey and hard surfaces to BGI spaces). See Figure 4.5 for a graphical representation of these tactical decisions inside the lumped city boundaries.



Figure 4.5: Graphical representation of the systemic design tactical decisions needed to achieve a water neutral London inside the lumped city boundaries marked in red.

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. It is important to note that the simulations in CityWat did not account for the long-term performance of the design options, as they were assumed to operate continuously. However, certain options, such as rainwater harvesting (RWH), may require periodic maintenance and a funding mechanism to ensure reliable and continuous performance. Other additional 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. 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 (see the next Chapter 5). In this part of the work, I presented the proof-of-concept of CityPlan-

Water and the use of spatial data is taken from the BGS dataset in large resolution (Figure B.1) and divided by the LSOA boundaries (Figure 2.2), 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 (see Chapter 5).

4.9 Conclusions

This chapter introduced a novel approach for the Water Neutrality (WN) concept for new urban developments. It applied the WN concept to the CityPlan framework and developed a new application called CityPlan-Water. The new version of the framework combines WN options from a systemic design perspective and evaluates urban water security at the 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 (i.e., tactical decisions for WN at city scale). The results from Chapter 4 highlight the significance of retrofit solutions, which have the potential to offset a substantial portion of the impacts on Urban Water Security (UWS), ranging between 16-45% depending on the indicator. This underscores the importance of spatial trade-off strategies, where spatial adaptation and retrofitting of buildings and impervious urban landscapes should be prioritised in planning decisions and land use.

The knowledge from this part of the 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.

Chapter 5

Supporting Decision-Making for Water-Neutral Urban Planning

Note: This chapter is based on a journal article that aims to be submitted in May 2023 and its expected cite will be: Puchol-Salort, P.; Rico-Carranza, E.; Beriro, D.; Boskovic, S.; Van Reeuwijk, M.; Mijic, A. (2023). Integrating water-neutral systemic design and planning decisions across different urban scales: WaNet Decision Support Tool. *Urban Sustainability*.

5.1 Introduction

Integrating social and environmental dimensions with urban infrastructure systems is crucial for achieving sustainable development (United Nations, 2015; Pandit et al., 2017). However, a significant challenge in urban water management is the limited availability of processed data and tools to support evidence-based decision making (Ashley et al., 2003; Zogheib et al., 2018). Within the decision-making process of the urban planning system, data is a compilation of information collected either in-situ or remotely, which is then transformed into evidence by key decision-makers (Hill and Symmonds, 2011; Eggimann et al., 2017). However, this transformation process is heavily influenced by the governance and policy context that shapes strategic decisions in systemic design, defining the purpose and boundaries of the study (Ahmadisharaf et al., 2015; Hammad et al., 2019).

Water Neutrality (WN) is introduced in previous chapters as a novel approach to evaluate the impacts on Urban Water Security (UWS) indicators, such as consumer demand, flood

risk, and river water quality, with the goal of minimising the impacts of new urban developments and offsetting the remaining impacts to pre-development levels (Nel et al., 2009; Hoekstra, 2018; Puchol-Salort et al., 2022). In Chapter 4, introducing the urban planning purpose of WN with systemic design generated an application of the framework called CityPlan-Water (Puchol-Salort et al., 2022). At the proof-of-concept stage, CityPlan-Water evaluated UWS indicators using the integrated water management model CityWat (Dobson and Mijic, 2020), in conjunction with spatial representation of London's urban form properties. The city-scale modelling provided a set of tactical decisions for water-neutral urban planning and defined a group of systemic interventions, including WN options in new homes, retrofitting existing homes, and adding new BG space.

With the advent of the digital era, there is a constant increase in the availability of raw spatial datasets in the UK from various sources (e.g., UK and London census, Central Government and local urban planning departments, British Geological Survey, etc.). However, most of these datasets are disaggregated and challenging for key urban stakeholders to comprehend (GLA, 2021; Nochta et al., 2021). In the context of Urban Water Security (UWS), the available data often cannot be directly used for decision-making purposes as they do not provide direct information about changes in the urban water system, and most infrastructure solutions are based on specific urban scales (Bichai et al., 2015; Jensen and Wu, 2018; Van Ginkel et al., 2018). Although the Greater London Authority (GLA) and Local Planning Authorities (LPAs) in several boroughs currently require evidence-based policy-making for water-neutral strategies (Futcher et al., 2017; GLA, 2021), there is a lack of knowledge on how to realistically implement Water Neutrality (WN) across different urban scales (Marzouk and Othman, 2020; Chen et al., 2021).

Spatial allocation is a complex problem that involves multiple stakeholders and whole-system uncertainties (House-Peters and Chang, 2011; Ni et al., 2014; Reid and Wood, 2022). Multi-Criteria Decision-Making (MCDM) methods are tools used in infrastructure planning to evaluate the balance between urban planning purposes and systemic design options (Jato-Espino et al., 2014; Kumar et al., 2017). In the current literature, there are several examples of MCDM methods addressing spatial allocation. For instance, Castro et al. (2014) developed a conceptual approach for ecosystem services trade-offs, combining spatial models with biophysical, social, and economic indicators. Van de Ven et al. (2016)

created the Adaptation Planning Support Toolbox (APST), which provided a spatial overview of potential design options for climate-resilient urban design and planning. Hammad et al. (2019) placed a strong emphasis on zoning and optimal allocation, developing a theoretical framework for strategic planning purposes. And Li and Zhou (2019) measured urban green spatial patterns based on urban morphology and surface characteristics at the city scale. While these examples offer valuable indicators for different stakeholders, there is still limited evidence of a tool that integrates both strategic and tactical decisions of systemic design and evaluates urban planners' preferences for new urban development and potential retrofit opportunities with WN design options.

Combining the systemic design concept with the decision-making process for water-neutral interventions will require integrated evaluation of often conflicting criteria in a data-driven tool. This tool begins with strategic decisions that define the urban planning purpose and system boundaries (Ahmadisharaf et al., 2015; Radmehr et al., 2022) and proceeds with tactical decisions obtained through modelling (Comes et al., 2011; Yang and Zhang, 2021; Lin et al., 2022). In Chapter 5, a prototype of a Multi-Criteria Decision-Support Tool (MCDST) for systemic design is developed. This computerised system facilitates new urban development allocation based on urban planners' preferences and aims to serve as an instrument for future water-neutral planning decisions.

This chapter presents three key contributions. Firstly, the CityPlan framework is enhanced with a new spatial data component to analyse current environmental and physical characteristics and provide insights into spatial allocation options for new development at various urban scales. This extension introduces a new application of the framework known as CityPlan-Place. Secondly, as part of the integrated evaluation cluster, a novel Water Neutrality Decision-Support Tool (WaNetDST) is developed to inform diverse urban stakeholders about systemic design options and facilitate evaluation for water-neutral development. Lastly, by assigning aggregated scoring values to selected spatial units, WaNetDST offers a quantitative and spatial approach to allocate new and retrofitting design options across different urban scales in London. Ultimately, the application of CityPlan-Place has the potential to transform the decision-making process for Local Planning Authorities (LPAs) and housing developers, fostering new dialogues among boroughs within the same city.

5.2 CityPlan-Place

The primary objectives of CityPlan-Place include processing GIS-based datasets, identifying the optimal allocation of systemic design options across different scales, and assessing the synergies between new development and retrofit interventions. Similar to previous applications of CityPlan, CityPlan-Place is based on the overarching framework and integrates three key components (Figure 5.1). The first component (blue cluster in Figure 5.1) encompasses the systemic design purpose of the framework (i.e., optimal allocation of new and retrofitting WN design options), the decision criterion (i.e., higher urban planners' preference and higher WN retrofit opportunity scores), and the planning (i.e., development scenarios and evaluation metrics). The second component (green cluster in Figure 5.1) comprises the design options portfolio, including Blue-Green Infrastructure (BGI), sustainable urban form, and WN design options. The third component (purple cluster in Figure 5.1) encompasses the integrated evaluation cluster and GIS urban form data. In this proof-of-concept of CityPlan-Place, the urban planning purpose is WN, and therefore, the impact evaluation is based on UWS indicators, which will be linked to the scores generated by the Multi-Criteria Decision-Support Tool (MCDST).

In this application of CityPlan-Place to urban WN, the framework is expanded to incorporate a data-driven Decision-Support Tool (DST) within the integrated evaluation cluster. The main objective of this DST is to optimise the allocation of water-neutral developments. Initially, Local Planning Authorities (LPAs) will utilise the DST to generate scoring maps based on their preferences for new development areas and WN retrofitting opportunities (Section 5.3). These quantitative maps then will serve as informative tools for urban developers, who will initiate the systemic design process within CityPlan at the early stages of development, following the same process as in previous applications (Section 5.4).

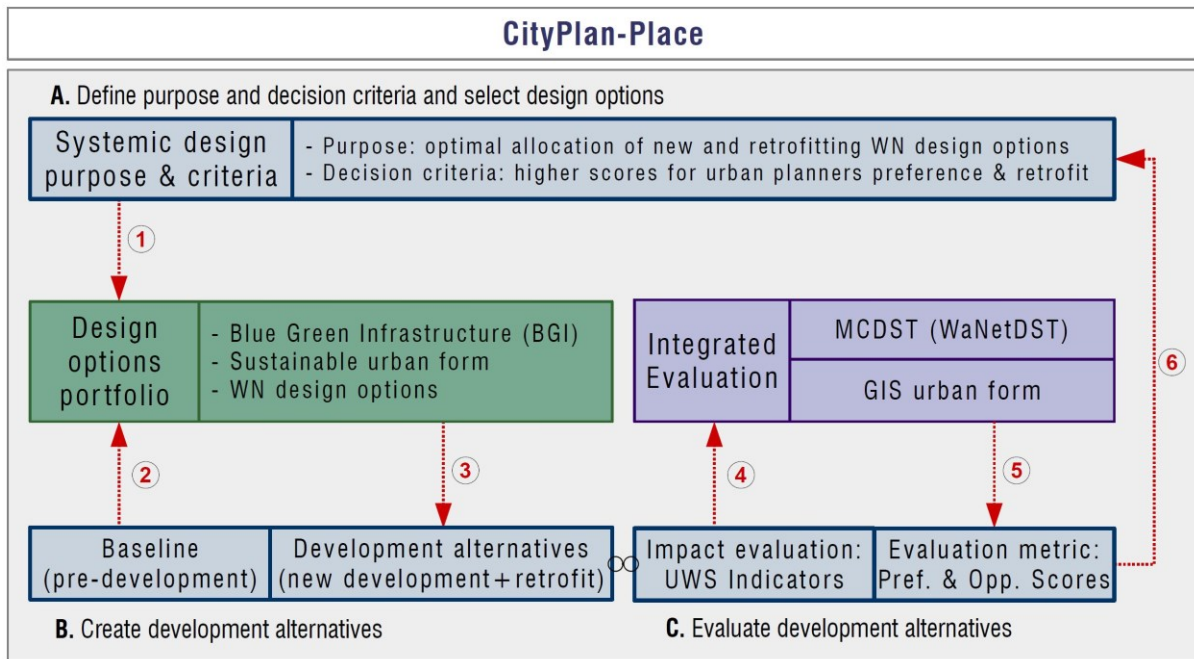


Figure 5.1: Methodology diagram of the CityPlan-Place systemic design and evaluation framework. The governance and decision-making actions are represented by the three letters (A, B, C), while the six steps inside the framework are represented by numbered red arrows.

5.2.1 Case study areas across scales

The CityPlan-Place framework and the novel WaNetDST are intended to operate across different urban scales. From larger to smaller scales, the main areas of study in this part of the work will be city, borough, and urban development site. At the city scale, the focus remains on London, which is divided into 32 boroughs, further sub-divided into smaller zones known as Lower Layer Super Output Areas (LSOAs) for statistical purposes (Figure 2.2). During the proof-of-concept stage of the CityPlan-Place framework and WaNetDST, all the information was collected and processed at the LSOA and borough levels.

At the borough scale, the main case study area is the London Borough of Enfield (LBE) located in North London (Figure 5.2). LBE is one of the case study areas within the CAMELLIA and VENTURA research projects (Figure A.1, Appendices). Covering approximately 83 km², the borough is composed of one-third residential houses, another third mainly consisting of Green Belt areas, and the remaining portion including commerce, industry, shops, transport, and other amenities (Enfield Council, 2021). As of 2017, Enfield's population was estimated to be around 285,100 citizens, with current

projections suggesting growth to a range between 293,500 and 303,800 by 2026 (GLA, 2021). The largest urban growth is anticipated in the southern and eastern parts of the borough, which also experience significant economic deprivation and social inequality. LBE is known for its abundance of green spaces, particularly surrounding the Green Belt in the North, as well as water reservoirs in the East (Bussi et al., 2021). These extensive green areas and water bodies can be observed in the land-use raster map provided by the British Geological Survey (BGS; Figures B.1 and C.1, Appendices).

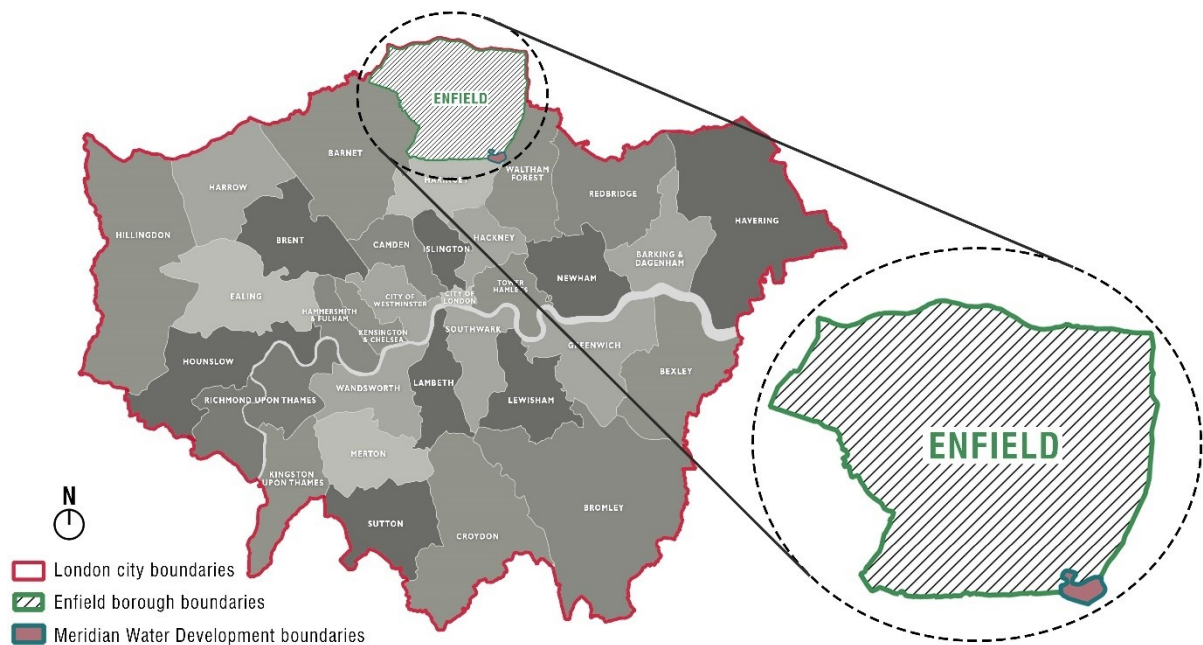


Figure 5.2: Case study areas in WaNetDST from city to borough to urban development site scale focusing on the London Borough of Enfield (LBE) and Meridian Water Development Plan (MWDP).

Within the LBE, several urban development projects are already underway, with the Meridian Water Development Plan (MWDP) being particularly notable. Spanning across an 85-ha site, this development aims to accommodate a total of 10,000 homes and a railway station (refer to Figure 5.2 for the MWDP location within London, and aerial views of the current development site and the developer's future vision in Figure C.1, Appendices). The project is expected to take 20-25 years to complete, divided into four stages, with construction on the first stage already initiated in 2021. The majority of the MWDP site consists of brownfield land that was previously used for industrial purposes. The vision for the MWDP site is to create a green and nurturing environment that not only integrates but also enhances the natural landscape and waterways of the neighbouring Lee Valley

Regional Park. Rendered images depicting the future vision of MWPD can be found in Figure C.2, Appendices.

One of the key distinctions between the MWDP in Enfield and the TMWDP in Greenwich (discussed in Chapter 3) is the involvement of different developers. In the MWDP, the developers are the LBE Council (Public Sector), whereas in the TMWDP, the developers are the Peabody Housing Association (Private Sector). This distinction aligns with the different scenarios explained in Section 2.2 and illustrated in Figure 2.1, Chapter 2, within the context of the urban planning application process. To facilitate a comparison between the two development sites examined in this PhD thesis, Table 5.1 presents their key properties along with additional comments.

Table 5.1: Comparison between Thamesmead Waterfront Development Plan (TMWDP) in Greenwich, and Meridian Water Development Plan (MWDP) in Enfield, being two of the largest and most important urban development plans in London during the next 20-30 years.

	Thamesmead Waterfront Development Plan (TMWDP)	Meridian Water Development Plan (MWDP)	Comments
Developers in charge	Peabody Housing Association (Private body)	London Borough of Enfield Council (Public body)	The developers collaborate and create partnerships with other private companies (e.g., large contractors)
Area	100 ha	85 ha	These are approximate areas. Both developments will be divided in several stages of smaller areas
Expected length	25-30 years	20-25 years	Approximate (delays are very common in urban planning and development)
Planned n. of houses (new)	11,500 homes	10,000 homes	Target by the end of the development expected length
Percentage of affordable houses	45-50 %	40-50 %	Expected figures (without considering gentrification effects)
Final parkland area	30-40 ha	10 ha	The total natural area after the development might vary depending on the specific urban designs
Cost / Investment	£ 8bn	£ 6bn	Approximate figures
Creation of new jobs	-	6,000 jobs	TMWDP predicts most people working in Central London with easy commuting
New connectivity	New DLR Station	New railway station	Meridian Water railway station already built and opened in summer 2019

5.3 Multi-criteria integrated evaluation

5.3.1 Water Neutrality Decision-Support Tool: WaNetDST

In this application of CityPlan-Place, the development of the Water Neutrality Decision Support Tool (WaNetDST) incorporates a Multi-Criteria Decision Support Tool (MCDST) based on systemic design principles. This tool combines selected datasets relevant to the urban planning purpose of Water Neutrality (WN) with ruling categories that define the logic statements for scoring these datasets (refer to Figure 5.3). The prototype of WaNetDST includes two types of ruling categories: one based on urban planners' preference for allocating new urban development, and the other based on WN retrofit opportunities. The rules for scoring in the WN retrofit opportunity category are derived from literature and expert advice, while the rules for urban planners' preference scoring are based on feedback obtained from participatory workshops conducted as part of the CAMELLIA and VENTURA research programmes. These workshops followed group model building principles (Richardson and Andersen, 1995). It is important to note that while the participatory workshops were significant for the overall research, their detailed organisation is not a key focus of this PhD thesis and is therefore not considered a contribution to the knowledge presented. The ultimate aim of WaNetDST is to provide insights into the synergies between new housing development and retrofitting existing infrastructure, offering numerical and visualisation outputs that facilitate informed and integrated planning decisions.

The functionality of WaNetDST is divided into three main phases or steps, as illustrated in Figure 5.3. In the first phase (Step 1), a series of spatial datasets related to the WN urban planning purpose are selected and processed, and scoring rules are defined. As I am aiming to develop the proof-of-concept of CityPlan-Place and a working prototype for WaNetDST, three datasets are initially linked to each Urban Water System (UWS) indicator (i.e., consumer demand, flood risk, and river water quality). These datasets were chosen based on the participatory workshops and meetings with water and geological experts conducted prior to the full development of the tool as part of CAMELLIA and VENTURA research programmes. Among publicly available options, three datasets in each category were identified as the most relevant. In the first prototype of WaNetDST, urban consumer demand is linked to population density, device efficiency, and irrigation levels, while flood risk is linked to elevation, land permeability (represented by the Runoff Coefficient,

RC), and surface water flooding. River water quality is linked to traffic density, sewage spills (reflected in Combined Sewer Overflow, CSO, maps), and green area density. In future stages, the number of datasets can be expanded to enhance the accuracy and resolution of the results. The detailed methodology for processing each selected dataset is explained in the subsequent Section 5.3.2.

