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Assessment of sustainable drainage strategies in urban water systems using urban water metabolism and multi-criteria decision analyses

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ABSTRACT

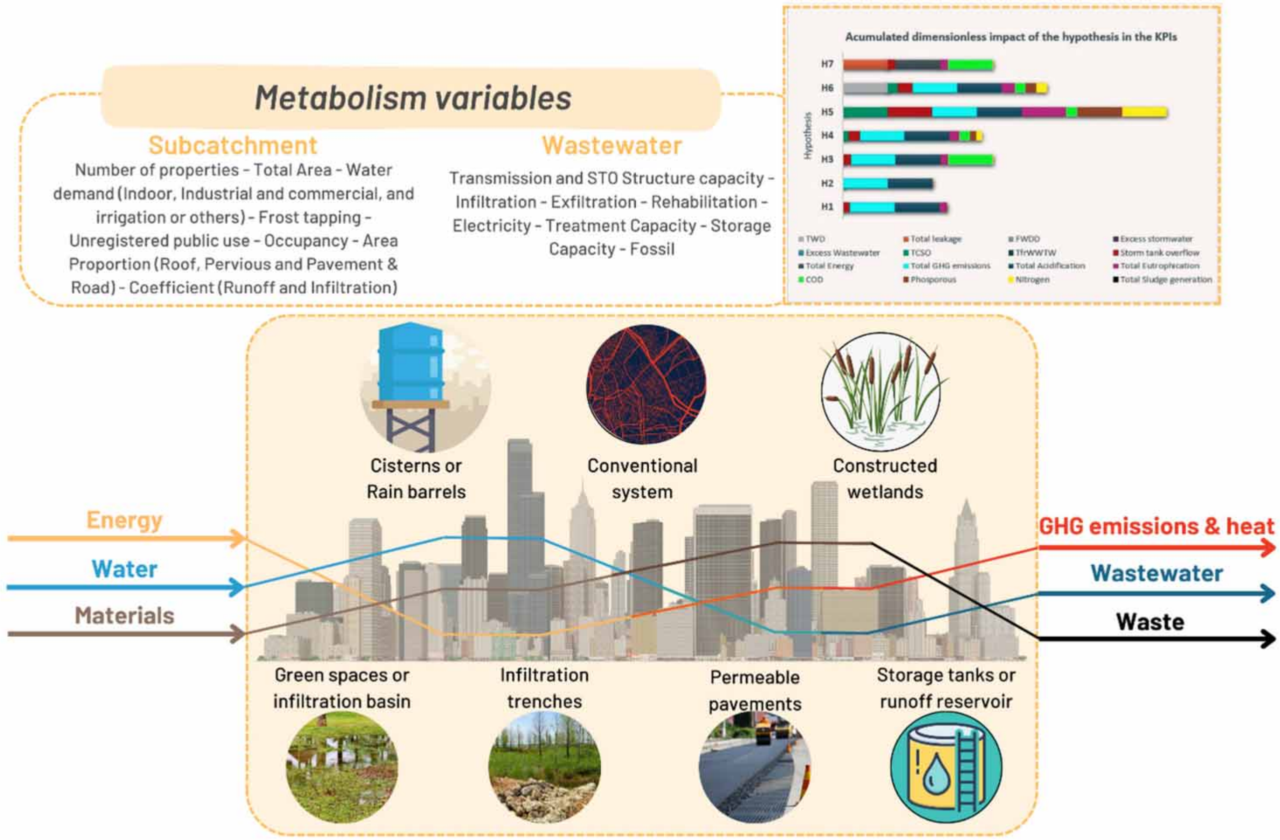
The simulation of urban water metabolism (UWM) allows for the tracking of all water, energy, and material flows within urban water systems (UWSs) and the quantification of their performance, including emissions into the air, water, and soil. This study evaluates seven drainage strategies (DSs) within conventional and sustainable urban drainage systems (SUDSs) using UWM and multicriteria decision analysis (MCDA). The DSs were designed to assess their corresponding UWM performances, employing key performance indicators (KPIs) related to sewer system balance, energy consumption, greenhouse gas (GHG) emissions, acidification, eutrophication, contamination, and sludge production. The outcomes were ranked using the compromise programming MCDA model. The top three strategies were permeable pavements, green spaces, and infiltration trenches and sand filters. The approach used for the evaluation of DS can provide valuable insights for decision-makers, support the promotion of sustainable integrated UWS management and adaptation, and accommodate design variations in urban drainage. Sensitivity analysis on uncertain parameters and KPI selection also contributed to robust and sustainable urban drainage solutions.

Key words: decision-making, metabolic system, performance, SUDS, urban drainage, WaterMet^2

HIGHLIGHTS

- Urban water metabolism is used to evaluate sustainable urban drainage strategies.
- The key performance indicators (KPIs) are calculated for the strategies in urban drainage systems.
- A compromise programming (CP) model is used to rank the strategies with respect to KPIs.
- WaterMet^2 and CP are efficient tools to assist decision-makers in the analysis of integrated urban water systems.

GRAPHICAL ABSTRACT



NOMENCLATURE

COD	Chemical oxygen demand
CP	Compromise programming
CSO	Combined sewer overflow
DS	Drainage strategies
U.S. EPA	United States Environmental Protection Agency
GHG	Greenhouse gas emissions
IUWM	Integrated urban water management
KPIs	Key performance indicators
MCDA	Multicriteria decision analysis
PAST	Paleontological statistics
PCA	Principal component analysis
SC	Subcatchment
STO	Storm tank overflow
SUD	Sustainable urban drainage
TCSO	Total of combined sewer overflow
TfrWWTW	Treated outflow from wastewater treatment works
TRUST	Transitions to the Urban Water Services of Tomorrow
TWD	Total water demand
UWS	Urban water systems
WMOST	Watershed Management Optimisation Support Tool

1. INTRODUCTION

Holistic sustainability assessment is essential for urban water systems (UWSs) to analyse the impact of various external factors and intervention strategies on the overall system performance (Venkatesh *et al.* 2015). Although the main objective is to improve the UWS performance, different perspectives should be observed since a massive use of resources is needed to change negative impacts on the environment, requiring a long-term multi-objective sustainability application (Behzadian & Kapelan 2015a). According to the United Nations, this approach is essential for sustainable development and accelerating climate change adaptation, for example, by investing in parks and urban agriculture to mitigate floods and heat islands (IPCC 2022).

Sustainable solutions have multiple advantages for UWS (Putri *et al.* 2023) and, hence, can be considered as the main alternatives to mitigate multiple related problems such as overflows, inundations, and flooding episodes, and promote urban resilience (Kourtis & Tsihrintzis 2021). Integrating existing conventional and sustainable systems is the best alternative, bringing multifunctionality to the system (Browder *et al.* 2019; Yang & Zhang 2021). Therefore, an unusual approach to performance analysis is necessary, aiming at the urban dynamics and adopting a holistic view to consider different directions (Behzadian & Kapelan 2015a).

Research on the planning process is crucial for decision-makers to enhance performance, standardise the processes, and simultaneously to reduce the dependence on conventional systems. Integrated urban water management (IUWM) is currently a known concept for decision-makers, addressing the impacts of changes on all indicators in UWS components. Implementing combined solutions requires collaborative analyses, as underscored by Mosleh & Negahban-Azar (2021). An integrated approach to UWS management has multiple benefits. Nowadays, a great diversity of available tools can show the efficiency of urban drainage systems. Nevertheless, these tools are usually chosen based on the goals of the decision-makers, making it challenging to standardise the impacts and their respective controlling metrics (Mosleh & Negahban-Azar 2021).

