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Systems Thinking in Water Neutrality Governance: Moving from system failures to resilient urban water systems

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ABSTRACT

Neutrality-oriented environmental policies shift from a static perspective of environmental policy goals to a dynamic view that considers counterbalances, offsets, and gains in the system, requiring governance approaches and institutions to embrace cross-system complexities and interactions. In the water sector, the concept of water neutrality (WN) leverages systemic design technical options that can enhance the resilience and counteracts climate change stresses, shocks and uncertainties. This research explores how systemic design solutions can be integrated into WN governance, taking into account the institutional challenges and cross-sectoral interactions in water systems. Through a case study of WN in Manchester, UK, we develop a Causal Loop Diagram (CLD) and show feedback mechanisms of WN governance, drawing from participatory system dynamics, a systems thinking method. The CLD maps out institutional pathways that cross link governance and hydrological system. We share insights into three fundamental dynamics of WN governance observed in the institutional pathways: temporal (timescales of climate impact and management decisions), boundary (hydrological and administrative alignment), and feedback dynamics (structure of how hydrological and governance systems interconnect). We further explore how participatory systems thinking support a move towards neutral and resilient water system and integration of systemic options.

1. Introduction

Water resources are essential for both human well-being and the future of sustainable development (United Nations [UN] Environment Programme, 2021). In the UK, Water Neutrality (WN) emerged as a notable concept in urban water management. Traditionally, WN focused on offsetting the additional water demand generated by new urban developments (Environment Agency, 2009). More recent studies have expanded the initial scope with two additional urban water security indicators - flood risk, and river water quality- helping decision-makers minimize and offset the environmental impacts of urban growth comprehensively (Hoekstra, 2008; Nel et al., 2009; Jensen and Wu, 2018; Puchol-Salort et al., 2022; Kumar et al., 2024). However, despite advances in global actions, almost at the halfway point of the 2030 agenda (UN 2015), only 15 % of the Sustainable Development Goals (SDGs) were on track (World Meteorological Organization, 2023). Climate change and extreme weather pose a substantial threat to the sustainability agenda, particularly in relation to the water-relevant SDG 6, which aims to ensure access to clean water and sanitation, impacting the availability and quality of water resources and, consequently, societal well-being (UN Water, 2023). In response to interconnected challenges, systems approaches are needed to support water systems move towards resilient and neutral systems (Albrecht et al., 2018; Mijic et al., 2024), requiring the water governance system to leverage dynamic interactions between environmental, social, economic, and administrative systems at various levels of society (Hoekstra, 2006; Rogers, 2003).

In this paper, we define WN governance as a holistic approach that promotes water system resilience by addressing three key urban water security indicators – consumer demand, flood risk, and river water quality through systemic design options. (Allan et al., 2018; Jensen and Wu, 2018; Kumar et al., 2024; Milman and Short, 2008; Rockström et al., 2009; Rodina, 2019) In practice, a range of institutional

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challenges have been reported within the governance system, such as fragmented decision-making due to duplication of efforts (Pahl-Wostl and Knieper, 2014; Lubell, 2013), poor information sharing and coordination (Biermann et al., 2009; Breen et al., 2018), and governance failures (Bakker et al., 2008; Young et al., 2015). In response, research suggests that institutional elements, structures, and arrangements need to be carefully designed within water governance systems (Fallon et al., 2022; Pahl-Wostl et al., 2010). Specifically, the institutions include laws, regulations, norms, rules, and incentives—that shape decision-making (Ostrom et al., 1993). Water governance in operations encompasses not only formal institutions such as policies and regulations, but also the informal institutions in which stakeholders "articulate their interests, exercise their legal rights, take decisions, meet their obligations, and mediate their differences". In this vein, research indicates that coordination alone is insufficient; decision-makers need to actively consider the interactions of social-ecological systems (Galaz, 2007). However, despite the calls for dynamic and resilient water systems, the dynamic aspects of the governance system and how they impact integrating systemic design solutions, remain largely unexplored.

In the water sector, several other concepts have emerged globally in recent years to promote dynamic and resilient water management, such as 'Sponge Cities' in China (Yin et al., 2021; Yuan et al., 2024), Water Sensitive Urban Design (WSUD) in Australia (Wong, 2006); and Blue Green Infrastructure (BGI) or Nature-Based Solutions (NBS) in Europe (Almaaitah et al., 2021). While these approaches differ in terminology and implementation, they share common goals of enhancing urban resilience, managing stormwater sustainably, and mitigating climate risks. When it comes to WN, the aspect of neutrality, in particular, embodies a foundational principle: each negative environmental impact should be systematically counteracted to neutralise its effects and strengthen climate resilience (OECD, 2023). Under this concept, integrating the systemic design options in decision-making is critical for the counterbalancing impacts (e.g., rainwater harvesting, greywater recycling systems, blue-green infrastructure, efficient appliances, or social campaigns, among others), supporting the system to build the capacity to cope with, adapt to, and/or fundamentally transform in response to immediate shocks (disturbances and disruptions) and long-term stresses (Fallon et al., 2022; Parkes et al., 2010; Holling and Meffe, 1996). For example, green infrastructure, as a WN design option, could support water management by enabling the permeable land to absorb water and alleviate pressure on grey infrastructure during flood events, hence increasing overall system resilience. Broadly, the shifts towards neutrality-oriented policies in environmental management have also been observed in other sectors, with a similar focus on ensuring no net harm to the environment and resilience of systems (Jos Delbeke and Peter Vis, 2019; United Nations Framework Convention on Climate Change, n.d.). Similarly, the 'net zero' target underscores the goal of balancing the amount of greenhouse gases emitted with the amount removed from the atmosphere by 2050 (UN, 2022). Also, 'biodiversity net gain' emphasizes how biodiversity loss created by developments needs to be counteracted (Defra, 2023). These neutrality-oriented policy concepts shift from a static perspective of environmental system policy goals to a dynamic view that considers counterbalances, offsets, and gains, requiring governance approaches and institutional dynamics to further integrate design options in the cross-sectoral interactions and complexities (Liu et al., 2024; Pahl-Wostl et al., 2010).

The complex institutional challenges in water governance and the need for dynamic transitions motivated us to bring in participatory systems thinking, grounded in the system dynamics field, which argues that decision-making fundamentally needs to work with the stakeholders (Pagani et al., 2025; Pluchinotta et al., 2024; Zhou et al., 2022) to understand dynamics across sectors or systems (Ahlström et al., 2020; Voulvoulis et al., 2022; Forrester, 1971). In complex environmental systems, decision makers need to allocate attention to various aspects of the system (Zhou et al., 2024). Systems thinking tools inherently have the aim to support decision-makers focus on the key interconnected relationships that are critical for trade-offs, unintended consequences, and leverage points (Meadows, 2008; Sterman, 2001). In particular, it emphasises feedback mechanisms, which emerges when changes in one part of the system trigger changes in other parts of the system, and in turn, influence the original part. Overall, governance responses are non-linear and dynamic that evolves with the water system (Lubell and Lippert, 2011; Parkes et al., 2010). Researchers have shown that governance can impact various parts of the system (Pahl-Wostl et al., 2010), and activate feedback in particular the interconnections between ecological and management systems (Coletta et al., 2021; Sivapalan et al., 2012). Hence, by bringing in systems thinking perspective and tool, we enrich the understandings of WN governance dynamics and how they can be focused on to support neutral and resilient water systems.

Our research aim is to understand how WN design can be systemically considered in the institutional dynamics of governance, mitigating potential fragmented or siloed activities for building water system resilience. We investigate: 1) What are the feedback mechanisms of WN governance, taking into account the interactions between the water system and governance system? 2) How can a systems thinking perspective help fosters water system neutrality and resilience? We explore our research questions through a case study of the Greater Manchester (GM) region in the UK. The Greater Manchester Combined Authority (GMCA), a devolved mayoral administration, sought support in tackling various interconnected challenges related to flood risk, brownfield land remediation, environmental degradation, and resilience to climate change (GMCA, 2023). The case study involved core members of the established a trilateral agreement which includes a focus on sustainable water management through water neutrality for GM (GMCA, 2021). To understand active decision-makers' views of WN governance, we used participatory system dynamics as a method to map out important system complexities. Specifically, we constructed causal loop diagrams (CLDs), which are word-and-arrow maps of a system, from interviews and participatory stakeholder workshops. The CLD includes feedback mechanisms of WN governance linking WN design options, climate change, hydrological impacts and institutional elements. The CLD was then used to facilitate discussions of how to integrate WN design options in decision-making. The case study is part of a larger research initiative focusing on supporting WN decisions through digital tools, and the CLD was later integrated into a prototype digital decision-making tool.

