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System Thinking for Sustainable Water Management: The Use of System Tools in Sustainability Transitions

Wan Izar Haizan Wan Rosely[1] · **Nikolaos Voulvoulis**[1]

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Abstract

Managing water resources to meet current social, economic, and environmental needs without compromising the ability to meet those needs in the future, requires water managers to look beyond jurisdictional boundaries and their immediate supply operations, protect shared water and marine environments, resources and ecosystems from pollution and overabstraction and deliver structural changes and resilient solutions to make the provision of water services sustainable. With a plethora of system tools increasingly available to support the sustainability transformation of water systems, sorting through their breadth and diversity to determine what is useful and what is not can be challenging. From a selection of 40 popular system tools grouped in terms of how they function, we review those most commonly used in water management through 35 water-related studies from the literature. Findings demonstrate that system tools are not a substitute for systems thinking and applying them alone does not qualify the development of systemic solutions. Systems thinking offers a powerful approach to first improving collective understanding of sustainability challenges related to water and then, in collaboration with a diverse group of stakeholders and the public, defining desired goals for water management and working together to make them a reality. System tools in that context can play an important role in facilitating the process and here we propose an overarching framework of how to select and apply available tools to facilitate a holistic, integrated, and interdisciplinary systems approach for water management and wider urban sustainability transitions.

Keywords Systems thinking · System tools · Urban water management · Sustainability · Collective understanding · Co-create vision · Enabling pathways · Leverage points

1 Introduction

Water management challenges are complex, the result of interactions between elements, agents, and processes occurring at multiple scales, and across social, economic, and environmental dimensions (Brown and Farrelly 2009; Pahl-Wostl et al. 2013). Like most

✉ Nikolaos Voulvoulis
n.voulvoulis@imperial.ac.uk

[1] Centre for Environmental Policy, Faculty of Natural Sciences, Imperial College London, SW7 2AZ, London, UK

sustainability challenges, they are complex not only because they involve multiple interacting agents but also because the context in which they operate keeps changing. These changes do not conform to linear or simple patterns, as many system elements are able to learn new things as they interact over time, creating new patterns (Dunn et al. 2017; Pahl-Wostl et al. 2013; Wan Rosely and Voulvoulis 2022). Water security, for example, as a complex challenge, requires investigation and intervention at various levels: ensuring access to water and sanitation for all households; addressing the safety and risk factors associated with water for both human and environmental health; tackling the political and technical hurdles related to water management and governance; and comprehending the interplay between the water cycle and the impacts of climate change (Mdee et al. 2022).

Climate change exacerbates water management challenges, and in its latest EU strategy on adaptation (2021), for example, the European Commission acknowledged the importance of transformative changes across all sectors and recognised the need for enhanced collaboration between adaptation action and water management authorities to achieve smart and sustainable water practises. Instead of focusing solely on isolated interventions such as concrete flood walls, actions should shift towards systemic solutions that could involve combining river restoration with wetland creation or flood forecasting and warning systems with innovative insurance mechanisms (EIT Climate-KIC 2021). Unlike traditional models of top-down, sector-by-sector initiatives, such solutions require systemic changes that need to be integrated, collaborative, and equitable (Wong et al. 2020). However, the methodologies and tools to develop such solutions remain vague and underdeveloped in the current literature, with the approaches adapted often being fragmented, with stakeholders acting in isolation and several users being left out.

Systems thinking is the ability to identify the 'constructs' of underlying complex problems as well as understand the broader context and appreciate interactions among levels as well as from a whole system's perspective (Leischow and Milstein 2006; NCI 2007). The term 'whole system' aims to capture notions of 'holism, integration, interconnectedness, organisation, perspective taking, nonlinearity, and constructivism' (NCI 2007). It highlights the importance of the circumstances, or context, in which an action is taken to understand its implementation and potential impact. Thus, it offers a powerful approach to first help understand complex water management challenges and then develop appropriate interventions for the system changes required to address them (Koseoglu 2021; Hjorth and Madani 2023). System solutions are known as leverage points because they leverage improvement throughout the system. They refer to any system component that can be changed and, as a result, can potentially lead to a cascade of additional changes throughout the system (Meadows 1999).

In practice, some see systems thinking as providing a powerful language to understand, communicate, and investigate complex issues (Koseoglu 2021; Bano et al. 2022), while others are confused by the sizable and amorphous body of theories, methods, and tools involved (Peters 2014). There are indeed several so-called 'system tools' available in the literature, as used in various disciplines, and in several applications. They are supposed to be the means (methods or techniques) used to collect, arrange, or generate information for understanding complex systems and analysing them as part of efforts to explore or design interventions to influence their behaviour towards desired goals (Kim 2000; Monat and Gannon 2015).

The benefits of applying systems thinking are particularly relevant to addressing water challenges, given their far-reaching impact on the sustainability of human development, healthy ecosystems, and economic prosperity; with solutions designed to maximise benefits and minimise negative consequences (Dunn et al. 2017; Bedinger et al. 2020; Wong et al. 2020; Polaine et al. 2022; Hjorth and Madani 2023). The overall aim of this study is, therefore, to contribute to the operationalisation of systems thinking in water management, and the delivery of truly systemic solutions to facilitate the sustainability transformation of water systems. From a plethora of system tools available, we identify a selection of the most popular (grouped in terms of how they function) and then review their application in water management through several water-related studies from the literature.

2 Methods

A traditional literature review with some aspects of the systematic review method was conducted to identify and present several popular system tools in terms of how they function. A thematic analysis was conducted by adapting the methodology used by Rahmati-Khameneh et al. (2011) and Wan Rosely and Voulvoulis (2022) to subsequently group them according to their design function. The use of these tools in a selection of thirty-five water-related studies was then reviewed, focusing on how well their application aligns with systems thinking. A keyword search was used for this selection as well as several criteria to guide the screening process with exemption given to studies that the researchers found useful in terms of offering additional insights. Further details on the methodologies used and the results of the thematic analysis can be found in the Supplementary Document.

Findings are presented in two parts, with the first part introducing forty popular system tools grouped according to their design function (typology), and the second part reviewing the application of the most common ones in the selected water-related studies (Haddaway et al. 2015; James et al. 2016; Wan Rosely and Voulvoulis 2022). Literature including peer-reviewed articles, chapters from academic textbooks, and grey literature (from websites, blogs, and proceeding papers) were used in both exercises.