Recent studies have analysed the urban drainage system performance in various indicators for analysing any conventional or sustainable drainage methods. They selected these indicators based mainly on the sustainability criteria in the literature, such as diffuse pollution, environmental impacts, quantity or quality indicators, professional consulting, or even randomly, as demonstrated by Yang & Zhang (2021), Seyedashraf *et al.* (2021), Ariza *et al.* (2019), Wang *et al.* (2017), and Novaes (2016). Several studies have focused on the decision-making between sustainable methods based on the system performance with respect to different key performance indicators (KPIs) (e.g., Santos *et al.* 2021, Seyedashraf *et al.* 2021, Yang & Zhang 2021, and others). However, the selection of KPIs has been usually arbitrary among large areas such as social, economic, and environmental aspects.

A dynamic metabolism model was developed to carry out the performance analysis of a sustainability assessment tool in the urban water department that considers the environmental change caused by urbanism and its impact on several fronts – such as water quality, climate change mitigation and adaptation, and environmental life cycle assessment – and also to improve their operations within the water–energy–carbon nexus (Venkatesh *et al.* 2014). Improvements that change these aspects of economic, social, and sustainable dimensions are mainly required to enhance system's performance (Venkatesh *et al.* 2014).

Urban metabolism refers to the chemical and biochemical processes that maintain life, which is similar to the human body definition of the word. A water metabolism corresponds to a circulatory process where input is transformed, generating some output, while providing something to the system (Venkatesh & Govindarajan 2014). The metabolism-based approach considers the mass stocks in the system and the inflows and outflows (of materials, energy, chemicals, emissions, and waste generation), considering the life cycle assessment and the urban water dynamics (Venkatesh 2013). The urban water metabolism-based approach behaves in the same manner but focuses on urban water flow and its processes (Venkatesh *et al.* 2014).

A comprehensive analysis of the UWS, which includes the urban drainage system, can be conducted through metabolic analysis, which means the number of resources that the UWS needs and how they can transform the natural conditions of the environment. This could be investment demand, operating costs, materials and chemical products, or change impacts, such as contaminant discharge and general emissions (Behzadian & Kapelan 2015b).

Studies on urban metabolism within the realm of UWS, including their subtypes like urban drainage systems, are conspicuously scarce. Our observation reveals a prevailing trend of limited analyses involving single KPIs and specialised publications focusing on specific facets of water systems, such as water supply or wastewater, urban planning, and management. Few studies have focused on urban drainage systems inside the urban metabolism concept, such as Fenner *et al.* (2019), Huang

& Hsu (2003), and Soto (2019). However, they still have not focused on the urban metabolism performance analysis as a basis to KPI selection for the stormwater system decision-making.

Therefore, this highlights the knowledge gap in sustainable urban drainage methods that include and delimit all these criteria and indicators. As a result, this study sets out to establish a framework for validating the selection of drainage strategies (DSs) and the relevant sustainability-based KPIs for their analysis. This was shown through an appropriate tool to evaluate the effects of the selected strategies on the system performance indicators. This can be used in the decision-making process to identify the best strategies in urban drainage systems.

A recent review of urban system performance analysis assessed the tools and how they are being used to analyse UWS. Notably, two cutting-edge tools emerged as key players in evaluating IUWM: the Watershed Management Optimisation Support Tool (WMOST) and the WaterMet² Model. The WMOST was created in 2013 by the United States Environmental Protection Agency (U.S. EPA) to serve as a public domain and is focused on local and specific watersheds. However, the tool primarily emphasises urban water quantity aspects within sustainable design, not being able yet to calculate water quality aspects and wastewater treatment options. These omitted functions are crucial, making it insufficient for the specific objectives of this study (Detenbeck *et al.* 2013). WaterMet² was developed in 2014 as part of the EU TRUST project (Behzadian & Kapelan 2015b) as a stand-alone tool, enabling metabolic analyses at both the city and large basin levels (Mosleh & Negahban-Azar 2021).

The WaterMet² software is specific for metabolism analysis and is shown as a potential tool to analyse the KPIs, being capable of measuring diverse system flows (water flow, energy flow, greenhouse gas emission (GHG) flow, acidification/eutrophication flow, chemical flux, pollutant flux, and quantifying the pipeline material flux). The model allows the quantification of many of these indicators, such as the operational and maintenance costs, or any risks and intervention analysis for the components (Behzadian *et al.* 2014).

This study also seeks to leverage the concept of urban metabolism as a decision-making tool in the planning phase, KPI selection, and adaptation processes. Anchored in urban transformation dynamics and their environmental repercussions, it serves as the underpinning for performance analysis, encompassing and underpinning commonly employed indicators. Our primary objective is to employ the WaterMet² tool to scrutinise the performance of sustainable urban drainage systems (SUDSs) through a metabolic lens, with the ultimate aim of elucidating how this approach can guide decision-making among various SUDS alternatives.

2. MATERIALS AND METHODS

2.1. Materials

The WaterMet² mechanism uses a water mass balance-based approach to simulate the urban fluxes and quantify the UWS performance. Likewise, it considers the operational dynamics of the system, including system construction, production, and maintenance. It is used to measure quantitative indicators based on the system's metabolic and sustainability performance, as well as other metrics. Its strength lies in the analysis of integrated UWS (Behzadian & Kapelan 2015a). It can analyse different flows, including water, energy, GHG emissions, pipe materials, chemicals, and pollutants. Furthermore, these fluxes are analysed temporally and spatially within the city subsystems (Behzadian *et al.* 2014). The details of the flows, their functions, equations, datasets, and KPIs can be found in the WaterMet² Report (Behzadian *et al.* 2014).

For building and simulating a WaterMet^2 model, an input dataset containing weather data and various parameters of the UWS are required, such as flow rates and local characteristics of subcatchments and water demands (Behzadian *et al.* 2014). For specific details on the dataset and spatial data, references can be found in the Supplementary Material.

2.2. Research method

The most effective option for storm drainage is determined through a decision-making process to enhance the optimal solution. This involves performing simulations, adjusting parameters, and running simulations as many times as necessary. Subsequently, the decision method is applied to the model outputs (Ferrans *et al.* 2022). Sensitivity analysis of the results is particularly useful for outcomes with a high level of uncertainty. This can be assessed by measuring the performance of an alternative based on specific criteria (Haddad & Sanders 2018). Figure 1 illustrates the decision-making process aimed at determining the optimal drainage alternative and its impact on metabolic outcomes.