There are two key contributions from this work. First, by engaging stakeholders from a real-world case study, we provide a diagram and understanding of institutional aspects in WN governance. Specifically, we highlight temporal (timescales of decision-making), boundary (hydrological and administrative alignment), and the feedback dynamics of how hydrological and governance systems interconnect as three fundamental dynamics of WN governance. Second, by building on these dynamic insights related to WN governance, we contribute to the conversations of broader WN and resilience literature using systems thinking. In particular, we demonstrate how specific systems thinking outputs, such as the CLD, can support insights towards a resilient and neutral system through participatory approaches.

2. Systems thinking in water neutrality governance

2.1. Water neutrality and the pursuit of water system resilience

Reducing water impacts due to new urban developments and increasing the adaptability of water systems in the face of growth and climate change and population growth requires the implementation of WN systemic design options (Kumar et al., 2024; Pereno and Barbero, 2020; Puchol-Salort et al., 2022). These WN design options (e.g., rainwater harvesting, greywater recycling systems, blue-green infrastructure, efficient appliances, or social campaigns, among others) are critical in enhancing water systems' capacity to cope with increasing stressors

(Blackmore and Plant, 2008), and hence becomes evident in increasing the capacity of urban developments to absorb impacts and adapt over time (Fig. 1).

Urban development incorporating WN design options from their early planning stages are better equipped to manage long-term stresses and respond to sudden shocks (van de Ven et al., 2016; Leigh and Lee, 2019), like excessive rain or droughts, compared to those that do not (blue curve in Fig. 1). WN design options proactively mitigate new development impacts by reducing total consumer demand (Dieu-Hang et al., 2017; Millock and Nauges, 2010), by enhancing flood resilience (Ferrans et al., 2022; Nesshöver et al., 2017), and by reducing pollutants discharged into rivers (Dobson and Mijic, 2020). Additionally, WN developments might respond more effectively to shocks and adapt and revert to their original state more swiftly than those without WN design options (Hoekstra, 2008; Pokhrel et al., 2022). See the graphical representation of the water system performance for WN versus non-WN development in Fig. 1.

Illustrative examples showcasing the potential nexus between WN design options and water system resilience include: a) urban developments with efficient appliances and rainwater harvesting systems exhibiting more resilience against droughts and water scarcity by significantly reducing water consumption (Bichai et al., 2015; Millock and Nauges, 2010; b) areas with blue-green infrastructure, such as wetlands or engineered raingardens, being better equipped to handle unexpected events such as flash flooding or torrential rain due to reduced water runoff and increased natural absorption (Kabisch et al., 2017; Keeler et al., 2019); c) urban developments with greywater recycling systems displaying enhanced recovery from water pollution spikes by reducing the nutrient discharges (phosphate and nitrogen) into rivers (Li et al., 2009). These examples highlight the value of implementing WN design options in urban planning in contrast to unplanned urban growth (Comes et al., 2011; van Ginkel et al., 2018), showcasing two divergent trajectories (Fig. 1).

For successful adoption of systemic design options, systemic initiatives are being advocated to support holistic approaches of water management, such as developing 'water-risk resilient infrastructures' and enhancing 'climate resilience' within the water sector (World Bank, 2022; World Meteorological Organization, 2023). However, the presence of environmental uncertainties not only can introduce risks into the hydrological system, like drainage systems becoming highly vulnerable to surface water flooding (National Infrastructure Commission, 2022), but can also challenges the governance systems when there is a lack of adequate regulations, structures, and institutional frameworks to ensure the equitable provision of water services (Bakker et al., 2008; Bakker and Cook, 2011).

2.2. Governance challenges, integrated decision-making and systems thinking in the water sector

In practice embracing systems complexity in water governance is challenging. Research suggests that a mismatch between shared power and coordination across organisations can lead to fragmented decision-making (Pahl-Wostl and Knieper, 2014; Lubell, 2013). Also, decisions and actions can be fragmented across institutions as a result of duplication of efforts, limited information sharing, and poor coordination across different levels (Biermann et al., 2009; Bakker and Cook, 2011; Dewulf et al., 2011; Breen et al., 2018). For example, there can be a mix of hierarchical administrative frameworks, networks, and market incentives in collaborations (Belmans et al., 2021; Parkes et al., 2010). When decision-making processes overlook or neglect the complexity of such institutional contexts, governance failures can occur, particularly affecting disadvantaged households negatively (Bakker et al., 2008; Young et al., 2015).

In the literature of water governance, the Integrated Water Resources Management (IWRM) was widely adopted, a widely adopted approach in managing water resources, refers to "a process which promotes the coordinated development and management of water, land, and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP, 2000, p. 22). Under this definition, the decision making is a process that promotes the coordinated development and management of water, land, and related resources to maximize economic and social welfare in an equitable manner while ensuring the sustainability of vital ecosystems. However, scholars also challenge the notion that IWRM is difficult to be operationalized due to the mismatched administrative and hydrological boudnaries, and an integrated

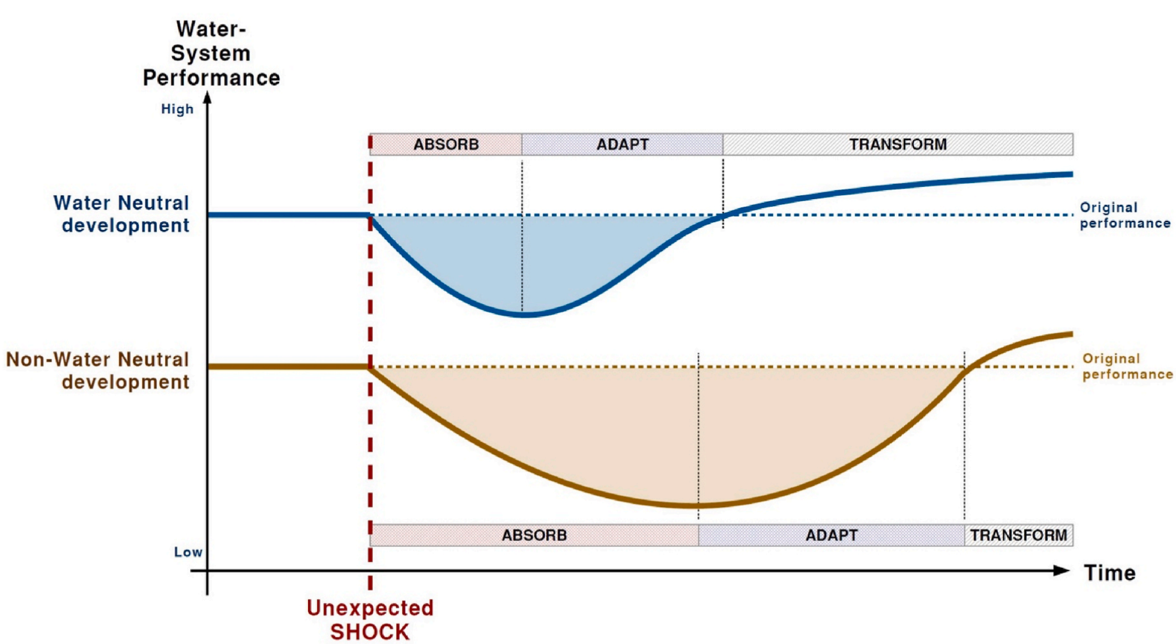

Fig. 1. Diagram that compares the hypothetical water-system performance between two different urban development scenarios against an unexpected shock into the system. A water-neutral development (in blue) with WN design options implementation presents shorter absorption and adaptation times (i.e., more resilience) while unplanned non-water-neutral Development (in brown) takes a longer time to absorb and adapt from the unexpected shock and move to the transformation state.

framework alone provides specific guidelines for governance plans when social and ecological uncertainties are as significant as abrupt changes to freshwater systems (Galaz, 2007).