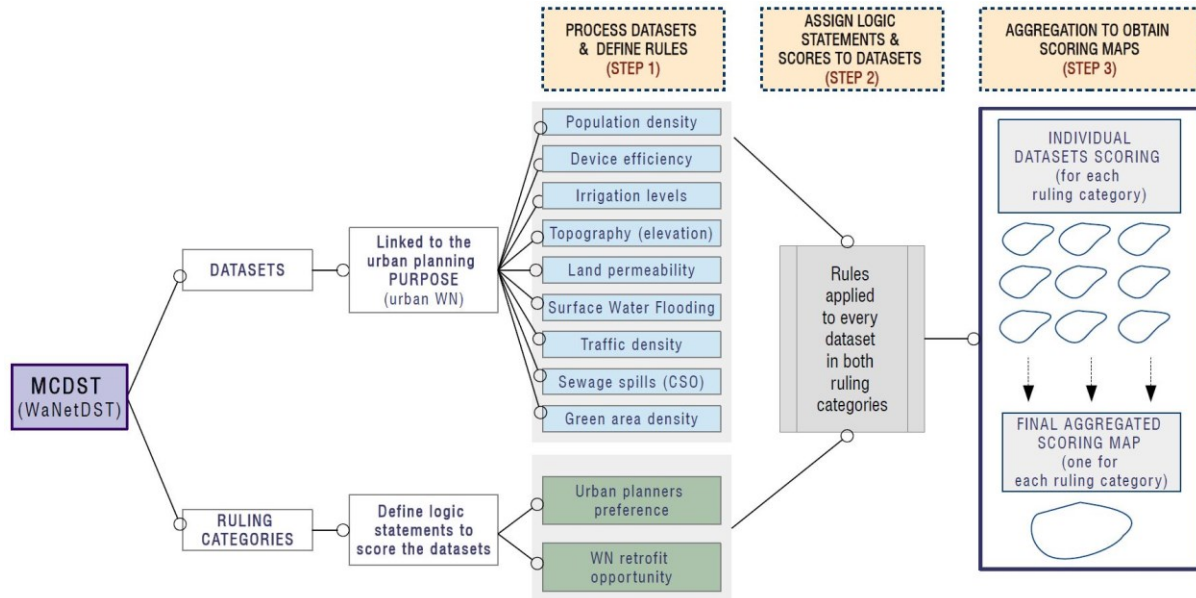


Figure 5.3: Diagram of the Multi-Criteria Decision-Support Tool (MCDST) based on the urban planning purpose of Water Neutrality (WN). The Water Neutrality Decision-Support Tool (WaNetDST) includes a series of datasets (blue boxes) and ruling categories (green boxes) and follows a three-step process to obtain aggregated scoring maps.

In the second phase (Step 2), after processing the selected datasets and defining the general rules, logic statements and scores are assigned to each dataset in each ruling category. The scores for urban planners' preference in allocating new urban development are based on the physical and environmental properties of the land. On the other hand, the scores for WN retrofit opportunities are based on the potential of a specific site to mitigate UWS impacts through the implementation of WN design options. The WN design options considered for the WN retrofit opportunity scoring align with those presented in Table 4.2 of Chapter 4. In this proof-of-concept, the WN design options are grouped based on their primary influence on each UWS indicator. For example, water-efficient appliances, water reuse systems, and social awareness campaigns are linked to consumer demand reduction and river water quality improvement, while Green Infrastructure (BGI) is linked to flood risk mitigation. The two ruling categories have separate logic statements and scoring values informed by expert advice and literature. Detailed information on all the statements

and scores for both ruling categories, including their linkages to UWS indicators and the nine selected datasets, can be found in Table 5.2 and Table 5.3.

Table 5.2: Urban planners preference rules table to allocate new urban developments with WaNetDST datasets linked to UWS indicators, logic statements, and scores. Based on expert advice obtained at participatory workshops (as part of CAMELLIA and VENTURA research projects).

Urban Planners Preference Rules			
UWS INDICATOR	Dataset	Logic statements	Scores
CONSUMER DEMAND	Population density	High-density urban areas are preferred over low-density areas because the existing infrastructure and network is likely to be more developed and potentially have more spare capacity. Low p. den. = 0; High p. den. = 10	Very low density (126-4,767 p/km ²) - 0 Low density (4,767-7,222 p/km ²) - 3 Medium density (7,222-10,326 p/km ²) - 5 High density (10,326-14,881 p/km ²) - 7 Very high density (14,881-92,722 p/km ²) - 10
	Device Efficiency (DE)	High DE areas are preferred over low DE areas because it would be easier to add new urban developments. Low DE = 0; High DE = 10	DE Level 1 (14.6 - 68.8) - 0 DE Level 2 (68.8 - 73.3) - 3 DE Level 3 (73.3 - 77.5) - 5 DE Level 4 (77.5 - 82.0) - 7 DE Level 5 (82.0 - 98.6) - 10
	Irrigation levels	Low irrigation level zones are preferred over high levels of irrigation in private gardens as they might impact grey water and increase the potential of basement flooding. Low irrigation = 10; High irrigation = 0	Very low priv. garden area index (0 – 0.01) - 10 Low priv. garden area index (0.01 – 0.2) - 7 Medium priv. garden area index (0.2 – 0.32) - 5 High priv. garden area index (0.32 – 0.51) - 3 Very high priv. gar. area index (0.51 – 0.92) - 0
FLOOD RISK	Elevation	Areas at low elevation are preferred over higher elevation because new development at high elevation have greater potential to cause increased flows and excess water overflow by propagation downstream. Low elevation = 10; High elevation = 0	Very low elevation (0.5 - 9.7 m) - 10 Low elevation (9.7 - 20.7 m) - 7 Medium elevation (20.7 - 32.8 m) - 5 High elevation (32.8 - 50.9 m) - 3 Very high elevation (50.9 - 201.2 m) - 0
	Land permeability (RC)	Low permeability areas (high RC) are preferred over high permeability areas (low RC) as buildings on permeable areas have a greater impact on the existing natural environment and increase borough's overall flood risk. Low RC = 0; High RC = 10	Very low RC (0.24 - 0.45) - 0 Low RC (0.45 - 0.51) - 3 Medium RC (0.51 - 0.57) - 5 High RC (0.57 - 0.63) - 7 Very high RC (0.63 - 0.86) - 10
	Surface water flooding (SWF)	Areas at low risk of SWF are preferred over areas with high SWF because the flood risk is higher and involves higher costs in terms of insurance and compulsory protection measures. Low SWF = 10; High SWF = 0	SWF Level 1 (Zone 1.94 - 3.34) - 10 SWF Level 2 (Zone 3.34 - 3.64) - 7 SWF Level 3 (Zone 3.64 - 3.75) - 5 SWF Level 4 (Zone 3.75 - 3.83) - 3 SWF Level 5 (Zone 3.83 - 4) - 0
WATER QUALITY	Traffic density	High traffic density areas are preferred over low traffic density areas as the existing infrastructure allows for less traffic needed in the area. Low traf. den. = 0; High traf. den. = 10	Very low traffic area index (0.02 - 0.15) - 0 Low traffic area index (0.15 - 0.19) - 3 Medium traffic area index (0.19 - 0.22) - 5 High traffic area index (0.22 - 0.26) - 7 Very high traffic area index (0.26 - 0.52) - 10

	Sewage spills	Low CSO sewage spills areas are preferred over high and frequent CSO sewage spill event areas as they adversely affect water quality and involve higher pollution costs. Low CSO = 10; High CSO = 0	Very short CSO spills (0-3 h/year) – 10 Short CSO spills (3-17 h/year) - 7 Medium CSO spills (17-67 h/year) - 5 Long CSO spills (67-143 h/year) - 3 Very long CSO spills (143-1733 h/year) - 0
	Green area density	Areas with low green density are preferred over areas high green density as vegetation provides pollutant removal and reduces the adverse effects on water quality. Low gre. den. = 10; High gre. den. = 0	Very low green area index (0.11 - 0.40) - 10 Low green area index (0.40 - 0.47) - 7 Medium green area index (0.47 - 0.54) - 5 High green area index (0.54 - 0.62) - 3 Very high green area index (0.62 - 0.92) - 0

Table 5.3: Water Neutrality (WN) retrofit opportunity rules table to allocate WN design options with WaNetDST datasets linked to UWS indicators, logic statements, and scores. Based on expert advice and literature review.

WN Retrofit Opportunity Rules			
UWS INDICATOR	Dataset	Logic statements	Scores
CONSUMER DEMAND	Population density	High-density urban areas present more opportunities to influence people's behaviour through education and social campaigns, and/or retrofit houses with water efficiency design options. Low p. den. = 0; High p. den. = 10	Very low density (126-4,767 p/km ²) - 0 Low density (4,767-7,222 p/km ²) - 3 Medium density (7,222-10,326 p/km ²) - 5 High density (10,326-14,881 p/km ²) - 7 Very high density (14,881-92,722 p/km ²) - 10
	Device Efficiency (DE)	Low DE areas present higher opportunities to retrofit existing homes with water efficiency design options. Low DE = 10; High DE = 0	DE Level 1 (14.6 - 68.8) - 10 DE Level 2 (68.8 - 73.3) - 7 DE Level 3 (73.3 - 77.5) - 5 DE Level 4 (77.5 - 82.0) - 3 DE Level 5 (82.0 - 98.6) - 0
	Irrigation levels	High irrigation level zones present higher opportunities to influence people's behaviour through education and social campaigns, and/or retrofit watering systems with water efficiency design options. Low irrigation = 0; High irrigation = 10	Very low priv. garden area index (0 – 0.01) - 0 Low priv. garden area index (0.01 – 0.2) - 3 Medium priv. garden area index (0.2 – 0.32) - 5 High priv. garden area index (0.32 – 0.51) - 7 Very high priv. gar. area index (0.51 – 0.92) - 10
FLOOD RISK	Elevation	High elevation areas present higher opportunities to implement BGI and have a higher influence for flood risk mitigation both upstream and downstream by propagation. Low elevation = 0; High elevation = 10	Very low elevation (0.5 - 9.7 m) - 0 Low elevation (9.7 - 20.7 m) - 3 Medium elevation (20.7 - 32.8 m) - 5 High elevation (32.8 - 50.9 m) - 7 Very high elevation (50.9 - 201.2 m) - 10
	Land permeability (RC)	Low permeability areas (high RC) present higher opportunities to implement BGI and mitigate flood risk. Low RC = 0; High RC = 10	Very low RC (0.24 - 0.45) - 0 Low RC (0.45 - 0.51) - 3 Medium RC (0.51 - 0.57) - 5 High RC (0.57 - 0.63) - 7 Very high RC (0.63 - 0.86) - 10
	Surface water flooding (SWF)	Areas at high risk of SWF present higher opportunities to implement BGI and mitigate flood risk. Low SWF = 0; High SWF = 10	SWF Level 1 (Zone 1.94 - 3.34) - 0 SWF Level 2 (Zone 3.34 - 3.64) - 3 SWF Level 3 (Zone 3.64 - 3.75) - 5 SWF Level 4 (Zone 3.75 - 3.83) - 7 SWF Level 5 (Zone 3.83 - 4) - 10

WATER QUALITY	Traffic density	High traffic density areas present higher opportunities to reduce that traffic and therefore reduce the pollutants in water bodies by influencing people's behaviour through education and social campaigns. Low traf. den. = 0; High traf. den. = 10	Very low traffic area index (0.02 - 0.15) - 0 Low traffic area index (0.15 - 0.19) - 3 Medium traffic area index (0.19 - 0.22) - 5 High traffic area index (0.22 - 0.26) - 7 Very high traffic area index (0.26 - 0.52) - 10
	Sewage spills	High and frequent CSO sewage spills areas present higher opportunities to reduced those events and improve water quality. Low CSO = 0; High CSO = 10	Very short CSO spills (0-3 h/year) – 0 Short CSO spills (3-17 h/year) - 3 Medium CSO spills (17-67 h/year) - 5 Long CSO spills (67-143 h/year) - 7 Very long CSO spills (143-1733 h/year) - 10
	Green area density	Low green density areas present higher opportunities to implement BGI and other retrofit options to improve river water quality. Low gre. den. = 10; High gre. den. = 0	Very low green area index (0.11 - 0.40) - 10 Low green area index (0.40 - 0.47) - 7 Medium green area index (0.47 - 0.54) - 5 High green area index (0.54 - 0.62) - 3 Very high green area index (0.62 - 0.92) - 0

The third phase (Step 3) involves aggregating the scores obtained in Step 2, which correspond to the urban planners' preference and WN retrofit opportunity categories. This aggregation process results in a series of GIS location maps that will be utilised by housing developers during the early stages of the planning application process. Step 3 is subdivided in two sub-steps for spatial and numerical assessment (Figure 5.3). In Step 3.1, individual maps are generated for each dataset, representing the scores for both the urban planners' preference and WN retrofit opportunity categories. In this proof-of-concept stage, a total of eighteen individual maps are produced (nine for each ruling category), although this number may vary depending on the selected datasets. These maps align with the information provided in Tables 5.2 and 5.3 and are processed using the open-source QGIS software, assigning the scoring value to each spatial unit (LSOA) as part of the tool's Attribute Table.

Subsequently, in Step 3.2, the scores from each dataset are averaged and combined to generate a single location map for each ruling category. In this proof-of-concept version of the tool, the weights assigned to each dataset are equal. However, in future iterations, these weights could be adjusted based on relevant literature or expert advice. This flexibility is particularly important when certain UWS indicators, such as flood risk, hold greater significance for the urban stakeholders employing the tool. The process for obtaining the aggregated scoring value within each ruling category follows

$$Rul. Cat. SV = \frac{\sum Dataset\ 1\ SV \times Weight\ 1 + Dataset\ [X]\ SV \times Weight\ [X] + \dots}{Total\ Number\ of\ Datasets\ [X]}$$

(3)

where Rul. Cat. means Ruling Category (i.e., preference or opportunity), SV means Scoring Value, and $W(x)$ means Weight.

In this proof-of-concept phase, a total of nine datasets are utilised, and each dataset is assigned an equal weight of one. Upon completion of the process, users of WaNetDST will have the ability to assess multiple strategic areas or urban development sites within the city. This assessment allows for a comparison of the potential synergies between the urban planner's preference for allocation and the actual opportunities available to mitigate UWS impacts through the implementation of WN design options. Since WaNetDST operates as an iterative process involving both urban planners and housing developers, the results obtained from the tool provide valuable feedback to the design options portfolio and the integrated evaluation cluster of CityPlan-Place. This feedback contributes to the overall goal of making informed decisions regarding water-neutral planning, fostering collaboration and facilitating the integration of water-neutral design options into urban development projects.

5.3.2 Datasets processing

As explained in the previous section, WaNetDST includes a series of datasets grouped to each UWS indicator (i.e., water demand, flood risk, and water quality). Some of these datasets are introduced in the tool from its raw source, while others need to be processed to obtain the required information. The datasets that need to be processed from other raw sources are: device efficiency, irrigation levels, land permeability (Runoff Coefficient, RC), traffic density, sewage spills, and green area density (shaded in blue in Table 5.4). The other datasets are directly introduced into the tool in its raw format from their original source (i.e., population density from UK Census, elevation levels from UK Ordnance Survey Open Data, and surface water flooding from the Environment Agency). In the following bullet-points, I explain the processing methods for each of the processed datasets before being included as part of the WaNetDST.

Table 5.4: Datasets introduced in WaNetDST, differentiating the type of data, if raw or processed, its original source, and the downloading links from their original sources. The rows shaded in blue are the datasets that need to be processed from their raw sources.

WN INDICATORS	Dataset	Type of data	Raw / Processed	Source	Link/s
CONSUMER DEMAND	Population density	Vector	Raw	UK Census	https://data.london.gov.uk/dataset/super-output-area-population-lsoa-msoa-london https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/datasets/lowersuperoutputareamidyearpopulationestimatesnationalstatistics
	Device efficiency (Directly linked to typology, age, and size of households)	Vector	Processed	Raw datasets: UK Census	https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families/articles/householdsandhouseholdcompositioninenglandandwales/2014-05-29
	Irrigation levels (Directly linked to private garden and population datasets)	Vector	Processed	Raw datasets: Office for National Statistics	https://www.ons.gov.uk/economy/environmentalaccounts/datasets/accesstogardensandpublicgreenspaceingreatbritain
FLOOD RISK	Elevation	Raster	Raw	UK Ordnance Survey Open Data	https://www.ordnancesurvey.co.uk/business-government/tools-support/open-data-support
	Land permeability (Linked to Runoff Coefficient, CR)	Raster	Processed	BGS Land-Use map	(Internal 2x2 m raster land-use map)
	Surface water flooding	Vector	Raw	Environment Agency	https://data.london.gov.uk/dataset/flood-risk-zones
WATER QUALITY	Traffic density	Linear	Processed	Department for Transport - UK Gov	https://roadtraffic.dft.gov.uk/downloads
	Sewage spills (Linked to CSO maps)	Point	Processed	The Rivers Trust	https://theriverstrust.org/key-issues/sewage-in-rivers
	Green area density	Vector	Processed	BGS Land-Use map	(Internal 2x2 m raster land-use map)

▪ House Efficiency Level

House Efficiency Level (HEL) would be necessary to calculate the Device Efficiency (DE) explained in the next section and used as one of WaNetDST datasets linked to consumer demand. The HEL is determined by the age of buildings and the intensity of use of different water devices. From the UK Census, it is possible to obtain the total number of buildings built in a particular time-range for each LSOA. However, as this information might be very complex and difficult to process, I divided the age of buildings in thirteen separate categories and calculated the total average building age in each LSOA unit. These thirteen age categories are assigned to different time periods following Table 5.3, where Level 0 is assigned to unknow building period and Levels 1 to 12 are assigned from the newest to the oldest building periods in years. Therefore, the larger the number of the age category is, the older the average building time in this zone will be.

Table 5.5: Building age category levels based on the years when buildings were built in London. Source: UK Census 2011.

Levels (Age category)	0	1	2	3	4	5	6	7	8	9	10	11	12
Period built (years)	Unknown	2012 - 2010	2009 - 2000	1999 - 1993	1992 - 1983	1982 - 1973	1972 - 1965	1964 - 1955	1954 - 1945	1944 - 1930	1929 - 1919	1918 - 1900	Pre 1900

The Average Age of Buildings in each zone is calculated using

$$\text{Average Age of Buildings} = \frac{\sum \text{Level (i)} \times \text{number of dwellings in Level (i)}}{\text{Total number of dwellings} - \text{Number of dwellings in Level 0}} \quad (4)$$

where $n = 1, 2, \dots, 12$. After calculating the Average Age of Buildings, the HEL in each zone is determined according to the following three efficiency levels:

- 1) before 1954 (Average Age of Buildings ≥ 8): low efficiency level;
- 2) 1955-1999 ($2 < \text{Average Age of Buildings} < 8$): medium efficiency level;
- 3) after 2000 (Average Age of Building ≤ 2): high efficiency level.

These three efficiency levels will determine the device intensities used in the Device Efficiency calculations (see Appendix D).

▪ Device Efficiency

As part of WaNetDST data processing, a novel criterion called Device Efficiency (DE) is developed to evaluate how water-efficient an LSOA unit is based on the device intensity in their households and without considering the real (but predicted) people's water usage behaviour. There are two types of DE that are calculated differently and then aggregated to obtain the overall DE value for each spatial unit.

The first type of DE is individually calculated for seven types of devices (i.e., dishwasher, kitchen tap, washing machine, bathroom tap, WC, bathtub, and shower). In this case, the larger the score for DE the more efficient is a specific device in one zone compared to the same type of devices in other zones. The second type of DE is the household DE which considers the total device intensity at LSOA units based on the household potential of water consumption. In this second case, the larger the household DE is, the smaller total intensity/potential water consumption will be, so the more device-efficient the households in this zone will be. To calculate the DE (both for individual devices and for households), there are a series of steps to follow that are summarised below and in Figure 3:

1. For each LSOA zone, the total number of each type of device per household is calculated. This is directly related to size and typology of households obtained from raw sources from the UK Census. See further explanation and tables for calculations of device number, intensity, frequency use, and duration in the Appendix D.
2. For each LSOA zone, the percentages of three efficiency levels are calculated. These percentages are consistent with the ones calculated for HEL in the previous Section 5.4.1.
3. For all seven types of devices, the values for each efficiency level are calculated by multiplying the total number of devices in Step 1 and the efficiency level in Step 2.
4. The total intensity of each device is calculated by multiplying the number of device and corresponding intensity in each different efficiency level to add them up.
5. The maximum and minimum total intensities obtained in Step 4 among all zones are found for each device.

6. The individual DE value is calculated using the following standardization equation where “max” and “min” are the maximum and minimum values obtained in Step 5, and “x” is the total devices intensity of one specific zone

$$\text{individual device DE} = \frac{\text{max} - x}{\text{max} - \text{min}} \quad (5)$$

7. For each LSOA zone, the mean of individual DE of the seven types of devices would be the final household DE value, used in WaNetDST data processing. For visualisation purposes, the final DE value will be divided in 5 different levels for the dataset map (Figure 5.6a).

See the flowchart with detailed steps to obtain DE values in Figure 5.4.

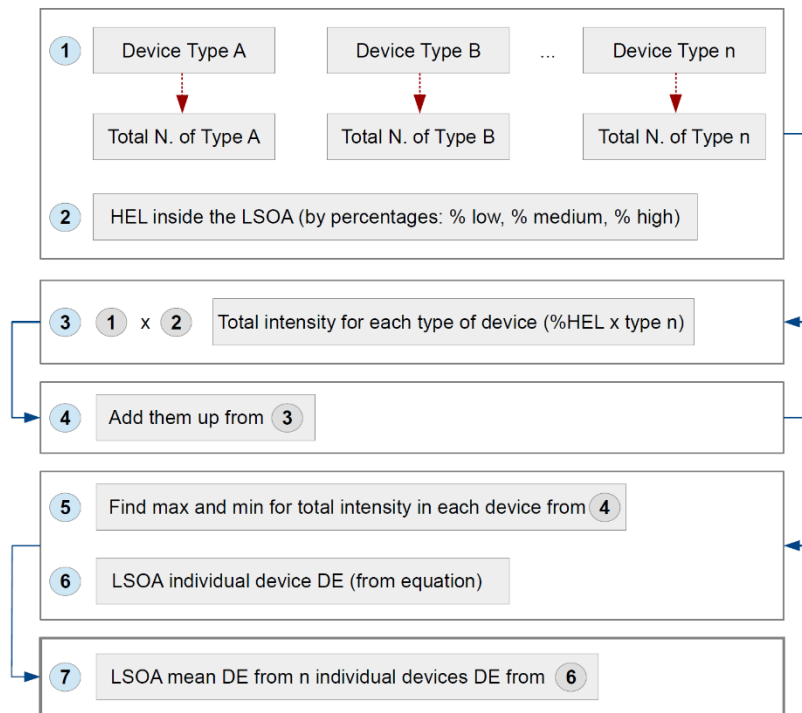


Figure 5.4: Flowchart for Device Efficiency (DE) calculation in each LSOA unit for WaNetDST. Adapted from Lu et al., 2021.