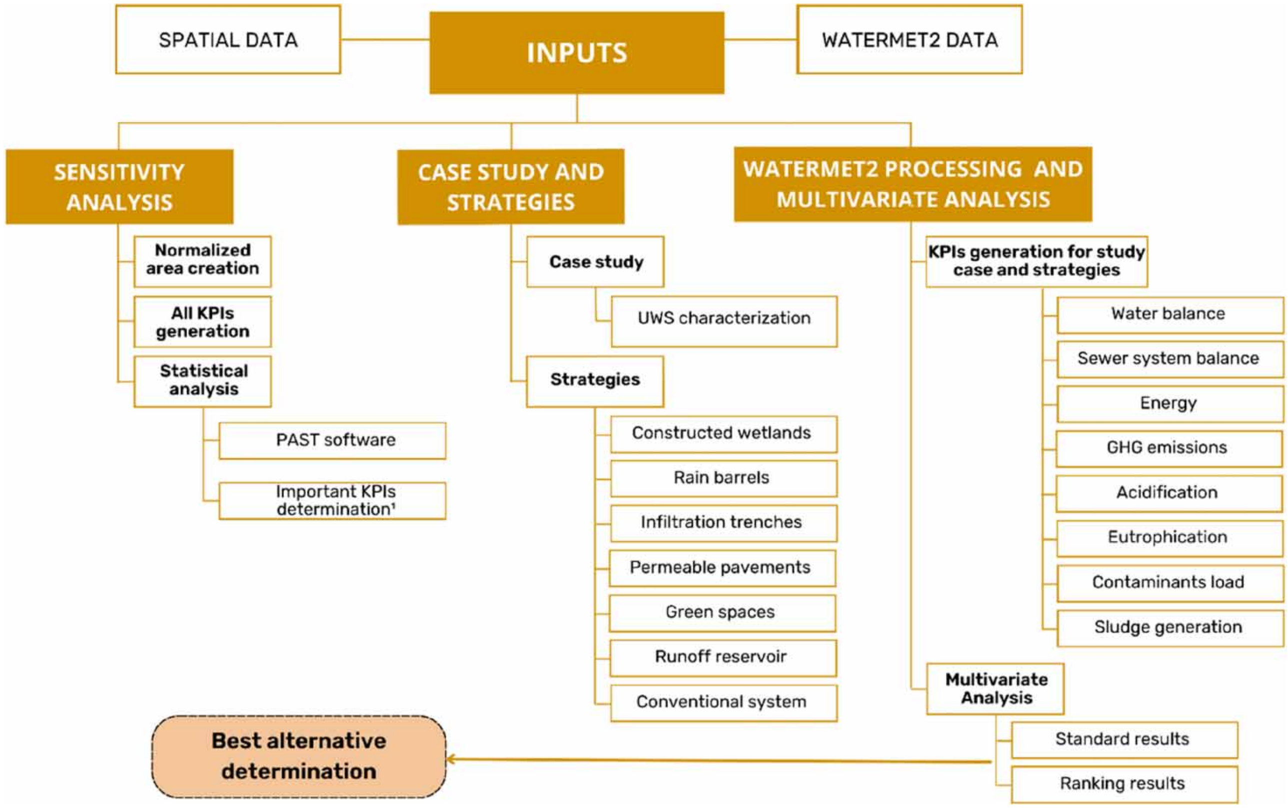


Figure 1 | Research structure summary.

2.2.1. Sensitivity analysis

To identify the most influential variables impacting the KPIs, we created a hypothetical scenario to conduct a sensitivity test. This determination is accomplished through a systematic application of statistical methods to analyse the results from WaterMet², identifying the variables that most affect the process. Figure 2 illustrates the test structure and flow applied for sensitivity analysis.

For this step, we constructed the structure assuming a single unit for each UWS component, and we utilised the default values provided by the system for the dataset. To simulate an ideal urban area in this analysis, we assumed that half of the area consists of commercial activities, while the remaining half comprises residential areas. This is based on the default data obtained from São Paulo City, as it represents one of the most urbanised areas (IBGE 2010). Other relevant details can be found in the Supplementary Material.

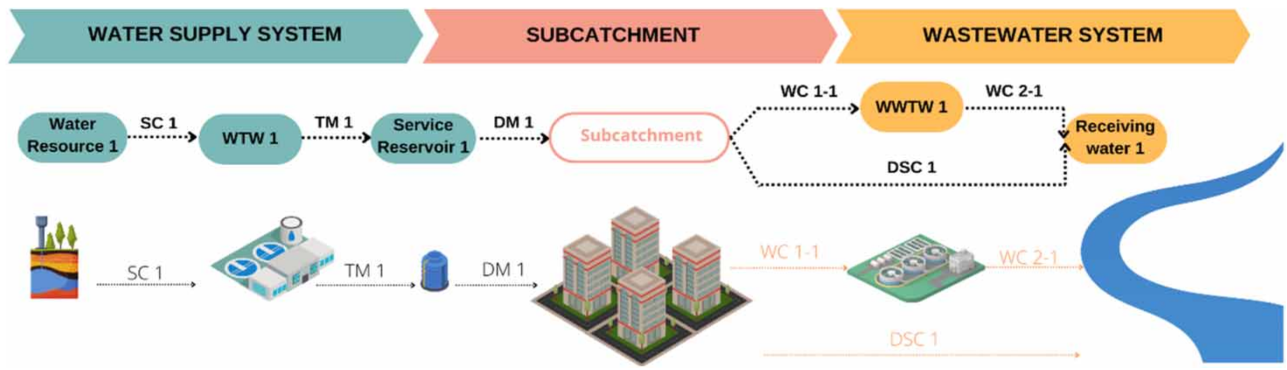


Figure 2 | Sensitivity test – UWS scheme.

In this phase, we established a simplified structure, considering a singular unit for each UWS component, and adopted the default dataset values provided by the system. In our simulation of an ideal urban area, we assumed an equitable division with half of the area designated for commercial activities and the remaining half allocated for residential purposes. Our selection of default data was grounded in insights gathered from São Paulo City and chosen for its representation of one of the most urbanised regions (IBGE 2010). More comprehensive elaboration can be found in the Supplementary Material.

We selected one KPI from each category, with specific subcategories chosen for the running simulation. These subcategories include water balance, fraction of water demand delivered, sewer system balance, energy, GHG emissions, acidification, eutrophication, contaminant load, and sludge generation. For the plot configuration, we chose to represent values in absolute terms in order to achieve a clearer understanding of the impacts.

Initially, we employed sensitivity analysis to simulate a 100% disturbance in different subcatchments and wastewater variables. These changes resulted in a response in the generated KPIs. In the sensitivity analysis, we examine the cumulative values of these KPIs within a planning horizon of 5 years to assess short-term impacts.

We chose the principal component analysis (PCA) method for this evaluation due to the large number of system variables. PCA is a technique that reduces the complexity of a dataset while retaining its most essential information. It achieves this by generating new variables called principal components (PCs), which are combinations of the original variables that have a significant impact on the process (Ringnér 2008). We selected the PAST (Paleontological Statistics) software because of its user-friendly interface and compatibility with Excel input dataset files. This software simplifies spreadsheet data entry, specifically for the disturbance results, and facilitates the calculation of PCA multivariate statistics (Hammer *et al.* 2001).