3 Results

3.1 A Typology of System Tools

Several tools referred to as ‘system tools’ or developed to contribute through specific functions in the application of systems thinking or systems studies were found to be used in various fields, among them public policy, health, environment, systems research, social studies, sustainability, systems engineering, and management. A brief description of the 40 popular system tools identified, their functions, and their main field of application can be found in Appendix 1 in the Supplementary Document. Through thematic analysis, they have been grouped into 10 categories based on their main function or purpose (Fig. 1). These categories are as follows:

- *Brainstorm:* tools that collect and gather information about complex situations and problems from different perspectives, dimensions, disciplines, scales, etc.
- *Identify actors and agents:* tools to determine stakeholders that are directly and indirectly affected by the systems. They are also often referred to as actors or agents.
- *Facilitate communication among stakeholders:* tools to facilitate effective communication and discussion or learning about problems or complex situations with stakeholders, to attain understanding and collaborate towards the shared vision.

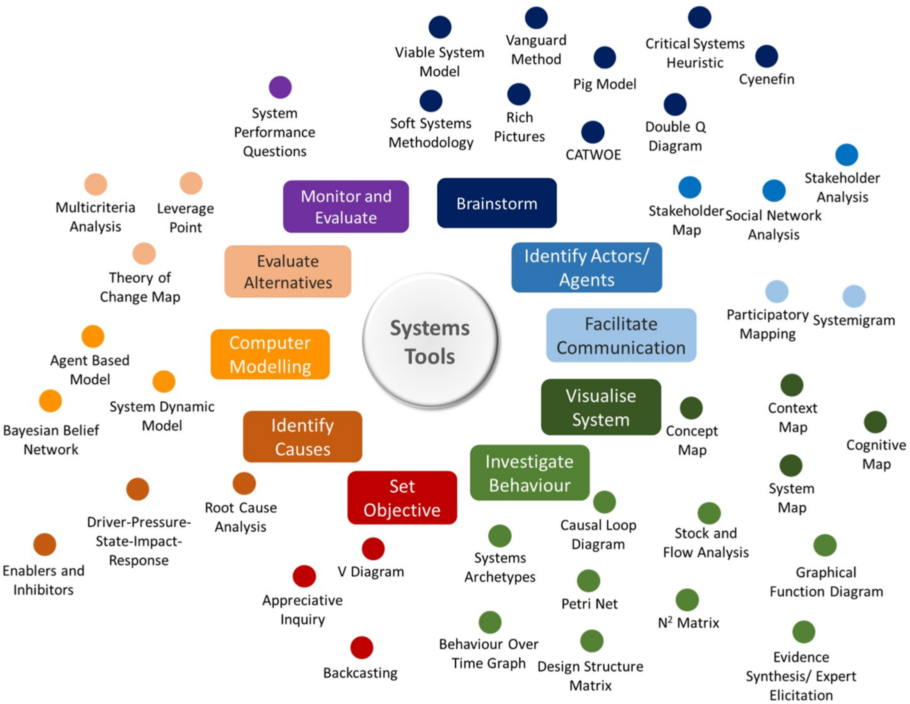

Fig. 1 System tools grouped based on their main functions (typology). (For references, see Tables 1 and 2, Appendix 1 in the Supplementary Document)

- *Visualise a system:* tools that help stakeholders to think about a complex situation or problem from a systems perspective by understanding the interrelationships between parts, elements, or agents within a complex system.
- *Understand behaviour:* tools that utilise information and data to describe how a complex system behaves or to understand patterns.
- *Set objectives:* tools used to develop visions or goals to be achieved from interventions made on the problems or issues.
- *Investigate causes:* tools for investigating the root causes of problems to identify effective interventions.
- *Computer modelling:* tools that apply information and data to simulate system behaviour through mathematical or computer modelling.
- *Evaluate alternatives:* tools for exploring potential solutions, comparing interventions, and evaluating alternatives, often based on selected objectives.
- *Monitor and evaluate:* tools for monitoring implementation—to understand what works, where it is working, why it is working, for whom, etc.

3.2 Application of System Tools in Water Management and Water-Related Studies

Despite the encouraging number of applications of system tools in water management and the increasing number of so-called ‘system solutions’ being selected or developed, overall, supportive evidence of success stories in their effectiveness in addressing water challenges is limited. Moreover,

their application in the selected studies was shown to be limited to a selection of a few tools used more frequently.

The most commonly used tool for brainstorming, a process critical to developing understanding of the challenges to be tackled, is Soft Systems Methodology. This is a participative approach emphasising the importance of considering all relevant stakeholders' views and opinions about a situation. However, findings revealed an inconsistent use of this methodology including departing from Checkland's original vision, involving stakeholders idiosyncratically (Bunch 2003; Markowska et al. 2020; Saeedi et al. 2022; Suriya and Mudgal 2013). Suriya and Mudgal (2013) for example, undertook brainstorming activities using this tool in participatory workshops to understand flooding and to develop a flood management strategy in Chennai (India). Although their application of the tool for brainstorming was demonstrated to help stakeholders explore an adaptive ecosystem approach for flood management, this was the case only for those from agencies directly involved in flood management and academicians with flood management expertise who were invited to participate in the study. Similarly, Bunch (2003) applied Soft Systems Methodology within an ecosystem approach involving stakeholders to support rehabilitation and management of an extremely polluted urban stream, the Cooum River (India). While the work identified multiple factors contributing to the problem including population growth, poverty, uncontrolled urban development, complex governance, and various environmental factors, such as tidal action and climate change, as slum dwellers were deliberately excluded from participating, the work could not be considered complete. Without inclusive participation, the study missed the opportunity to collaboratively working with authorities and government agencies to tackle water issues and engage with those affected the most. In this regard, the application of tools to identify stakeholders such as Stakeholder Analysis or Stakeholder Influence Mapping can be used to improve representation of system actors for both understanding the challenges and increasing participation for delivering change.

Other brainstorming tools such as Pig Models, Critical Systems Heuristics, Vanguard Method, Viable System Model, and Cyenefin have not been widely used in water management. Rich Pictures, CATWOE, and Root Definition Tool have been used to some extent for—problem identification, problem situation, and root definition (Bunch 2003; Markowska et al. 2020; Saeedi et al. 2022; Suriya and Mudgal 2013). In most of cases, however, researchers only applied conventional methods and techniques such as Document Analysis, Quantitative Data Mining, and Analysis or Expert Elicitation for conceptualising complex water challenges, and without using conceptual models to capture the understanding of the systems involved (Markowska et al. 2020).

