Blue-Green Systems

Are we planning blue-green infrastructure opportunistically or strategically? Insights from Sydney, Australia

Martijn Kuller IWA (iD)[a,b,*], David J. Reid[c,d] and Veljko Prodanovic IWA[a]

[a] School of Civil and Environmental Engineering, UNSW, Sydney, NSW 2052, Australia
[b] Swiss Federal Institute of Aquatic Science & Technology (Eawag), Überlandstrasse 133, Dübendorf, Switzerland
[c] Georges Riverkeeper, Sutherland, NSW 2232, Australia
[d] Department of Environment, Land, Water and Planning, Victorian Government, Melbourne, VIC 3002, Australia
*Corresponding author. E-mail: martijnkuller@gmail.com

(iD) MK, 0000-0002-2555-9113

ABSTRACT

Strategic placement of water-sensitive urban design (WSUD) is essential in optimising its performance and maximising co-benefits. However, little is known about the current placement and interconnectedness between WSUD assets and the performance of current planning strategies. We evaluated the placement of existing WSUDs in a highly urbanised catchment in Sydney, Australia. We used a three-step process: (1) compiling a comprehensive spatial asset database, (2) performing spatial correlation analysis between asset locations and biophysical, urban form and socioeconomic variables and (3) using a novel approach to facilitate holistic understanding through analysing asset locations compared with the outcome of the spatial suitability analysis tool (SSANTO). WSUD coverage was generally low, with clustering in some municipalities. Placement was constrained by physical variables, such as slope, limited space and varying land uses. However, placement was not detectably influenced by most socioeconomic variables. SSANTO's suitability score at asset locations was only slightly higher than average, suggesting that the placement of existing WSUD was opportunistic, rather than strategically planned. Further development and implementation of tools able to account for spatial constraints will help guide future WSUD placement as a component of green urban stormwater management.

Key words: asset database, ecosystem services, nature-based solutions (NBS), spatial analysis, stormwater management, strategic planning

HIGHLIGHTS

- We compiled a comprehensive spatial database of water-sensitive urban design (WSUD) assets in a large urban area.
- There was clear consideration of urban form and biophysical variables, but not of socioeconomic variables in WSUD placement.
- Using a novel suitability analysis tool, we holistically analysed levels of strategic placement of current WSUDs.
- There was very limited evidence of strategic planning, and a more systematic approach to WSUD placement is needed.

1. INTRODUCTION

1.1. Rise of, and barriers to green infrastructure planning

The natural water cycle is severely altered in urbanised regions dominated by impervious surfaces. Three separated and centralised systems are used to transport water across urbanised landscapes: the water supply system; the sewage system and the stormwater system (Brown *et al.* 2009). The issues associated with traditional water management in urban areas, such as flooding and water quality decline, are likely to be exacerbated by projected surges in population in already highly urbanised regions, such as the Sydney metropolitan region, in combination with broad-scale changes in the availability of water owing to climate change (GSC 2018).

There is growing recognition for the need for a shift to a broader framework for the holistic management of the urban water cycle, with water sensitive urban design (WSUD) as a central pillar (Coombes 2018). WSUD relieves some of the burdens on centralised infrastructure, by restoring components of the natural water cycle and using stormwater close to where it falls. The potential benefits of WSUD include: minimising effluent generation and

maximising reuse opportunity; reducing potable water demand and utilising stormwater as a fit-for-purpose supply; treating stormwater and wastewater for reuse or discharge; restoring a more natural hydrology in urban catchments; protecting waterway condition by controlling pollutant in discharges and enhancing aesthetic and recreational values for local communities (Hussey & Kay 2015). Further proven benefits include: alleviation of the urban heat island effect (Steeneveld et al. 2014); a rise in the value of property after nearby construction of WSUD; improvements in residents' health and well-being, stronger community connection and lower crime rates (Fletcher et al. 2015; Ferguson et al. 2018). Large-scale WSUD can support high biodiversity (e.g., Kazemi et al. 2009). The design and distribution of WSUD largely influence the extent to which this long list of beneficial outcomes is realised (Deletic et al. 2018).

The complexity of considering a range of variables into solving a multifaceted problem, often requiring retrofitting of existing systems, makes it challenging for WSUD assets to reach their full potential (Thévenot 2008; Deletic et al. 2018; Zhang et al. 2020). Another challenge for WSUD planning is WSUD's reciprocal relationship with the urban landscape, of which it is an integral part (Kuller et al. 2017). Although the development of the technical and regulatory frameworks required to guide WSUD design and planning is relatively advanced, the question of how best to incorporate the wide range of location-specific variables likely to influence decision-making during the WSUD planning process is still unclear (Kuller et al. 2018b). A preferable planning process would consider a range of hydrological, socioeconomic, environmental and ecological requirements to maximise WSUD outcomes at broad scales (Coyne et al. 2020). Such holistic spatially based WSUD planning methods are increasing in popularity (Sharma et al. 2012), but more development and testing are required before their practical application (Kuller et al. 2018a).

1.2. Spatial analysis of current practice

The exploration of current WSUD planning and design across broad scales can be informed by analyses of the types and positioning of existing WSUD assets (Coutinho-Rodrigues et al. 2011). Such analyses show that in Australia a common WSUD planning strategy is for assets to be added when an opportunity arises during other works (Kuller et al. 2018a; Tjandraatmadja 2019), which is less beneficial than a more strategic approach (Schifman et al. 2017). Unfortunately, learning from current practice is hampered by a lack of geospatial inventories of green infrastructure worldwide. Besides the studies mentioned in Australia, only a few studies in the United States report on spatial analysis of current assets (e.g., Chan & Hopkins 2017; Mandarano & Meenar 2017; Porse 2018; Baker et al. 2019). We found no such research from other parts of the world. While these existing studies bring some important insights into the factors related to the locations of green infrastructure, their results cover limited spatial variables, geographic contexts, their findings are inconsistent with each other (partly due to different spatial analysis methodologies) and rely on variable quality and completeness of asset. This lack of studies worldwide is owing to the absence of centrally managed reliable and complete asset databases, and the restrictive cost of their compilation for research.