2.2.2. Case study and DSs

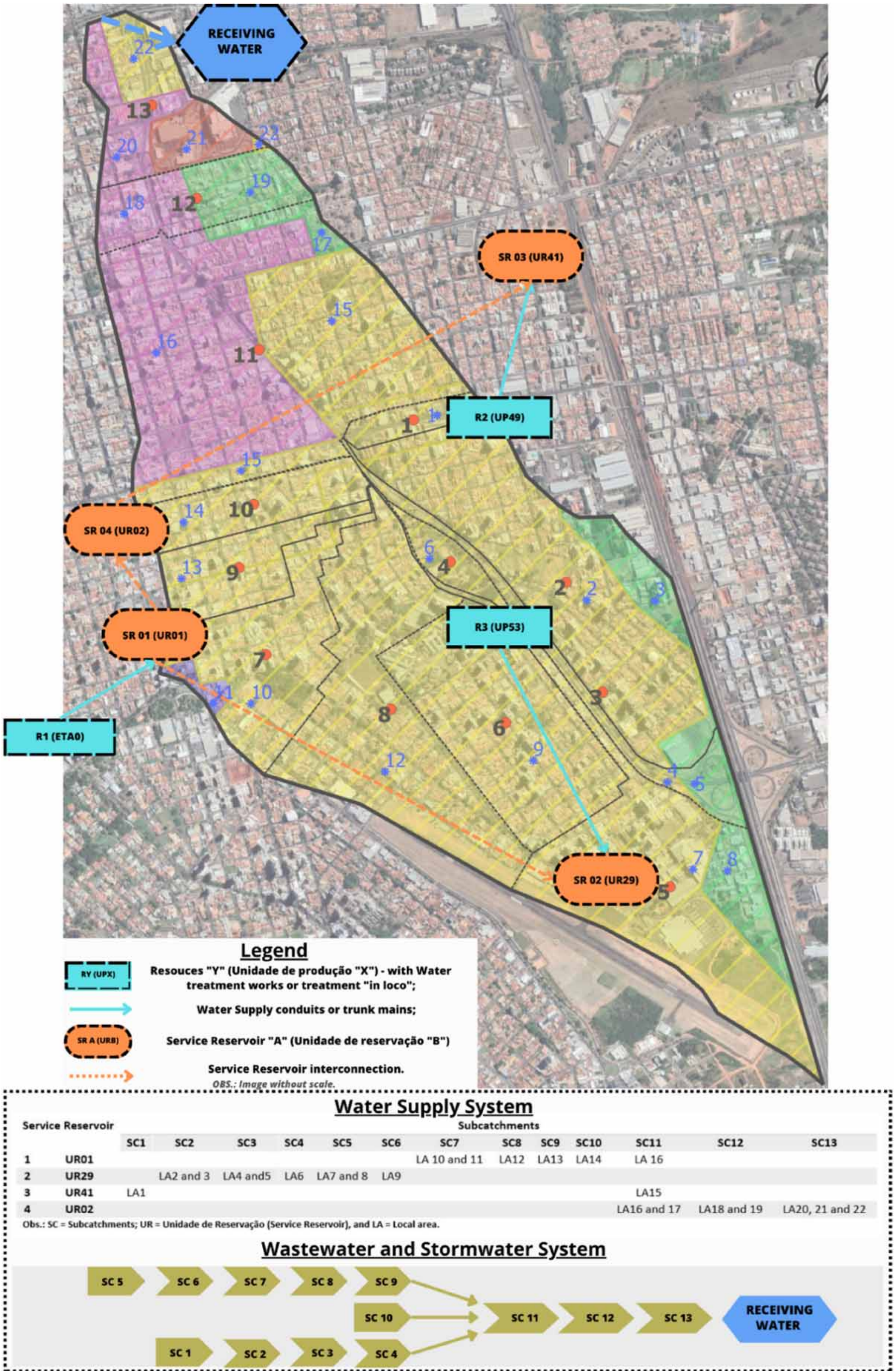
To illustrate the proposed approach, we applied it to an existing urban drainage system. The selected study area is located in the municipality of Bauru, in the state of São Paulo, Brazil. This area, located within the Bauru River watershed, includes important water bodies that receive rainwater runoff as well as the complete discharge of domestic effluents (SMMA 2008). The chosen area is confronted with significant challenges, including high levels of impermeabilisation and deficiencies in the drainage system. These issues result in recurring episodes of flooding and inundation (IPMET 2022). The urban basin has its mouth at the intersection of Nations Units Avenue with Nuno de Assis Avenue, which is located at latitude and longitude coordinates of −22.312 and −49.069, respectively. It is called 'Córrego das Flores' or 'Ribeirão das Flores' (Flower stream), and the respective basin is shown in Figure 3.

The local administration has established guidelines to address these drainage issues through municipal laws, although the implementation process has been progressing slowly. These guidelines encompass various measures, such as land use policy, sustainable recovery of valley bottoms, containment works, administrative measures for water containment (including the control of land use by basin and the control of works), channel dredging, incentives for cisterns use and retention devices, as well as 'zero impact' policies in new neighbourhoods and subdivisions, encouragement of drainage pavement projects, conservation units, and rainwater reuse in existing buildings. Of particular note is the mandatory requirement for rainwater reuse in new buildings that exceed 300 m² (PMB 2017b).

The classification data were structured in a manner that closely resembled the sensitivity test. The area was divided into 13 subcatchments, each corresponding to specific city zones numbered from 1 to 13. For more information on subcatchment details, refer to the Supplementary Material. A summary of the water system scheme for the study is presented in Figure 3. The water supply system is represented by a single surface water abstraction point, with various reservoirs interconnecting before supplying the subcatchments (DAE and HIDROSAN 2014a). On the other hand, the wastewater system operates independently by collecting surface runoff through pipelines and discharging it into receiving water bodies. A similar approach is followed for the storm drainage flows (Ampla 2016a).

Seven DSs were suggested, with the first one closely resembling the conventional system, i.e., do 'nothing' or business as usual (BAU). This strategy was the first one used in the case study, as detailed in Table 1. The WaterMet² model is built by setting fixed values and UWS components for water supply and wastewater, as well as storm drainage configurations. Subsequently, we modified and adjusted the strategy characteristics, as outlined below. Detailed instructions on how to complete the WaterMet² forms can be found in the Supplementary Material.

Our primary objective is to provide a robust basis for well-informed decision-making and to facilitate a meaningful comparison of these drainage system concepts. Hence, it is crucial to thoroughly investigate the metabolic implications of



Service Reservoir		Subcatchments												
		SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11	SC12	SC13
1	UR01							LA 10 and 11	LA12	LA13	LA14	LA 16		
2	UR29		LA2 and 3	LA4 and5	LA6	LA7 and 8	LA9							
3	UR41	LA1										LA15		
4	UR02											LA16 and 17	LA18 and 19	LA20, 21 and 22

Obs.: SC = Subcatchments; UR = Unidade de Reservação (Service Reservoir), and LA = Local area.

Figure 3 | Catchment UWS scheme, where R represents the resource, SR or UR represents the service reservoir, LA represents the local area, and SC the subcatchment. *Source*: structure adapted from Ampla (2016b).

Table 1 | Strategy nomenclature and application

Strategy name	Strategy number	Application
Conventional system	ST01	BAU
Constructed wetlands, green roofs, bioretention ponds, and bioretention cells	ST02	Park areas
Storage tanks and rain barrels (decentralised system)	ST03	All residences
Infiltration trenches and sand filters	ST04	Roads centre square and side beds
Permeable pavements	ST05	50% of the pavement area
Green spaces (tree pits, dry ponds, raingardens, grassed swales, and infiltration basin)	ST06	All available areas
Storage tanks and runoff reservoir (centralised system)	ST07	Percentual of daily minimum demand per capita

each individual model. As a result, in devising our scenarios, we concentrated solely on distinct system types, as delineated and subsequently simulated below.

ST01: the conventional system simulation is conducted based on the case study described earlier, as the case study model only utilises conventional drainage methods. This strategy serves as a reference for comparing the impacts of the different alternatives. Note that all DSs are applied to the available permeable public areas, as shown in Figure 4.