Pahl-Wostl (2007) made an explicit reference to systems thinking in its work and emphasized the potential of systems thinking to understand the concept of "integrated", as managing human-technology-environment complexity involves explores hidden drivers, system behaviors, and systemic responses. Such complexity, as Folke et al. (2004) suggested, present as interlinkages between ecosystems and social systems, as well as economic systems. Governance complexity can also arise due to the diverse institutional roles and functions of various administrative levels and stakeholders across different locations, including villages, municipalities, catchment areas, and river basins (GWP, 2000). Additionally, addressing social-ecological systems may involve a wide range of variables if decision-makers want to adopt a broad rather than a narrow perspective (Bodin and Tengö, 2012). For instance, when different perspectives are involved in various aspects of the system (e.g., ecosystem with social, health/well-being, or all of them), there could be different priorities in strategizing watershed management. Therefore, participatory approaches are supportive to comprehend such complexity (Parkes et al., 2010). These aspects of complexity suggest the various role of adopting participatory systems thinking to enhance our understanding of WN governance towards neutral and resilient water systems.

3. Case study context: Greater Manchester, UK

We explored the idea of WN governance in a case study in the Greater Manchester (GM) region in the UK. GM has a solid industrial history that still attracts substantial investment for regeneration and urban revitalisation. Housing in Manchester is diverse and includes older Victorian terraced houses from the industrial revolution, suburban areas with detached and semi-detached houses, and a growing number of new mix-use developments that include housing, offices, and industry infrastructure (GMCA, 2023).

The GM region stands out for its unique water supply and infrastructure features. It has historically relied on its waterways for economic prosperity, which remains vital to the city's identity. The region has three main river valleys: the Irk in the north, the Medlock in the centre, and the Mersey in the south. The Irk and Medlock rivers converge to form the River Irwell, acting as a boundary between Manchester and Salford. The River Mersey flows through the southern part of the city, eventually connecting to the Manchester Ship Canal. Adequate management of these waterways and surface water is crucial for flood prevention.

Aiming to move towards WN governance, the Greater Manchester Combined Authority (GMCA), United Utilities (UU; water company) and the Environment Agency (EA; a UK Government and regulatory body with environmental responsibilities) established a trilateral agreement which includes a focus on sustainable water management for GM (GMCA, 2021). Specifically, GMCA is a Mayoral Combined Authority with strategic powers to improve the social, economic, and environmental well-being of the GM region. UU have specific responsibilities as a drainage and water company, providing support for water resources and future infrastructure in the region. The EA role focuses on sustainable water use, flood risk management, climate change scenarios and other catchment-based environmental strategies. As part of this trilateral agreement, these organisations selected several geographical areas of interest, of which the GM part of the Upper Mersey catchment area was a key focus (Fig. 2). The Upper Mersey was selected by the trilateral group as the study area for conversations and participatory activities studied in this paper. Fig. 2 shows a map of the Upper Mersey catchment inside the GM extent and its location inside the UK.

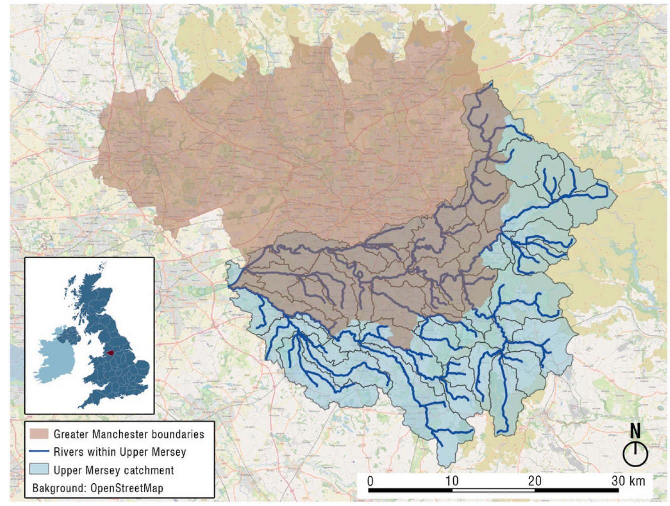

Fig. 2. Upper Mersey Catchment area and its rivers within the Greater Manchester boundaries, also marked in red on the UK map.

4. Methods

In the project, we employed participatory system dynamics to produce Causal Loop Diagrams (CLDs). CLDs is one of the systems thinking tools to qualitatively describe complex interconnections between variables and feedback mechanisms (Richardson, 2011). Belonging to the broader family of systems dynamics, this method—unlike computer-based simulations—focuses on defining system boundaries and mechanisms across stakeholder groups and fostering a shared understanding of the system. Throughout the process, we engaged with nine participants from the trilateral group (UU: n = 3; EA: n = 2; GMCA: n = 4) and two participants from local councils (n = 2). In particular, the engaged members of the trilateral group actively participated in driving WN initiatives, as outlined in the group's agreements. Since the trilateral group predated the research case study, participants were directly selected from its core members. When external stakeholders, such as local council members, were involved, their participation was facilitated by the trilateral group to ensure alignment with the WN initiatives. The trilateral group were established since 2021, representing key roles in water management, thus the direct involvement of the group ensured comprehensive coverage of the core responsibilities agreed and required to drive WN initiatives.

Our approach included different stages, namely problem scoping, CLD development, and validation & action. Fig. 3 shows a schematic representation of these iterative steps, which is described in more detail in the following sections. Here we provide an overview of the engagement activities across the entire project. The details of each engagement stage are included in the supplementary material.

The case study started with a stakeholder workshop with the trilateral group in March 2022 for problem scoping. We asked participants to map critical stakeholders to achieve sustainable future water management. We also asked them to share specific problems/concerns and prioritise the shared concerns. Then participants drew behaviour over time graphs depicting the past and anticipated future trends of selected problem elements. At the end of the workshop, participants agreed on the focus of the case study being the complexities of WN governance in the Upper Mersey catchment.

The second stage of the system approach focused on CLD development, which is comprised of interviews and a full day workshop with eight participants from the trilateral group. During interviews and workshops, participants were asked to share their perspectives on governance and to express their agreement or disagreement with specific variables/links. Individual interviews in August 2022 aimed to generate a list of governance variables that influence WN in the Upper