As both academics and practitioners increasingly recognise the need for strategic planning of WSUD, planning support systems (PSSs) are called for and applied in planning processes (Klosterman 1997; Geertman & Stillwell 2012). PSSs are a set of computer-based tools designed to assist planners in data collection and simulation, spatial and temporal analysis, scenario modelling and outcome performance evaluation during the planning process (Geertman & Stillwell 2004). PSSs are aimed to provide interactive, integrative and participatory procedures for dealing with non-routine, poorly structured decisions, particularly focusing on long-range problems and strategic issues, such as is required for inclusion of WSUD in integrated urban water management. Inventories of PSS for WSUD planning have been made at several moments in time, starting with Elliott & Trowsdale (2007) and followed by reviews by Lerer et al. (2015), Kuller et al. (2017) and most recently Ferrans et al. (2022). GIS-based planning support tools with visual outputs have proven particularly beneficial for communication between stakeholders during WSUD planning (Smith et al. 2013). Although the tools reviewed are mostly applied to aid future WSUD planning and implementation, their outputs can also be compared to past planning outcomes to provide a more complete understanding of the level of strategic planning behind past management decisions compared to previous studies. We adopted this novel approach for a large and highly urbanised area: the Georges River catchment in Sydney, Australia, using a novel spatial suitability analysis tool (SSANTO) to evaluate the strategic level of current WSUD placement from a comprehensive asset database.

1.3. Study objectives

As it is unclear to what extent current planning practices fulfil the objectives of WSUD formulated by practice and academia, the aim of the study was to assess the level of strategic placement of current WSUD assets in a large urban area. We achieved this by (1) compiling a comprehensive and accurate spatial WSUD inventory database, (2) statistically analysing the type, location and size of assets in our database to individual suitability variables and (3) using state-of-the-art spatial suitability modelling outputs. We thus explored the extent to which a range of biophysical, urban form and socioeconomic variables influenced the positioning of existing WSUD infrastructure across the catchment. While the existing approach executed in (2) allows us to compare the drivers behind WSUD placement between urban contexts, our novel approach in (3) allows high-level exploration of the level of catchment-based strategic WSUD planning. We provide discussion and practical recommendations to guide improvements in the methods for future strategic placement of WSUD assets in urbanised areas. Combining a hard to come-by spatial asset database with a novel approach to use PSS outputs to analyse existing asset locations, our study offers a rare insight into the current legacy of past decision-making.

2. METHODS

Our approach consisted of three separate preparatory steps, followed by a spatial statistical analysis. The preparatory steps were: (1) compilation of a spatial WSUD database, in collaboration with local government and followed by a thorough validation, (2) collecting a range of spatial data (suitability variables) to use for spatial statistical analysis in relation to WSUD locations individually and (3) use all spatial suitability variables to run an SSANTO and analyse suitability at the locations of assets. The output of the first stage included a shapefile of WSUD assets with information on type, size and location, and the output of the third step included three types of raster-based suitability maps of the case study area. Following these three steps, the subsequent data analysis first explored spatial WSUD distribution, followed by an analysis of WSUD locations for each suitability variable and finally analysing overall suitability for WSUD implementation to current WSUD distribution. The three remaining subsections each provide further detail on one of the three steps and subsequent spatial statistical analysis.

2.1. Study area and WSUD data compilation

Our study focused on the highly urbanised Georges River catchment, in southern Sydney (Figure 1). The exact study area (930 km^2) was delineated by the boundaries of seven local councils, from which our primary data were acquired. Approximately 1.4 million residents live within the study area (Australian Bureau of Statistics, 2016 Census). Given that WSUD is designed to counter the impacts on waterways flowing through densely populated areas, the highly urbanised area was defined to incorporate all suburbs with population densities of >500 residents per square kilometre (Australian Bureau of Statistics, 2016 Census), which were mainly in the north and west of the study area (Figure 1).

We created a geo-located WSUD database by compiling, harmonising and validating asset inventory data supplied by seven local councils. We classified WSUD assets of increasing footprint as follows: plant boxes and pits, rain gardens and bioretention systems, swales, ponds, lakes, and basins (including natural waterbodies), and constructed or semi-constructed wetlands. When we found that neighbouring councils used different terminology for similar WSUD assets, we harmonised the information to fit in the above-mentioned categories. Although adequate information was provided by most councils, the validation of some WSUD assets was necessary it was not possible to clarify the type, size or location of the asset from the information in the datasets. We followed a two-step data validation procedure: (1) Localising assets on Google Earth to determine type, surface area and exact location if possible, otherwise (2) asset visits in 2019 to establish the aforementioned information. The outcome of this procedure was a comprehensive and accurate spatial database of existing WSUD infrastructure for a large part of Sydney's urban area. We gathered summary statistics from our database including median, total and relative number of systems and system area, as well as area serviced by WSUD. The latter was calculated backward using the asset area (see Melbourne Water 2005, chap. 2): typical values are available for the area of WSUD assets compared to the impervious area they treat. For simplicity, we assumed adjustment to be 1 (disregarding the influence due to the geography and rainfall on WSUD performance and the safety design factor). The results were then compared to a similar study executed in Melbourne to draw some parallels (Kuller *et al.* 2018a). Data sources for the suitability variables are provided in Supplementary Material, Table S1.
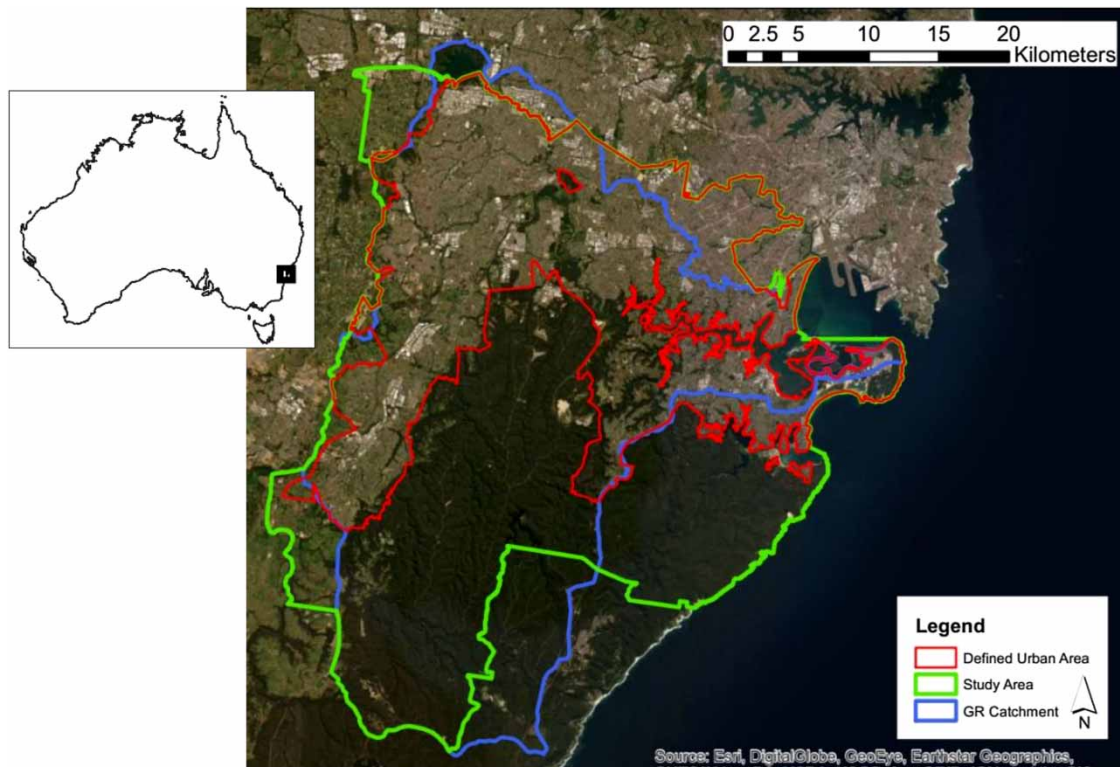
Figure 1 | Boundaries of the Georges River catchment (blue line), study area (green line) and highly urbanised area within the study area (red line). The Georges River catchment covers the southern part of the Sydney metropolitan area on Australia's east coast.