ST02: the constructed wetlands are recommended for stormwater treatment, mainly the surface water flow wetlands (Fletcher *et al.* 2020), which is chosen for this study. This type of wetland contains a specific type of vegetation that slowly filters the water as it passes through, degrading and absorbing pollutants (Fletcher *et al.* 2020). Since constructed wetlands for runoff water treatment require a significant amount of space due to the need for a sedimentation basin and an outlet structure (Lopez *et al.* 2018), this study focuses on their application only in park zones in the study area. The park areas are transformed into constructed wetlands, accounting for 50% of the total area. These wetlands are designed based on a model from an external study, which has a size of 1,910 m^2 and a depth of 2 m (including 10 cm of free edge). This design allows for the treatment of a total of 3,629 m^3 of treated runoff (Lopez *et al.* 2018).

ST03: rain barrels are implemented in all the residences and businesses in the region. The idea is aligned with certain government programmes that have shown progress in providing incentives to install cisterns in residences located in semi-arid areas to meet the water needs (Secretaria Nacional de Desenvolvimento Regional e Urbano 2019; ASA 2022) that are 20 L per capita according to the World Health Organization (Herkenhoff 2020).

ST04: infiltration trenches are also called filter drains, which are considered an application adjacent to roads in their centre square and in the side bed. The trenches are designed with 1 m depth, which also aids in pollutant removal (Ballard *et al.* 2015).

ST05: the selected permeable pavements in this strategy consist of porous asphalt, which is applied to 50% of all pavements. Even when compared to cases where the sole function is flood attenuation through infiltration, it still has a positive impact. This is primarily due to its capacity for pollutant removal. In this case, the total infiltration type involves direct infiltration into underground waters, without the need for an additional drainage system (Ballard *et al.* 2015).

ST06: green spaces are assumed in this strategy in all the available areas (Figure 4), and a method involving the creation of ditches with appropriate depths is applied with infiltration directly to groundwaters. In this strategy, the water will infiltrate, and this type of SUD can be applied in many places due to the variety of applicable surface materials (Ballard *et al.* 2015).

ST07: this strategy includes a centralised runoff reservoir similar to those proposed for storage tanks and rain barrels. Since the centralised system usually has a significant volume of water and storage size, a water pump is used to return this water back to the water system. The water pump for this simulation is selected based on the ones used for system correction in the city, with a consumption rate of 0.014 kWh/m^3 (PMB 2019), which can be used for non-potable public uses.

The BAU is simulated in WaterMet² using values from the water supply, wastewater (including the drainage system), and subcatchment datasets. Subsequently, based on the sensitivity results, each of the six strategies is simulated individually by modifying the specific settings of relevant strategies. The variables used in the tool comprise aspects of the drainage system, wastewater data (specifically related to treatment and drainage system types), water supply data (pertaining to

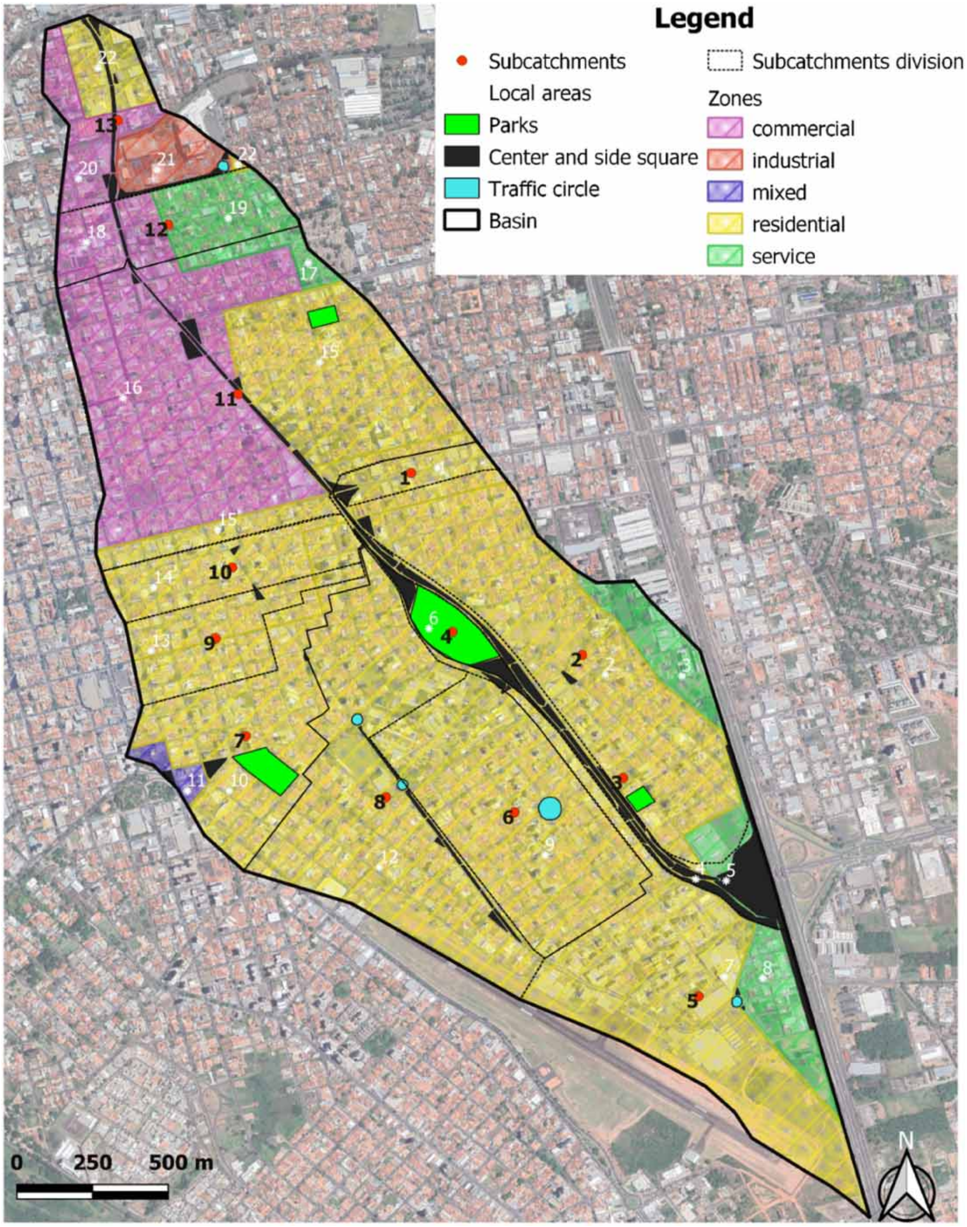


Figure 4 | Catchment public areas available for DS implementation.

water reuse), and subcatchment data (relevant to infiltration or structural changes). This range of modifications and input methods is aligned with the objectives of this study. The input system characteristics of different drainage system types provide metabolism performance of the UWS due to the storm drainage alterations.

Both the case study and sensitivity tests are conducted with a short-term planning horizon of a period of 5 years (SMDU 2012). While using an annual time step for analysing the KPI, the comparisons between strategies are made using only the accumulated values for the entire planning horizon. We also select those UWS components to ensure a comprehensive evaluation of the entire urban system and generate accurate results.