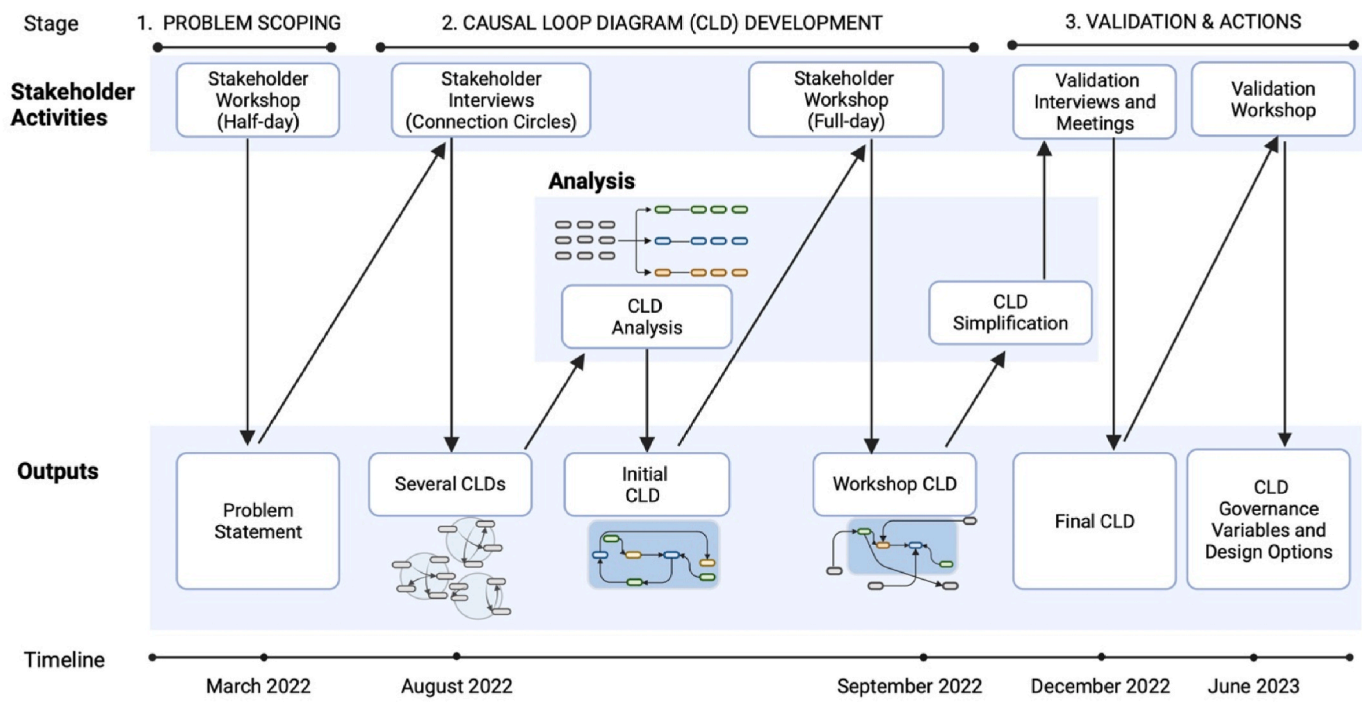

Fig. 3. Schematic diagram of methods and stages. Figure was created using BioRender.com.

Mersey catchment and the variables' interconnections. We then asked them to connect the variables through links with arrows. To understand linkages between hydrological and governance system, we selected three key decision-making variable from the hydrological model being used in the project: run-off coefficient, water demand, and attenuation volume (Dobson et al., 2023). Before the workshop, we analyzed individual interviews and constructed an initial CLD based on the connection circles. In September 2022, we met with participants from the trilateral in a full-day workshop. We then asked participants to develop a CLD as the group's shared representation of an important system structure by revising and expanding the initial CLD. In the CLD development stage (see Fig. 3), two workshop facilitators from the system dynamics team took the lead in driving the activities. For the process, during the interviews and workshops, researchers followed a pre-developed agenda focused on gathering participants' experiences and knowledge about the system. The CLDs were simplified and aggregated (see the supplementary information on structure development) to present concise information about the system, as requested by the participants. To ensure the validity of the CLDs, we further presented them to participants for review as shown in Fig. 3.

The final stage included simplifying the diagram, validating the CLD, and discussing the connections between governance and WN design options. We also held a final validation workshop with the trilateral group representatives in June 2023. We extracted the governance variables from the CLD, and asked workshop participants to identify which of their organisations are responsible for managing governance-focused variables across four WN design options. Hence after the validation, we had the finalised CLD and the applications of CLD in facilitating discussions across groups.

Overall, the case study is part of a broader research initiative involving an interdisciplinary team working on systems dynamics of governance, integrated systems modelling, interface, and engagement activities. The governance systems analysis conducted from March 2022 to June 2023 (see Fig. 3) was a component of the broader initiative spanning from October 2021 to April 2024. During the initial problem-scoping stage, as well as the validation and action phases, the process involved collaboration across research team. The primary output is to provide practical evidence-based governance insights in the form of CLDs, and be integrated into an online decision-making platform.

5. Results

The CLD illustrates the variables and their feedback loops that interconnect institutional aspects of governance with their impacts on the water system. In this section, the CLD is described by unfolding 1) the risk of system failures and water neutrality; 2) the cascading impacts of climate change and urban growth; and 3) how a reactive mode in governance is activated by system failures. These causal mechanisms are presented in Figs. 4–6 respectively[1]. We then present how the specific WN design options are related to the governance arrangements in Fig. 7. The supplementary material provides quotation examples for these pathways and institutional variables.

5.1. Risk of system failures in water systems

The first section of the CLD describes mechanisms around three system failures: flooding, water quality and water deficits (Fig. 4). *Risks of system failures* refer to disruptions or shocks in the water system that could lead to adverse environmental impacts. These risks can be mitigated by WN design options, which involve mechanisms that change consumer demand, permeable land, and collected and treated water.

The sewer system is a network of pipes, pumps, and treatment facilities. A combined sewer network that collects both surface and household foul water is a common infrastructure in England. As the central part of Fig. 4 shows, two sources contribute to the *combined sewer water*: *household foul water* and *excess water* from the rainfall that is not absorbed by the permeable land. Specifically, when households use water in their homes, increased *consumer demand for water* (see the

[1] In original interviews, we used two colours to represent different link types, whereas in workshops, we used '+' and '−' symbols in SD software instead. In response to stakeholders' preferences for simple visuals in the CLDs— in the final CLD, presented in this paper, we used solid and dotted lines to show relationships. Clarification on link types was consistently sought from participants throughout the study.