▪ Irrigation levels

From the Office for National Statistics (source link in Table 5.4), it is possible to obtain a raw dataset that informs about the number of public parks and private gardens by London MSOA (Middle Layer Super Output Areas), this being a larger spatial unit than LSOA. The number of private gardens is assumed to be directly linked to the amount of irrigation water consumed in each spatial unit. But first, it is necessary to have all the datasets introduced in WaNetDST at the same resolution, so the raw private gardens dataset needs to be transformed from MSOA to LSOA units. To achieve this transformation, I assume that there will be a larger number of private gardens in the units where there are more inhabitants (population). I obtain the total number of private gardens in each LSOA unit that will be linked to the existing irrigation levels in each spatial unit (this being part of the UWS impact for consumer demand) following

$$LSOA_Private\ Garden\ Area = \frac{MSOA\ Private\ Garden\ Area}{MSOA\ Total\ Population} \times LSOA\ Total\ Population \quad (6)$$

▪ Land permeability

The Runoff Coefficient (RC) values are used as a proxy for the land permeability level in each spatial unit. Following the land-use raster map internally obtained from BGS, it is possible to correlate each land-use category to a certain runoff coefficient. Based on two different sources (i.e., USA Surface Water Ambient Monitoring Program, and the USA Hydrological Analysis and Design), I assume a normalised value for each land use (third column in Table 5.6). All the land cover categories and runoff values are found in Table 5.6. Once I link these assumed RC values to each land cover category, the next step is to aggregate and obtain the mean RC value in each LSOA unit based on the land-use percentages contained in each unit. The mean RC value in each LSOA follows

$$LSOA_RC\ Value = \sum \frac{RC\ Value\ in\ each\ LSOA\ LC\ category \times Area\ in\ each\ LC\ Category}{LSOA\ Total\ Area} \quad (7)$$

where LC means Land Cover.

Table 5.6: Runoff coefficient values assumed as part of the land permeability dataset of WaNetDST (far right column) based on two different sources (middle columns) and linked to land cover categories from BGS map (far left column).

Land cover	Source 1 (USA Surface Water Ambient Monitoring Program)	Source 2 (USA Hydrological Analysis and Design)	Assumed Runoff Coeff. (RC) value
Water	-	Water body 1	1
Tree canopy	Mainly shrubs/ scrubs 0.15	-	0.15
Low vegetation	Pasture 0.05-0.45	Mainly grasses 0.25	0.2
Bare soils	Bare soil 0.2-0.6	Compacted non-vegetated land 0.5	0.4
Traditional buildings	Roof 0.75-0.95	Black roofs 0.85	0.9
Impervious surface	Drives and walks 0.75 - 0.85	Asphalt 0.85	0.8
Impervious roads	Drives and walks 0.75 - 0.85	Asphalt 0.85	0.8
Impervious roadside	Drives and walks 0.75 - 0.85	Asphalt 0.85	0.8
Pervious roadside	Gravel road 0.3-0.7	-	0.6
Tree over impervious surface	Gravel road 0.3-0.7	-	0.6
Tree over impervious road/roadside	Gravel road 0.3-0.7	-	0.6
Tree over pervious roadside	Gravel road 0.3-0.7	-	0.5
Rail	Railroad yard areas 0.2-0.4	-	0.3
Bridge/structure	Streets concrete 0.8-0.95	Cement 0.85	0.9
Tidal water	-	Water body 1	1

It is worth noting that elevation data, while not included in the land permeability (RC) dataset, is integrated and aggregated with the other datasets during the data processing in WaNetDST. As a result, the RC is combined with the effect of elevation (slope) in the final WaNetDST aggregated scoring maps (Step 3, Figure 5.3). Detailed elevation values are provided in Figure 5.6.

▪ Traffic density

From the Department of Transport of the UK Government (source link in Table 5.4), it is possible to obtain a raw dataset that informs about the traffic density in the main roads and streets in London (and other parts of the country). As I need all the information introduced in WaNetDST at the same spatial resolution, I need to transform this raw traffic dataset from linear data (roads and streets) to polygon data (LSOA units). This is performed with a vectorial conversion plugin that joins attributes by location inside the QGIS tool.

▪ Sewage spills

From The Rivers Trust organisation (source link in Table 5.4), it is possible to obtain a raw dataset that informs about the location, number, duration, and intensity of sewage spills in London (and other parts of the country). As I need all the information introduced in WaNetDST at the same spatial resolution, I need to transform this raw CSO (Combined Sewers Overflow) dataset from points (specific coordinates where the spills occur) to polygon data (LSOA units). This is performed with a vectorial conversion plugin that joins attributes by location inside the QGIS tool.

▪ Green area density

In a similar way as the analysis and visualisation of London's urban form properties in Section 4.3.2, the total amount of green space in each LSOA unit is obtained by aggregating several land-use categories from the land-use raster map internally obtained from BGS. These land-use categories are: tree canopy, low vegetation, and tree over pervious roadside. These layers are aggregated and introduced into the Equation 2 (Chapter 4) from Oke et al. to calculate the area index in each LSOA spatial unit, following

$$GS\ Area\ Index = \frac{LSOA\ (Tree\ Canopy + Low\ Vegetation + Tree\ Over\ pervious)\ Area}{Total\ LSOA\ Area} \quad (8)$$

where GS means Green Space.

5.3.3 Ruling categories visualisation

In Step 2 of the process (Figure 5.3), after assigning the scoring values, the visualisation of location maps and their corresponding numerical values becomes crucial for the development of WaNetDST. Consistency and clarity are important aspects to ensure coherence across all the maps in WaNetDST. In Tables 5.2 and 5.3, the information from the datasets is divided into five intervals, evenly distributed based on equal counts quantile. This approach, facilitated by the QGIS tool, organises groups with an equal quantity, resulting in evenly distributed shading on quantile-based maps.

To maintain consistency and facilitate interpretation of the scores across all location maps, a color-coding scheme is employed. For the urban planners' preference scoring, a range of oranges and reds is utilized, with darker red indicating lower preference and lighter shades representing higher preference. Conversely, for the WN Retrofit Opportunity scoring, different shades of blue are used, with lighter blue indicating lower opportunity and darker shades indicating higher opportunity. Refer to Table 5.7 for a detailed breakdown of the color-coding scheme.

Table 5.7: Colour-coding used in WaNetDST for the Urban Planners Preference and Water Neutrality (WN) Retrofit Opportunity scoring following 5 rating intervals and scoring levels based on equal counts quantile distribution.

WaNetDST scoring colour-coding based on equal counts quantile distribution			
Urban Planners Preference Scoring			
Rating Interval	Scoring Level	Approximate scoring values rates	Colour
1	Very low	0-3	
2	Low	3-4	
3	Medium	4-5	
4	High	5-7	
5	Very high	7-10	
WN Retrofit Opportunity Scoring			
Rating Interval	Scoring Level	Approximate scoring values rates	Colour
1	Very low	0-3	
2	Low	3-4	
3	Medium	4-5	
4	High	5-7	
5	Very high	7-10	

5.4 Systemic design across scales

In line with the systemic design concept applied to urban planning decision-making, WaNetDST incorporates the selection of design options as an integral part of the CityPlan-Place framework. This process involves combining strategic decisions formulated by policy bodies, which establish the boundaries and purpose of urban planning, with tactical decisions derived from modelling, which define numerical targets for interventions aimed at achieving the urban planning purpose (both depicted as white boxes in Figure 5.5).

In this context, the strategic decisions encompass the goals set by the Greater London Authority (GLA) and Local Planning Authorities (LPAs) to promote urban water neutrality at various scales (depicted as blue boxes in Figure 5.5). The tactical decisions, on the other hand, refer to the water neutrality targets established at the London scale, as discussed in the previous Chapter 4. These targets involve the implementation of water neutrality design options for 522,870 new homes, retrofitting of 432,500 existing homes, and the addition of 19 km² of new Blue-Green (BG) spaces within the city's land area (as illustrated in Figure 4.5, Chapter 4; and depicted as green boxes in Figure 5.5).

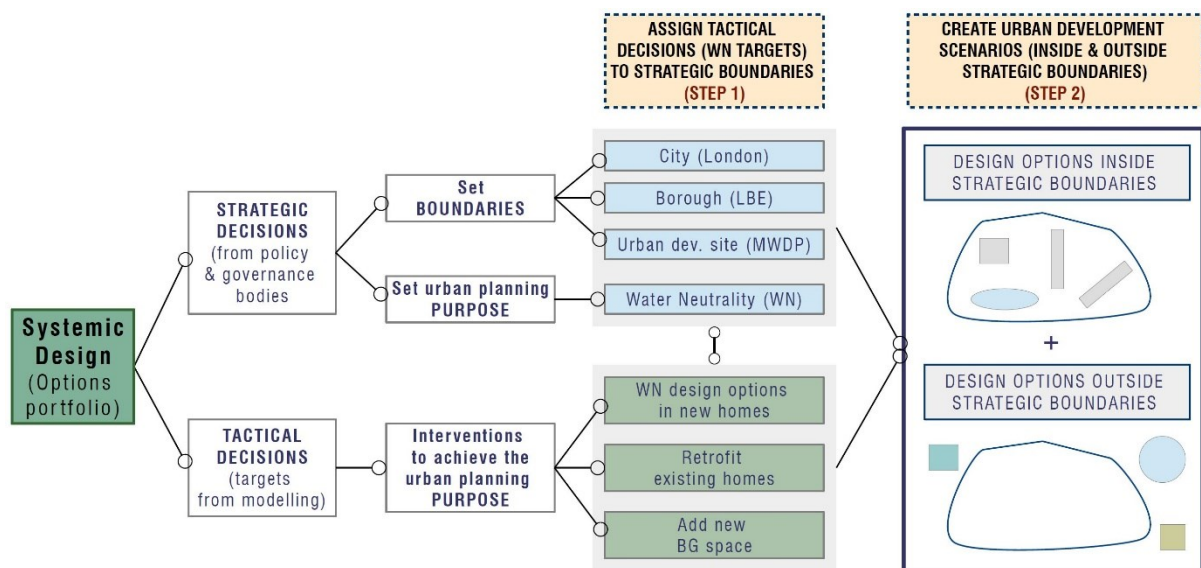


Figure 5.5: Diagram of the systemic design process applied to decision-making to select a series of design options and based on the urban planning purpose of Water Neutrality (WN). The process combines a series of strategic decisions (blue boxes) and tactical decisions (green boxes) to develop a series of urban development scenarios in a two-step process.

These targets are intended to be incorporated into the Local Plans of boroughs and, together with Neighbourhood Plans (NPs), will guide the decision-making process for

granting planning permission to urban developers within the urban planning application process (as depicted in Figure 2.1, Chapter 2).

The systemic design process applied to urban decision-making consists of two primary phases or steps, as depicted in Figure 5.5. In the first phase (Step 1), the tactical decisions, represented by the water neutrality (WN) targets, are allocated to specific strategic boundaries, such as the city, borough, or urban development site. In this case, the WN targets obtained at the London scale (city) are distributed to the LBE based on its housing target specified in the New London Plan (12,460 new homes; GLA, 2021). Similarly, the WN targets will be allocated to the Meridian Water Development Plan (MWDP) based on its projected housing target (10,000 new homes; Enfield Council, 2021). Once the strategic boundaries for the systemic design study are defined, urban planners, including architects and engineers (as illustrated in Figure 2.1, Chapter 2), can explore and compare various design scenarios, including both business-as-usual (BAU) and WN scenarios.

Consequently, in the second phase (Step 2), a series of urban development design scenarios are formulated, encompassing actions within the strategic boundaries (e.g., implementing WN design options and Blue-Green Infrastructure (BGI) in new homes) as well as outside the strategic boundaries (e.g., retrofitting existing infrastructure). Similar to the systemic design process presented in the previous Chapters 3 and 4, this Step 2 commences with an assessment of the baseline conditions (pre-development) that serve as the basis for driving design and land-use changes across all design scenarios. The outcomes of this systemic design process, applied to the LBE and MWDP as an initial proof-of-concept, are presented in the subsequent Section 5.5.3.

5.5 Supporting decisions for water-neutral urban planning

5.5.1 Analysis and visualisation of processed datasets

The processing of datasets in Step 1 of WaNetDST (Figure 5.3) involves generating individual visualisation maps for each dataset before assigning any scoring value. These maps are considered crucial for understanding the water neutrality (WN) urban form properties in conjunction with those depicted in Figure 4.3, Chapter 4. The raw dataset maps for Elevation and Surface Water Flooding can be found in Figure 5.6, while the processed datasets (highlighted in blue in Table 5.4) are visually presented in Figure 5.7.

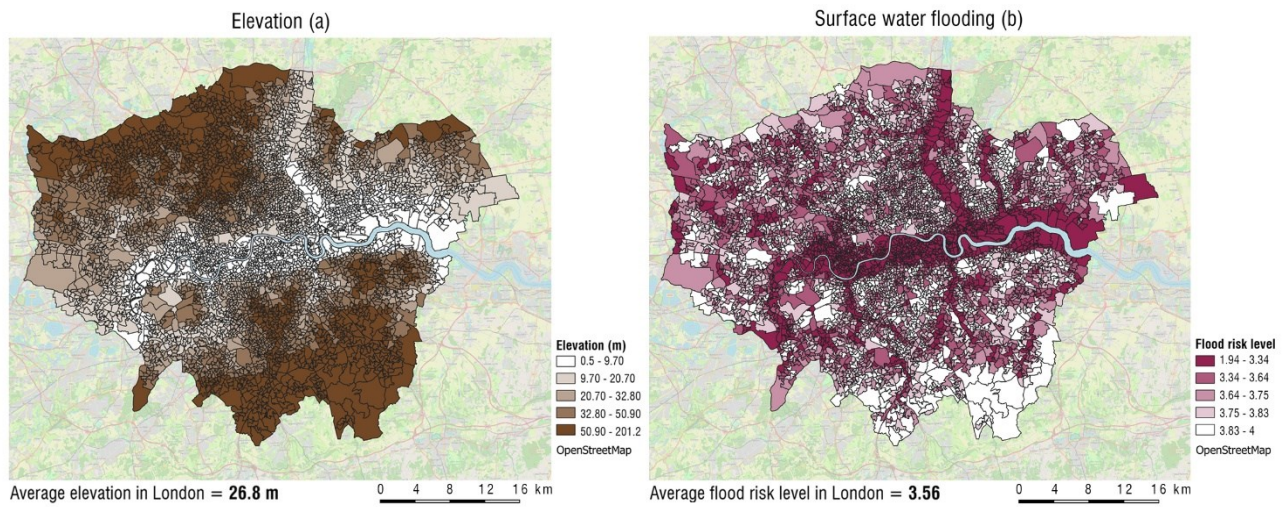


Figure 5.6: WaNetDST raw datasets visualisation maps for elevation (a) and surface water flooding (b).

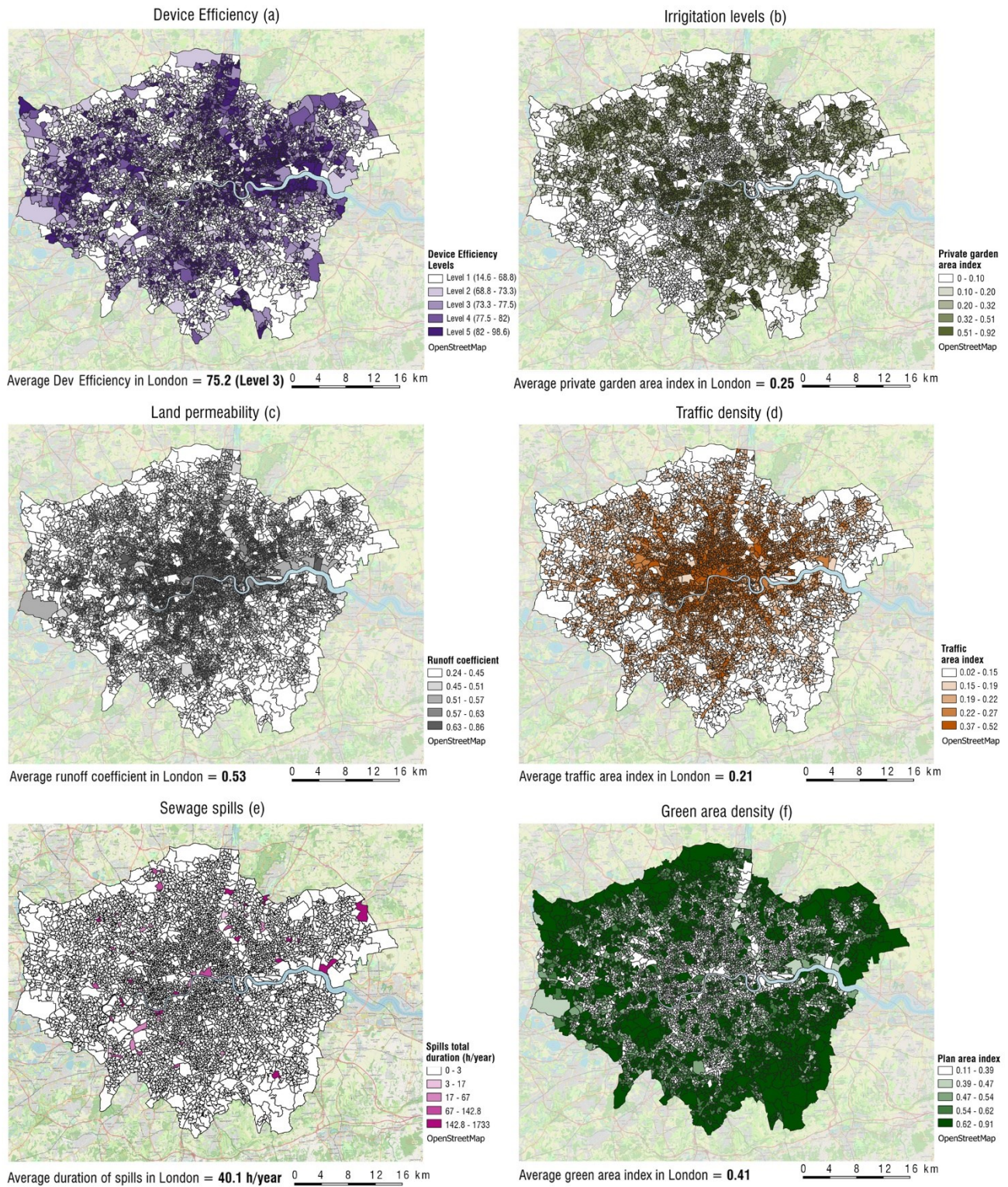


Figure 5.7: WaNetDST processed datasets visualisation maps informing about key WN urban form properties for UWS evaluation.

As shown in the previous chapter, the population density maximum value is 92,722 people/Km² and minimum of 15,924 people/Km², with an average across London of 5,195 people/Km² (Fig. 3e, Chapter 4). Now, looking at Figure 5.6 of raw datasets, the elevation

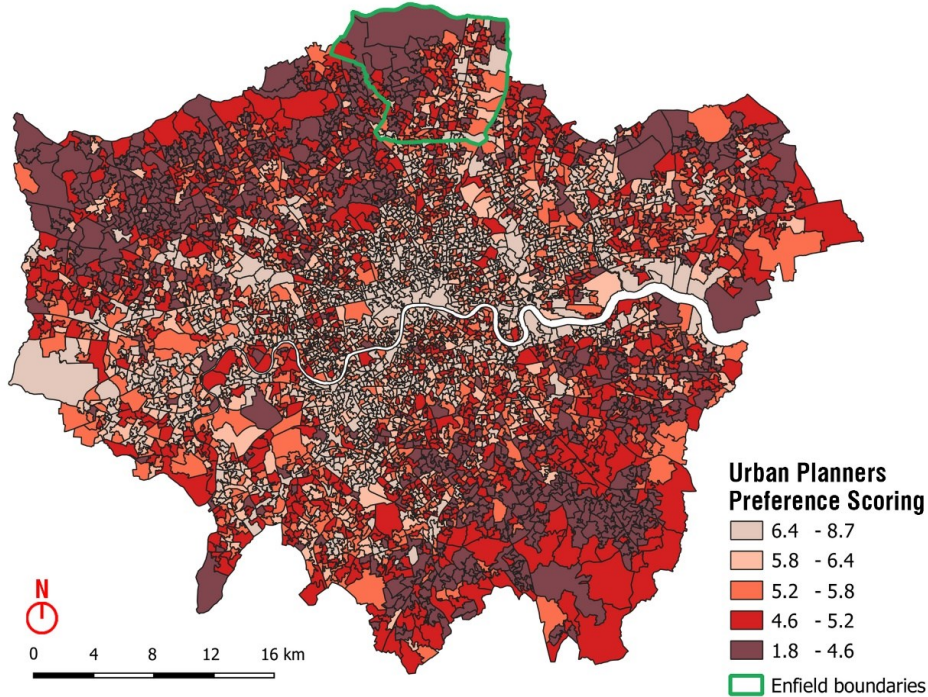
map ranges from 0.5 m to 201.2 m, with an average altitude across London of 26.8 m (Figure 5.6a). Moreover, the distribution of surface water flooding is mainly concentrated near rivers and large water bodies, with the most affected LSOAs presenting an average flood risk level between 1.94 and 3.34, and the ones at lower risk presenting a flood risk between 3.83 and 4 (Figure 5.6b). Moving to processed datasets in Figure 5.7, the DE score ranges from 14.6 to 98.8 around London's LSOAs, with an average score of 75.2 (Figure 5.7a). Private gardens area index (used as a proxy for irrigation levels) ranges from 0 to 0.91, with an average value across London of 0.25 (Figure 5.7b). Regarding land permeability, some LSOA units show a maximum RC of 0.86 while others present an average RC of 0.24, with an average value in London of 0.53 (Figure 5.7c). Traffic density maximum area index is 0.52 and minimum of 0.02 with an average across London of 0.21 (Figure 5.7d). The relatively high traffic density is concentrated around the centre, although other high traffic veins can be seen from the centre to the outskirts of the city. The sewage spills duration ranges from 0 to 3 hours per year in the lowest LSOA units up to 1,733 total hours of sewage spills per year in the most affected LSOA units (Figure 5.7e). Most of these long sewage spills episodes are very localised, while the majority of spatial units do not present any spills. Finally, the green space area index ranges from 0.11 to 0.62, with an average across London of 0.41 (Figure 5.7f).