To describe the spread or distribution pattern of WSUD, we applied the average nearest neighbour distance method using ArcMap. The method is used to measure the average distance of the centroid of each WSUD asset to the nearest neighbouring WSUD and compares this value to a hypothetical average distance of random points to their nearest neighbour. The output index, near neighbour ratio (NNR), is the ratio of the observed average distance over hypothetical average distance. This method reveals a clustering pattern when it is less than 1, or a uniform or dispersed pattern when it is greater than 1.

2.2. Univariate WSUD analysis

We applied a similar approach to analyse the spatial distribution of WSUD assets as in Metropolitan Melbourne (Kuller *et al.* 2018a) in order to verify and compare results. To assess the strategic placement of WSUD, we analysed the following spatial variables:

- **biophysical** including slope and distance to natural perennial waterway;
- **urban form** including streetscapes, and surrounding land uses (as classified by Bach *et al.* (2015));
- **socioeconomic** including local population density, median income, education level, participation in community work as proxy for sense of community, portion of voters at the nearest polling station who voted for the Australian Greens Party at 2019 election as proxy for strong environmental engagement, Index of Relative Socioeconomic Advantage and Disadvantage (IRSAD), Index of Economic Resources (IER) and Heat Vulnerability Index.

We measured urban form and biophysical variables at the same scale as WSUD assets, by overlaying the respective GIS layers (i.e., land uses, slope and waterways) with the geo-located WSUD assets. We analysed the effect of our spatial variables for each type of WSUD asset by recording the distribution of values for each biophysical variable at the WSUD location. We statistically compared these values to the total distribution of values of that variable over the study area, using the data at randomly generated points within the constraints of the study area. We used approximately 100 times the number of WSUD assets as the number of random points (i.e., 25,000 random points). If both distributions were similar, the suitability variable had no discernible

effect on the positioning of WSUD assets. Finally, we assessed the abundance of WSUD assets found in street-scapes compared to all other urban landscapes, as earlier research indicates a strong over-representation in streetscapes (Kuller *et al.* 2018a).

We acquired socioeconomic data from the Australian Bureau of Statistics (ABS), which provides data aggregated on the suburb level. For statistical comparison of WSUD locations and such spatially aggregated data, we need to aggregate the service provided by WSUD in a certain suburb. To this end, we aggregated the characteristics of WSUD into the calculation of a single parameter: *Relative WSUD* (RW). RW is calculated from the proportional surface area covered by WSUD, with adjustments for the type of WSUD, surrounding impervious surface area and local hydrology (for details of the calculation of RW, see Kuller *et al.* 2018b). An RW of 1 indicates that a particular area (in our case suburb) has adequate WSUD assets to service the entire area, while an RW of < 1 indicates that more WSUD assets are required to service the area and an RW of > 1 indicates that there is some redundancy in the WSUD assets for the area (e.g., to treat runoff from upstream areas). To calculate RW, we needed adjustment factors to account for the treatment capacity of WSUD assets in the local climatological and geological context. We used adjustment factors from the Great Dividing Range in the state of Victoria (Melbourne Water 2005), as they most closely matched the mean annual rainfall in the study area, for which adjustment factors had not yet been calculated. We acknowledge that applying adjustment factors from another region neglects to account for geological and other differences between regions, and it would be useful to expand the area across which adjustment factors are available. We generated the proportional imperviousness with a PSS called Urban Beats (Bach *et al.* 2020) and calibrated with high-resolution aerial images. Given that the calibration process was more accurate at smaller spatial scales, the Prospect Creek sub-catchment was used for this component of the study. This sub-catchment is located in the northeast of the broader study area and had both diverse land uses and relatively high coverage of WSUD assets. Socioeconomic variables were measured at larger spatial scales than individual WSUD assets. For each analysis of a socioeconomic variable, the WSUD data had to be aggregated to the same spatial scale as the variable being considered (e.g., suburb). Sources of data and the scale at which each variable was measured are shown in Supplementary Material, Table S1. Non-parametric Spearman's rank correlations (Spearman 1904) were used to test for significant (i.e., $p < 0.05$) correlations between each socioeconomic variable and RW, using SPSS v.25 (IBM).