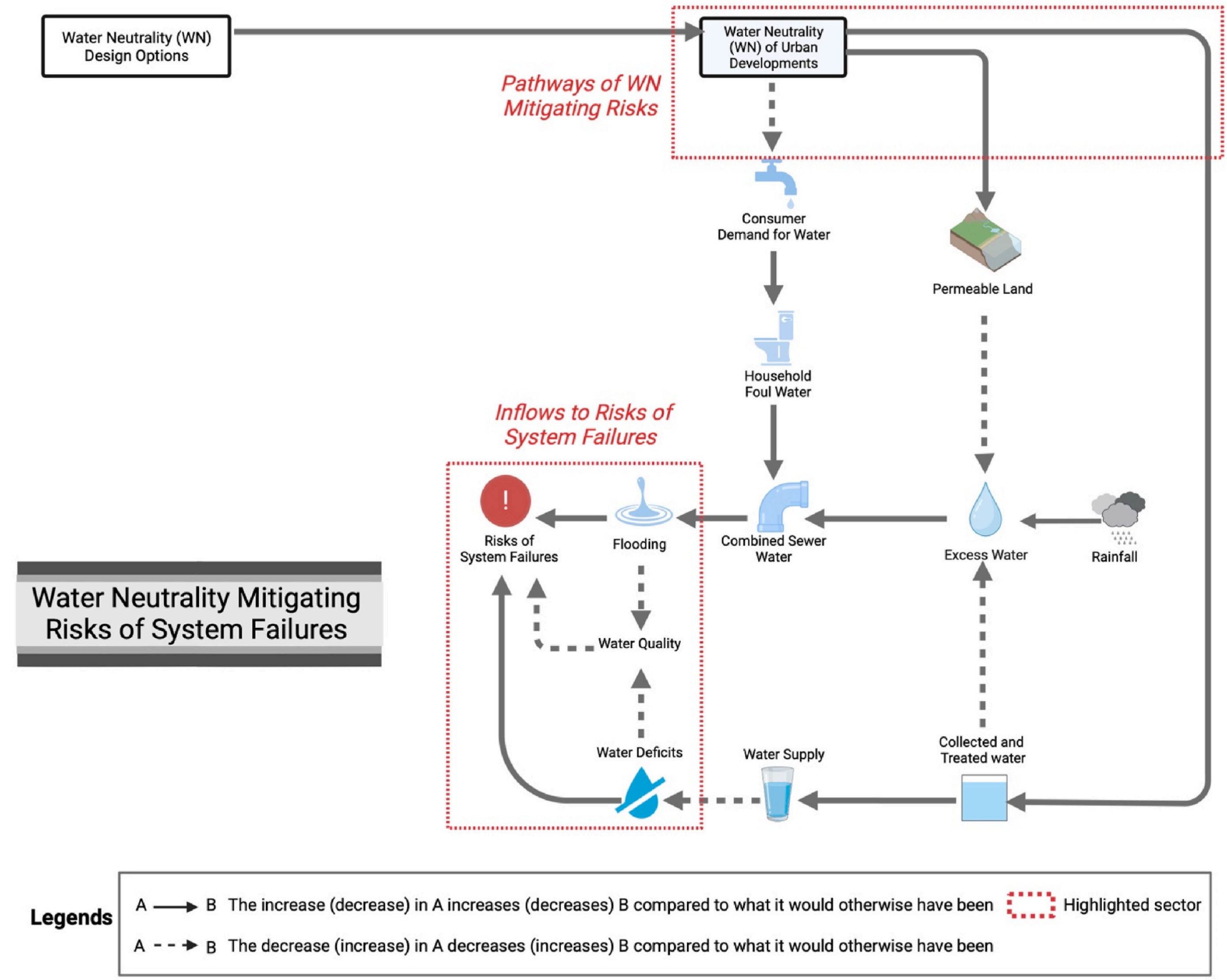

Fig. 4. Water Neutrality (WN) mitigating risks of system failures. Solid line represents positive causality, indicating that the increase (decrease) in the cause increases (decreases) the effect variable compared to what it would otherwise have been; and the dotted line represents negative causality, indicating that a decrease (increase) in the cause decreases (increases) the effect variable compared to what it would otherwise have been [1]. Figure was created using BioRender.com.

variable with the tap/faucet picture) results in a higher *household foul water* inflow into the combined sewer. *Rainfall* (see the variable in the very right of the figure) increases *excess water*, which refers to the amount of water that exceeds the storage capacity, bringing in another primary source of *combined sewer water*. As the *combined sewer water* increases, so does the risk of combined water overflow when the capacity of the sewer system is exceeded, which can lead to *flooding*, increasing the *risks of system failures*.

While the sewer system itself has certain levels of capacity to prevent excess and untreated water from contaminating drinking water supplies and hydrology ecosystems, it is important to note that when the sewer network's capacity to manage water inflow and discharge is excessed, *flooding* can also decrease *water quality* in open water systems (rivers, lakes, or beaches), increasing the *risks of system failures*. Another risk of system failure was linked to *water deficit*. The shortage of water occurs when there is not enough water collected and treated for *water supply*. A *water deficit* can compromise *water quality* as well because it reduces the availability of water for dilution, flushing, and effective treatment.

The important role of WN design options in facilitating *water neutrality of urban developments* has been widely agreed upon in interviews and group workshops. Participants suggested that three WN pathways could help mitigate system failures: 1) reducing *consumer demand for water*, which reduces *excess water* in the system, 2) increasing *permeable land* that can hold *excess water* in the soil instead of in the combined sewer and therefore mitigate flood risk, and 3) providing *collected and treated water* to improve both water supply and water quality.

5.2. Cascading effects of urban developments and climate change

The second section of the CLD shows how specific *urban developments* and *climate change* cascade into risks in the system, which is highlighted in the red boxes in Fig. 5. *Urban developments* refer to new developments arising from the delivery of housing and associated or unexpected planning permissions at the local planning authority level. *Urban developments* increase *consumer demand for water*, which increases *household foul water*, increasing *combined sewer water* and then *flooding*.

In addition, *urban developments* very often involve the removal of *permeable land*, such as green spaces and wetlands, which reduce the capacity of the catchment to absorb rainfall and pollutants, increasing

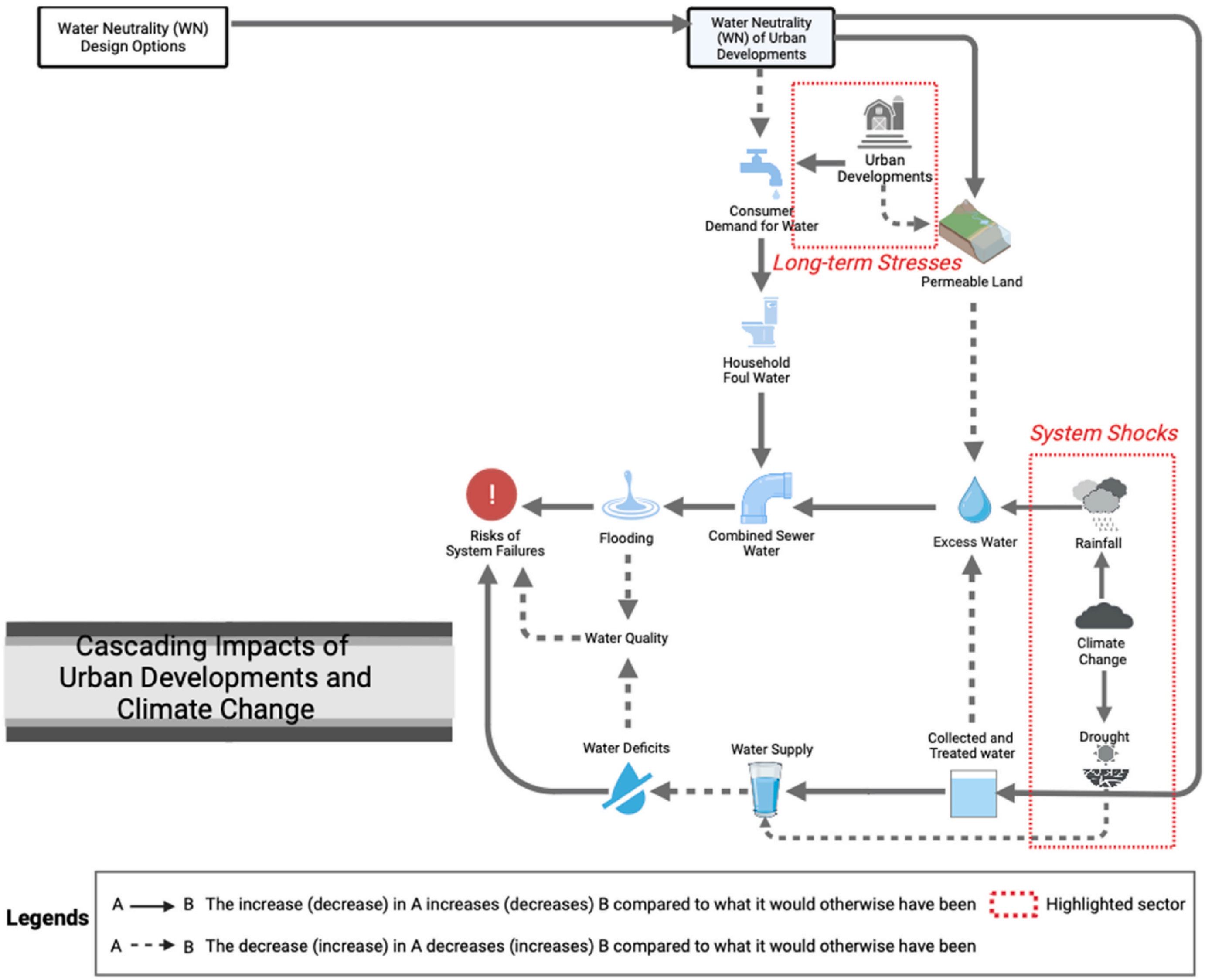

Fig. 5. Cascading impacts of urban developments and climate change. Figure was created using BioRender.com.

excess water and *combined sewer water* and eventually *flooding*, collectively impacting the river *water quality*. Participants agreed that the new developments need to be designed with WN in mind instead of being retrofitted in the future. As one interviewee said, "new developments should not add to the cost burden [of managing water] for the future" (GMCA 03).

Another variable that cascades into risks to the system is *climate change*, which was described as "a major stressor on the environment's capacity to support the growth" (EA 05). The interviewee from the local council validated the concern about climate change and the impact on combined water overflow. *Climate change* intensifies the risks of *flooding* and *water quality* due to intense *rainfall events,* posing challenges to the combined sewer system. Additionally, it tightens the risk of *water deficits caused by* insufficient water supply during *droughts*.