5.5.2 Decision-support maps for new and retrofit water-neutral development

Upon processing the nine maps for each dataset, I assign the scoring value to each dataset according to the logic statements in Tables 5.2 and 5.3. I then aggregate their values using Equation 3 (Section 5.3.1) and obtain two overall aggregated maps: one for urban planners' preference and one for WN retrofit opportunity (Figure 5.8). While establishing a clear pattern for WN purposes across the entire city is challenging (as each LSOA has its own properties derived from the datasets and rules integrated into the tool), I observe a reduced preference for new urban development in numerous peri-urban zones. These areas typically feature larger green spaces and existing houses (Figure 5.8a). Conversely, the opportunities to implement new WN design options receive higher scores in the city centre and densely populated neighbourhoods characterised by paved, impervious areas and ageing infrastructure (Figure 5.8b). The overall aggregated maps, like the ones shown

in Figure 5.8, are intended to be included in the Local Plans by LPAs in subsequent stages of the work. They are aimed to serve as guidance for urban planners and housing developers in formulating various WN urban planning scenarios.

(a) Aggregated urban planners' preference scoring map



(b) Aggregated Water Neutrality retrofit opportunity scoring map

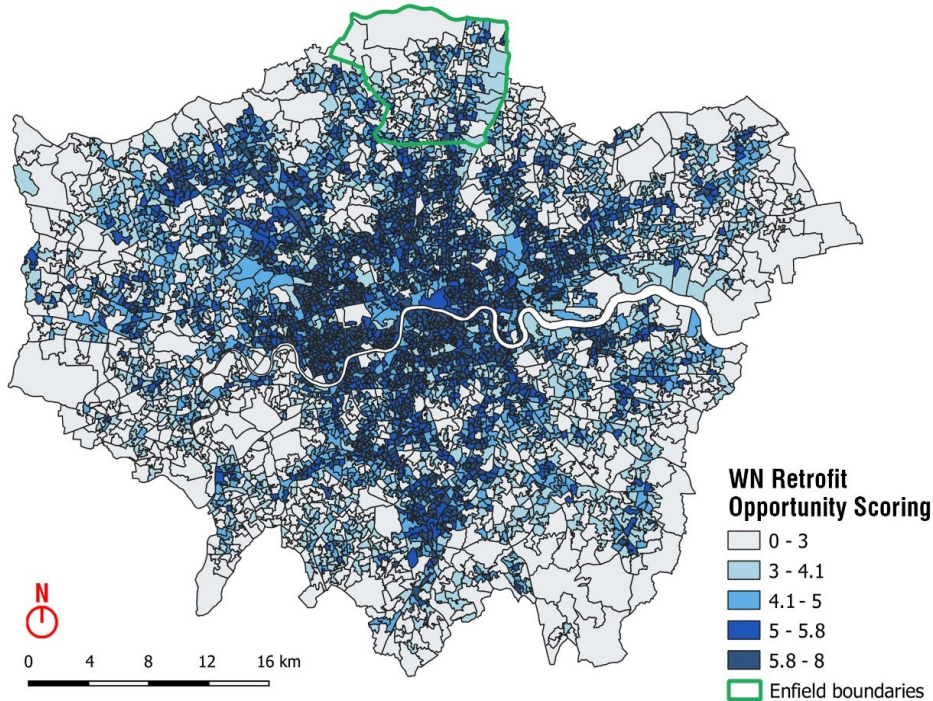


Figure 5.8: WaNetDST aggregated urban planners' preference scoring map (a) and aggregated Water Neutrality (WN) retrofit opportunity scoring map (b) at London city scale following the aggregation of the nine datasets linked to UWS indicators scoring values with Enfield boundaries marked in green.

5.5.3 Systemic design scenarios from development site to borough scale

As outlined in Section 5.3.1, WaNetDST offers the capability for cross-scale evaluation, presenting significant potential to inform various urban stakeholders. Once the scoring maps for urban planners' preference and WN retrofit opportunity are obtained at the city scale (Section 5.5.2), I have developed a conceptual platform that seamlessly integrates the aggregated results from both scoring categories into a unified Virtual Decision Room (VDR). This innovative virtual platform can take the form of a web-based interface or a plugin within QGIS, providing insights into WN synergies resulting from future urban development within a borough.

The purpose of the VDR is to assist Local Planning Authorities (LPAs) and urban developers during the initial stages of the urban planning process, facilitating informed and collaborative decision-making for water-neutral design. In this phase of the research, I collaborated closely with urban planners from the Local Borough Entity (LBE) as part of the CAMELLIA and VENTURA research projects. The LBE boundaries and the Metropolitan Water Development Plan (MWDP) were selected as the primary case study areas (Figure 5.2). Within the VDR, the exploration begins by examining the urban planners' preference within the borough boundaries, presenting the aggregated scoring values at the Local Super Output Area (LSOA) resolution (Figure 5.9). Users of the VDR have the ability to select an existing proposed urban development site or explore new areas to assess their potential for WN implementation. In this instance, the focus is on the MWDP boundaries (highlighted in darker turquoise in Figure 5.9), which exhibit a high preference for development based on the urban planners' preference scoring (score = 6.2).

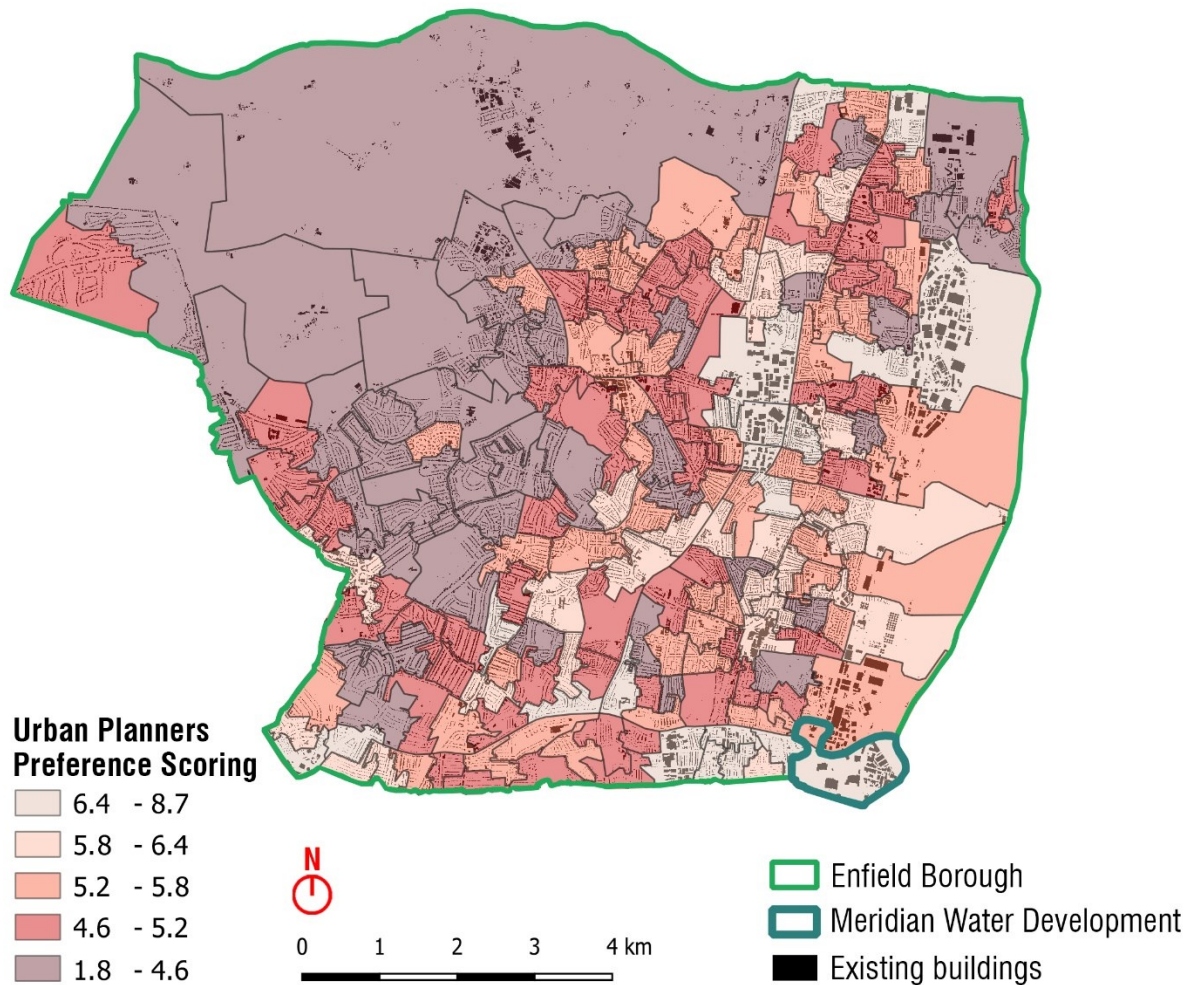


Figure 5.9: WaNetDST aggregated urban planners' preference scoring map at the borough scale in the London Borough of Enfield (LBE) with existing buildings shaded in black and Meridian Water Development Plan (MWDP) marked in dark turquoise.

MWDP presents a high scoring for development based on urban planners' preference, but in order to be considered a water-neutral urban development it must achieve the WN targets obtained from modelling (i.e., tactical decisions). Following the systemic design process outlined in Section 5.4 and Figure 5.5, the initial step (Step 1) involves assigning WN targets to specific strategic boundaries. In the case of MWDP, it encompasses the strategic boundaries within the LBE and has a housing target of 10,000 new homes to be accomplished by the end of the development project (LBE, 2021). According to the results of the integrated water management simulation presented in Chapter 4, the WN targets for MWDP would involve implementing WN design options in 10,000 new homes (Scenario F, Table 4.4, Chapter 4), retrofitting 8,272 existing homes with efficient appliances and Rainwater Harvesting (RWH) systems (Scenario K, Table 4.4, Chapter 4),

and adding 363,380 m² (36.34 ha) of Blue-Green Infrastructure (BGI) space to the existing land in London by transforming non-BGI areas into BGI (Scenario L, Table 4.4, Chapter 4).

The second step (Step 2) adheres to systemic design principles and entails developing a series of urban planning scenarios during the early stages of the design process, both within and outside the strategic boundaries of MWDP. As discussed in Chapter 3 and Section 5.4, it is essential to analyse the current land conditions (i.e., baseline) before formulating new scenarios.

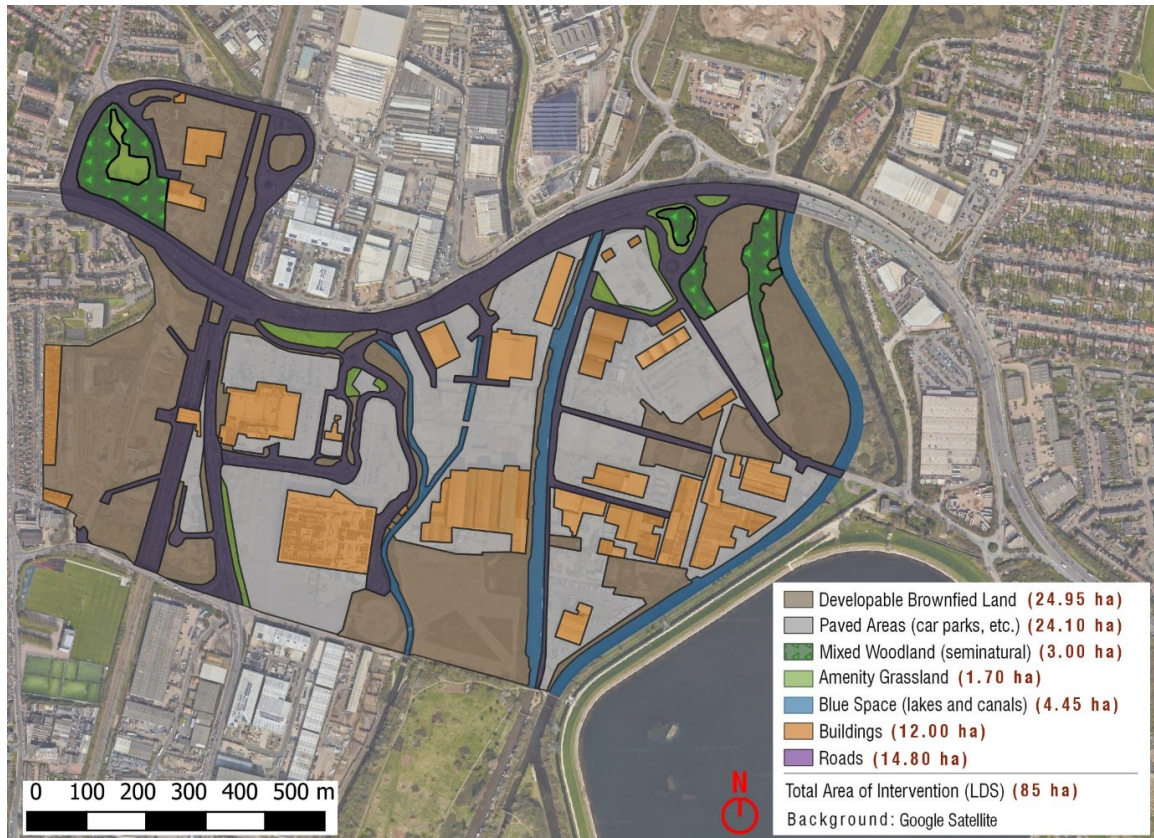


Figure 5.10: Pre-development land-use map or ‘baseline’ for Meridian Water Development Plan (MWDP).

The pre-development land conditions of the MWDP site (Figure 5.10) predominantly consist of developable brownfield land (29.4%) and paved areas (28.4%), which may include parking spaces and former industrial sites. Only 3.5% of the land comprises mixed woodland, while 2% is comprised of amenity grassland and 5.3% encompasses blue spaces such as lakes and canals, which collectively constitute the total BGI space within the pre-development site. Furthermore, existing buildings occupy 14.1% of the land, primarily comprising industrial and commercial structures with a small proportion of older residential units, while traditional impervious roads account for 17.4% of the land. These

baseline conditions, characterised by significant areas of developable brownfield and impervious industrial land, align with the high aggregated score of 6.2 obtained for development from the urban planners' preference map (Figure 5.9).

Once the baseline conditions are analysed and the selection of a new urban development site is determined, the Virtual Decision Room provides valuable information about the WN retrofit opportunities at the borough scale (Figure 5.11). In the case of the MWDP site (marked in dark turquoise in Figure 5.11), it exhibits a relatively low score for WN retrofit opportunity (Score = 3.2). Therefore, it would be advisable to explore other LSOA units outside the development boundaries that offer higher scores, as they would better facilitate the achievement of the required WN retrofit targets.

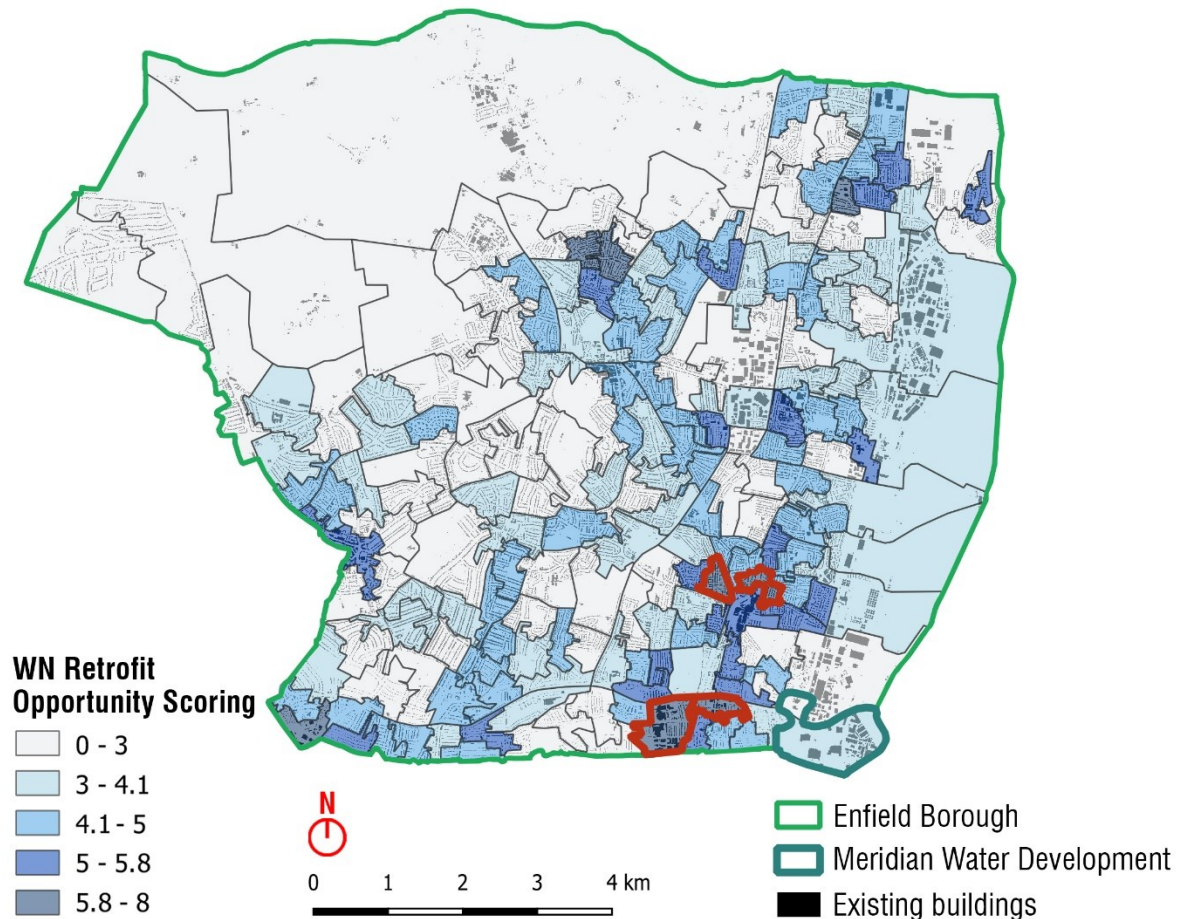


Figure 5.11: WaNetDST aggregated WN retrofit opportunity scoring map at the borough scale in the London Borough of Enfield (LBE) with existing buildings shaded in black, Meridian Water Development Plan (MWDP) marked in dark turquoise and LSOAs units selected for retrofit marked in red.

In this proof-of-concept stage, I have arbitrarily selected four LSOAs located in close proximity to the MWDP site (marked in red in Figure 5.11) with WN retrofit opportunities above 5.8. These LSOAs will serve as strategic locations for implementing systemic design options outside the designated development boundaries. By focusing on these areas with higher retrofit opportunities, it becomes possible to enhance the overall water-neutral performance of the MWDP project and contribute to the attainment of WN targets.

It is important to note that the selection of LSOAs for retrofit implementation can be further refined and optimised based on more comprehensive criteria, stakeholder inputs, and in-depth analysis. The Virtual Decision Room serves as a tool for facilitating informed decision-making and collaborative discussions among relevant stakeholders, helping to identify the most suitable areas for implementing WN retrofit options and ensuring the successful integration of water-neutral practices in the MWDP and other urban development projects.

Following the systemic design process, I begin by examining the proposed design by developers in a Business-as-Usual (BAU) scenario, where no water-neutral (WN) design options are implemented in new buildings and no retrofit interventions take place. The representation of this BAU scenario can be seen in Figure 5.12, and it is evident that this scenario will not achieve water neutrality.

BAU Scenario (proposed design)



Figure 5.12: Proposed design for Meridian Water Development Plan (MWDP) in the Business As Usual (BAU) scenario with no WN design options or retrofit implemented either inside or outside the development site boundaries.