Fuzzy Cognitive Mapping and Participatory Model Building have also been used to engage stakeholders and brainstorm through workshops (Martinez et al. 2018; Mehta et al. 2019; Pagano et al. 2019; Pluchinotta et al. 2021). Pluchinotta et al. (2021) applied a participatory process in developing a system dynamic model for sustainable urban water management for Ebbsfleet Garden City (UK). The study demonstrated that participatory modelling using Causal Loop Diagrams for systems mapping, can help stakeholders better visualise the interrelationships of the different parts and variables of a complex water system. The use of these tools allowed for a collective learning process when dealing with system complexity, enhanced stakeholders' understanding of system interdependencies and enabled the co-creation of options for attaining sustainability.

System Dynamic Modelling, Agent-based Modelling and Bayesian Belief Networks were among the most popular computer-based modelling tools used in the studies reviewed. Their wider application in water management has also been reviewed by several authors (Heath and Hill 2010; Huber et al. 2018; Phan et al. 2016, 2021). System Dynamic Models, for instance, have been popular in assisting decision-making, particularly in the management of water supply and demand, water quality, irrigation systems, reservoir operation, and other aspects of integrated water management (Phan et al. 2021). Through a wide range of system dynamic software packages, they have been applied to examine dynamic interactions of biophysical elements of several complex water systems. Scenarios ranging from institutional and social (Kotir et al. 2016; Madani and Mariño 2009), technological and engineered (Jiang et al. 2020; Teegavarapu and Simonovic 2014), ecosystem-based (Pluchinotta et al. 2021) as well as for potential climate change impacts (Joshi et al. 2020) have also been incorporated in system models to understand potential implications for managing water systems. However, despite their advantage in helping conceptualise dynamic interrelations between variables in water systems, more than 50 percent of system dynamic modelling applications for water management reviewed by Phan et al. (2021) did not use system mapping, with only 2 percent of them dwelling into the system archetypes of feedback mechanisms involved in the dynamic behaviour of water systems.

Indeed, applications of Systems Dynamic Models seem to focus too much on describing and validating models of complex water systems, which can be overwhelming and divert attention from setting clear end goals or system objectives for the challenges they are tackling. This also contributes to oversimplification of system dynamics, often the result of a lack of deep understanding of the system, theory, or methodologies to handle the complexity of the wider environment, such as the cities and societies and their social dimensions that influence the urban water systems modelled (e.g., Kandiah et al. 2019; Joshi et al. 2020; Rojas et al. 2022). Even when models aspire to capture different dimensions of a water system, this often proves challenging mainly due to data issues- a lack of relevant and low-uncertainty data and indicators. With limited engagement with stakeholders (Phan et al. 2021), such models end up relying heavily on experts' input or modellers' disciplinary knowledge, insufficient to tackle system complexity. These models are often also unable to capture the historical dimension of the system's dynamic behaviour as well as past failures and experiences, both important components of applying systems thinking in understanding water management challenges.

On the other hand, Agent-based Modelling better appreciates actors' or agents' decisions as critical determinants of the complex and adaptive nature of water systems and was demonstrated to facilitate decisions at a smaller scale or related to specific issues such as in the case of selecting water-saving alternatives (Castonguay et al. 2018; Kandiah et al. 2019). It has been used to simulate scenarios based on interactions between agents and the environment such as exploring and projecting consumer behaviour in response to the implementation of certain water policies and measures (Castonguay et al. 2018; Kandiah et al. 2019; Koutiva 2019). For instance, Koutiva (2019) applied Agent-based Modelling to simulate household responses to future water demand management strategies and drought conditions in the city of Athens (Greece). The work suggested that water price change strategies do not achieve a substantially higher decrease in water demand than awareness-raising campaigns and restrictions, and highlighted the need for a more adaptive approach, using new 'test-bed' tools for stress-testing and assessing the resilience of the urban water system, as a new way of designing, evaluating, and managing water policy strategies. Better than most modelling works that often simulate only a part of the system and miss opportunities for wider system change, their model still only covered domestic users, limiting its potential to address overall water security concerns in Athens. Without considering commercial and industrial users, responsible for 22 percent of water use, as well as leakages in distribution networks accounting for 28 percent of the total water supply in the city, it seemed unlikely for Athens to satisfy its water security ambition.

Bayesian Belief Networks have been applied as a system tool to facilitate decision-making related to water quality, groundwater, irrigation water, and water supply management that offers a greater advantage in dealing with data availability as it provides a wider opportunity for expert inputs (Phan et al. 2016). For instance, Pagano et al. (2018) applied the tool integrated with Geographic Information Systems to prioritise interventions on drinking water supply infrastructure under emergency conditions such as earthquakes, based on their vulnerability using variables such as flow, diameter, relevance and redundancy of the pipes. Whereas Kabir et al. (2015) used Bayesian Belief Networks to investigate the probability of failure of water mains using structural integrity, hydraulic capacity, water quality, and consequence factors to facilitate decisions for maintenance, rehabilitation or replacement of pipes to best reduce water loss through leakages. Although these tools can help water companies to maintain, rehabilitate or replace pipes that are at risk of failure, no matter how effective their application is, will not necessarily tackle leakages completely, if critical issues such as the overall state of aging networks are not addressed from a whole system perspective. Worse, without other complementary strategies, water companies will continuously have to respond to incidents of water leaks as well as investing in other sources of water to substitute the amount lost through leakages, as in the case of leaks in London (Thames Water 2021).

Computer-based modelling tools were also used to engage stakeholders in developing a greater understanding of the complexity of water systems in some of the studies reviewed, but overall a lack of collaboration or interactions between engineers, analysts, and other stakeholders such as decision-makers, the public, and water managers meant that most studies missed out on the integration across fields of research and other forms of knowledge such as that from urban planners, social scientists, local experts, and residents in the application of modelling tools. Pouladi et al. (2020) for example used Agent-based Modelling to explore farmers' decisions when investigating the role of agriculture in the catastrophic shrinkage of Urmia Lake (Iran), showing that farmers' financial conditions, ownership of farmland and the employment of household members have had significant impacts on their decisions and activities. The farmers' poor financial situation was the main reason for planting water-intensive crops such as alfalfa and sugar beet and illegally abstracting groundwater to maximise crop yields, as quick ways to maximise profits. Similarly, when Singto et al. (2020) applied Bayesian Belief Networks to engage local stakeholders to better understand conflicts over the construction of a dam proposed by the government in Thailand, the engagement process revealed limited consultation and a lack of shared benefits for affected local stakeholders to be the main reason for opposition to the dam.