As shown in Fig. 5, the impacts of *urban developments* and *climate change* are highlighted as areas of concern for future water system resilience, posing long-term stresses and system shocks. Participants have highlighted the effects and complexity of how these factors accumulate: "specifically climate change, but also all these things about how demographic change, environmental change, legislation, regulatory expectations and all that, [the challenge is] how all these things add up to put extra demand on the system, and how do we actually secure that resilience in those services giving the extra demands that we can expect." (UU 02). The quote underscores the challenge of maintaining water system resilience against cumulative and cascading effects within various system parts.

5.3. Reactive governance feedback loops of decision-making

The third section of the CLD describes the mechanisms of governance. Fig. 6 presents the feedback loops between the hydrological system (right part of the figure) and governance (left part of the figure). It details how the risks of system failures trigger WN governance (as highlighted in a red box in Fig. 6), which provides *WN design options* that increase *WN of urban developments* to mitigate *risks of system failures*, forming four feedback loops that are highlighted using four colours in Fig. 6 (in dark blue, purple, green, and light blue). *Risks of system failures* create a connection between the two systems, forming balancing feedback processes that reduce risks.

A shared segment of WN governance pathways is the increase of funding *and actions for climate change*, which increases management across time scales, increasing *integrated governance of WN*. Funding *and actions for climate change*, as a starting point of the governance system, were directly linked with *risks of system failures*, as described by a

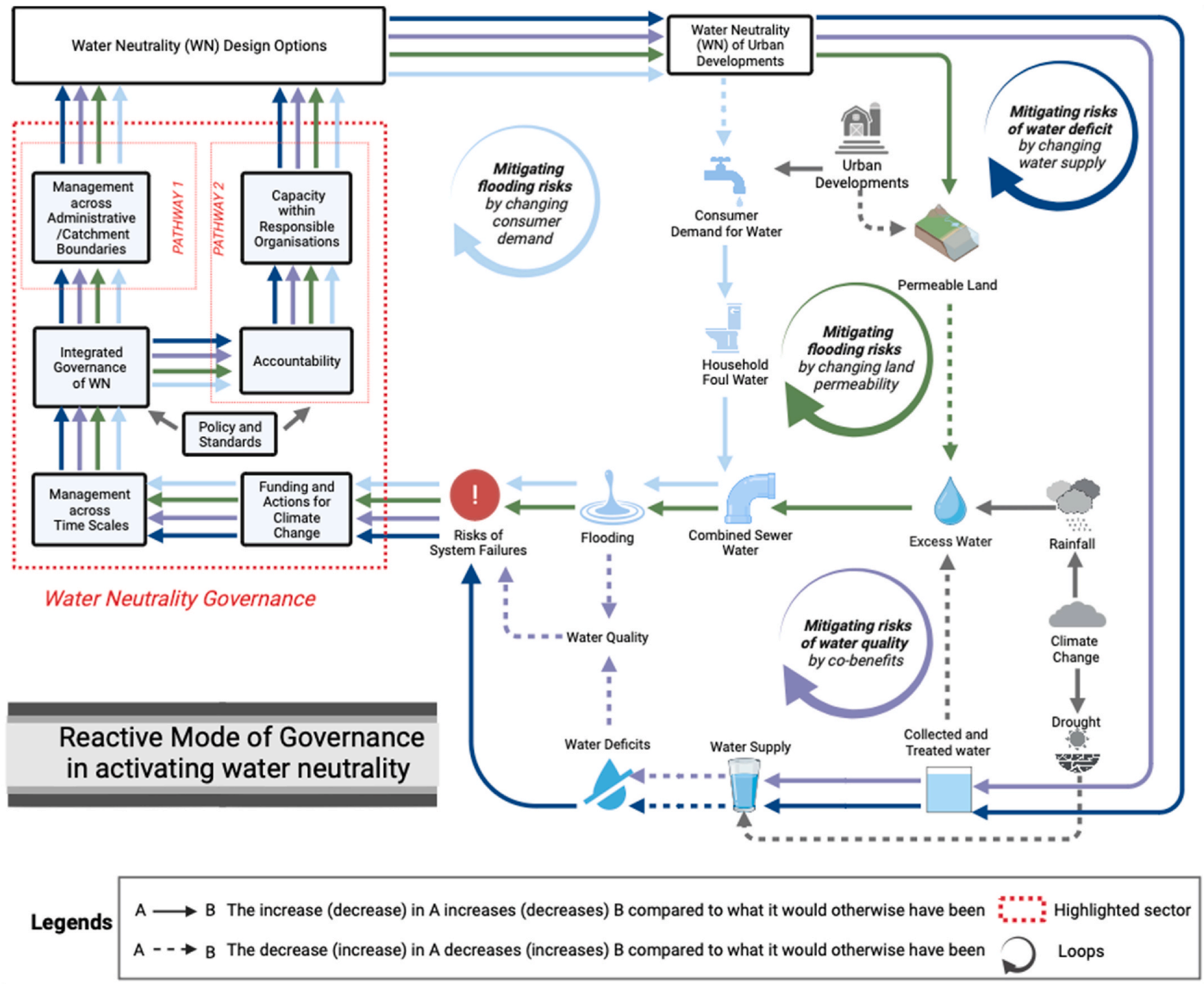

Fig. 6. Reactive modes of governance in activating Water Neutrality (WN). Each feedback loop is highlighted with a unique colour: light blue, green, dark blue, and purple. In CLDs, reinforcing loops indicate that the change of one variable (increase or decrease) will reinforce the direction of the change after travelling around the loop. Balancing loops indicate that the change of one variable (increase or decrease) would be counteracted somewhat by a change in the opposite direction after travelling around the loop. The four loops presented in this CLD are balancing loops. Figure was created using BioRender.com.

participant, "adaptation and mitigation [as climate change actions] had turned [as an approach in addressing] flood resilience, because they would cover the whole system" (EA 06). Participants mentioned the idea of funding for the lifelong management of assets, emphasising that prioritising funding towards climate change mitigation could result in improved investment and more comprehensive management of water system.

Funding and actions for climate change increase the *management across time scales*. Participants mentioned that the private sector, such as UU, needs to conduct formal and regulatory price reviews for the charges it makes to its customers. This links to its ability to make future investment decisions, which sometimes do not match the varying lengths of policy cycles. It was suggested that Local Authority funding schemes also need to be decided on a yearly or longer cycle basis. The fixed timeline that UU needs to adhere to for their price review can result in disparities with the timelines observed in the public sector. Also, UU pointed out that the issue of water leakage tends to re-emerge due to the lack of adequate financial resources allocated for addressing the failure in each of these policy or investment cycles.

When funding objectives and actions are aligned, it increases the potential for pooling resources jointly to finance WN projects, leading to *integrated governance of WN*. In the CLD, this refers to shared decision-making among multiple stakeholders with aligned timelines for decisions, funding, and actions against the cascading risks of climate change and urban developments.

There are two divergent pathways interconnecting *integrated governance of WN* and WN design options. The first pathway regards the governance by how multiple stakeholders collaborate across boundaries. The *integrated governance of WN* can increase *managing across administrative and catchment boundaries*, which increases the provision of WN design options. Participants described the challenge that river catchments do not correspond to administrative boundaries at country or district levels. A critical reason is that the natural flow of water can be across multiple catchments with different administrative boundaries: “You can do what you can within this catchment. But then if you don’t get the equal buying from the catchment downstream, then you can’t solve your problem because it’s out of your control almost” (UU 01). With *integrated management across timescales*, participants said that

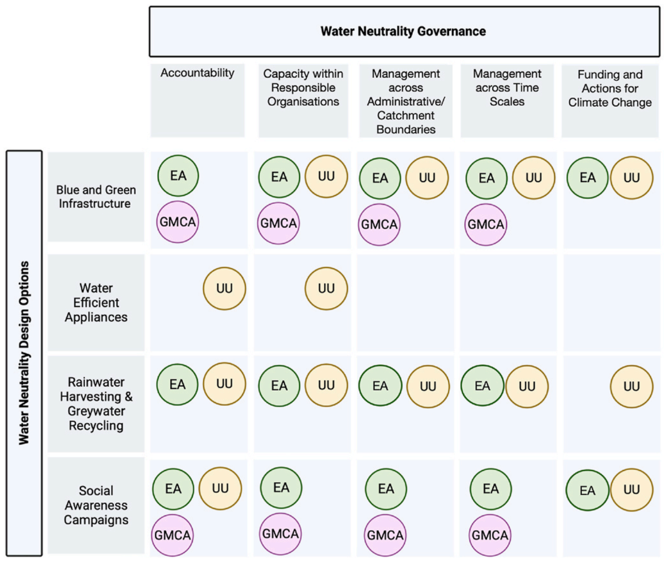

Fig. 7. Water neutrality design options linked to institutional factors in governance. Each circle represents an organisational group responsible for a water neutrality design option within its respective institutional factor. (EA: Environment Agency; GMCA: Greater Manchester Combined Authority; UU: United Utilities = water company). Figure was created using BioRender.com.