In the BAU scenario, the built-up area with high-density buildings will occupy 13.75 hectares of land, accounting for 16.2% of the total land. Additionally, the largest proportion of land, amounting to 23.30 hectares (27.4% of the total land), will be occupied by built-up area with medium-density buildings. As highlighted in Section 5.2.1, developers in the MWDP express their intention to create a green and nurturing environment upon project completion. Therefore, I assume a significant reduction in paved areas, reducing it from 24.10 hectares to 0.90 hectares. Furthermore, there will be a substantial increase in green and blue infrastructure (BG space), totalling 31.85 hectares, which will represent 37.5% of the total land. Lastly, there will be a minor reduction of 1 hectare in the road area, decreasing it from 14.80 hectares in the pre-development baseline to 13.80 hectares.

By comparing the BAU scenario with the desired goals of creating a water-neutral and environmentally friendly development, it becomes clear that significant design modifications are necessary. The subsequent design options will aim to integrate water-neutral practices, such as efficient water management systems, green infrastructure, and sustainable land-use patterns, to achieve the desired water-neutral outcome for the MWDP project.

The subsequent step involves the development of multiple water-neutral (WN) design scenarios and the assessment of their WN levels based on the modelling targets. These WN design scenarios comprise planning within the selected development area (WN Development) as well as the corresponding WN design options outside the development area required to meet the modelling targets (WN Retrofit). The scoring maps derived from WaNetDST provide insights into the potential of specific spatial units to implement WN design options. Areas with a WN retrofit opportunity score above 5 indicate a higher potential for implementing WN design options within the existing infrastructure compared to areas with scores below 5. For this proof-of-concept of the Virtual Decision Room (VDR) in WaNetDST, I have developed two WN design scenarios.

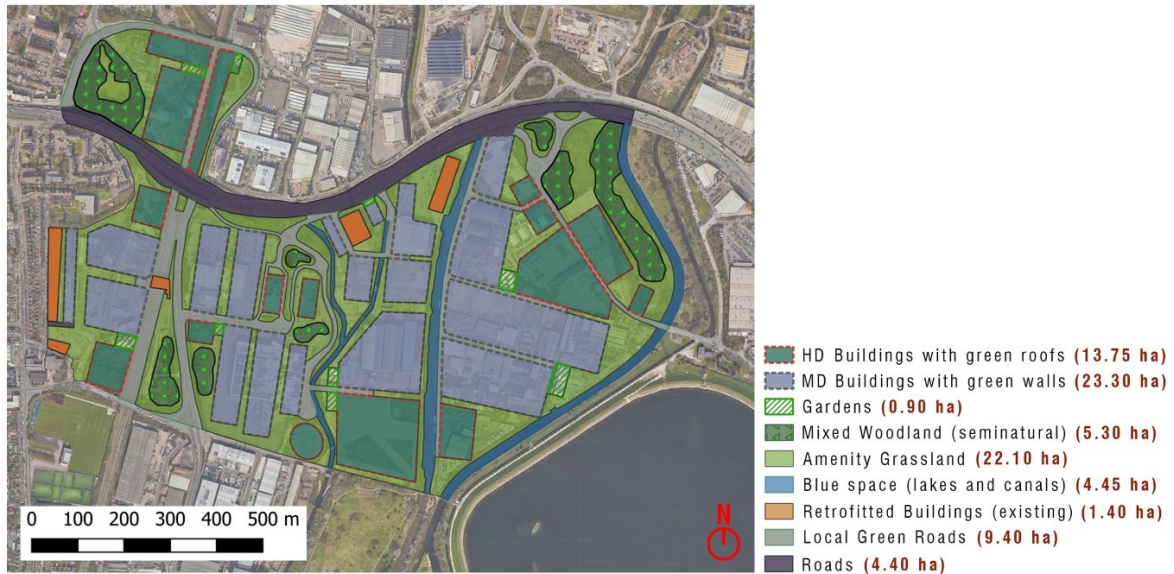
In the first scenario, WN Development Scenario 1, the building distribution follows a business-as-usual (BAU) pattern, with WN design options integrated into new buildings such as green roofs, green walls, efficient appliances, rainwater harvesting (RWH), and greywater recycling (GWR) systems (Figure 5.13a). The map represents the built-up area with high-density buildings (13.75 ha, 16.2% of the total land) as 'HD Buildings with green roofs', while the built-

up area with medium-density buildings (23.30 ha, 27.4% of the total land) is depicted as 'MD Buildings with green walls' (Figure 5.13a). The number of dwellings per hectare (ha) in these built-up areas aligns with the target of achieving 10,000 new homes set by the LBE Council and is estimated based on building typologies (refer to Table C.1 in the Appendices).

In WN Development Scenario 1, I assume that the existing residential buildings within MWDP (occupying 1.40 ha) undergo retrofitting with efficient appliances and RWH systems. Considering a medium-density distribution of 250 dwellings per ha, the total number of retrofitted homes within the strategic boundaries amounts to 280. However, to reach the target of retrofitting 8,272 existing homes, an additional 7,992 homes need to be retrofitted outside MWDP. The total amount of BG space around the buildings remains the same as in the BAU scenario, namely 31.85 hectares, representing a net addition of 22.70 ha (after subtracting the pre-development BG space of 9.15 hectares based on the baseline conditions). Since these 22.70 ha of new BG space fall short of the target of 36.34 ha, a minimum of 13.64 ha of new BG space must be added outside the development boundaries.

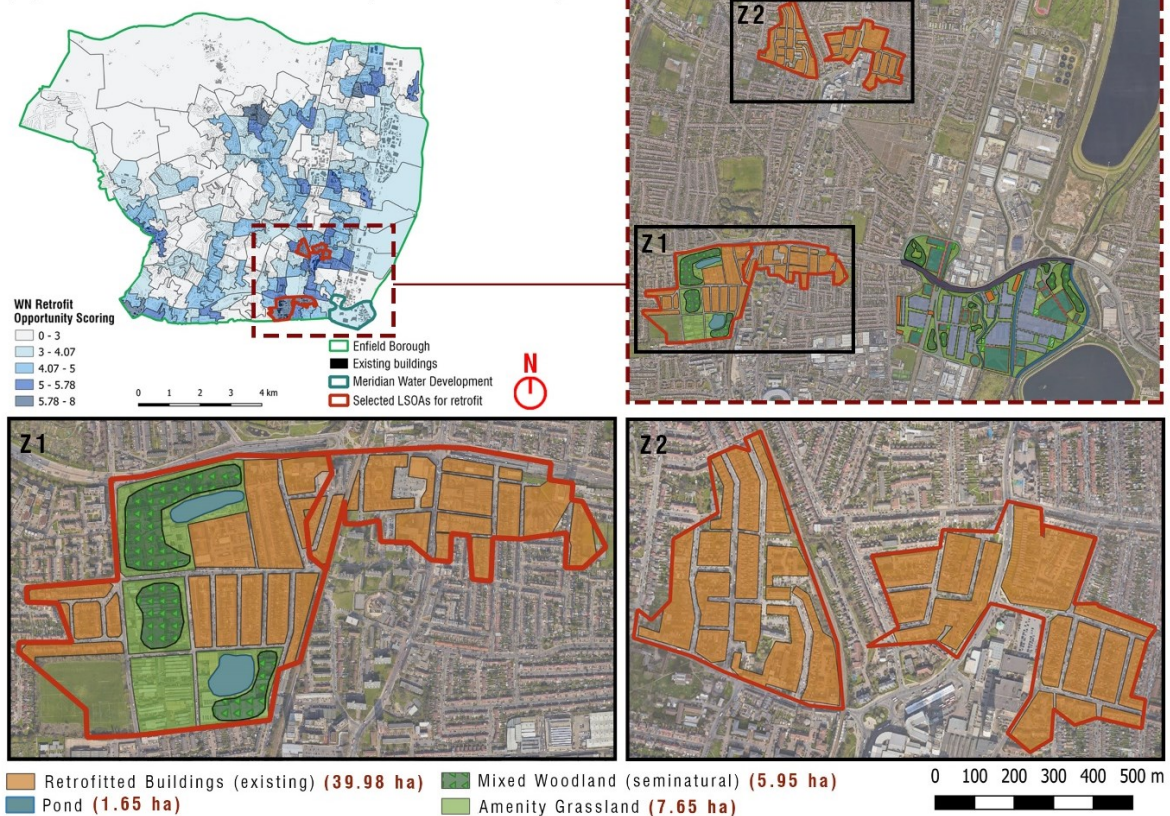
Considering that WN Development Scenario 1 fails to achieve the WN targets for BG space and building retrofit inside the MWDP boundaries, I introduce WN Retrofit Scenario 1 (Figure 5.13b). In this systemic design scenario implemented outside the strategic boundaries, I transform industrial and brownfield land into new BG space within one of the LSOA units selected from the WN retrofit potential map (highlighted in red in Figure 5.11). Additionally, a minimum of 7,992 existing homes distributed across the four LSOAs with high WN retrofit scores (above 5.8, Figure 5.11) need to be retrofitted. In this specific example, the total BG space added to the borough outside MWDP boundaries amounts to 15.35 ha, exceeding the required 13.64 ha. Moreover, there are a total of 7,996 existing homes, assuming 250 homes per ha across an area of 39.98 ha (Figure 5.13b).

(a) WN Development Scenario 1 (inside MWDP)



New homes = 10,000 h. (Developers' target)
 Retrofitted homes = 280 h. < 8,272 -- Needs retrofitting 7,992 existing homes outside MWDP boundaries
 New BG space added to site = 22.70 ha < 36.34 ha -- Needs adding 13.64 ha of BG space outside MWDP

(b) WN Retrofit Scenario 1 (outside MWDP)



Retrofitted homes = 7,996 h. > 7,992 -- Achieves WN target outside MWDP boundaries
 New BG space added to borough = 15.35 ha > 13.64 -- Achieves WN target outside MWDP boundaries

Figure 5.13: Water Neutrality (WN) Development Scenario 1 for Meridian Water Development Plan (MWDP) based on WN design options implemented in a BAU distribution (a) and WN Retrofit Scenario 1 that adds BG space and retrofits existing buildings outside the development boundaries (b), with two zoom-in windows (i.e., Z1 and Z2).

Next, I proceed to develop the second WN design scenario, WN Development Scenario 2, which adopts a more compact distribution and allows for a larger amount of BG space surrounding the buildings (similar to Scenario 3 for TMWDP mentioned in Chapter 3; Figure 3.9). Figure 5.14a illustrates WN Development Scenario 2, where high-rise buildings with WN options occupy 13.30 ha (15.7% of the total land), and medium-density buildings with WN options occupy 8.40 ha (9.9% of the total land). The estimation for the density of new buildings, based on the target of 10,000 new homes set by the LBE Council, can be found in Table C.1.

Consistent with WN Scenario 1, I assume that all new buildings incorporate WN design options (depicted on the map as 'HD Buildings with green roofs' and 'MD Buildings with green walls'), while existing residential buildings follow a medium-density distribution of 250 dwellings per hectare. Consequently, the total number of retrofitted dwellings within the MWDP boundaries remains at 280 existing homes (Figure 5.14a). Since this is the same number of retrofitted homes within the boundaries as in WN Scenario 1, the total target for retrofitting outside the MWDP boundaries remains at 7,992 existing homes. However, increasing the building density enables a significant amount of BG space within the MWDP boundaries, totalling 50.50 ha (59.4% of the total land). This area represents an additional 41.35 ha of BG space added to the borough's land, exceeding the required 36.34 ha from the WN targets.

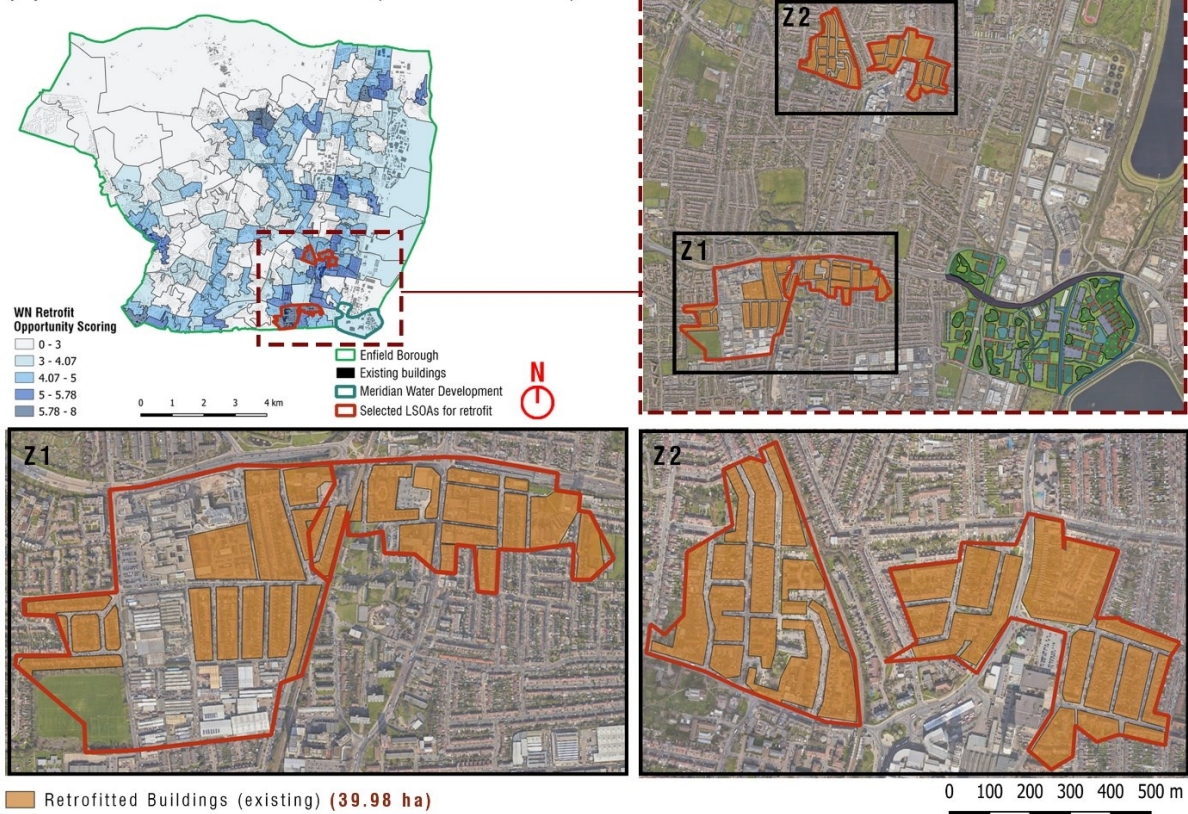
As initially anticipated, in this second scenario, the systemic design achieves WN targets for BG space within the MWDP site but falls short of achieving the building retrofit targets within its boundaries. Therefore, I develop Retrofit Scenario 2 (Figure 5.14b), where 7,996 existing homes are retrofitted across the four LSOAs selected in Figure 5.11, assuming a density of 250 existing homes per hectare. In this second scenario, both the addition of BG space within the boundaries and the building retrofit outside the boundaries surpass the targets calculated from modelling.

(a) WN Development Scenario 2 (inside MWDP)



New homes = 10,000 h. (Developers' target)
Retrofitted homes = 280 h. < 8,272 -- Needs retrofiting 7,992 existing homes outside MWDP boundaries
New BG space added to site = 41.35 ha > 36.34 ha -- Achieves WN target inside MWDP boundaries

(b) WN Retrofit Scenario 2 (outside MWDP)



Retrofitted homes = 7,996 h. > 7,992 -- Achieves WN target outside MWDP boundaries

Figure 5.14: Water Neutrality (WN) Development Scenario 2 for Meridian Water Development Plan (MWDP) based on a more compact distribution and larger area of BG space around buildings (a). BG targets are achieved inside MWDP boundaries, so WN Retrofit Scenario 2 only retrofits existing buildings outside boundaries (b; and including two zoom-in, Z1 and Z2).

5.6 Discussion

The chapter makes two key contributions. Firstly, it introduces a new application of the CityPlan framework called CityPlan-Place, which focuses on optimal spatial allocation. In this proof-of-concept, the framework is applied to achieve water-neutral urban development. Supporting this allocation is the Water Neutrality Decision Support Tool (WaNetDST), which is the second key contribution of the chapter. WaNetDST provides numerical and visual results to facilitate informed and integrated planning decisions. Figure 5.8 illustrated city-scale evaluation of water neutrality trends based on the land's physical and environmental properties. And Figures 5.9 and 5.11 demonstrated its usability at smaller scales, such as boroughs or strategic development zones. Using the tool, users like Local Planning Authorities (LPAs) or housing developers can identify baseline conditions (Figure 5.10) and develop systemic design scenarios to meet water neutrality targets (Figures 5.13 and 5.14). This entire process sets systemic conditions for urban planning, ultimately guiding the detailed design of future urban developments.

WaNetDST serves as an informative decision-support tool, offering both quantitative (numerical scoring results) and qualitative (visualisation maps) information. By comparing the Business-as-Usual (BAU) scenario with two WN design scenarios, the results highlight the significance of urban distribution and design parameters in achieving water neutrality targets within and outside development boundaries. As discussed in Chapter 3 for NC evaluation, a more compact distribution with high-rise buildings proves effective in meeting (and even exceeding) water neutrality targets for BG space within the development boundaries (Figure 5.14a). Although this chapter focuses on borough and urban development site scales, the systemic design process can be applied to other scales, such as localised strategic zones within a borough or even regional and national scales.

The first prototype of WaNetDST presents, however, a series of limitations. Currently, the datasets used are open-source and publicly available, with manageable data sizes. However, in certain cases, the datasets might need special permission (licence) to be downloaded, be difficult to be shared with the public, or require special software to be processed. Datasets may also differ in resolution, with some boroughs having more detailed data on flood risk while others rely on national studies with larger resolutions. In the first prototype of WaNetDST, I processed nine datasets grouped by the three UWS indicators, but this number can be expanded in future iterations. Some examples of

datasets that could influence the UWS indicators, and therefore WN levels, are orientation (linked to solar radiation and surface reflectance, which influence water quality and nutrients in micro-habitats; Hafeez et al., 2019); amount of rain (linked to the amount of water naturally received, therefore influencing the amount of water consumed from RWH systems, and to the level of flood risk; Fowler et al., 2021; Wu and Guo, 2021); climate (warm temperatures being linked to the amount of water consumed and water supply availability; Tao et al., 2020); level of income (linked to the amount of water consumed; Domene and Saurí, 2006); or wastewater treatment plant technology (linked to the quality of the water released to the rivers and other natural water bodies; Carey and Migliaccio, 2009); among others. In addition to these suggested datasets and being aware of the occasionally limited data availability, groundwater recharge plays a crucial role in achieving WN, especially in areas where groundwater is a significant source of freshwater (De Vries and Simmers, 2002; Al Atawneh, Cartwright and Bertone, 2021). Some of the key advantages that groundwater recharge might provide include: a) Increased water supply; b) Enhanced drought resilience; c) Reduction in surface runoff; d) Support for sustainable land use; and, e) Numerous biodiversity and ecosystem benefits (Javadi et al., 2021; Mensah et al., 2022). Additionally, the land uses that represent BGI in buildings as part of the systemic design process are currently two-dimensional and only include green roofs and green walls at this stage; however, systemic design could capture other tridimensional blue green space typologies (e.g., hanging gardens or inter-floor gardens at multiple levels), increasing the benefits of the design options.

Another limitation of WaNetDST is the subjectivity of input related to logic statements from experts and urban planners involved in its development. For instance, while most experts in participatory workshops agreed on the logic statement for population density (preferring high-density urban areas due to developed infrastructure and supply networks), some members believed the opposite could be argued, preferring to avoid additional pressure on already stressed areas. Furthermore, the primary users of WaNetDST at this stage are top-level decision-makers like LPAs and housing developers. However, future stages aim to incorporate a more inclusive bottom-up approach involving community groups and non-profit environmental organisations as part of the advisory board. This future participatory engagement might be handled with System Dynamics group modelling workshops (Pluchinotta et al., 2021), accurately analysing the contributions from each participant, and translating their feedback into Casual Loop

Diagrams that will qualitatively inform about potential leverage points inside the studied urban system (Vennix, 1996; Hovmand, 2014).

One direction for future work in WaNetDST involves scoring aggregation at the borough level and the development of a trading system among boroughs within the same city. This would allow Local Planning Authorities (LPAs) from different departments and governance bodies to trade based on their specific housing targets and current environmental properties. In the context of London, certain boroughs may face challenges in fully achieving their water neutrality (WN) targets, such as having high housing targets but low WN retrofit opportunities (Table C.2, Appendices). By implementing this trading system, boroughs can trade with other planning authorities to implement required WN design options outside their boundaries. This trading system could potentially be transformed into a credit system, similar to nitrogen pollution credits used by Gu et al. (2021), where boroughs will exchange WN credits based on their WN retrofit opportunity situation. Similar approaches have been explored in other studies (e.g., McDonald and Kerr, 2011; Lee, 2021; Hu and Zheng, 2021). The spatial map showing the aggregated WN retrofit opportunity scores at the borough level in London, along with their numerical values, can be found in Figure C.3 and Table C.2, Appendices.