Multicriteria Analysis and Driver-Pressure-State-Impact-Response are two of the most popular decision-making tools used in water management. Multicriteria tools have been frequently used for evaluating alternatives or project options related to water challenges. Water companies have applied such tools to evaluate water recycling options- source, route of effluent transfers, treatment technology and capacity (RAPID 2021); options to reduce water leakage in pipe networks (Cunha et al. 2020): and agriculture water management alternative measures (Psomas et al. 2018). These tools have also gained popularity among policymakers for assessing issues on the ground (Hassan et al. 2019), mapping risk areas (Cordão et al. 2020), and developing various frameworks for assessing the performance of water services, policies, and the overall impacts of certain decisions and strategies (Aboelnga et al. 2019; Cunha et al. 2020; Marttunen et al. 2021). Multicriteria Analysis has also been used to assess suitable project sites (Fuentes and Vervoort 2020) and shortlist water management strategies (Michailidou et al. 2016; Psomas et al. 2018; Zyoud et al. 2016). However, in several cases, the application of this tool was demonstrated to fail to offer an alternative perspective in addressing water problems particularly when the criteria selected and used to compare alternatives were shown to be subject to the narrow perspective of interested decision-makers. This is often down to employing consultants who already have their 'on-the-shelf solutions' to address specific water problems, with the needs of stakeholders other than their clients being ignored. Saying that, Multicriteria Analysis has the potential to develop a more holistic picture of water systems through the selection of appropriate criteria. Unfortunately, it is rarely applied to get a deeper understanding of how water systems work and how problems occur in them, considering the organisational, political, economic, environmental, ethical, and sociological components behind them. Although it offers a way to compare alternatives, the lack of clear system objectives or vision often means that even the best performing alternative might not be enough to make such vision realise.

Driver-Pressure-State-Impact-Response has been applied as a system tool to develop solutions by targeting the causes of water management problems: identifying and addressing the sources of pollution when tackling water quality issues and water resources conservation (Al-Kalbani et al. 2015; Gari et al. 2015; Shammi et al. 2019; Wang et al. 2015). It was used in several of the studies, for instance, to assess performance and evaluate past policies affecting water management (Shammi et al. 2019; Wang et al. 2015) or assess the performance of urban water management systems such as with its application in the City Blueprint Framework and Urban Water Security Dashboard (Koop and van Leeuwen 2015; van Ginkel et al. 2018). Overall, its applications, however, seem largely aimed at strengthening the justification of specific alternatives and not addressing complex water issues from a systems perspective. Strategies or decisions made with this tool tend to focus on reducing the pressures causing the problems, often without the 'drivers' that are causing the pressures to arise. Although some studies do apply it to produce more reliable water modelling works, such works remain descriptive, with no evidence of contributing to the systemic changes required to achieve sustainability. Preferred solutions derived from applying this tool (Gari et al. 2018; Rehman et al. 2019) similar to multicriteria applications (applications (Cunha et al. 2020; Psomas et al. 2018; RAPID 2021) might still fail to address root causes and target symptoms instead. The application of these tools alone also creates the perception of a singular 'optimal solution' to identify amongst the alternatives, thereby missing the opportunity to learn from past failures and experiences.

Other than decision-making, brainstorming, understanding behaviour, investigating causes and modelling, system tools have also been used for risk mapping exercises, and assessment and selection of project sites (Cordão et al. 2020; Fuentes and Vervoort 2020) (see mapping exercise in Table 2 of Appendix 1 in the Supplementary Document). Still, approaching water challenges from a whole system's perspective is rarely observed except for the work of D'Agostino et al. (2020) where Backcasting was used. The work demonstrated how stakeholders can be empowered when given the opportunity to decide the future they want through the application of this tool. Backcasting was used as a method to identify measures to improve local water management policies focusing on agricultural use. During the workshop, stakeholders discussed and debated on a shared overall goal, identified barriers that could hinder its achievement and pursued an agreed-upon list of the measures needed. With a clearer vision of 'where they want to go from here', the application of Backcasting was demonstrated to be an effective platform for stakeholders to develop ownership of complex water issues and a willingness to collaboratively work towards the desired sustainability goals. However, the proposed policies and measures ended being centralised on irrigation management. This was a side effect of only involving stakeholders from the agriculture sector, that resulted in strategies targeting other influential subsystems that in many ways contributed to the current unsustainable state in the area studied, not being considered. A more inclusive selection of stakeholders, such as by using the Stakeholder Influence Map, could perhaps have made the work more robust.

Overall, in the studies reviewed; system tools were widely used in addressing water issues, with authors describing in detail their methods, listing their advantages and the benefits expected from their application, but largely, there is no clear evidence that the challenges they tackled had been resolved or even understood from a whole systems perspective. Several researchers have even developed bespoke systems methodologies by combining several methods and techniques to carry out specific functions such as brainstorming, visualising systems, studying interrelationships, modelling system behaviour, or facilitating communication depending on the objective of their studies (e.g., Pagano et al. 2019; D'Agostino et al. 2020; Pluchinotta et al. 2021) but their overall approach still fell short of addressing challenges effectively. Their limited research scope and too much emphasis on using tools and methodologies as a way of qualifying and rationalising their approach seem to have limited the potential to deliver truly systemic solutions (e.g., Kotir et al. 2016; Psomas et al. 2018; Pouladi et al. 2020; Nabiafjadi et al. 2021). This allows us to conclude that there is a real need for better adopting systems thinking in addressing water challenges, a way of thinking that goes above and beyond the application of system tools and the selection of system solutions, a dynamic process of transformation that needs to inform the selection of tools, enable the development of system solutions, and empower society to implement them effectively to achieve sustainability.

4 Discussion

In 2002, the International Institute for General Systems Studies (IIGSS) drew up an inventory of systems techniques and tools and came up with more than 1,200 tools, "ranging from the familiar to the downright obscure" (see The Systems Genealogy by Williams n.d.). This is perhaps why it is rather challenging to sort through the breadth and diversity of system tools to determine what is useful and what is not, as well as how to apply the ones selected from a true systems perspective. Tools are sold mostly by consultants as a recipe, that seems easier to follow to come up with an answer instead of understanding the challenges from a systems perspective first and then addressing them appropriately (Al-Kalbani et al. 2015; Fuentes and Vervoort 2020; Kabir et al. 2015; Reid and Wood 2023). By the definition of complexity, the context of every complex system is different (Boulton et al. 2015) and tools have to simplify complexity to allow them to work across a wide range of challenges. This simplification of complexity inherent in each type of tool selected could be considered equivalent to ignoring complexity if this selection is not informed by systems thinking and an advance ability to observe, embrace, and manage complexity. It is this tension between methods and principles, that often leads to the misunderstanding of system tools as systems thinking. Indeed, *systems thinking* and *applying 'system tools'* are often used interchangeably, leading to a vague distinction between them.