2.3. Spatial suitability analysis

To provide a benchmark of strategic placement for WSUD assets, we required comprehensive spatial suitability modelling for our study area. SSANTO is a novel spatial WSUD planning tool (Kuller *et al.* 2019) we designed to give WSUD location suitability suggestions based on built-in GIS-based multi-criteria decision analysis (Malczewski & Rinner 2015). SSANTO is based on a suitability framework that allows the user to define the purposes of WSUD planning, seeking either suitable available spaces for WSUD ('Opportunities'), spaces that most need WSUD to overcome existing issues ('Needs'), or a combination of opportunities and needs (Kuller *et al.* 2017).

SSANTO allows users to define the type and weighting of multiple variables to obtain suitability maps for different types of WSUD assets to generate colour-coded a 'Needs' map, an 'Opportunities' map, plus a hybrid 'Combined' map, presenting spatial suitability on a scale from 0 (low) to 100 (high). The Needs map accounts for ecosystem services provided by WSUD such as provisioning, regulating and cultural perspectives, to assist with answering 'where is the need for the benefits of WSUD highest'. The Opportunities map accounts for bio-physical, socioeconomic, local planning and government variables to assist with answering 'what do technologies need for optimal functioning' (Kuller *et al.* 2017). In theory and depending on the availability of data, SSANTO can produce suitability maps for any combination of relevant variables and spatial scales, depending upon the user-defined purpose of WSUD planning (see, e.g., Webber & Kuller 2021). We applied the tool to the Prospect Creek sub-catchment in the northwest of the broader study area, as this sub-catchment has abundant and diverse WSUD assets. All relevant variables for which data were available were used to run SSANTO and create suitability maps (Table 1). We applied expert weightings that were validated during a case study in Melbourne (Kuller *et al.* 2019) for this study to represent the most up-to-date validated expert opinions on WSUD in Australia. We also used alternative weighting methods to compare, including equal weighting (all variables get the same weight) and entropy weighting (weights depend on information density of the data), against expert weights. The number of assets in our database only allowed statistically significant analysis for rain gardens and bioretention

Table 1 | Suitability variables and expert weightings used for the modelling of rain gardens and bioretention systems (RB) and ponds, lakes, and basins (PLB) in the Prospect Creek sub-catchment, using SSANTO (modified from Kuller et al. (2019))

	Category	Variable	WSUD types		Expert weighting
Opportunities	Biophysical	Slope	RB	PLB	100
		Distance to landfill site	RB	PLB	80
		Distance to sports fields	RB	PLB	–
	Socioeconomic	Education level	RB	PLB	10
		Sense of community	RB	PLB	20
		Environmental awareness	RB	PLB	20
	Planning & government	Utility infrastructure	RB	PLB	70
		Land value	RB	PLB	20
		Street width/type (estimated)	RB		–
		Lot size		PLB	50
		Land ownership	RB	PLB	70
		Cultural heritage	RB	PLB	30
		Geological heritage	RB	PLB	20
		Natural heritage	RB	PLB	30
		Distance to airports		PLB	60
Needs	Provisioning	Irrigation demand	RB	PLB	80
	Regulating	Effective imperviousness	RB	PLB	100
		Total imperviousness	RB	PLB	80
		Heat vulnerability	RB	PLB	60
	Cultural	Visibility	RB	PLB	60
		Social cohesion	RB	PLB	40
		Green cover	RB	PLB	60
		Recreation		PLB	40

systems, as well as ponds, lakes, and basins. SSANTO's analysis was raster-based, using a customisable cell size of 20 m×20 m.

Locations of WSUD assets were overlaid on the combined suitability map, allowing assessment of whether current WSUD placement follows areas of higher suitability. Quantitatively, we made such analysis by comparing the mean suitability at the locations of WSUD assets to the overall mean suitability of the study area. A higher positive difference indicates that more WSUD locations follow highly suitable areas as identified by SSANTO.

3. RESULTS AND DISCUSSION

3.1. WSUD distribution

Across the study area, 263 WSUD assets were recorded (Table 2; Figure 2(a)). Cumulatively, WSUD asset footprints constituted 2.8% of the total study area. Wetlands, ponds, lakes, and basins take up considerably more land area than other WSUD assets, with each individual swale also being relatively large. Compared to Melbourne (see

Table 2 | Descriptive statistics and average nearest neighbour ratio for different types of WSUD assets within the study area (NNR of < 1 indicates that assets occur in clusters, where associated $p < 0.05$)

| WSUD type	No. of assets	Total area (m²)	% of total No.	% of total area	Median size (m²)	Serviced area (ha)	% of total serviced area	NNR	p-value
Boxes and pits	39	117	15	<1	3	0.6	<1	0.004	<0.001
Rain gardens and bioretention	110	103,634	42	8	77	498	15	0.235	<0.001
Swales	3	1,203	1	<1	222	4	<1	Inadequate data	
ponds, lakes, and basins	75	871,364	29	67	4,154	2,084	64	0.530	<0.001
Wetlands	36	325,811	14	25	5,280	679	21	0.593	<0.001
All WSUD	263	1,302,129	100	100	654	3,266	100	0.391	<0.001
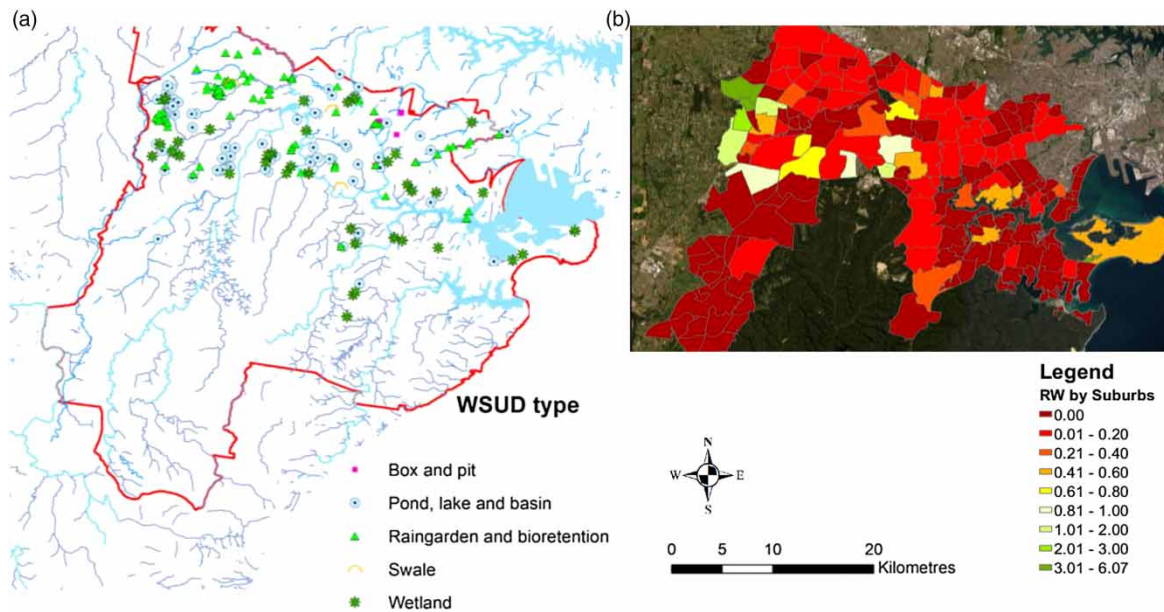
Figure 2 | (a) WSUD distribution in the Georges River catchment and (b) WSUD service level by suburb measured by RW.