Furthermore, while the information in this proof-of-concept stage was collected and processed at the LSOA and borough levels, future stages are expected to employ finer resolution maps and smaller spatial units. This would allow for more accurate opportunity scoring in WaNetDST, which can be linked to different types of land, such as greenfield, brownfield, or existing buildings. Connecting design options with land-use types will provide insights into the development capacity within each spatial unit. For example, implementing WN options in new homes would be feasible in greenfield and brownfield areas (new developable land), while retrofitting would only be possible in existing buildings (refer to Table 5.9). This additional level of complexity and accuracy in the DST results would enhance the understanding of the capacity for development in each specific spatial unit.

Table 5.8: Capacity for water-neutral urban development table comparing the land-use types with the three tactical decision categories, where green tick means developable and red cross means non-developable.

CAPACITY FOR WATER NEUTRAL URBAN DEVELOPMENT				
Land-Use Types		Greenfield	Brownfield	Existing Buildings
Tactical Decision Categories	Implement WN options in new homes	✓	✓	✗
	Retrofit existing homes	✗	✗	✓
	Add new BG space	✗	✓	✓

Finally, as previously introduced, the development of a Virtual Decision Room (VDR) will be one of the key points for future work. The VDR will automatically provide information on WaNetDST results and will be utilized by Local Planning Authorities (LPAs) and their Statutory Consultees, including organizations like the Environment Agency, Natural England, the Greater London Authority, and Thames Water, among others. These stakeholder groups will engage with the VDR in a controlled environment under the guidance of the tool developers. The VDR will facilitate informed decision-making during the early stages of the urban planning process. Ultimately, the systemic design process, supported by tools like WaNetDST and the VDR, will inform policies and recommendations for water-neutral urban planning, which will be incorporated into Local and City Plans.

5.7 Conclusions

Chapter 5 introduces the third application of CityPlan, known as CityPlan-Place, which employs a fully data-driven approach as part of its integrated evaluation toolkit. This application enables the optimal allocation of new urban developments while identifying environmental synergies across various urban scales. By combining CityPlan-Place with the previously discussed applications, CityPlan-Ecos and CityPlan-Water, the flexibility and extensive implementation of CityPlan as an expandable, dynamic, and multi-purpose framework are demonstrated. The spatial allocation component of CityPlan-Place has the potential to significantly reduce the environmental impacts of urban development in cities and foster public acceptance of transformative infrastructure interventions.

Building upon the water-neutral tactical decisions derived at the city scale in Chapter 4, a novel Multi-Criteria Decision Support Tool (MCDS) called WaNetDST was developed. In its initial prototype, WaNetDST incorporates nine datasets linked to the three Urban Water Security (UWS) indicators and provides informative visualisations and numerical assessments of systemic conditions for achieving water neutrality in London. Future stages of the work will involve expanding the DST to include a larger number of more accurate datasets and incorporating input from additional stakeholders, such as Statutory Consultees and community groups, to benefit from their expert advice. Ultimately, the integration of CityPlan-Place and WaNetDST will enhance participatory and systemic design approaches for sustainable urban planning.

Chapter 6

Summary and Conclusions

The first objective of this thesis was to conduct a comprehensive analysis of the UK's urban planning system, including an examination of key challenges and stakeholders involved in its process and operation. The second objective was to develop an integrated urban planning framework that could enhance urban sustainability and protect urban water security. The final objective was to demonstrate the applicability of this framework through several applications. To achieve these aims, I developed an infrastructure ecology framework called CityPlan, which promotes integrated urban planning across multiple scales in London. CityPlan is based on the systemic design concept, which combines traditional design and systems thinking approaches to consider the entire urban system holistically. CityPlan is a flexible and dynamic framework that can be adapted to individual urban systems, such as water, transport, energy, land, housing, etc., and linked to their environmental interdependencies, such as air and water quality, sanitation, carbon neutrality, economy, health, recreation, and wellbeing. The following sections provide a summary of this thesis (Section 6.1) and its key research contributions (Section 6.2) as well as a series of recommendations for future work (Section 6.3). In Section 6.4, a list of implications and conclusions is presented.

6.1 Summary of thesis

Increasing pressures from urban populations and global climate change are threatening the natural environment and human well-being in our cities (United Nations, 2014; Committee on Climate Change, 2019). These pressures are most evident in large metropolitan areas like London, which is the focus of this work. The consequences of these pressures might be irreversible if urban planners and policymakers do not transform the way they design, plan, and govern our urban environments. Therefore, the key motivation of this PhD thesis was to guide and inform decision-making processes toward sustainable and water-neutral urban development.

In Chapter 1, a general overview of current urbanization pressures and environmental patterns in our cities was provided. It included a background and literature review of key concepts within the thesis (e.g., infrastructure ecology, systemic design, urban ecosystem services, water neutrality, spatial allocation, systemic design options, etc.). These key concepts were linked to the purposes and components that will shape the infrastructure ecology framework. Chapter 1 reviewed the existing evaluation tools for urban sustainability and emphasised the need for integrated urban planning. Finally, it presented the aims and structure of the thesis.

In Chapter 2, I analysed the UK's planning system and focused on London as the main case study area for this work. This analysis was emphasised as a key element to identify relationships and collaborations between urban stakeholders, which will ultimately inform the development of the infrastructure ecology framework. Although London's future development is the focus of this PhD thesis, the integrated sustainability framework has the potential to be extrapolated to other areas or countries in the world. In that instance, a new analysis of their planning system and application process will be required.

In Chapter 3, I presented the generic infrastructure framework called CityPlan. This part of the work set the scene and presented the general vision of the PhD, establishing its theoretical framework and the baseline for the next chapters. CityPlan's aim was to provide a common language for key stakeholders to design sustainable and resilient urban environments. This thesis applied the CityPlan framework to three different purposes in three different applications.

The first application of the framework was called CityPlan-Ecos and focused on Urban Ecosystem Services (UES) and Natural Capital (NC) evaluation. This application used NC indicators as a proxy for generic levels of urban sustainability and looked at the Thamesmead Waterfront Development Plan (TMWDP) as the main case study area. Four urban design scenarios were developed for TMWDP to compare different levels of environmental impact. These levels were measured with the Natural Capital Planning Tool (NCPT; Hölzinger et al., 2019), which was selected for being commonly used in the urban planning context in the UK and provided numerical but qualitative scores for several UES. Findings from CityPlan-Ecos confirmed the importance of pre-planning design evaluation and showed that a more compact building distribution with larger areas of Blue Green Infrastructure (BGI) will increase the level of UES provided, which are understood as the number of benefits that citizens obtain from the natural environment and represent a good measure for urban sustainability. Although the sustainability assessment was performed at the urban development scale, larger scales might be considered in future stages, such as city, regional, or national levels. Additionally, the Natural Capital Planning Tool (NCPT) presented a series of important limitations, and more comprehensive tools might be included as part of CityPlan-Ecos.

In Chapter 4, CityPlan focused on the urban water management system and developed the second application of the framework called CityPlan-Water. This application focused on the Water Neutrality (WN) concept and evaluated Urban Water Security (UWS) at the city scale. Several urban design scenarios were explored and evaluated with the integrated water management model CityWat (Dobson and Mijic, 2021). As part of the integrated evaluation in CityPlan-Water, design options were added to CityWat's code, and a novel Water Neutrality Index was proposed to evaluate UWS indicators. The results from this part of the work were based on the 10-year housing target in London (GLA, 2021) and provided valuable insights about the level of implementation needed to minimise UWS impacts of new developments. Key findings from CityPlan-Water indicated that to fully offset the UWS impacts from new developments, it will be necessary to retrofit almost the same number of existing houses with water-neutral design options. These WN targets were understood as the tactical decisions of systemic design. Although the results were very valuable at the city scale, finer resolution models, such as semi-distributed or GIS-based water management models, might be used in the future to assess UWS indicators at the borough or urban development scales.

In Chapter 5, CityPlan was based on the spatial allocation of systemic design options and developed the third application of the framework, called CityPlan-Place. This application explored the optimal location for new development and building retrofit across different urban scales. As part of its integrated evaluation cluster, CityPlan-Place developed the Water Neutrality Decision-Support Tool (WaNetDST). This data-driven decision-support tool included nine datasets linked to the three UWS indicators and provided an informative cross-scale visualisation and numerical assessment of the systemic conditions for water-neutral London. Focusing on the WN tactical decisions obtained at the city scale in the previous Chapter 4, a systemic design exercise aided by data processing was performed on a new urban development plan. Two WN scenarios were tested against the Business As Usual (BAU) scenario in Meridian Water Development Plan (MWDP) in the London Borough of Enfield. Results showed that systemic design and building typologies considerably influence the level of achievement of WN targets inside strategic boundaries. At this stage, WaNetDST was presented as an initial prototype, but it will be expanded with a larger number and more accurate datasets in future stages of the work. The work presented in Chapter 5 combined all the knowledge developed in the previous chapters and supported the systemic design process with targets obtained from modelling and data-driven techniques. Although in this case, I continued to focus on the urban planning purpose of WN, this framework could be applied to any other urban planning purpose or individual system.

Overall, CityPlan demonstrated a strong potential for digitally-enhanced decision-making across different urban scales. Combining design and evaluation inside the framework revealed a considerable capacity for data-driven and digital strategic planning decisions, which can guide different groups of stakeholders such as housing developers, Local Planning Authorities, and water companies, among others.

6.2 Summary of contributions to knowledge

Urban planning communities, both scientific and practical, require an integrated systems framework to facilitate sustainable urban planning and water security, particularly in light of climate crises and environmental degradation. The primary contribution of this thesis is the development of such a framework, called CityPlan, which enables a comprehensive decision-making process by combining design and evaluation within the UK planning system. This framework provides a foundation for linking the planning process with data-driven and model-supported decisions that take into account both sustainability targets and design options that enable their achievement.

Another significant contribution is the insights gained through the CityPlan applications, which have indicated the importance of multiple urban sustainability purposes. The results have highlighted the critical link between sustainability assessment using a range of tools, the creation of sustainability targets, and the role of systemic urban design in achieving those targets. These contributions have several implications for future urban planning:

- To maximise a range of urban ecosystem services (UES) in a new urban development, an integrated assessment of different systemic design scenarios should be conducted at a pre-development stage, taking into account the physical properties of the land and the housing targets of urban stakeholders.
- Water neutrality targets can be established at the city scale and guide urban planners on the necessary level of interventions in new developments and the required retrofitting in existing homes to achieve WN.
- City-scale WN targets can be spatially redistributed and combined with data-driven approaches to inform the design of new urban developments and related retrofit plans that need to be implemented simultaneously to meet the WN targets.

6.3 Recommendations for future work

The framework presented in this thesis provides valuable methods to inform decision-makers towards sustainable and water-neutral urban planning and design. However, several recommendations for future work could be explored to make it more comprehensive and dynamic. These recommendations are:

- New framework applications

In this thesis, CityPlan is mainly focused on the urban water management system. However, CityPlan could be applied to other urban systems (e.g., transport, energy, land, or housing, among others). Its general structure and iterative process will remain identical, and only the purpose, decision criteria, and evaluation tools will need to be adjusted.

As a hypothetical example applied to the energy system, CityPlan could be focused on the planning purpose of urban carbon neutrality and become CityPlan-Energy (see mocked diagram in Figure 6.1). In this hypothetical example, the decision criteria will be based on offsetting urban carbon footprint, and a novel Carbon Neutrality Index will be developed based on integrated modelling (similar to the Water Neutrality Index presented in Chapter 4). CityPlan-Energy will provide carbon-neutral targets that will be achieved by implementation of carbon-neutral design options, sustainable urban form, and Blue Green Infrastructure.

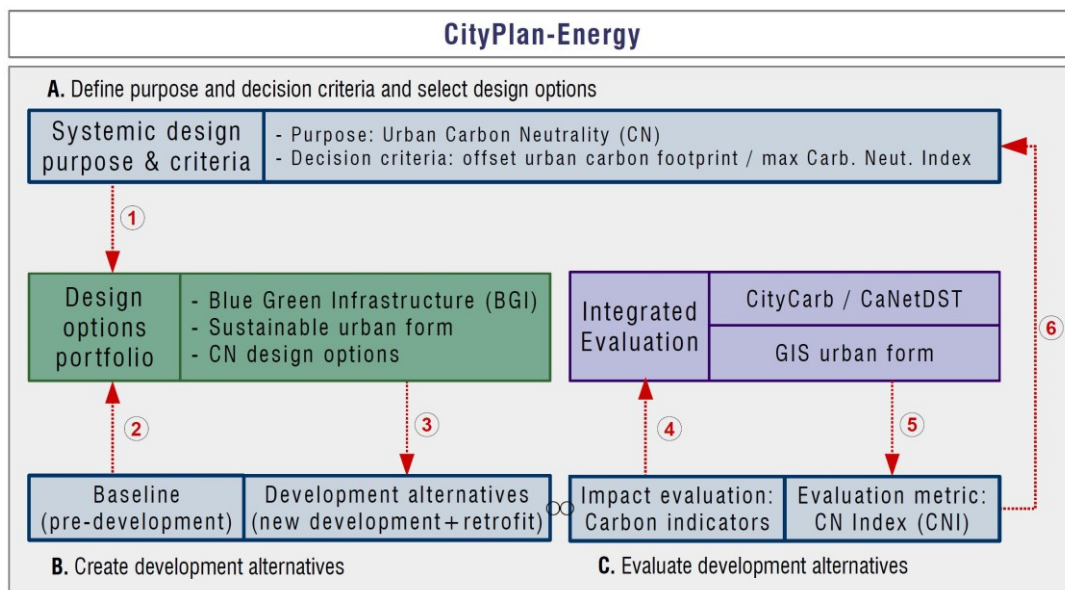


Figure 6.1: Mocked diagram of the hypothetical CityPlan-Energy systemic design and evaluation framework.

In the case of generic applications such as CityPlan-Place, the framework could look at optimal allocation of design options based on other indicators. For instance, it could be based on carbon emissions indicators for transport infrastructure design options; or on biodiversity indicators for landscape and infrastructure design options; or on air quality indicators for energy efficiency design options; among others. At the same time, these new applications of CityPlan-Place will consequently develop new versions of the Decision-Support Tool, which will introduce other datasets and different rules for preference and retrofit opportunity based on expert advice. In that instance, new trading systems across different scales (borough, city, etc.) might appear, exchanging credits for air quality, carbon emissions, biodiversity, or any other environmental metric chosen by key urban stakeholders. Ultimately, CityPlan could combine all the indicators and design options from several urban systems and become a radically integrated and systems-based evaluation and design framework.

- Expand the design options portfolio

Humans are a fundamental component of our urban ecosystems (Oke et al., 2017). There is a consistent agreement in literature that human activities significantly affect the environmental performance of new urban developments and that those activities can be included as a part of urban design options (Erell et al., 2015; Keeler et al., 2019). Hence, a new addition called socio-ecological patterns might be added to CityPlan's design options portfolio. This addition will include sustainable ways of transport (active travel, car ownership, etc.); working patterns (office-based vs. remote working, this being especially relevant after covid-19 pandemic); and, people's behaviour (energy and water consumption, etc.); among others.

- Expand the integrated evaluation

One direction for future work will be to expand the integrated evaluation of CityPlan with new models and approved certifications. One example of making CityPlan more dynamic would be to include cost-benefit analysis for proposed new urban developments. In this scenario, variables such as future maintenance and long-term benefits to businesses and society of the BGI and the water infrastructure systems will be included (Winch et al., 2020). This information will be beneficial both to developers and Local Planning Authorities (LPAs). One of the tools that might be used together with GIS spatial data is

BEST (Benefits Estimation Tool; CIRIA, 2019; row 6, Table 1.1). This tool estimates the cost of BGI under different scenarios, assigning a monetary value to the benefits they provide. Although this tool does not provide an accurate figure for the benefits from each design option, it might potentially inform decision-makers at the early stages of the systemic design process.

Approved certifications are considered a popular instrument for urban planning decision-making processes (Hewitt et al., 2019; Gouda and Masoumi, 2018; Lamy et al., 2021). Therefore, the integration of approved certifications combined with modelling results could enhance the sustainability assessment inside CityPlan. In this scenario, urban indicators will be assessed and validated against some of the most relevant approved certifications for sustainable urban design such as BREEAM Communities (Building Research Establishment Environmental Assessment Method; BRE Global, 2017), LEED-ND (Leadership in Energy and Environmental Design; USGBC, 2012), CASBEE-UD (Comprehensive Assessment System for Built Environment Efficiency; IBEC, 2014) or PASSIVEHAUS (Passive House Institute, 2020). See a detailed review of urban sustainability certifications and water efficiency labelling schemes in Appendix E.

Although these certifications sometimes have limitations (Kaur and Garg, 2019), there are sources in the literature that have sought a revised method, with the Comprehensive Assessment Method for Sustainable Urban Development (CAMSUD; Ali-Toudert et al., 2020) being one of the most attractive options. CAMSUD provides a detailed study of the most widely-used urban rating systems around the world, comparing their strengths and weaknesses. CAMSUD is divided into eight categories and 40 criteria, which could be linked with different indicators within CityPlan. As an initial prototype of this aspect of the work, I conducted a review of water-efficient labelling schemes and developed the prototype of a Water Efficiency Certificate (WEC; see Appendix E.3). In this hypothetical application, CityPlan would combine modelling simulations with the Water Efficiency Certificate and demonstrate real impact to urban stakeholders, such as designers, housing developers, and policy-makers.

Finally, in this PhD, I only used historical data for both climate and other types of information. In future stages, both CityWat and WaNetDST (or any other selected evaluation tool) will include future climate change scenarios and conduct simulations based on future predictions. This will enable a more comprehensive understanding of

future results and the ability to realistically plan long-term projects such as the Thamesmead Waterfront Development Plan (TMWDP) or the Meridian Water Development Plan (MWDP), which are designed in different phases that span the next 20-30 years. In addition, other selected models could provide dynamic population trends and apply Life Cycle Assessment (LCA) methods to urban design and planning (Bidstrup et al., 2015; Mirabella et al., 2018). An additional direction for future work will involve to connect the UES and NC assessment developed in Chapter 3 with the WN impact assessment in Chapter 4 and the spatial allocation based on UWS indicators developed in Chapter 5. This will help to integrate different purposes of the CityPlan framework and to take a more holistic approach by evaluating and improving the criteria and objectives of the assessment.

▪ Explore urban system boundaries

In urban systems, physical boundaries rarely align with decision-making and governance boundaries (Boeing, 2018; Turner et al., 2020). Exploring this complexity is a promising direction for future work in the sustainability evaluation of CityPlan across scales. As an example of this complexity, I conducted a preliminary study of water management boundaries within the London Borough of Enfield (LBE). The LBE contains three river catchments (Turkey-Cuffley Brook, Salmons Brook, and Pymmes Brook; see Figure 6.2). The boundaries of these three river catchments do not perfectly overlap with the boundaries of the LBE or the boundaries of the Deephams Waster Water Zone (WWZ). While some of these boundaries are purely physical (river catchments), others are more closely tied to decision-making and governance (e.g., wastewater zones and borough). This situation highlights the great complexity of water management at the borough scale and provides inspiration for future research.

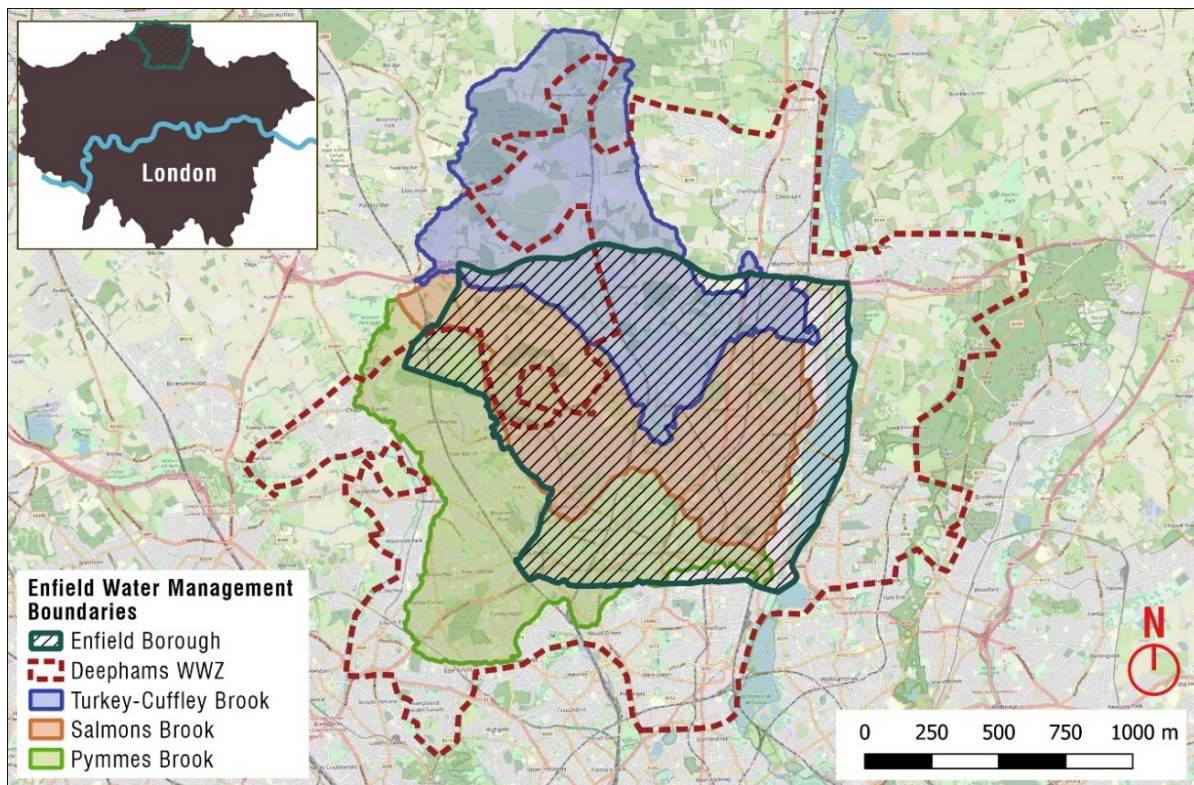


Figure 6.2: Map of the various water management areas and boundaries surrounding the London Borough of Enfield. The location of Enfield is also indicated on the top left corner of the London map.