To ensure that system solutions do not become a buzzword, and the process for deriving them does not end up being pointless or misunderstood, greater clarity and rigour is required in both the selection and application of tools. Monat and Gannon (2015) propose selection criteria for good system tools, among which are that the tool must be widely applicable to most systems, not just a narrow sub-category of systems described in the systems thinking literature, apply the systems thinking concept, and aim to enhance understanding of the existing systems. Several guidelines on how to choose appropriate system tools have also been proposed based on purposes, methodologies, system complexities, and underpinning theories (Allen and Kilvington 2018; Jackson 2019; ESCAP 2019; Van Leeuwen et al. 2016). It is the application of systems thinking that allows for the selection of appropriate tools to use when addressing water challenges; exploring all system *interrelationships* (context and connections), *perspectives* (each actor has their unique perception of the situation), and *boundaries* (agreeing on scope, scale and what might constitute an improvement), to understand systems in a truly holistic manner (Jackson 2019).

A systems approach to addressing sustainability challenges requires new tools, including data, methods, theories, and statistical analyses different from those traditionally used in linear approaches. No single discipline can provide these tools. Therefore, it is necessary to approach these challenges with a collaborative team of investigators who bring knowledge and expertise from a variety of disciplines and sectors (Leischow and Milstein 2006). The theoretical frameworks and methodologies that result from such collaboration can generate new conceptual syntheses, new measurement techniques (e.g., social network analysis), and interdisciplinary fields of inquiry (e.g., urban water studies) with the capacity to tackle the complex sustainability challenges related to water (Wong et al. 2020).

Even for the term 'systems thinking', which has become a discipline that goes beyond a collection of tools and techniques, there are several perspectives. Tools like brainstorming tools, structural thinking tools, dynamic thinking tools, as well as computer-based tools have become popular when looking for solutions, but systems thinking is more strategic (Monat and Gannon 2018), offering the context for the application of these tools. Systems thinking is first and foremost a diagnostic tool that can help to assess problems before taking action. It helps to ask questions before arriving at conclusions and prevents making and relying on assumptions, the lowest level of knowledge. Applying systems thinking to address complex challenges requires deep understanding of how things truly work through critical and interdisciplinary thinking, and an ability to consider multiple disciplinary perspectives, analyse the strengths and weaknesses of those perspectives, and integrate their insights to produce a new, more comprehensive understanding of these challenges. The term 'understanding' refers to the ability of obtaining and enhancing knowledge to a level that facilitates the ability to understand "why something has happened or is happening (insight) and to anticipate and identify potential outcomes (foresight)" (Dewey 1933; The Development Concepts and Doctrine Centre 2020). It is about applying judgement to both make sense of, and recognise the significance of, facts in a given context, as well as recognising the system's relationship with other things: its operations, functions, consequences, causes, and potential applications (Dewey 1933).

The connection between the means and the outcome is the essential and fundamental aspect of all understanding. The Development Concepts and Doctrine Centre (2020) categorizes understanding into three forms: i) *Individual*, each person's interpretation of facts, influenced by personal experience and peer pressure, ii) *Collective*, as the shared perspective held by members of different groups that have their ethos, creed, and identity, shaped by organisational cultures, rituals, stories, and norms; and iii) *Common understanding*, the ability to understand the perceptions of groups other than our own and establish a common baseline for communication, interpretation, and action. Groups may possess varied kinds of collective understanding that may involve divergent interpretations of the world and events, including how they view each other (Ross et al. 2015; Garrity 2018; Government Office for Science 2022). Moreover, collective understanding dictates how we form attitudes and opinions and how we behave or function (Checklands 1999; Boulton et al. 2015; Ross et al. 2015). Therefore, working within, between, and across multiple groups with different understandings provides opportunities to encounter diverse perspectives. Achieving common understanding is possible when institutions, professions, communities, and other groups collaborate.

Developing collective understanding is a gradual process that requires time. Indeed, inadequate time to develop, examine, or update a shared understanding of the challenges we face could result in greater risk, negative consequences, or missed opportunities (Boulton et al. 2015; Stroh 2015). This also emphasises the necessity of 'learning and adapting together' when improving collective understanding (Ross et al. 2015; Government Office for Science 2022). Learning and adapting together allows us to develop collective understanding more rapidly, taking into account the changing situation, enabling better mitigation of unforeseen consequences, more effective utilisation of opportunities and an increased ability to influence events. A collective understanding of the underlying structures that drive events and patterns that contribute to a system's behaviour is critical. Although knowledge derived from information is a significant factor in building understanding (Boulton et al. 2015), it is subject to change due to various factors such as the context, the actors' roles, politics, and power.

One of the critical aspects of systems thinking, is the principle that systems should be understood and treated not as big machines, but instead as living organisms. Nicholson (2013) differentiates a machine and an organism based on their purposes, with machines having an external purpose (operate towards an end that serves the interests of their maker or user), whereas organisms have an internal purpose in the sense that its actions are aimed at maintaining their own organisation and acting on their own behalf. Organisms are self-organising, self-producing, self-maintaining, and self-regenerating systems, although not entirely self-sustaining. This is why reductionism may be sufficient to explain machines but not organisms (Kesić 2016). Therefore, before studying the structure and behaviour of an urban water system, we need to be clear about its function and role from a whole-systems perspective. Having a clear function for an urban water system is critical in investigating how to improve it later; considering that the desired state is the state that allows it to deliver its 'function'.

The function of an urban water system can vary depending on the perspective used to view it. Some may see urban water systems as having infrastructure and services to supply safe water for urban dwellers and treat wastewater produced by water users to be safely released back into the environment. Some others may find its function to regulate water flows within urban systems to ensure well-being and biodiversity while protecting the wider environment and ensuring cities' resilience against extreme events such as floods and droughts. Whereas others may look at it as one of the critical supporting systems of cities that allow them to thrive socio-economically. To understand the urban water systems from a systems perspective, we need to first recognise them as the functional unit of an urban system in which parts, elements, and actors continuously interact with one another and their surroundings (Santelmann et al. 2019; Koseoglu 2021; Puchol-Salort et al. 2021; Wan Rosely and Voulvoulis 2022; Hjorth and Madani 2023). Therefore, in establishing its function, we need to collect information from multiple perspectives, dimensions, disciplines, and sectors, using various sources of information such as reports, research findings, databases, monitoring data, experts' elicitations, and input from stakeholders.