Figure 1 in Kuller *et al.* (2018a)), the relative number of the two smallest system types (boxes and pits as well as rain gardens and bioretention) is larger, while the footprint between small and large systems is similar. In Melbourne, the dominant WSUD type in terms of footprint is wetlands, while in our case study ponds, lakes, and basins represent the largest area. Given that there are 1.4 million residents in the study area, there were over 5,000 residents for each WSUD asset and over 10,000 residents for each rain garden.

Mapping of RW for each suburb indicated that most suburbs have low WSUD coverage (i.e., RW < 0.40, Figure 2(b)). Among a total of 185 suburbs, 7 suburbs have an RW greater than 1. This means that WSUD in these suburbs services a catchment area larger than the suburb itself, so WSUD devices are over-represented in those suburbs. 114 suburbs have no WSUD, most of them are upstream and south of the downstream region. Suburbs with higher RW values tended to occur in clusters (Figure 2(b)). Analyses of nearest neighbour ratios confirmed that WSUD assets occurred in clusters (also see Figure 2(a)), with more clustering of smaller assets than larger assets (Table 2). Smaller systems could be concentrated in streetscapes, explaining their high level of clustering (see Section 3.2). The observed clustering may be reflective of the retrofitting of WSUD in established urban areas being constrained by limited opportunities, with the need for publicly owned patches of space to become available, such as occurring at road renewal sites (Kuller *et al.* 2018b). It may also reflect that the needs of WSUD vary between suburbs and/or that there is a preference for the placement of new assets close to previous assets that have been embraced by the local community. Finally, certain municipalities might have a stronger focus on WSUD strategies, leading to spatial clustering in those municipalities.

3.2. Univariate WSUD analyses

3.2.1. Biophysical variables

Over three-quarters of WSUD assets occurred on slopes <5%, lower than expected if WSUD were positioned randomly, as the median slope for random points was 6.4% (Figure 3(a)). The distance to waterways provides a somewhat more mixed picture. For smaller WSUD assets (i.e., box and pit, and rain garden and bioretention systems), the distance between WSUD assets and nearest perennial waterways was greater than can be expected if WSUD were positioned randomly (Figure 3(b)). However, for larger assets, distance to nearest waterway appeared closer to random. WSUD placement in relation to these variables indicates adherence to best practice recommendations within the study area. It was unsurprising that slope influenced positioning of WSUD, as it is widely recommended that WSUD assets should be on slopes of 1–5% (Melbourne Water 2005). The positioning of smaller WSUD assets away from perennial waterways suggests that they were designed as on-site pollution control measures, which is preferable to 'end-of-pipe' solutions (Fletcher *et al.* 2015). This is supported by the fact that such recommendations are mentioned in local council guidelines (e.g., Campbelltown City Council
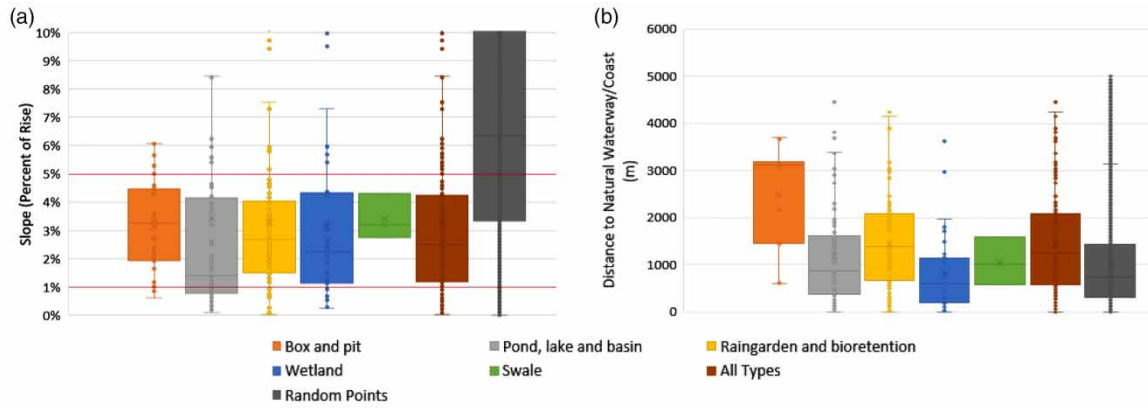
Figure 3 | (a) Slope of land for different types of existing WSUD in the study area. (b) Distance between different types of WSUD and nearest perennial waterway in the study area. Boxes show 25th and 75th percentiles, whiskers show 5th and 95th percentiles. The red lines in (a) represent the ideal slope boundaries for WSUD implementation.

2009). Conversely, the positioning of larger assets in relation to nearest waterway likely reflects that most were randomly located in areas where there happened to be available space and/or natural accumulation of water, pointing at their primary function as flood control measures.