2.2.3. Multivariate analysis and decision-making

The values generated by the WaterMet² enable us to quantify the impact of each strategy on the KPIs. Subsequently, we utilise a multicriteria decision analysis (MCDA) to rank these strategies based on their performance. The KPIs are distributed evenly based on the fluxes, considering the sub-criteria outlined in Table 2.

Table 2 | Criteria weights

Criteria/fluxes	Criteria weight (%)	Sub-criteria/KPIs	Sub-criteria weight (%)
Water balance (m^3)	12.50	Total water demand	4.17
		Total leakage	4.16
Sewer system balance (m^3)	12.50	Excess stormwater	2.50
		Excess wastewater	2.50
		TCSO	2.50
		TfrWWTW	2.50
		STO	2.50
Energy (kWh)	12.50	Total energy	12.50
GHG emissions (tonne CO_2-eq)	12.50	Total GHG emissions	12.50
Acidification (tonne SO_2-eq)	12.50	Total acidification	12.50
Eutrophication (tonne PO_4-eq)	12.50	Total eutrophication	12.50
Contaminants (tonne)	12.50	COD	4.17
		Phosphorous	4.17
		Nitrogen	4.16
Sludge (tonne)	12.50	Total sludge generation	12.50

The discrepancy in values and units of the KPIs highlights the need for standardisation to facilitate future comparisons and interrelations (Carvalho 2006). This normalisation is performed using Equation (1), which represents a direct proportion transforming the values between 0 and 1 (Canales 2009).

$$f\,i'(x) = \frac{fi^{\text{best}}(x) - fi(x)}{fi^{\text{best}}(x) - fi^{\text{worst}}(x)} \tag{1}$$

where $fi'(x)$ is the standard calculated performance of strategy 'x' for criterion 'i'; $fi(x)$ is the calculated performance of strategy 'x' for criterion 'i'; $fi^{\text{best}}(x)$ is the best-calculated performance of all strategies for criterion 'i'; and $fi^{\text{worst}}(x)$ is the worst calculated performance of all strategies for criterion 'i' (Canales 2009).

The compromise programming (CP) method involves measuring the distance of proposed alternatives from an ideal point in order to achieve an accurate solution that aligns with the preferences of decision-makers (Behzadian & Kapelan 2015a; Cecagno *et al.* 2019). Given the progressive nature of objective attainment and the inherent challenge of reaching the ideal point, this work used the nearest one known as the 'goal point' (Cecagno *et al.* 2019).

The distance between the calculated alternative and the ideal point can be described as follows (Gershon & Duckstein 1983):

$$\text{Lp}(x) = \left[\sum_{i=1}^{n} \propto_i^p \left| \frac{fi^{best}(x) - fi(x)}{fi^{best}(x) - fi^{worst}(x)} \right|^p \right]^{\frac{1}{p}} \tag{2}$$

where $\text{Lp}(x)$ is the distance in CP; $\propto_i^p$ is the weight for each criterion; p is the weight of the maximum deviation of the mathematical function; and the rest is already described in Equation (1); the p-value was considered 2 because of the mathematic adjustments to consider the Euclidean distance (Gershon & Duckstein 1983).

3. RESULTS AND DISCUSSION

3.1. Sensitivity results

3.1.1. Normalised results

After running the model simulation in WaterMet², results are generated with a minimal number of inputs, demonstrating its capability to simulate UWS of any size using a streamlined dataset. Additional information and graphics can be found in the Supplementary Material.

The results show that the total monthly energy consumption ranges from 138,000 to 143,400 kWh. Notably, electrical energy accounted for 80% of the total energy, and the total GHG emissions exhibit a similar pattern, with 96% of GHG emissions originating from electricity and embodied energy. This is often a result of the use of chemicals in the processes and pipeline materials.

It is evident that the major contribution of energy and GHG emissions in the UWS is from electricity consumption, which highlights the need for concentrated efforts in this section. To put it into perspective, the average monthly electricity demand of 140,70 kWh and GHG emissions of 29.50 tonnes CO_2-eq are equivalent to the annual electricity consumption of seven households and the burning of 26.29 gallons of diesel fuel, respectively (EPA 2022).

Based on these results, for the next analysis, we only considered the total values of eutrophication, acidification, GHG emissions, energy consumption and contaminants. We also looked at the single result of sludge generation, as well as the multiple results of total water demands, total leakage, fraction of water demand delivered, total combined sewer overflows (TCSO), and total storm tank overflow (STO).

3.1.2. PCA results

The short-term sensitivity simulation results for each KPI under disturbance were analysed using the PAST software to identify the PC. Following the PCA quantification, it was found that PCs 1, 2, and 3 collectively accounted for 98.20% of the cumulative variance proportion in the data, indicating their significant influence as the most influential variables.

The variables that most affected PC1 were *irrigation and other water demand, frost tapping, industrial and commercial demand, rehabilitation, electricity, fossil fuel usage, treatment capacity,* and *storage capacity*. In the case of PC2, the most influential variables included the *number of properties, indoor water demand, occupancy, infiltration coefficient,* and *exfiltration*. On the other hand, for PC3, the *total area* emerged as the predominant factor. Notably, the *transmission capacity* was the only variable that did not influence the principal component and, consequently, the KPIs. This underscores the importance of all variables in the process. Further details can be found in the Supplementary Material. Therefore, in our case study analysis, we meticulously considered all variables in accordance with the analysed strategies.

3.2. Case study results

3.2.1. Bauru catchment results

Table 3 displays the WaterMet² results for the case study, which corresponds to the UAB. This table presents the absolute values of the KPIs. These results have been also validated by comparing them with corresponding measurements of the same components.

In 2013, the Water and Wastewater Department (DAE) of Bauru City published a report containing annual data for the water supply and wastewater systems. According to this data, the department produced 77,38 m³/day of water out of a

Table 3 | Bauru catchment results for the simulation period (i.e., 5 years)

KPIs		Results for BAU
Water balance (m³)	**Total water demand (m^3)**	1.67×10^7
	Total leakage (%)	5.11×10^6 (31%)
Sewer system balance (m³)	**TCSO**	5.50×10^6
	STO	2.03×10^7
Energy (kWh)	**Total energy**	2.45×10^7
GHG emissions (tonne CO_2-eq)	**Total GHG emissions**	5.90×10^3
Acidification (tonne SO_2-eq)	**Total acidification**	17.0
Eutrophication (tonne PO_4-eq)	**Total eutrophication**	9,699
Contaminants (tonne)	**COD**	477.0
	Phosphorus	3,113
	Nitrogen	1,330
Sludge (tonne)	**Total sludge generation**	3.84×10^4

total consumption of 190,28 m³/day by the catchment. This production represents 40% of the total water demand delivered by the department.

Additionally, according to both private and public well maps, it was observed that the suburban areas of the city are mainly supplied by the public department, while central areas depend on other sources (which were not considered in this study). This implies that the proportion supplied by the public department may be even smaller (DAE and HIDROSAN 2014b), possibly corresponding to around 30% of the total water demands delivered from public sources calculated in WaterMet². According to the DAE document, the total water demand (190,28 m³/day) is equivalent to 500 L/d per capita. This figure can be compared to the 788.8 m³ per capita over 5 years, which is equivalent to 440 L/d per capita as calculated by WaterMet². This calculation not only validates the total water demand but also ensures a water balance within the system.

The water balance values fell within the normal range, and the total water demand amounted to 440 L/d per capita. This is considered normal because Bauru's UWS experiences a loss of nearly 50% of the produced water.