After establishing the function and its role within the wider urban system, studying its structure and exploring how it operates and delivers its function is next. The structure of an urban water system can be very complex (Dunn et al. 2017; Franco-Torres et al. 2020), but there are several approaches to studying it. Visual Diagrams can be very useful for exploring the variables and interactions that form the structure of an urban water system (Pluchinotta et al. 2021). For instance, using System Mapping, the three man-made subsystems of the urban water system- the treatment and distribution system of water supply; the collection and treatment of wastewater before returning to the environment; and stormwater and rainwater runoff drainage systems to prevent flooding can be explored and subsequently mapped to show they are linked to form parts of the wider natural water cycle (Wong et al. 2020). System maps can be expanded with variables that make up the subsystems and influence how the urban water system behaves. Arrows can be used to connect variables as well as to the subsystems. The other way to do this is by starting with the natural water cycle approach. Tools for mapping systems such as Causal Loop Diagrams can be developed by researchers studying the system using several different sources of information (Ram and Irfan 2021). Such tools can also be used for stakeholders to communicate their understanding of systems, particularly in groups, and allow them to stimulate discussion, collect and structure information and visualise elements of the systems and their interrelations more clearly. They are easy to manage and can be developed gradually to comprehensively visualise the entire system.

Stock and Flow Analysis and Behaviour Over Time Graphs based on quantitative data can be useful for exploring patterns of urban water systems' behaviour (Madani and Mariño 2009; Monat and Gannon 2015; Pagano et al. 2018; Pluchinotta et al. 2018). System Dynamic Modelling, Agent-based Modelling and Bayesian Belief Networks can be used to further explore the dynamic behaviour of urban water systems (Berglund 2015; Meran et al. 2021; Phan et al. 2016, 2021), while more advanced modelling approaches such as a Digital Twin City, can even attempt to simulate the entire urban water system from a whole systems perspective (Cai et al. 2022).

The development of collective understanding supported by the use of these tools is a process that needs to be participatory. The selection of tools will depend on each case, but their use should allow the following: i. collect information from different perspectives or dimensions and organise it to see the system more clearly (Government Office for Science 2022); ii) set boundaries to determine which factors should be included when tackling an issue (DEFRA 2022) and iii) understand the interactions involved that make a system behave the way it does and why and how it reached its current state (Meadows 2009). Data and information are critical in this process. However, apart from the need to have appropriate data management infrastructure, common issues with data have always been associated with the ability to cope with its variety and volume, velocity, complexity, security, and value (Katal et al. 2013), as well as issues of transparency, openness, justice, diversity and equity, which can strengthen people's trust in institutions and encourage greater public participation in decision-making (Koop 2019; Rojas et al. 2020; World Bank 2017). Critical elements for developing deep whole system understanding are summarised in Fig. 2.

Once a collective understanding of the system in its current state has been developed, the next step is co-creating the vision (DEFRA 2022; Voulvoulis et al. 2022), which is normally done once a sense of urgency for the change has been created and a powerful guiding coalition among stakeholders and the general public has been formed. Normative Visioning is often used as a tool to develop a desirable future scenario or vision for a particular domain, such as a city, a region, or a sector, based on normative values and principles (D'Agostino et al. 2020). This is used in strategic planning and policymaking to guide decision-making and action towards a desirable future in a variety of contexts (e.g., urban planning, regional development, environmental management, and social policy) and can serve as a basis for policy development, implementation, and evaluation. The normative vision is

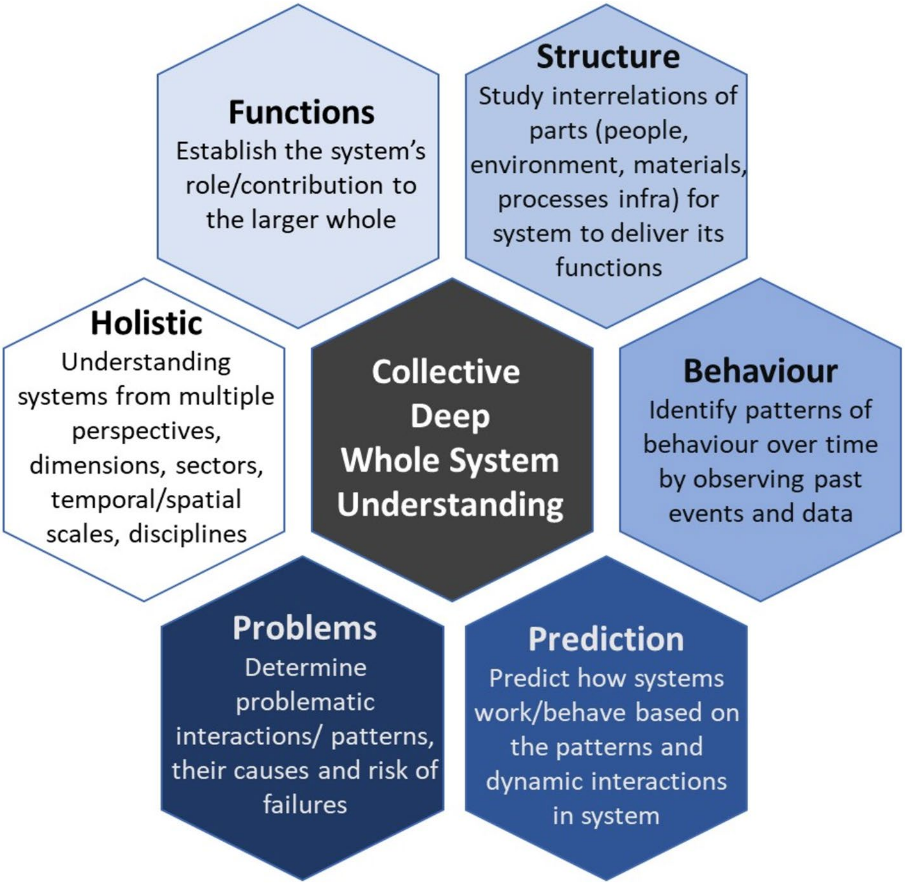

Fig. 2 Critical elements for understanding a system

developed not based on a prediction of what will happen, which is usually the outcome of a forecasting approach based on dominant trends, nor it is treated as a vision of the future to prepare for rather than changing it, hence hindering other possible alternatives that break the trends (Dreborg 1996). In fact, regardless of dominant trends, the vision is developed to determine what should happen (D'Agostino et al. 2020) based on a set of normative criteria agreed upon collectively to reflect the values and aspirations of all actors and stakeholders in relation to sustainability and attributes of the desired state such as prosperity, equity, social justice, biodiversity protection and economic efficiency.