3.2.2. Urban form variables

We can observe large differences between land-use types and WSUD prevalence. Similar to findings from Melbourne, we found the highest number of large assets in parks and gardens as well as reserves and floodways (Kuller *et al.* 2018a). There is a high number of assets in streetscapes (road), where smaller, more types of assets can be found, such as rain gardens and tree pits (Figure 4; Supplementary Material, Figure S1). The over-representation of number of assets in streetscapes is apparent, as almost half of the assets are located in streets, which represent only 9.1% of the study area (Supplementary Material, Figure S1). In terms of area, WSUD in streets is underrepresented, and the highest asset footprint is found in parks and gardens. In the residential areas, where WSUD can bring the most benefits (including socioeconomic), there is a clear lack of assets,
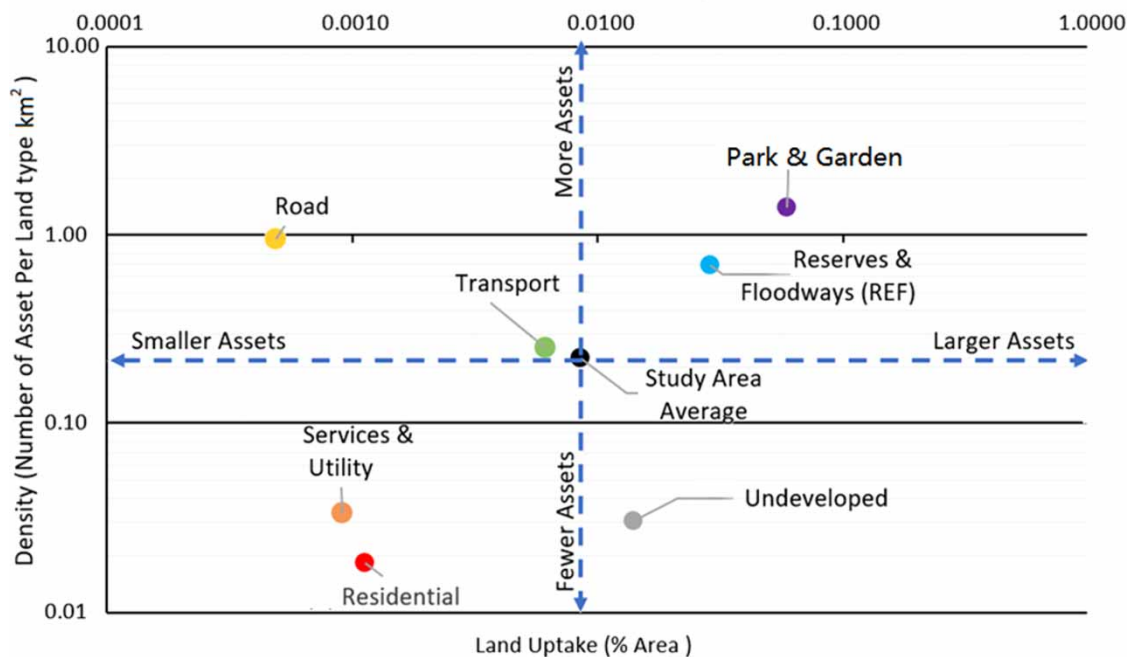

Figure 4 | WSUD abundance by land-use type.

with some smaller WSUDs present. These results highlight the current implementation strategy, where WSUD tends to be implemented when an opportunity occurs.

3.2.3. Socioeconomic variables

We found only a weak relationship of socioeconomic variables with asset locations. One variable was statistically significantly, negatively correlated with RW, albeit still rather weakly: sense of community (Table 3). These results suggest that no consideration was given to socioeconomic criteria when planning WSUD in the study area. Thus, current planning does not appear to account for the implementation of WSUD in communities that might be more accepting (e.g., high environmental awareness) or more in need of its benefits (e.g., communities vulnerable to urban heat). Our findings are not in line with findings from Melbourne, where strong relationships were found between WSUD locations and socioeconomic variables (Kuller *et al.* 2018a). However, these relationships stemmed from a common underlying driver: distance to city centre. As our study area was relatively homogeneously far from the city centre of Sydney, such effect could not be expected as strongly for our case.

Table 3 | Correlations (two-tailed Spearman's ρ) between socioeconomic variables and 'RW' across the study area.

Variable	ρ	*p*-value	*n*
Population density	−0.012	0.867	185
Median income	−0.102	0.167	185
Property price	−0.047	0.555	162
Education level	0.012	0.874	184
Sense of community	**−0.156**	**0.047**	**184**
Environmental awareness	−0.075	0.361	149
IRSAD[a]	−0.061	0.414	182
IER[b]	0.020	0.786	182
Heat vulnerability	0.102	0.166	185

[a] Index of Relative Socio-economic Advantage and Disadvantage (ordinal, arbitrary scale).
[b]Index of Economic Resources (relative indicator, ordinal index with arbitrary scale).
n presents the number of data points. The bold value indicates that the correlation is significant at the 0.05 level (2-tailed).

3.3. Spatial suitability analysis

The maps for needs, opportunities and combined for rain gardens and bioretention systems, generated by SSANTO, show that the suitability for such systems varied considerably with location across the Prospect Creek sub-catchment (Figure 5). Similar patterns were observed for the suitability of ponds, lakes, and basins. Although the suitability at the location of current WSUD assets is consistently higher or equal to mean suitability in Prospect Creek, the differences are relatively small (Figure 6; Supplementary Material, Table S2).

The two indicators, mean and percentage of assets with scores above 70, show the average scores and the number of locations with high suitability scores for WSUD locations. When the difference is positive (Figure 6; Supplementary Material, Table S2), WSUD systems are positioned in more suitable locations compared to catchment average, and vice versa. If the difference is close to 0, WSUD locations are close to random, and it is likely the planning processes did not take suitability variables into account systematically.

The results for current rain gardens and biofilters (RB) suggest that the placement of these assets followed a slightly strategic approach both in terms of where the environment offers opportunity for WSUD implementation, as well as where the urban context could most benefit from WSUD. This can be concluded as we observe higher suitability for both 'opportunities' and 'needs', especially across a small number of 'highly suitable assets' (suitability score over 70; Figure 6). As our results in Section 3.2 show, no relationship between heat vulnerability and WSUD location, and only a weak relationship between sense of community and WSUD locations, the findings here must stem from one of the other criteria that underlie 'needs', e.g., imperviousness or green cover (both received a high weighting: Table 1). The results for 'opportunities' are likely driven by biophysical and urban form variables, as socioeconomic variables showed no strong relationship with WSUD positioning (Section 3.2).