"working less in silos. You will be working more across catchments. And you will be working more across administrative [boundaries]" (EA 05).

Another pathway is informed by structured regulatory frameworks. In particular, *policy and standards* were identified as being important for enhancing the organisations' *accountability* for compliance with WN requirements. The formal and legal requirements outlined in policies, along with specific targets set by standards can increase the *accountability* of actors involved in WN. Participants stressed the idea that increased *accountability* enhances the *capacity within responsible organisations,* such as shared roles in cost-sharing, strategic frameworks, and knowledge-sharing across organisations. However, in comparison to climate change standards, WN standards at the organisational level varied: "I think if we could pass forward in 10 years and have sort of kind of water neutrality on the same kind of weight as carbon and net zero, which are really strong across the GM system at the minute. But we don't really have one standard definition for water neutrality as a strategy point of view" (EA 06).

5.4. Water neutrality governance and water neutrality design options

The CLD was used to discuss how to embed technical design options in WN governance. Fig. 7 reports how stakeholders perceive their organisations as being responsible for managing the governance variables across four WN design options. The circles with abbreviations represent the organisations that are perceived to be responsible for managing specific domains.

For blue and green infrastructure, there was a consensus that EA and GMCA are accountable for their management. Additionally, it was agreed that all stakeholders need to collaborate across administrative and catchment boundaries, temporal scales, and funding resources to effectively manage climate change impacts. There were also shared responsibilities identified for social awareness campaigns, such as addressing the prevalent practice of paving over gardens in local communities. For rainwater harvesting and greywater recycling, it was viewed as joint responsibilities between UU and the EA. For water-efficient appliances, UU's accountability and capacity were identified, with users also directly playing an important role in ensuring accountability.

Funding and actions for climate change are critical in steering WN governance, as described in the CLD (Fig. 6). EA and UU stood out for their potential in bringing in funding and investments. Despite the shared roles particularly for blue and green infrastructure, and social awareness campaigns, a few challenges in establishing aligned funding mechanisms are reported, specifically regarding engaging other actors in funding resources. For example, WN may not be a priority as the local authority might focus on other concerns more directly relevant to human health like human health and homelessness. Consequently, there is competition between WN and other priorities. It was explained that flooding, sometimes being perceived as a less frequent issue, can result in its lower prioritisation in disaster risk management and the allocation of associated funding. Also, the implementation of blue and green infrastructure takes up developable areas, which can negatively impact profitability and viability for developers, thereby decreasing their motivation to fund.

6. Discussion

This section critically discusses the following points: contributions to the WN governance with the temporal, boundary, and feedback dynamics highlighted; and contributions to move towards a neutral and resilient systems with systems thinking.

6.1. Water neutrality governance: temporal, boundary and feedback dynamics

Previous research indicated that the governance of water systems is often fragmented due to mismatches in institutional arrangements, such as power, coordination, and rules (Biermann et al., 2009; Bakker et al., 2008), preventing the achievement of neutrality and resilient water systems. To address this gap, we made a conceptual connection of WN to resilience and highlight the importance of embedding systemic design options, and we mapped WN governance pathways with stakeholders in a real-world case study in Manchester. By doing so, we presented practical and tangible institutional pathways that integrate systemic design options taking into account the institutional challenges and cross-sectoral interactions in water systems (see Figs. 4; 5; 6). We emphasize that three fundamental dynamics of WN governance must be aligned to integrate systemic design options: temporal, boundary, and feedback dynamics.

First, we observed that the temporal dynamics, which encompass the timescales of climate impact (short-term or long-term) and management (the political and strategic planning cycle and funding), play a crucial role in shaping the institutional alignment for all systemic design options. Our CLD revealed that funding and actions for climate change are essential to be leveraged towards mitigating water system failures. However, there are various perspectives towards the long-term stresses versus immediate impacts in socio-ecological systems. For instance, the long-term system stresses from urban developments are perceived at a different timescale than immediate system shocks, such as intensified rainfall. The infrequency of such failures in the short term obscures the risk, revealing a system that is currently operating at a rather high level of risk and a low level of mitigating actions. The climate change temporal perceptions are also relevant to the varying timescales of funding and investment, which play a fundamental role in how the governance system responds. Our research aligns with the research conducted in this area, which suggests that organisations' perceptions of the timing of risks and theiractions relevant to climate change may be biased (Bleda et al., 2023). For instance, they might select events that fall within their current management procedures. One notable finding is that funding conflicts often arise due to mismatches between the political and strategic planning cycles across sectors. As WN governance may include both public and private sectors, the alignment between organisations and regulatory bodies may fail due to the diverse timescales perceived or frequency of policy changes, which was also found in the housing sector (Zhou et al., 2022) . Therefore, for effective governance of WN, the integrated decisions should encompass perceived timelines for decision-making in response to the cascading risks posed by climate change.

Second, our CLD revealed that effective management requires synergies of catchment and administrative boundary alignment. Hydrological boundaries are defined by the nature of water flows, and administrative boundaries are based on political and jurisdictional considerations. Interestingly, as identified in the feedback loops and governance pathways (see Fig. 6), establishing shared temporal scales is the first step in initiating both boundary-based responses and policy-based accountability frameworks. As hydrological studies show, different water events operate on varying temporal and spatial scales (Salvadore et al., 2015). For example, groundwater processes occur over longer periods and in larger urban areas, while stormwater drainage functions on shorter timescales and in smaller areas. Thus, our CLD suggests that recognizing these hydrological spatial-temporal differences of water systems can be crucial for decision-makers to align strategies effectively towards embracing temporal-boundary dynamics of WN governance. A failure to align the boundary and temporal dynamics can lead to fragmentation of services and interventions, as organisations might prioritise their own goals rather than the shared goals.

Last, the feedback loops of the CLD show that moving towards resilient water systems requires shifting to identifying risks and adapting proactively instead of reacting to system failures. Specifically, a range of institutional variables are identified including accountability, capacity, management across administrative and catchment boundaries, timescales, funding and actions for climate change, and capacity (see Figs. 6 and 7). These variables formed pathways of providing WN design options that counteract the risks of system failures, interconnecting the WN governance system and hydrological systems. However, in the feedback loops, these balancing mechanisms suggest that WN systemic design options are activated after the system failure happened, which brings a critical insight that while the system-failure-oriented loops form balancing mechanisms that counteract stresses and shocks in the system, they do not necessarily lead to resilient systems if the consequences are severe and cause substantial and irreversible harm to ecological and population health, or if the institutional level fails to adapt to the risks. Hence, adaptive paradigm still needs to consider how to build system resilience proactively (Mijic et al., 2024) to fundamentally shift the system to resilience-based decision-making. This involves ensuring that the water system is resilient to uncertainties, with resilience-based loops (i.e., embedding WN design options to maintain water system resilience rather than responding to risks of failures with reactive counteracting loops) and insitutional alignments in place.

6.2. Moving towards a neutral and resilient system through participatory systems thinking

While systems thinking has been widely adopted in the community for exploring cross-system interactions (e.g. Pahl-Wostl, 2007), our study offers new insights about the role of systems thinking, and broadly how the outputs, such as the CLDs, can be used to support shared understandings of neutral and resilient system (section 6.2.1) and integrate of systemic options in governance (section 6.2.2).