Developing a vision establishes the foundation for the change by investing time and effort in agreeing, through a process of debate and buy-in, on the direction and expected outcomes of the change (D'Agostino et al. 2020). This vision, or 'desired state' is the picture of the future we want to achieve and captures the collective desire for reaching such a state. The process clarifies the general direction of the change and simplifies decision-making by helping to minimise disagreements and confusion when detailed discussions take place (Bengston et al. 2020; Quist 2007). It also motivates individual parties to take action in the right direction including understanding why they should change and how they would benefit from the actions they take. Co-design is the practice by which users are not simply consulted as part of a development process, but become active, creative collaborators in the process of change (D'Agostino et al. 2020; DEFRA 2022; Government Office for Science 2022). The process goes by many names, including participatory practice, co-creation, co-curation, and participatory design, among others. It is not just about effective design outcomes, but also about agency, empowerment, ownership, and democracy.

For water management, designing the desired state is creating a shared sustainability vision of the urban water system and what urban water management aims to achieve. In creating the sustainable vision, it is equally important to look at the urban water system as part of the wider socio-economic structures and development, moving beyond and across sectoral contexts and outside traditional boundaries (Dunn et al. 2017; Franco-Torres et al. 2020; Wong et al. 2020) and transcending urban water and city systems, considering global sustainability visions (UN-Water (United Nations Water) 2021). The process must also go beyond the specific quantitative values commonly used to measure sustainability. The reason for this is that the persistent problems of urban water systems require major changes focusing on dominant trends that have become part of the problem (e.g., population growth, migration, global food and energy demand, urbanisation, and climate change). For instance, poverty and inequality often lead to a lack of access to water supply and sanitation systems, among other environmental issues affecting it (Sharma et al. 2017; World Bank 2017). Some externalities cannot be satisfactorily solved in markets, for instance, the failure of institutions or political biases to ensure everyone has access to a regular supply of water and adequate infrastructure (Hoekstra et al. 2018; Van Leeuwen et al. 2016). Additionally, solutions to tackle water problems may take a considerable amount of time to yield positive results, underscoring the necessity of setting long-term targets for stakeholders to remain committed to sustainability pathways.

The sustainability problems we want to address at this point are viewed as the gap between the vision we have established for the urban water system and its current unsustainable state. Systems understanding that has been acquired earlier in the process, can help establish root causes, which in turn can help identify leverage points for reaching the desired state (Fischer and Riechers 2019). For example, empowering stakeholders and people to make better decisions (e.g., through incentives or constraints), as well as changing the conditions that drive their actions, can result in system changes leading to the desired state. Nguyen and Bosch (2013) demonstrated this in the case of the Cat Ba Biosphere Reserve (Vietnam): instead of focusing on protection or conservation efforts, a holistic development policy for the area was proposed to alleviate poverty first, the root cause of the problems, by focusing on tourism and agriculture industries that enabled the conservation of biodiversity and natural resources in Cat Ba. A clear vision of a desired sustainable future also allows us to work backwards to determine what policy measures should be implemented to guide transformation towards that future. Backward-looking analysis or Backcasting can be a useful tool to explore enabling pathways that connect the desired future to the present by identifying milestones that can guide the interventions required for closing the gap (Dreborg 1996; Government Office for Science 2022; Quist 2007). It can also help identify and create the enabling conditions to facilitate the transition to the desired state, for example, by tackling root causes and applying interventions at leverage points (Fischer and Riechers 2019). According to Meadows (1999), there are 12 places to intervene in a system (Abson et al. 2016). The deepest leverage points for transformative change lie in changing the underpinning values, goals and world views of actors that shape the emergent direction in which a system is oriented. This is done by setting and resetting the goal of a system, shifting mental models or mindsets out of which the system arises, and having the capability to transcend paradigms.

Exploring leverage points based on potential root causes identified through systems thinking and participatory processes can accelerate the sustainability transformation (Davelaar 2021; Fischer and Riechers 2019). Multicriteria decision-making tools can be used to weigh and prioritise strategies or actions for tackling root causes or creating enabling conditions for urban water sustainability (Abdullah et al. 2021; Psomas et al. 2018), and modelling tools can facilitate decision-making through scenario building and analysis projecting the effectiveness of interventions or potential problems that may arise from them.

Finally, as the behaviour of a complex system is full of uncertainties and adapting to changes is critical (Bano et al. 2022), continuous monitoring and evaluation of what does, and does not work is essential to ensure that implementation does not divert from the desired goals, continuing the transition towards sustainability (DEFRA 2022; Government Office for Science 2022). Theory of Change Maps and Systems Performance Questions can be used as tools to monitor and evaluate systemic actions for change (Government Office for Science 2022). The latter applies a whole systems perspective to understanding what works, where it is working, why it is working and for whom, to plan further changes to ensure implementation remains on the right trajectory towards the sustainability vision or desired state. Nevertheless, any monitoring or evaluation tool can only be useful as long as the collective understanding of the system, its function, structure and behaviour that underpins implementation continues to be accurate over its evolution with time. The inherent uncertainty of the complex systems we deal with requires continuously updating knowledge and information, testing and revising our understanding of how they work (Peters 2014; Bano et al. 2022), to modify when and how to intervene to accelerate the transition to the desired state (Boulton et al. 2015). Corrective measures or realignment of interventions when required must be data-driven and participative. To do this, the right infrastructure for supporting collective learning must be in place, empowering people to learn, unlearn, and relearn about the urban water system as it evolves with time so they can respond to changes accordingly and without deviating from the shared sustainability vision, even collectively revising that vision if necessary.

We need to be humble about the fact that we can never have sufficient information, achieve certainty about a system's dynamism (Boulton et al. 2015), and keep rethinking the challenges as the system changes and evolves (Pahl-Wostl 2002; Bano et al. 2022). This means confronting the root causes of issues (rather than symptoms) by transforming structures, customs, mindsets, power dynamics, and policies, and strengthening collective power through the active collaboration of diverse people and organisations. Sustainability transformation needs to be rooted in shared goals to achieve lasting improvement and address the challenges we face at a local, national, and global level. To solve seemingly intractable problems, we need to move beyond incremental change to real transformation (Davelaar 2021; Fischer and Riechers 2019; Meadows 1999). The success of such transformation rests in our ability to shift the complex systems in which those problems exist. Figure 3 summarizes the steps of this transformation process for the transition to sustainability, and in Fig. 4, the system tools reviewed in this study are mapped onto this process, in an attempt to contribute to the operationalisation of systems thinking in addressing sustainability challenges.