While for 'needs' we observe slightly higher suitability at asset locations for ponds, lakes, and basins (PLB), 'opportunities' are heavily unutilised judging from the apparently random distribution of these assets (Figure 6). These results suggest that for larger assets, little to no strategic consideration has been taken in their spatial
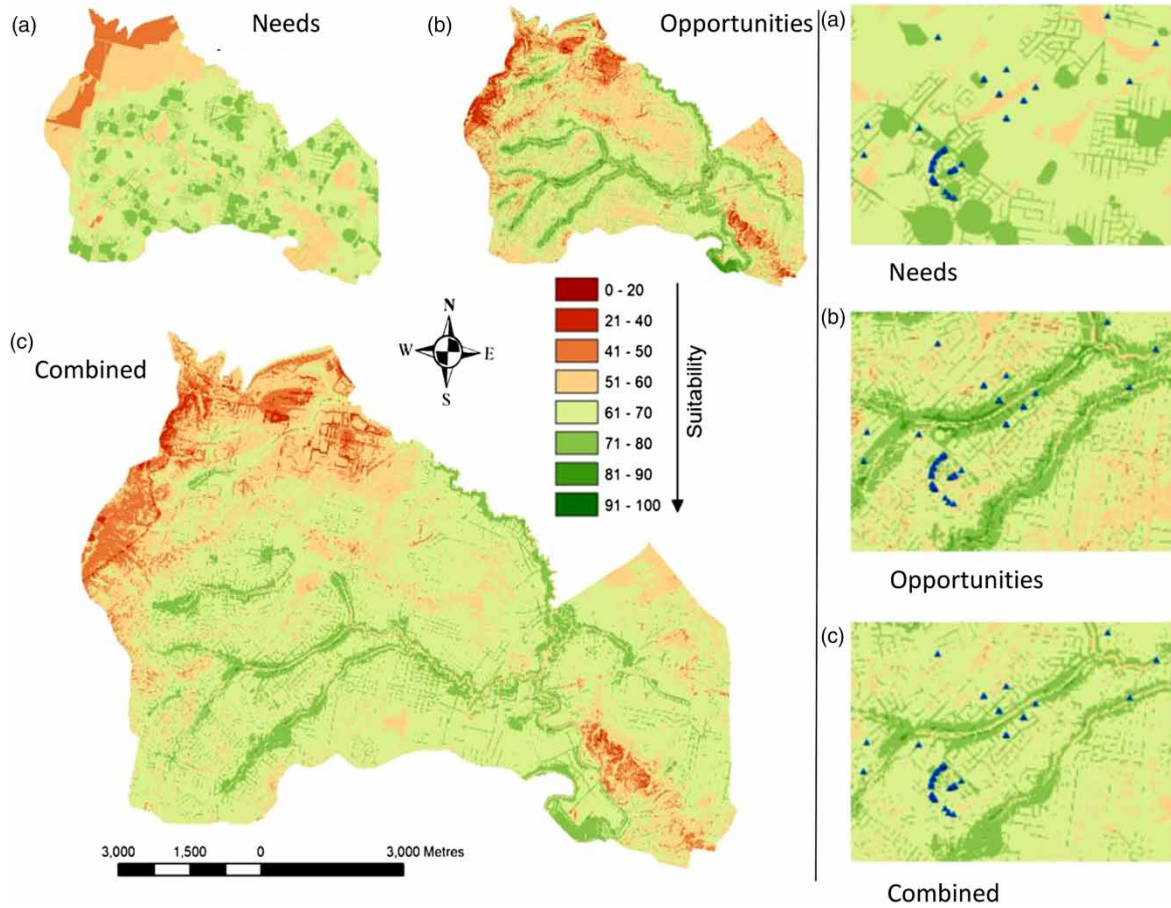
Figure 5 | Left: SSANTO output maps for rain gardens and bioretention systems in the Prospect Creek sub-catchment. Right: Map zoom with bioretention systems overlaid (blue triangles). (a) Suitability map for 'Needs'; (b) suitability map for 'Opportunities' and (c) suitability map for 'Needs' and 'Opportunities' combined.
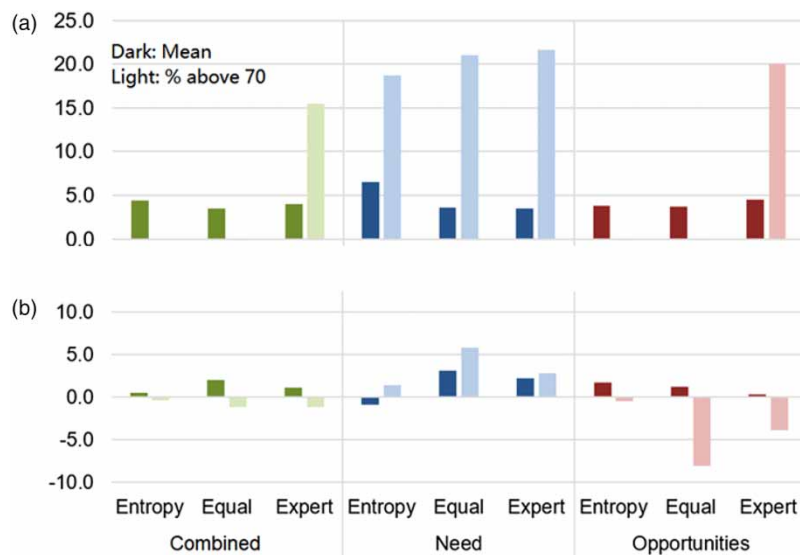

Figure 6 | Comparative suitability score between locations of rain gardens and biofilters (a) or ponds, lakes, and basins (b) and overall mean suitability in Prospect creek, using different weighting methods. Dark coloured bars: difference in mean catchment suitability scores and current WSUD suitability, across different weighting methods. Light coloured bars show the difference between the percentage of assets with suitability score higher than 70 with the mean percentage of area over suitability score 70, as representatives of 'high suitability assets'.

implementation. Indeed, there were significantly fewer systems on locations with suitability scores over 70 than should be expected. Comparing the distribution and mean suitability scores between WSUD locations and the overall catchment confirm these findings (for details, see Supplementary Material, Figure S2). Some anecdotal evidence illustrates our findings that larger assets were not strategically placed, as two large lakes were located in the direct vicinity of airports, within the distance that is considered unsafe for bird strikes with airplanes.