- Stakeholder and community engagement

Participatory modelling exercises are particularly attractive to policy and decision-makers in urban planning and design (Rauch et al., 2017; Ataman and Tuncer, 2022). Very often, a diverse group of stakeholders presents different visions of the same issue, making it difficult to achieve a common understanding and consensus (Head, 2022). Therefore, an effective approach to understanding these decision-making processes and connecting multiple, often conflicting, stakeholder goals is through participatory System Dynamics techniques (Eker et al., 2018; Király and Miskolczi, 2019; Pluchinotta et al., 2021).

As part of the expert advice needed in CityPlan-Place and the development of WaNetDST in Chapter 5, I have already collaborated with the System Dynamics team inside CAMELLIA and VENTURA research projects. In this case, we engaged with Local Planning Authorities and their advisory groups to obtain feedback about the logic statements and scoring of datasets. However, in addition to these preliminary activities and considering CityPlan's iterative process, a potential direction for future work would be to expand the engagement to community groups and develop new participatory processes based on System Dynamics. These participatory processes will start at the pre-planning stage and develop design-consultation exercises in the form of group modelling workshops (Richardson and Andersen, 1995).

Finally, collaboration with industry and policy groups would be very valuable to test and practically implement decision-support and evaluation tools, such as Virtual Decision Rooms (VDRs). These VDRs will deliver the systemic design conditions to wider audiences and professionals, presenting a strong potential to be included as part of a City or Local Plan development process. In the end, the development of VDRs and stakeholder participatory platforms may enable the development of novel software for commercial or public-use purposes in engineering and urban design practices.

6.4 Implications and conclusions

Human civilization has had a profound impact on our planet in recent decades, resulting in numerous environmental stresses. Extensive use of natural resources and land transformation for urbanisation and agricultural purposes have led to widespread air and water pollution, scarcity, habitat loss, and climate change. These stresses are impacting our planet's ecosystems, resulting in a decline in biodiversity, wellbeing, and the provision of other essential ecosystem services. Additionally, the rapid growth of urbanisation and industrialisation is increasing the demand for energy, water, and other resources, creating further pressure on the natural environment. As a result, the need to address these issues and develop a more sustainable approach to planning our cities has become increasingly urgent.

Having these environmental issues in mind and after analysing the UK's urban planning system, this PhD thesis presented the proof-of-concept of an infrastructure ecology framework called CityPlan. This framework enables improved assessment and decision-making for multi-stakeholder urban development projects, following an iterative process that links design options with an evolving integrated evaluation toolkit. All results are spatially represented in GIS format to achieve more reliable and accurate results, as I strongly believe that good graphical representation is key to making results more understandable and shareable among numerous stakeholders. In this thesis, I developed three applications of CityPlan based on three individual systemic design purposes: a) urban ecosystem services (as a proxy for generic levels of urban sustainability); b) water neutrality (as a novel approach within the water management system); and c) optimal spatial allocation of design options (looking at synergies between developers' preferences and retrofitting opportunities). The three framework applications demonstrated CityPlan's flexibility, with great potential for being extended to other urban systems.

In conclusion, this thesis has made a significant contribution to the field of urban planning and sustainable design. By examining the results from CityPlan based on three different purposes, this study demonstrated the importance of digitally-enhanced and evidence-based decision-making in urban planning. Further research in this area is needed to expand the evaluation toolkit and design portfolio of CityPlan and to actively involve community and industry groups to achieve a more comprehensive study. As a final point, I believe the work presented in this thesis will help to reduce urban environmental stresses, promote new dialogues among urban stakeholders, better inform urban planners, and ultimately support a more sustainable urban future for homeowners and residents.

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Appendices

Appendix A: Supporting information and results for Chapter 3

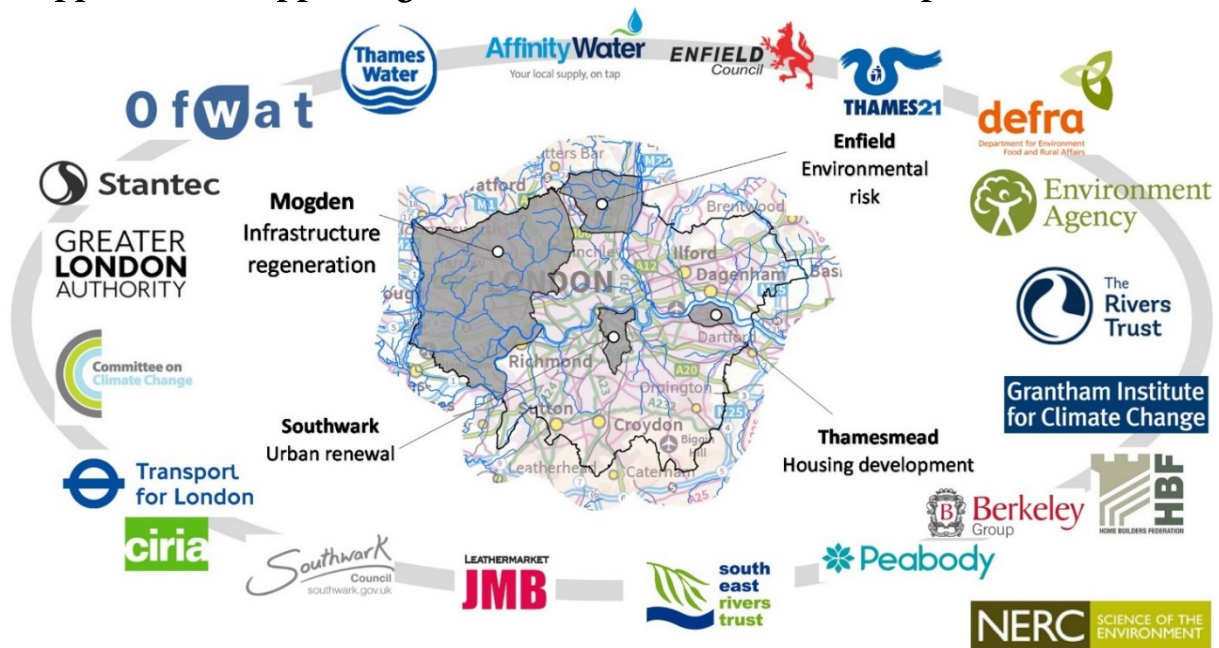


Figure A.1: Case-study areas inside CAMELLIA research project (London map) and partners involved (logos around the map). Source: © CAMELLIA programme.

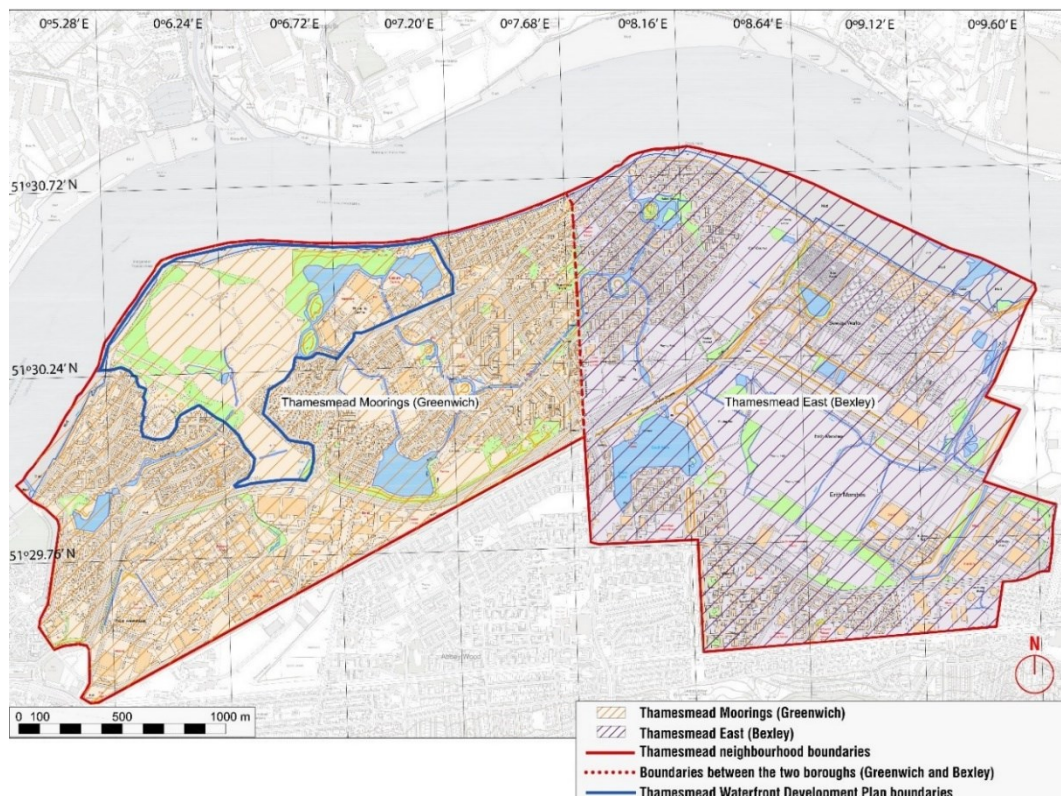


Figure A.2: Thamesmead's boundary map between two London boroughs: Greenwich and Bexley. Also, the Thamesmead Waterfront Development Plan area is circled by the blue line.



Figure A.3: Historic picture of children on Thamesmead's raised walkways (left) and the same features now seen as a symbol of urban decay (right). Source: © George Plemper (left) and Getty Images (right).



Figure A.4: Aerial views of the current development site for Thamesmead Waterfront Development Plan (TMWDP, marked in red above) and Peabody developers' vision for the TMWDP by the end of the development construction period (marked in red below). Source: © Lendlease Corporation and Peabody Housing Association.

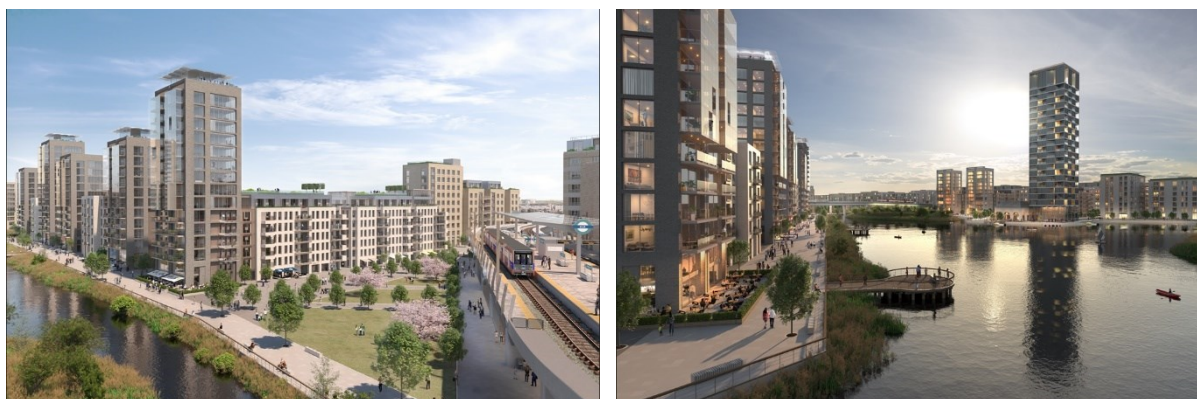


Figure A.5: 3D rendered images for future's Thamesmead Waterfront Development Plan (TMWDP) by the end of the development construction period. Source: © Lifschutz Davidson Sandilands (LDS) Architects and Peabody Housing Association.

Table A.1: Estimated densities for the built-up areas for every urban design scenario studied in Thamesmead Waterfront Development Plan (MWDP) and compared to Peabody's target of 11,500 new homes. Note: Scenario 1 and Scenario 2 are calculated as "gross density", considering that all these hectares are completely occupied as solid and compact buildings blocks.

ESTIMATED DENSITIES FOR TMWDP SYSTEMIC DESIGN SCENARIOS

SCENARIO 1 - BAU

Land-use	N. of ha	Dwellings per ha	Total n. of dwellings in this land-use
High-density	28.75	300	8625
Medium density	15.88	172	2731
Low density	2.44	60	146
TOTAL N. OF DWELLINGS	11503		

SCENARIO 2

Land-use	N. of ha	Dwellings per ha	Total n. of dwellings in this land-use
High-density with green roofs	28.75	300	8625
Medium density with green walls	18.32	157	2876
TOTAL N. OF DWELLINGS	11501		

SCENARIO 3

Land-use	N. of ha	Dwellings per ha	Total n. of dwellings in this land-use
High-density with green roofs	10.02	960	9619
Medium density with green walls	8.68	217	1884
TOTAL N. OF DWELLINGS	11503		

SCENARIO 4

Land-use	N. of ha	Dwellings per ha	Total n. of dwellings in this land-use
High-density with green roofs	5.73	1500	8595
Medium density with green walls	8.82	330	2911
TOTAL N. OF DWELLINGS	11506		

Note: These calculations consider developer's housing target of 11,500 new homes in TMWDP site.

Appendix B: Supporting information and results for Chapter 4

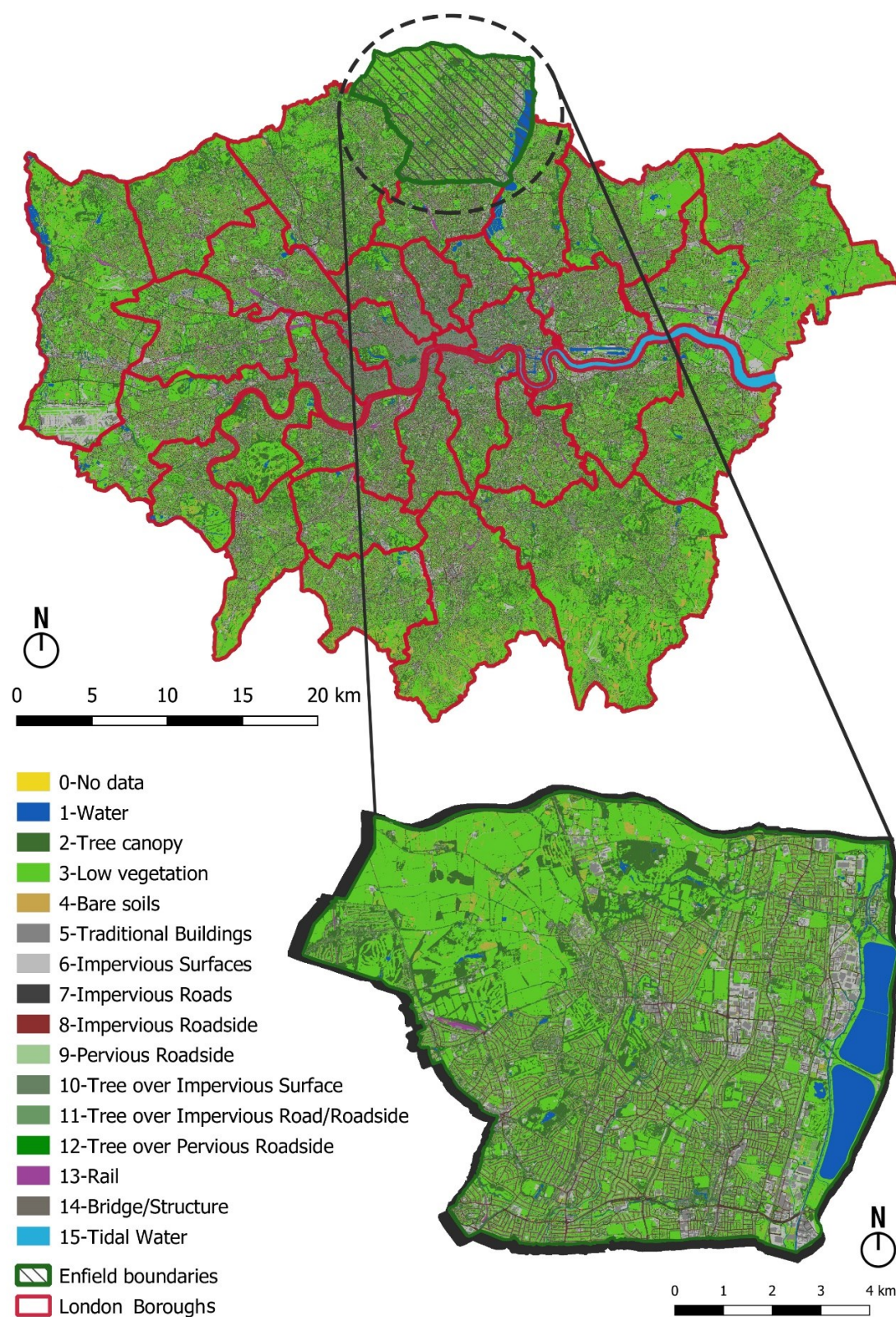


Figure B.1: London's land-use 2x2 m resolution raster map with borough boundaries marked in red (above) and London Borough of Enfield (marked and shaded in green, above; and shaded zoom, below). Adapted from © British Geological Survey.

Table B1: Variables in the systemic design scenario development for CityPlan-Water in London. The data shown in this table is introduced in the CityWat evaluation model. Data sources: British Geological Survey landcover dataset and Census 2011.

Systemic Design 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)
London area (km ²)	1,572.12	1,572.12	1,572.12	1,572.12	1,572.12	1,572.12	1,572.12	1,572.12	1,572.12	1,572.12	1,572.12	1,572.12	1,572.12	1,572.12
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
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 B2: Results of the Urban Water Security (UWS) indicators in absolute numbers from the CityWat model in each scenario at city scale: 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

Appendix C: Supporting information and results for Chapter 5



Figure C.1: Aerial views of the current development site for Meridian Water Development Plan (MWDP, marked in red above) and Enfield Council developers' vision for the MWDP by the end of the development construction period (marked in red below). Source: © Hawkins Brown and London Borough of Enfield Council.



Figure C.2: 3D rendered images for future's Meridian Water Development Plan (MWDP) by the end of the development construction period. Source: © Hawkins Brown and London Borough of Enfield Council.

Table C.1: Estimated densities for the built-up areas in the three systemic design scenarios studied in Meridian Water Development Plan (MWDP) and compared to Enfield Council's target of 10,000 new homes. Note: BAU Scenario and WN Scenario 1 are calculated as "gross density", considering that all these hectares are completely occupied as solid and compact buildings blocks.

ESTIMATED DENSITIES FOR MWDP SYSTEMIC DESIGN SCENARIOS			
SCENARIO 1 - BAU			
Land-use	N. of ha	Dwellings per ha	Total n. of dwellings in this land-use
High-density	13.75	406	5583
Medium density	23.30	190	4427
TOTAL N. OF DWELLINGS	10010		
WN SCENARIO 1			
Land-use	N. of ha	Dwellings per ha	Total n. of dwellings in this land-use
High-density with green roofs	13.75	406	5583
Medium density with green walls	23.30	190	4427
TOTAL N. OF DWELLINGS	10010		
WN SCENARIO 2			
Land-use	N. of ha	Dwellings per ha	Total n. of dwellings in this land-use
High-density with green roofs	13.30	640	8512
Medium density with green walls	8.40	178	1495
TOTAL N. OF DWELLINGS	10007		

Note: These calculations consider developer's housing target of 10,000 new homes in MWDP site.

Table C.2: Water Neutrality (WN) tactical decisions in each London borough based on the 10-year housing target from the New London Plan (GLA, 2021) and the housing and BGI retrofit targets obtained from integrated modelling in Chapter 4 (brown columns in the middle). Those are then compared with the aggregated WN retrofit opportunity scoring per borough (blue column on the right).