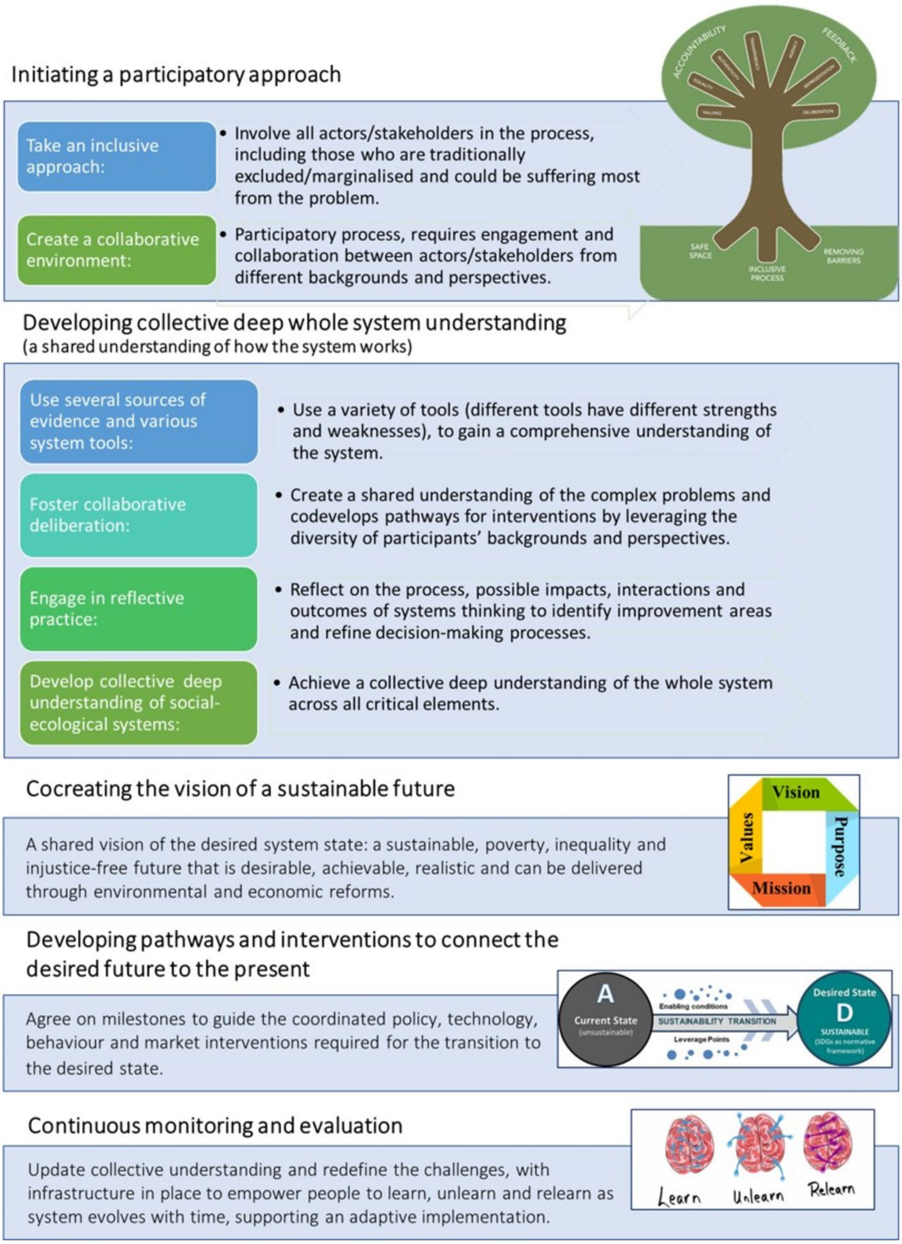

Fig. 3 The sustainability transformation process

5 Conclusions

System tools are not a substitute for systems thinking and applying them alone does not qualify the development of truly systemic solutions. It is the transition from applying 'system tools' to the system application of tools that has the greatest potential to deliver the

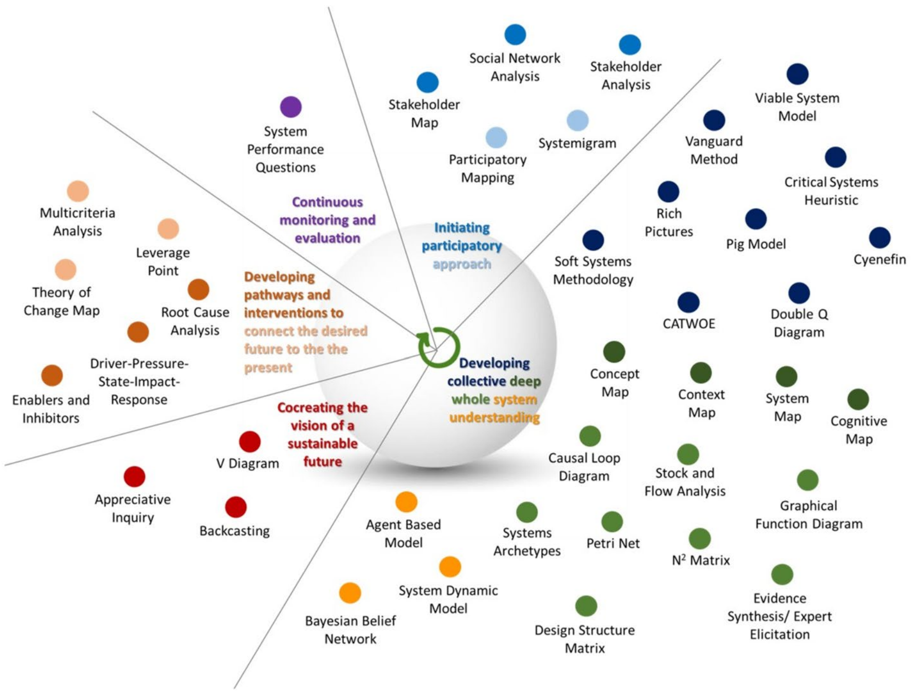

Fig. 4 System tools that can facilitate the transformation needed for the transition to sustainable water systems

system change required for reaching sustainability, and system tools in that context can play an important role facilitating the process. Systems thinking offers a powerful approach to first improving our collective understanding of how the urban water system works and then, in collaboration with a diverse group of stakeholders and the public, defining desired goals and working together to make them a reality. The strategic selection and application of tools can allow a strong baselining of metrics relevant to planning programmes of measures and appropriate investment for reaching sustainability. Systems analysis can enable programmes of measures to be optimised for public value, environmental resilience and other benefits, taking into account local variations in baseline in increasing detail. A systemic view opens up new possibilities in planning with these multiple objectives in mind, ultimately delivering better integration of sector, environmental, economic, and social outcomes and delivering the whole system transformation required for sustainability to emerge.

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Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

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