According to the city's sanitation plan, a wastewater treatment facility is currently under construction. The facility is intended to treat 100% of the city's effluent, but it is not yet operational. The basin's sewage is being discharged directly into the Bauru River (PMB 2017a), which makes it challenging to determine whether the values of wastewater overflow are within normal limits. The plan also reports an energy consumption of 1.10 kWh/m³ for water treatment (PMB 2017b) and a consumption of 0.30 kWh/m³, totalling 1.40 kWh/m³ of electricity consumption (direct energy). Compared with the 2.40 kWh/m³ calculated by WaterMet², the difference can be explained by the embodied energy (indirect energy) from the chemicals used in wastewater treatment.

GHG emission values in WaterMet² are calculated in units of KPIs per capita to facilitate a more precise comparison. The calculated rate is 0.288 tonnes of CO_2-eq per capita. The IPCC value for the average emissions in Brazil is 0.275 tonnes of CO_2-eq per capita (Minx *et al.* 2021), indicating only a slight margin of error.

Total acidification and eutrophication are indirectly determined for all types of GHG emissions, considering their associated chemicals, materials, energy sources, and emissions from by-products (Behzadian *et al.* 2014). The total eutrophication was higher than the acidification due to the high amount of phosphorus and nitrogen compounds (nitrate) in this eutrophication process, with most of them coming from wastewater systems. The elevated levels of contaminants, such as nitrate and phosphorus, also explain the significance of chemical oxygen demand (COD), which is typically directly proportional to the concentration of contaminants.

According to the DAE document, the excess water and the wastewater generated by the water treatment are discharged into the river without any additional measures (DAE and HIDROSAN 2014c). As a result, it becomes impossible to validate the sludge generation as calculated by WaterMet².

3.3. DS results

3.3.1. Individual DS results

Each strategy was simulated in WaterMet², and the results of the analysing KPIs for each strategy is shown in Table 4. In the wetland's strategy, it can be seen that KPIs related to water balance, energy consumption, GHG emissions, total acidification, contaminants, and sludge generation remained unchanged. There is also a minor reduction in the TCSO, although it is insignificant. However, the STO increased by 161,210 m³. This increase could be attributed to the utilisation of impermeable wetlands, a strategy applied to previous areas, which, in turn, increases runoff and, consequently, the volume of collected water.

The installation of rain barrels on all properties had a negligible effect on the TCSO. However, it had a favourable impact on the STO, reducing the need for public STO by 19,327 m³. When compared to the planned construction for the catchment, this reduction corresponds to a 30% decrease in the size of the larger centralised stormwater tank or even the possibility of eliminating the smaller one (HIDROSTUDIO engenharia 2016).

The implementation of infiltration trenches in roadside beds would result in a slight reduction in contaminant concentrations. Moreover, this method exhibits significant improvements in infiltration performance and the redirection of water towards groundwater sources.

Likewise, the use of permeable pavement demonstrated significant improvements in reducing STO, with a reduction of 49,373 and 845,860 m³ in total combined sewer and STO, respectively. This results in a decrease of 27 m³/day in the combined sewer overflow and 464 m³/day in the STO over a period of 5 years. Additionally, this method effectively reduces contaminant levels, with only a negligible impact on eutrophication.

Table 4 | KPIs for the DS

KPIs (cumulative values over 5 years – absolute values)		DS: Centralise drainage reservoir	Green spaces	Permeable pavements	Infiltration trenches	Rain barrels	Constructed wetlands	Conventional system
Water balance (m^3)	Total water demand	1.67×10^7	1.67×10^7	1.67×10^7	1.67×10^7	1.67×10^7	1.67×10^7	1.67×10^7
	Total leakage	5.11×10^6	5.11×10^6	5.11×10^6	5.11×10^6	5.11×10^6	5.11×10^6	5.11×10^6
	FWDD	0.31	0.31	0.31	0.31	0.31	0.31	0.31
Sewer system balance (m^3)	TCSO	5.50×10^6	5.49×10^6	5.45×10^6	5.49×10^6	5.50×10^6	5.50×10^6	5.50×10^6
	STO	2.03×10^7	2.01×10^7	1.94×10^7	2.02×10^7	2.03×10^7	2.05×10^7	2.03×10^7
Energy (kWh)	Total energy	2.45×10^7	2.45×10^7	2.45×10^7	2.45×10^7	2.45×10^7	2.45×10^7	2.45×10^7
GHG emissions (tonne CO_2-eq)	Total GHG emissions	5.90×10^3	5.89×10^3	5.89×10^3	5.89×10^3	5.89×10^3	5.89×10^3	5.89×10^3
Acidification (tonne SO_2-eq)	Total acidification	17.0	17.0	17.0	17.0	17.0	17.0	17.0
Eutrophication (tonne PO_4-eq)	Total eutrophication	9,698	9,697	9,688	9,698	9,698	9,700	9,699
Contamination (tonne)	COD	477.0	477.0	477.0	477.0	477.0	477.0	477.0
	Phosphorus	3,113	3,113	3,113	3,113	3,113	3,113	3,113
	Nitrogen	1,331	1,331	1,331	1,331	1,331	1,331	1,331
Sludge (tonne)	Total sludge generation	3.84×10^4	3.84×10^4	3.84×10^4	3.84×10^4	3.84×10^4	3.84×10^4	3.84×10^4

The implementation of DS with green spaces has a larger impact in terms of area coverage, but it has a minor effect to offset the number of construction zones that are needed. Nevertheless, it still demonstrates a favourable impact when compared to conventional systems. This strategy has a significant effect on reducing the TCSO and the STO, resulting in a positive impact on pollutant removal.

In summary, several alternatives demonstrated positive impacts on the KPIs, bringing them closer to the ideal point. For instance, infiltration trenches, permeable pavement, and green spaces have a positive impact on total eutrophication, STO volume, and TCSO. Rain barrels are also found to reduce TCSO. However, some alternatives have negative impacts, particularly constructed wetlands on STO and overall eutrophication levels.

The use of permeable pavements is also found to be the most effective strategy in terms of its positive impact on the system. However, it is important to note that these strategies did not significantly influence other KPIs, such as pump usage, fossil fuel consumption, and other forms of water treatment. This underscores the need for further studies to explore various contextual combinations and their potential impacts.

3.3.2. Multivariate analysis

Figure 5 was generated using standardised results (see the Supplementary Material for software data details). It provides a comprehensive representation of the proportional impacts, illustrating how each strategy affects a different number of KPIs and the corresponding proportion of these impacts.

Figure 5 displays the normalisation and comparison of results based on Equation (1). The normalised outcomes fall within the range defined by the minimum and maximum alterations. Each bar on the graph represents a range closer to the ideal solution, without the use of weights. Consequently, it becomes evident that sustainable DS ST05 (permeable pavements) and ST06 (green spaces) have a higher impact on the KPIs, while ST02 (constructed wetlands) has the lowest impact. Strategies ST05 and ST06 have a significant influence on almost all KPIs and exhibit the highest unitary disturbance values among the alternatives, making them the most impactful choices.