Finally, we did not find any systematic differences between different weighting methods. While some small differences in outcomes exist between weighting methods (Figure 6), e.g., higher positive difference in suitability with entropy weights for RB and 'needs', they were not systematic (i.e., negative difference in suitability with entropy weights for PLB and 'needs'). The only systematic effect was for expert weighting, which resulted in the consistently higher placement of RB assets in highly suitable areas (score over 70). This could signal that if planners used some of the criteria included in SSANTO for their asset implementation, they might have used weights similar to our expert weights, pointing at the generalisability of these weights for RB across both contexts.

3.4. Limitations and further research

While comprehensive asset databases like the one we used for our research are very rare, it is not perfect. We needed to validate certain assets manually in terms of location and size. Furthermore, for the spatial analysis, we used the centroid of assets as their location, meaning that irregularly shaped larger systems could fall completely outside their centroid. The variables quality, lack of availability, and temporal and spatial resolution mismatch of secondary spatial data pose another problem for the accuracy of our analyses and all multi-criteria spatial exercises (Malczewski & Rinner 2015). Certain variables are proxies for the variables we are trying to measure, such as the case for environmental awareness.

We used RW as a measure of WSUD coverage in a statistical area (e.g., suburb), taking services from all WSUD together when correlating them to socioeconomic factors. Future research could explore the potential for separating such correlations by WSUD type to determine whether differences between, e.g., larger and smaller systems exist. Such differences could, e.g., occur due to the differences in implementation flexibility between a highly adaptable rain garden and a much larger and less flexible constructed wetland. The flexibility of rain gardens could make it easier to follow recommendations based on suitability analysis than is the case for wetlands.

PSSs such as SSANTO prove notoriously hard to validate. Suggestions for performance evaluation have been made by Pelzer (2017) and te Brömmelstroet (2013), but no standardised validation or performance evaluation procedures currently exist. Recently, Malczewski & Jankowski (2020) suggested combining knowledge-driven approaches with data-driven approaches in order to include both the subjective and objective aspects of decision-making, and make outcomes more insightful and representative. To follow this suggestion, we used previously elicited weightings from practitioners in Melbourne to increase representativeness in the Australian context. We then implemented these elicited weighting alongside data-driven entropy weights, as well as neutral equal weighting. Furthermore, SSANTO testing included comparing its outputs to strategic decision-making outcomes of an environmental consultancy in Melbourne (Kuller et al. 2019). Future research should focus on the development of standardised PSS performance evaluation criteria and procedures to enhance the credibility of PSS and their outcomes.

Further research should focus on comparing our findings to urban contexts outside the United States and Australia. Investments in the establishment of large WSUD databases could not only benefit such research, but would be invaluable to assist in monitoring, benchmarking and comparing the performance of cities worldwide. Using WSUD databases, we could draw important lessons from the successes and failures of current practice to improve the future planning of green infrastructure.

4. CONCLUDING REMARKS

Maximising the benefits and optimising the performance of WSUD require strategic planning that considers a diverse range of influential variables. The compilation of an extensive asset database revealed that our study area in southern Sydney had a high proportion of smaller assets (i.e., rain gardens) and relatively low proportions of wetlands and swales, and was relatively underserviced. Univariate analysis uncovered the same patterns of biophysical and urban form variables driving WSUD placement through their constraining nature. Assets were overrepresented in streetscapes, parks and floodways, where space was available and public investments simplified. However, we found little evidence that socioeconomic variables were considered in asset placement. The

clustering of particularly smaller asset types, but also service coverage in general, points towards the different investment strategies between the various local governments in our research area, with limited evidence of coordination between them for stormwater management across the catchment. Using an integrated PSS, it was possible to consider a diverse range of variables related to both opportunities and needs for WSUD placement at the sub-catchment scale. Comparing the locations of assets to the suitability maps generated by our PSS revealed that only slight consideration of important aspects of strategic planning is currently given, particularly for smaller asset types. The greater consideration seems to be given to criteria on the needs side, uncovering a slightly stronger focus on optimising the benefits from WSUD assets compared to implementation opportunities. Overall, the difference between suitability at actual asset locations is not much higher than average.

All these findings suggest that *ad hoc* decision-making and opportunistic planning were important drivers behind the *status quo*. The apparent lack of strategic planning aligns with anecdotal evidence from practitioners, who explain that WSUD is mostly implemented on an *ad hoc* basis wherever capital works are planned or public land and funding becomes available. Our findings are also in line with the scarce similar research performed so far in comparable contexts (Kuller *et al.* 2018a, 2018b; Tjandraatmadja 2019), as well as with broader WSUD planning literature. Moreover, we found that the novel approach to spatially analyse WSUD locations relative to the output of a PSS aimed at strategic planning offered valuable insights into the level to which current WSUD placement could be considered strategic. It offered a valuable addition to traditional spatial univariate analysis, approaching our research aim in a more holistic, integrated manner. We suggest repeating such approach for different contexts using different PSSs to further improve our understanding of current and future planning of WSUD. As we transition from the early adoption phase towards mainstreaming of WSUD, it is an opportune time to explore and capitalise on existing planning support tools that can aid a strategic approach for the planning of future WSUD. Strategic planning of WSUD and verifying their benefits with multiple variables are challenging, and it is suggested that planning support tools can make the process much quicker and more reliable, with further user-defined choice inputs. The tool used for our study is one of several available PSSs geared towards this objective. Integrated WSUD catchment management approaches should aim to optimise natural catchment scale benefits, rather than only benefits within local government authority areas. Ultimately, a strategic approach should aid in realising the full range of benefits for WSUD, increase acceptance of WSUD across the broader community and facilitate the successful integration of WSUD into urban landscapes.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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