6.2.1. Elicitation of shared understandings of neutral and resilient system

In light of the calls to view policy goals as a dynamic rather than a static process, we introduce insights on how participatory systems thinking can support neutrality policies, drawing from the example of considering how the system counteracts. Also, while systemic design options may vary (as shown in Fig. 6), the various options were connected by a reactive balancing loop—creating an impact first and then counteracting it. This basic balancing loop essentially reduces the system's impact (in this case, flooding and combined severe water). However, the various delays in the governance system could cause irreversible damages to the system. This aligns with the reservations of neutrality policies such as net zero (Biermann et al., 2009; Kemfert, 2021) and biodiversity net gain (Simpson et al., 2021), which argue that the counteracting loops are fragile with delays and various accountabilities. Therefore, we suggest for WN, the governance system actively engage with the system for institutional alignment on the temporal, boundary and feedback dynamics to proactively prepare the system's movements towards of neutrality goals.

The participatory workshops suggest that a potential role of systems thinking in facilitating direct participatory conversations about how systems evolve over time embracing complexity (Meadows, 2008; Voulvoulis et al., 2022). A critical observation of our case study is that such institutions, along with the ecological system, evolve over time. Even when stakeholders across various sectors in water management share mechanisms (Nesshöver et al., 2017), the importance of institutional mechanisms can still be unique to each organisation (Fig. 7). Effective decision-making requires comprehending shared rules in the institutions that coordinate actions among multiple decision centres (Ostrom, 2008; Pluchinotta et al., 2021). And institutional dynamics are not just beneficial for addressing exogenous impacts related to climate change (Huntjens et al., 2012; Lubell, 2013; Pahl-Wostl et al., 2010), but also critical for establishing endogenous, coordinated, and consistent actions needed *within* the governance system(Zhou et al., 2024). Hence, our application of CLD in facilitating such conversations in practice showed the possibility of using participatory systems thinking to facilitate such conversations and align organisations' perceptions of the system for collaborative decision-making (Pluchinotta et al., 2022).

6.2.2. Integration of systemic design options into decision making

Integrated water management and WN view aligned decisions on water flows and water quality crucial for water resilience. However, as our CLD show, such processes may not activate the institutional mechanisms required if the above-mentioned dynamics are not aligned, leading to potential system fragmentation. We suggest that integrated decisions are not solely grounded on intention of collaboration but also on specific coordination on institutional pathways regarding timing of climate impacts (temporal dynamics), its intersections with boundaries between administrative and hydrological domains (boundary dynamics). These dynamics, when aligned, could unlock multiple design options such as BGI, rainwater harvesting and grey water recycling, and social awareness campaigns. For example, while water-efficient applications were considered more relevant to water companies, the shared alignment in temporal dynamics impacts the accountability that is essential for this technical option. And among all the design options, we highlight that the governance must actively approach climate change rather than merely adapt to it in decision-making, in order to minimize system failures (feedback dynamics).

In our case study, the CLD was instrumental as a boundary object in identifying key decision variables linked with water system modeling (Dobson et al., 2023) to further support decision-making. The CLD was integrated into adigital tool called as virtual decision room (Ventura Water), offering decision-makers an online platform to test water management strategies and reconsider the underlying mechanisms. This integration aligns with the trilateral groups' commitment to a shared digital evidence base, enhancing trilateral and broader institutional capacity in GM. The application of systems thinking and the incorporation of the CLD into the digital tool provide a foundation for broader governance discussions offering decision-making support. This suggests that to foster a resilient system, engaging in modeling and in conversations about governance can help the governance system effectively prepare for and adapt to emerging challenges.

6.3. Limitations and future research

This study has a few limitations. While we have explored the practical aspects of governance, the CLD is shaped by participants' perspectives, and the development of the CLD and its validation involved a small group of key case study stakeholders. As we were interested in understanding how WN governance can be activated, we primarily engaged with the Manchester trilateral group to map the system and explore their joint decision-making processes. While the participants provided valuable insights based on their roles—such as representatives from water companies and statutory agencies- it would be beneficial to include broader sectors and participants in future work. This could involve, e.g. incorporating public opinions on water issues, consulting experts, and engaging with wider business stakeholders in the water sector, such as housing developers. Hence, while in occasions some links could be generic (e.g. the permeable land influenced by housing, climate change brining the funding and grants), in future studies, it could be worthwhile to understand how the institutional mechanisms are applicable to other contexts. Despite the limitations of sample size and specific setting, the CLD proves valuable in illustrating critical feedback mechanisms within WN governance, as perceived by an active governance team driving WN initiatives. Since the trilateral group was actively engaged in WN actions, the CLD highlights potential institutional mechanisms that could be applicable to future cities and contexts.

Although this analysis is rooted in the case study of Manchester, the underlying methodology and conceptual approach can be generalised to other urban settings with distinct hydrological and governance complexities. Cities worldwide experience similar system failures (flooding, water quality deterioration, and water scarcity) due to infrastructure limitations and shifting environmental pressures. The causal mechanisms captured in this CLD, particularly the feedback relationships between consumer demand, land permeability, and water supply, remain relevant across diverse urban environments. The systemic interactions between these factors suggest that comparable WN interventions could be explored in cities facing increasing climate risks, aging infrastructure, and growing water demands.

Another limitation to the scope of the paper is its focus on getting a qualitative understanding of the interacting aspects related to WN governance, rather than a scope on formal resilience model analysis, which requires computer-based system dynamics modeling (Zhou and Zhang, 2022). Although there is separate research within our project scope that involves hydrological simulation modeling, the primary objective of the paper is to explore the interactions in WN governance through a real-world case study. While all systems vary, and the CLD was developed for a specific case study, the CLD captures a few general characteristics of the governance sy—which encompasses the boundaries, feedback, and temporal aspects of institutions—contribute to governance failures. By learning from the governance aspects through participatory approaches of systems thinking, the mechanisms identified can serve as a foundation for future modeling endeavors, such as stock-and-flow modeling. These models can potentially integrate hydrological aspects with governance mechanisms to simulate policies and their effects.

Additionally, the governance systems analysis is part of the project's broader scope of developing a digital decision-making platform that supports integrated governance and water system modeling. The project lasted from 2022 to 2024, and the research team jointly documented and analyzed the engagement of the operations of transdisciplinary research processes. In the case study, the trilateral agreement set the stage for the co-development of the UK's first Integrated Water Management Plan (IWMP), which was adopted by all three organisations at CEO level (GMCA, 2023). The IWMP provides guidelines for partnerships to align temporal and boundary dynamics that were identified in the CLD, such as including commitments and actions to accelerate natural flood management for wider sustainability benefits. However, a formal evaluation of the CLD's specific use was not conducted within the project scope due to personnel and time constraints. Consequently, the absence of a formal evaluation has left the impact of the CLD on stakeholders' operational decision-making uncertain, despite the progress made by the GM team through their IWMP. Future research should investigate how the insights garnered from the system's complexity, and the application of systems thinking might support an ongoing shift in governance, moving from a reactive mode to a more proactive approach.

7. Conclusion

Building on a case study in Manchester, UK, we explored how WN governance can integrate systemic design options into decision-making. Through participatory system dynamics, we found that while specific systemic design options may vary, the options were connected to governance system via reactive balancing loops— first creating impacts, and then counteracting risks. Our analysis reveals that effective adoption of design options requires alignment across three critical dynamics: temporal, boundary, and feedback mechanisms. The case study demonstrates how alignment of these dynamics, combined with targeted solutions, can support water system resilience. The case study from the water sector offer insights for advancing broader environmental neutrality policies, highlighting the need to institutionalize dynamic processes that proactive address-rather than merely react to-system impacts.

CRediT authorship contribution statement

Ke Zhou: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Pepe Puchol-Salort:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Irene Pluchinotta:** Writing – review & editing, Conceptualization. **Darren Beriro:** Writing – review & editing, Writing – original draft, Project administration, Data curation. **Ana Mijic:** Writing – review & editing, Funding acquisition. **Nici Zimmermann:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

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Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.145655.

Data availability

The data that has been used is confidential.

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