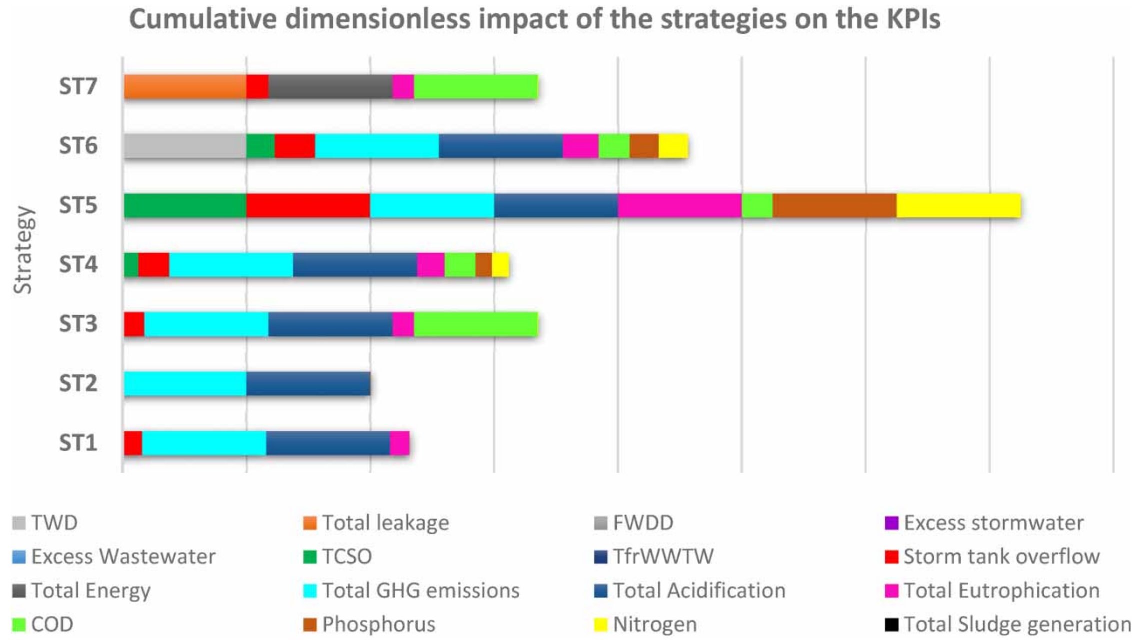


Figure 5 | Cumulative dimensionless impact of DS on KPIs.

Notably, it is important to highlight the sensitivity of the software to their incomes, given the extensive application of these systems. The DS with a more pronounced impact on the KPIs are those applied across an extensive physical area, highlighting the tool's sensitivity. These findings align with the study's objectives, which focus on evaluating the capacity to select appropriate DSs for specific subcatchment characteristics.

On the other hand, the strategy ST02 yields the least favourable results in terms of KPI impact, affecting only total GHG emissions, acidification, and eutrophication. This can be explained by the system's application in areas with permeable surfaces, which reduces infiltration zones, slows down the water flow, and retains it in impermeable locations during treatment.

It is worth noting that all strategies have an impact on certain KPIs, highlighting the effectiveness of WaterMet² in achieving the specific goals of the decision-maker. Furthermore, the most consistently influenced KPIs across all strategies are total GHG emissions, demonstrating significant variability. Approximately 85% of the strategies affect total GHG emissions, STO, total acidification, and total eutrophication. This indicates that these KPIs are strongly influenced by the characteristics of the strategies.

By applying Equation (1) to these values, we are able to collect data to calculate the Euclidean distance of the strategies from the ideal solution, as described in Equation (2), and subsequently rank them which are given in Table 5.

After assigning equal weights to the criteria, we consistently observe that permeable pavement and green spaces are the top-ranking strategies with respect to their influence on the KPIs. This holds true even when weights are not taken into account,

Table 5 | Ranking of the sustainable DS

Strategy number	Strategy name	Euclidean distance	Ranking
ST01	Conventional system	0.2361	5
ST02	Constructed wetlands, green roofs, bioretention ponds, and bioretention cells	0.2458	6
ST03	Storage tanks and rain barrels (decentralised system)	0.2313	4
ST04	Infiltration trenches and sand filters	0.2285	3
ST05	Permeable pavements	0.1983	1
ST06	Green spaces (tree pits, dry ponds, rain gardens, grassed swales, and infiltration basin)	0.2194	2
ST07	Storage tanks and runoff reservoir (centralised system)	0.2596	7

as evidenced by the normalised results. However, the ranking for the worst (i.e., the lowest rank) strategy changed, which can illustrate the significant impact of the decision-maker's preferences on the best option. In summary, for this case study, permeable pavements have proven to be the most individually efficient drainage alternative, particularly due to their extensive application area. This aligns with findings from other studies that have also identified permeable pavements and green spaces as the best options for high-density urban areas (Putri *et al.* 2023). These conclusions are based on the equal weights that were applied. If the decision-maker prioritises different flows or KPIs, the best option may change accordingly.

The KPIs used in this study are aligned with recent research, which has identified water quantity and quality modelling as some of the most studied indicators. Furthermore, there has been a growing emphasis on reducing spatial scales in research, aiming for more precise multi-objective analyses. However, it is worth noting that the majority of studies have been carried out at the city and catchment levels. However, WaterMet² can incorporate household and neighbourhood data and unify the effects at the city scale that all contribute to integrated urban analysis (Ferrans *et al.* 2022).

We also examine the impact of implementing urban DSs in catchments and neighbourhoods on city-scale metabolism performance indicators. The results highlight the impact of these urban DSs on various KPIs, allowing for the selection of the most suitable options or their combination. The ranking of these strategies can assist decision-makers in selecting these systems or devising combinations to improve the metabolism-based performance of UWS.

4. CONCLUSIONS

This study aims to introduce the urban metabolism concept as a suitable approach to support decision-makers in the urban drainage assessment process in a comprehensive way. These correspond to the characterisation of the strategy and the simulation in a specific tool. Thus, this proposal aims to assist the simulation process by providing alternative results, indicating which sustainable strategy could be the most effective for the final solution.

The PCA showed that all variables analysed were important to the process and had a significant impact on at least one KPI. This demonstrates a direct effect on the results and operation, making it ideal to combine with other design instruments.

The case study analysis illustrated that the WaterMet² tool can generate metabolism-based performance indicators of UWS that closely resemble measured indicators. It measures the catchment water metabolism characteristics and enables decision-makers to quantify the conditions of urban dynamics. This tool was also sensitive to design variations in the properties that were typically used to represent the characteristics of urban drainage systems, which makes it a valuable decision-assistant tool. Moreover, it allows for the standardisation of KPI selection for assessing urban drainage systems and determining the best alternative, which, in this case study, was the permeable pavement. However, the weight used in the analysis and the importance of specific KPIs can strongly influence the ranking and selection of strategies.

In conclusion, this study aims to fill the gap in continuous temporal resolution that exists in short-term analyses. This is achieved through the use of the WaterMet² tool. It also examines the impacts of applying drainage system concepts at the catchment scale and evaluates how these variations influence the performance of urban metabolism at the city-scale simulations.

For future works, it is important to diversify the alternatives by associating or modifying the energy consumption using high-impact treatment SUD and other types of systems to observe their impacts on KPIs such as energy and GHG emissions. Additionally, the case study should consider the local climate characteristics and analyse how the localisation and the climate variations can influence the results. Furthermore, when studying the specific contaminants that can be carried out by the urban drainage systems, it is important to track the forever chemicals such as the per- and poly-fluoroalkyl substances and other emerging organic and inorganic materials in the air, microplastics, and others, instead of solely relying on conventional contaminants.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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