WN TACTICAL DECISIONS (TARGETS)					WN RETROFIT OPPORTUNITY SCORING
(From the New London Plan, 2021)			(From integrated modelling simulations)		
Planning Authority	Ten year housing target (N. homes)	Percentage from total London target (%)	Retrofit housing target (N. homes)	BGI retrofit target (m ²)	
Barking & Dagenham	19,440	3.7	16,080	706,409	4.9
Barnet	23,640	4.5	19,554	859,028	4.1
Bexley	6,850	1.3	5,666	248,915	1.7
Brent	23,250	4.4	19,232	844,856	7.2
Bromley	7,740	1.5	6,402	281,255	2.2
Camden	10,380	2.0	8,586	377,187	1.1
City of London	1,460	0.3	1,208	53,053	4.3
Croydon	20,790	4.0	17,197	755,465	2.2
Ealing	21,570	4.1	17,842	783,809	3.1
Enfield	12,460	2.4	10,306	452,770	4.1
Greenwich	28,240	5.4	23,359	1,026,182	4.6
Hackney	13,280	2.5	10,985	482,567	3.7
Hammersmith & Fulham	16,090	3.1	13,309	584,677	6.8
Haringey	15,920	3.0	13,168	578,499	4.9
Harrow	8,020	1.5	6,634	291,430	5.9
Havering	12,850	2.5	10,629	466,942	1.9
Hillingdon	10,830	2.1	8,958	393,540	3.4
Hounslow	17,820	3.4	14,740	647,541	2
Islington	7,750	1.5	6,411	281,619	4
Kensington & Chelsea	4,480	0.9	3,706	162,794	7.4
Kingston	9,640	1.8	7,974	350,297	3.1
Lambeth	13,350	2.6	11,043	485,111	5.6
Lewisham	16,670	3.2	13,789	605,753	3
London Legacy Dev. C.	21,540	4.1	17,817	782,718	-
Merton	9,180	1.8	7,593	333,582	5.3
Newham	32,800	6.3	27,131	1,191,883	4.7
Old OakPrk Royal D. C.	13,670	2.6	11,307	496,739	-
Redbridge	14,090	2.7	11,655	512,001	4.7
Richmond	4,110	0.8	3,400	149,349	2.3
Southwark	23,550	4.5	19,480	855,758	2.9
Sutton	4,690	0.9	3,879	170,425	5
Tower Hamlets	34,730	6.6	28,727	1,262,015	5.1
Waltham Forest	12,640	2.4	10,455	459,311	2.8
Wandsworth	19,500	3.7	16,130	708,589	2.2
Westminster	9,850	1.9	8,148	357,928	6.2
TOTAL (LONDON)	522,870	100.00	432,500	19,000,000	

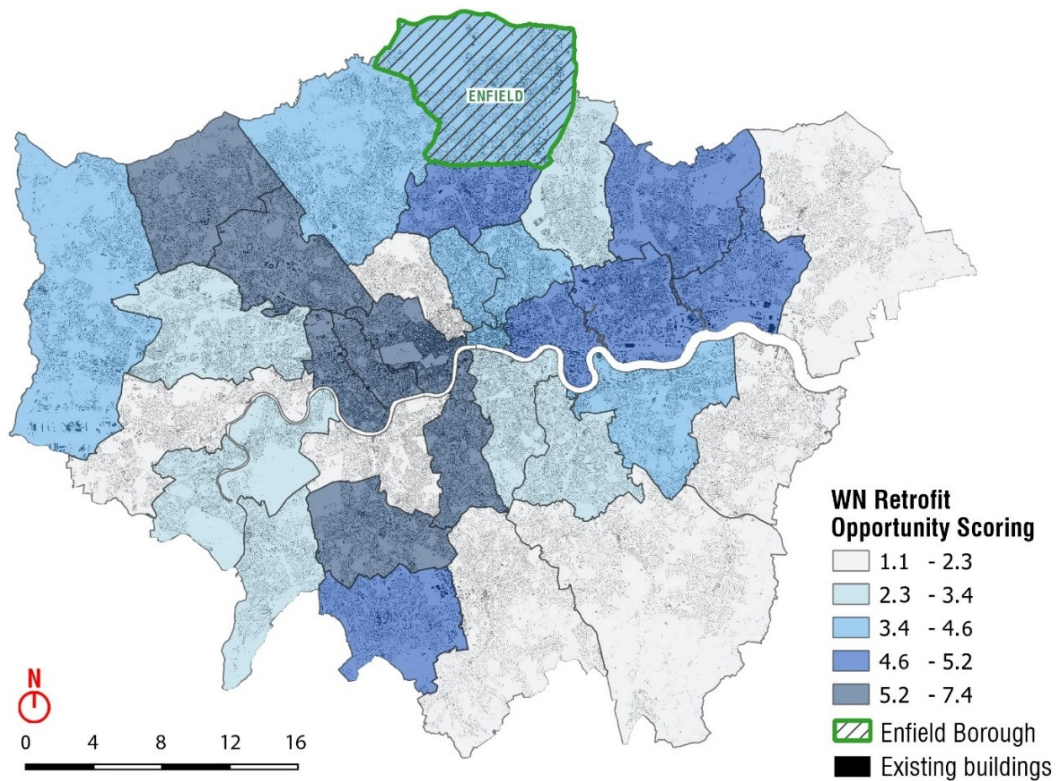


Figure C.3: WaNetDST aggregated WN retrofit opportunity scoring at borough scale in London, highlighting the London Borough of Enfield in green.

As a practical example for this hypothetical trading system at borough level, I looked at the LBE as our main case study area (marked in green in Figure 5.15). The LBE presents an aggregated WN retrofit opportunity score of 4.1, which might be considered relatively low compared to its housing target of 12,460 new homes (see all numerical values in the Table C.2, Appendices). In this case, the LBE could partially achieve the WN targets inside its own boundaries and then trade with other boroughs to fully achieve WN (in a similar logic as the systemic design process shown in Figure 5.13 and Figure 5.14). Good examples of boroughs that could trade with the LBE are found in the city centre like Westminster (i.e., WN retrofit opportunity scoring = 6.2), Kensington and Chelsea (i.e., WN retrofit opportunity scoring = 7.4), or Hammersmith and Fulham, (i.e., WN retrofit opportunity scoring = 6.8; Figure 5.15 and Table C.2). In addition, it might be the case that one borough is more concerned about one of the UWS indicators (e.g., one borough presents more flood risk impacts, while another is higher in terms of consumer demand pressures). In that case, they could trade with certain WN design options that mostly improve the UWS indicator from which they are mostly affected (see Table 4.2, Chapter 4). In the end, once a certain number of credits are exchanged and a series of WN options implemented, the aggregated WN retrofit scoring of both the buyer and the seller would become lower and datasets of the DST updated.

Appendix D: Supporting information for Device Efficiency calculations

This Appendix D includes the allocation of device number, intensity, frequency use, and duration for the Device Efficiency (DE) calculations. The first step to calculate the DE and the average Per Capita Consumption (PCC) will be to allocate a certain number of devices to each household and determine their efficiency properties. Based on the UK Census, there are three types of buildings typologies: a) bungalow, b) flat-maisonette, and c) house. The latter containing three sub-categories: c1) terraced, c2) semi-detached, and c3) detached. In addition, housing buildings will generally contain two types of water devices: 1) kitchen devices, and 2) bathroom devices. The number of these two types of devices will be closely related to the number of kitchen/s and bathroom/s in each household. Therefore, after connecting the building typologies and the size of households, I assumed only one kitchen per household (independently of the household size) and different number of bathrooms depending on the number of bedrooms inside the house (Table D.1).

Table D.1: Number of assumed bathrooms for the Device Efficiency calculations based on building typology and size of households. Adapted from Lu et al., 2021.

Number of bedrooms	Building Typology				
	Bungalow	Flat-Maisonette	House		
			Terraced	Semi-detached	Detached
		Number of bathrooms			
1	1	1	1	1	1
2	1	1	1	1	1
3	2	2	2	2	2
4+	3	3	3	3	3

Following a similar logic, I need to calculate the total number of devices in each building typology and size of housing. In this case, I assume one kitchen tap and one washing machine per household (independently of the household size), and add a correction of 50% of households owning a dishwasher (dishwasher ownership percentage from Holst, 2020). In addition, the number of WCs and the number of bathroom taps will be equivalent to the number of bathrooms per household. Finally, to calculate the number of bathtubs or showers in each case, I assume the values in the following Table D.2 and Table D.3.

Table D.2: Number of assumed bathtubs for the Device Efficiency calculations based on building typology and size of households. Adapted from Lu et al., 2021.

Number of bedrooms	Building Typology				
	Bungalow	Flat-Maisonette	House		
			Terraced	Semi-detached	Detached
	Number of bathtubs				
1	0	0	0	0	0
2	0	0	0	0	0
3	1	1	1	1	1
4+	1	1	1	1	1

Table D.3: Number of assumed showers for the Device Efficiency calculations based on building typology and size of households. Adapted from Lu et al., 2021.

Number of bedrooms	Building Typology				
	Bungalow	Flat-Maisonette	House		
			Terraced	Semi-detached	Detached
	Number of showers				
1	1	1	1	1	1
2	1	1	1	1	1
3	1	1	1	1	1
4+	2	2	2	2	2

Following the three HEL explained in Section 5.3.2, low HEL will present the highest intensity and high HEL the lowest intensity. These three HEL linked to the efficiency values in housing water devices will determine the device intensity necessary to calculate the DE. As water devices might present different standards depending on the manufacturing country, I averaged the values from several labelling schemes across the world (see review section in Appendix E.2). The next Table A1.4 shows averaged efficiency ranges for minimum and maximum number of litres (l) for several devices based on the classified labelling schemes in Table E.1.

Table D.4: Average efficiency ranges in litres (l) for several types of devices. Adapted from Lu et al., 2021.

Water devices	Range of efficiency values	
	Minimum (l)	Maximum (l)
Shower (l/min)	6.9	12.1
Bathroom tap (l/min)	3.7	8.6
Kitchen tap (l/min)	5.6	11.6
Dishwasher (l/wash)	12.2	17.8
Washing machine (l/wash)	44	66
WC single flush (l/flush)	4.1	6.0
WC dual flush total discharge (l/flush)	4.0	6.3
WC dual flush low discharge (l/flush)	2.8	4.0

However, this efficiency values should be adjusted and calibrated based on the real conditions of water consumption in (London Energy Saving Trust & Environment Agency Wales, 2012; Vieira, Jorge and Covas, 2017) and following the three HEL explained in 5.4.1. In this case, I average the WCs of single and dual flush only in type of device, and assume the total number of litres (l) per use of shower and bathtub. Hence, the efficiency values in each device based on the the three HEL in London and used for the DE calculations are the ones in Table D.5:

Table D.5: Average efficiency ranges in litres (l) for several types of devices in London following the three Housing Efficiency Levels (HEL). Adapted from Lu et al., 2021.

Water devices	House Efficiency Level (HEL) in London		
	Low	Medium	High
Shower (l/min)	10	8	6
Bathroom tap (l/min)	8	6	4
Kitchen tap (l/min)	12	8	6
Dishwasher (l/wash)	15	12	9
Washing machine (l/wash)	66	55	44
WC (l/flush)	6	4.5	3.5
Bathtub (l/use)	150	120	100

Finally, the efficiency (number of litres, l) needs to be combined with the frequency of use (Table D.6), which follows the end-use model by Blokker et al. (2010), and adjusts the database from UK Research Department (2015) to a achieve a closer value to the current actual average daily PPC in London. The frequency use values assumed for the DE calculations are the ones in Table D.6:

Table D.6: Average frequency use (times/day per person or per household) and duration (min if applicable) for several types of devices in London. Adapted from Lu et al., 2021.

Water devices	House Efficiency Level (HEL) in London	
	Frequency (times / day)	Duration (min)
Shower (l/min)	0.6 t / person / day	10
Bathroom tap (l/min)	4.1 t / person / day	6
Kitchen tap (l/min)	12.6 t / household / day	0.27
Dishwasher (l/wash)	0.25 t / household / day	-
Washing machine (l/wash)	0.3 t / household / day	-
WC (l/flush)	6 t / person / day	-
Bathtub (l/use)	0.44 t / person / day	-

Appendix E: Supporting information for approved certifications

E.1 Urban planning certifications

There are numerous urban sustainability assessment and certification systems being used all over the world. Urban sustainability certifications are generally designed to reduce the adverse environmental impacts and improve the quality of life. Five popular urban sustainability certifications (i.e., BREEAM-Communities, LEED, Green Star, DGNB-NSQ, and CASBEE-UD) are reviewed in this Appendix E from the aspect of boundary, lifecycle, assessable types, international usages, methods of rating, and procedures:

- BREEAM-community is a British sustainability assessment system (Building Research Establishment Environmental Assessment Method; BRE Global, 2017). The scope of BREEAM usually ranges from moderate to large development including buildings, infrastructure and master-planning projects. Its lifecycle starts from new construction, goes to in-use and ends at refurbishment. BREEAM can assess multi-used regions (Ali-Toudert et al., 2020). It is mainly used in the UK but also has some international uses.
- LEED is another rating system for green building developed by the US Green Building Council (USGBC). LEED ND stands for LEED for Neighbourhood Development and explores sustainable neighbourhoods' development (Leadership in Energy and Environmental Design; USGBC, 2012). LEED works for the entire lifecycle phases in new urban development from

plan to operation and maintenance after the development finishes. All types of building can be assessed and it has been used globally.

- Green Star-Community is an Australian voluntary rating system. By protecting ecosystem and biodiversity, improve resilience, relieving the bad impacts of climate change and improving the quality of life, the objectives of Green Star are transforming the built environment to a more sustainable condition. Its assessment lifecycle includes development plans and the implementation of the plan when design and constructions are being carried out. A mix of buildings are only eligible to be assessed when they are within class 1 to class 9 set by the Australian building code (Ali-Toudert et al., 2020). It is applicable in Australia.
- DGNB-NSQ originated in Germany. The scope refers to urban district where two or more buildings stand along with the surrounding public areas (Ali-Toudert et al., 2020). Its lifecycle phase covers from the beginning to the completion of urban district (Zeinal Hamedani and Huber, 2012). DGNB-NSQ assesses both residential non-residential buildings but with strict proportion requirement as a prerequisite which is 10% and 90% for residential and non-residential buildings respectively (DGNB, 2012). It is used in the Europe with European standards and norms but is trying to be adopted internationally (DGNB, 2012).
- The last is CASBEE-UD which is a Japanese method for rating the performance of the built environment and has different tools for buildings, market promotion, cities, heat island and many other categories (IBEC, n.d.). Its assessment phase is usually the completion phase but sometimes interim suggestions are recommended (DGNB, 2012). This assessment scope of this method includes both housing and non-housing buildings but expressed in percentage (IBEC, 2014). It mainly works for development in Japan and some Asian countries (IBEC, 2014).

As for the methods of rating, except for Green Star-community which lacks verification, all the other systems give quantitative ratings for sustainable targets when possible but if the targets cannot be quantified, the qualitative assessment will be given (Ali-Toudert et al., 2020). The rating levels of these systems are referred to local standards of laws (Ali-Toudert et al., 2020) which are different from how the rating looks in this work which follows the real situation of water consumption levels. The certification procedures are similar because the documentation and relevant systematic compilation preparation are the first step and the documentation will be sent to certification body directly through a professional software. And

also, because the accredited assessor will start the certification which includes the certification body's formal confirmation and skill exhibition for certification exams usually provided by each system's author or its affiliated institutions (Ali-Toudert et al., 2020). The length of validation varies from system to system.

E.2 Water efficiency labelling schemes

Water efficiency labelling schemes are used to assess the efficiency of water using devices with regard to the volumes or flows (Jorge, 2014). The water labelling on the products can help customers to take better decisions when choosing their ideal water-using devices. A mandatory water labelling scheme was predicted to contribute to more than 1600 Ml/d of water saving by 2045, £36 billion of utility bills saving per household and 50 Mt of CO₂ emission reduction in England in 25 years (Waterwise, 2019). Different water efficiency labelling schemes are used nationally or internationally focusing on one or few specific markets. If schemes could be promoted all over the world, then the cross-market benefits would be significant (Burton et al., 2019). Table E.1 shows a summary of six water efficiency labelling schemes all over the world which are used in this work to determine the efficiency ranges of devices.

Table E.1: Summary of six water efficiency labelling schemes used worldwide separated by country, name, voluntary vs mandatory, and leading stakeholders. Adapted from Lu et al., 2021.

Area / Country	Name of the Water Efficiency Labelling Scheme	Voluntary / Mandatory	Led by
Australia	WELS	Mandatory	Government
Australia / New Zealand	AS/NZ 6400:2016	Mandatory	Government
EU	WELL	Voluntary	Industry
Portugal	ANQIP	Voluntary	NGO
UK	CSH	(withdrawn)	Government
USA	WaterSense	Voluntary	Government

E.3 Water Efficiency Certificate prototype

Based on the data collection and processing stage explained in Section 5.2.2, I developed the prototype of a certification called the Water Efficiency Certificate (WEC). WEC is a document that can be used for water efficiency evaluation and provide water saving suggestions. House Efficiency Level and Device Efficiency (Section 5.3.2) are two important criteria to develop the WEC. WEC contains the following information: building physical characteristics, water efficiency rating, DE rating, potential water bills saving, and recommendations. Although the WEC is not a formal certificate and still needs administrative approval, it can be the basic framework for a more comprehensive water sustainability evaluation system in the future.

Although the WEC can perform at different urban scales (from city to individual households), at this stage, it was developed at the borough level as a working example to be consistent with the work in previous sections and collaboration with Local Planning Authorities. Therefore, PCC and DE (both household and individual devices) were aggregated and visualised at the borough level to be consistent with the scale set for the certificate. These aggregated values at a borough scale were the ones used in the certificate.

The certificate contains four parts. An example brochure for the Enfield borough is shown below (Figure E.1). The first part introduces basic physical characteristics of the borough including the name, borough code, average household size, daily water consumption, DES and HAI. The aim of this WEC is to firstly compare with people living around to know whether the assessed region is water efficient or not, then secondly tell the residents the potential water bills saving if they could all use the most efficient devices and finally give some water saving recommendations to help residents to save more.

The Second part is water efficiency rating. The less the water consumption is, the better the grade will be. The third part contains estimated annual cost and potential annual saving of devices and water bills. The efficiency levels of devices are also included in the table on page 2. The savings are calculated by comparing current situation and proposed situation where all the devices belong to high efficiency level. The methods of improving water efficiency could also be change according to other considerations. The last part is recommendations of

other actions except installing efficient devices to save more water and use water more efficiently.

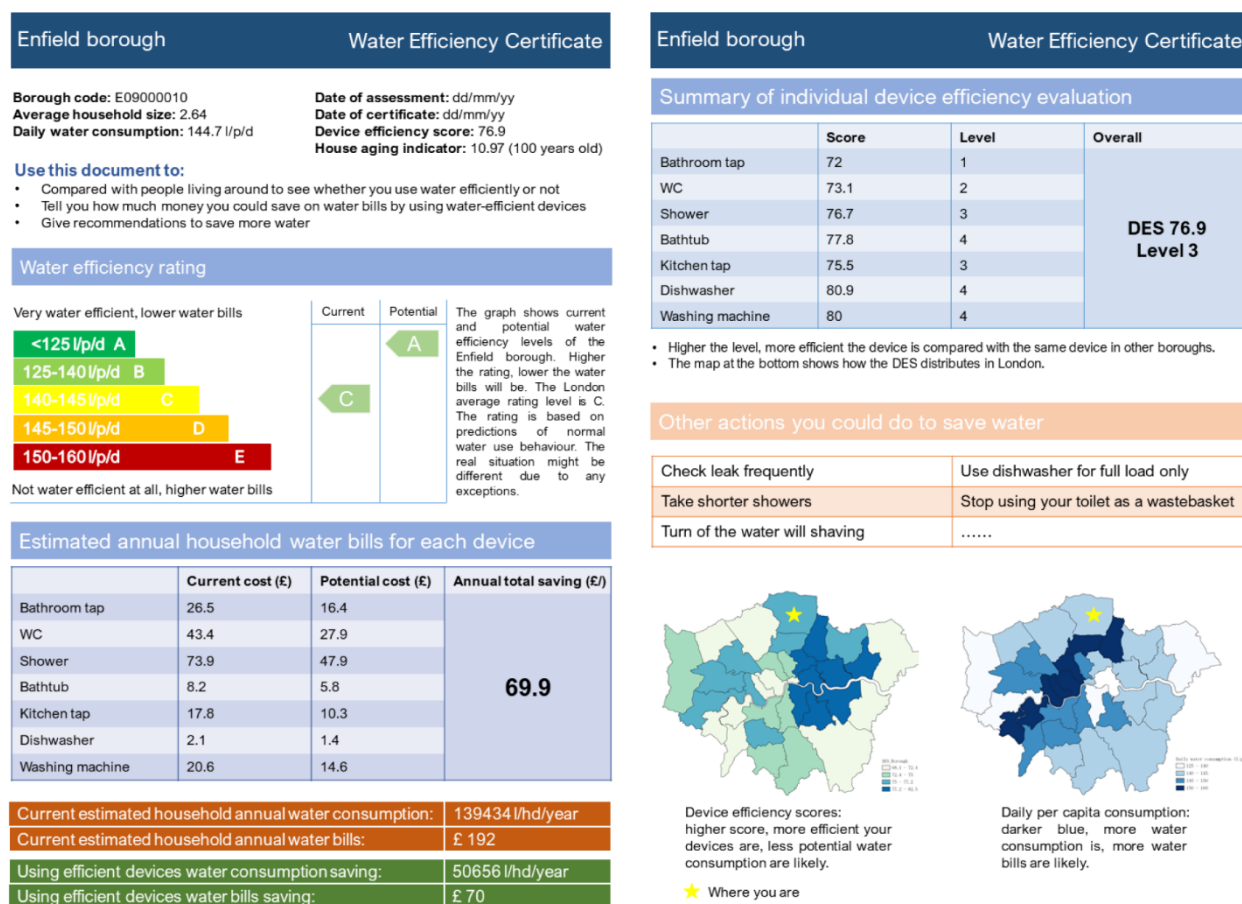


Figure E.1: Mocked diagram of the Water Efficiency Certificate (WEC) focused on the London Borough of Enfield (LBE). In this case, the DES is 76.9 (Level 3) and potential annual savings are £69.9 per household if efficient appliances are installed. Adapted from Lu et al., 2021.

**Imperial College
London**

