What drives the location choice for water sensitive infrastructure in Melbourne, Australia?

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Highlights

- We analysed one of the most extensive Water Sensitive Urban Design geo-databases
- Biophysical and urban form-, but not socio-economic factors drive WSUD placement
- Distance to metropolitan centre and age of development drive WSUD abundance
- Wetlands are most prominent in Melbourne, followed by raingardens and ponds & lakes
- WSUD planning critically needs improved asset inventory development moving forward

Abstract

Distributed and green urban drainage infrastructure known as Water Sensitive Urban Design (WSUD) is increasingly being implemented in cities globally to combat climate change and urbanisation effects. Rigorous consideration of the urban context in terms of biophysical, socio-economic and urban form related factors is crucial for optimal design outcomes. The extent to which the urban context is considered in current planning and decision-making processes remains unclear. This study investigates this relationship between current WSUD infrastructure in Melbourne (Australia) and each of the aforementioned factors for the first time. We obtained and pre-processed one of the most extensive and complete geo-located WSUD asset databases in the world (containing over 2,000 WSUD assets), and undertook an evidence-based analysis of WSUD planning outcomes. Relationships were investigated using spatial analysis techniques (e.g. overlaying), as well as a number of statistical methods (e.g. exploratory regression). It was found that biophysical and urban form factors strongly explained variability in WSUD location choice, while socio-economic factors appeared to be overlooked. Our findings imply that the current WSUD planning practices are primarily governed by standard engineering design. Opportunistic WSUD planning leads to unintentional outcomes that fail to capitalise on the full potential of WSUD benefits. Increased investment in asset inventory development and analysis is critical to inform WSUD planning moving forward. Knowledge gained from this and additional studies can further planning through application in planning-support systems, to deal with the complexity and diversity of the broad set of decision criteria.

Keywords: Water Sensitive Urban Design (WSUD), Low Impact Development (LID), Sustainable Urban Drainage Systems (SUDS), Urban Planning, spatial analysis

1 Introduction

Water Sensitive Urban Design (WSUD) refers to the introduction of distributed 'green' technologies in the urban landscape for stormwater treatment, detention and reuse with the primary aim to protect and restore natural waterways, decrease the risk and severity of floods and diversify sources of water supply (Dietz, 2007; Wong and Brown, 2009; Woods Ballard et al., 2007). This innovative approach to water management and similar concepts (e.g. Low Impact Development (LID), Sustainable Urban Drainage Systems (SUDS) and Best Management Practice (BMP)) are increasingly being implemented around the world as a strategy to adapt to the pressures of increasing urbanisation and climate change on urban water management (Fletcher et al., 2014; Wong and Brown, 2009). Aside from the abovementioned benefits, WSUD serves a broader set of functions, such as increasing the aesthetic value of neighbourhoods (Backhaus and Fryd, 2013; Dobbie and Green, 2013), providing recreational space (Dobbie and Green, 2013; Wong and Brown, 2009), mitigating urban heat island effects (Coutts et al., 2012; Mitchell and Cleugh, 2006; Steeneveld et al., 2014), and educating communities about urban sustainability (Lundy and Wade, 2011; Rijke et al., 2008). WSUD is a relatively young addition to urban planning practice and although technical design guidelines have been developed, rigorous and experience-based information on the relationship between urban planning and water management is lacking (Sharma et al., 2012). Anecdotal evidence from municipal planning practitioners suggests that WSUD practice has predominantly been driven by 'opportunistic' approaches in both infill developments (retrofitting rain gardens in road renewal sites), or greenfield developments (leaving WSUD integration as the last planning consideration), which may result in less than optimal planning outcomes (Allan, S., personal communication, 1 September 2015; Innes, S., personal communication, 23 October 2015; Chaffin et al., 2016; Fronteira et al., 2014). WSUD implementation and management guidelines necessary to prevent such opportunistic approaches are scarce (Roy et al., 2008) and largely issued on local (municipal) scale. Only for new (greenfield) developments is centralised regulation present (DELWP, 2017).

A growing body of literature reports on the factors that determine the 'suitability' of a location for WSUD implementation (e.g. Ashley et al., 2004; Ellis et al., 2004; Martin et al., 2007; Scholz, 2006). Traditionally, various abiotic (non-biological) biophysical factors (hereafter simply referred to as 'biophysical') are considered for design and placement of WSUD and stipulated in guidelines (e.g. Melbourne Water, 2005; Woods Ballard et al., 2007), such as hydrology (e.g. rainfall), soil, slope and imperviousness. However, recent literature suggests that a wider variety of spatially variable factors can impact the functioning of these technologies, including socio-economic and urban form (e.g. Barbosa et al., 2012). For example, high public literacy and awareness of the function and benefits of WSUD may improve community acceptance and interaction with WSUD. Such literacy and awareness, in turn, is expected to be more easily attained by communities with high environmental awareness and higher education levels, as is the case for public acceptance of similar green innovations such as water recycling schemes (Dolnicar et al., 2011; Domènech and Saurí, 2010).

Besides suitability, the 'need' for WSUD varies spatially, due to the diverse benefits green technologies offer for storm water quantity, quality and amenity (Ashley et al., 2013; Marlow et al., 2013; Wong and Brown, 2009). For example, neighbourhoods with low levels of greenery significantly benefit from the introduction of WSUD, while relatively pristine waterways benefit more from pollution mitigation than degraded waterways (Walsh et al., 2005). Public exposure to WSUD is high in frequently visited open spaces such as train stations and shopping precincts. Hence, optimising WSUD placement requires the planning process to consider a wide variety of factors. Opportunistic planning approaches overlook these factors, reducing the benefits obtained from WSUD (Schifman et al., 2017).

Growing knowledge about ‘suitability factors’ is accompanied by a growing number of planning support tools for WSUD. Various planning frameworks incorporate some form of suitability assessment based on multiple factors/criteria (e.g. Jin et al., 2006; Lee et al., 2012). Although these tools predominantly focus on biophysical factors, there is an encouraging trend towards incorporation of a wider variety of aspects, including socio-economic factors (e.g. E2STORMED, 2015; Fronteira et al., 2014; Viavattene et al., 2008). Application of such tools and frameworks could drastically improve planning practices without overly increasing their complexity (Geertman and Stillwell, 2004; Lee et al., 2012; Vonk et al., 2005). Nevertheless, currently available planning-support systems remain underused for a number of reasons including lack of relevance and user-friendliness (te Brömmelstroet and Bertolini, 2008; Vonk et al., 2005). This raises the question to what extent biophysical, socio-economic and urban form factors have been guiding planners’ decision-making processes to date.

However, no structured investigation has been conducted to examine location choices for WSUD in metropolitan regions, assessing the impacts of the abovementioned factors. The difficulty of acquiring data on the location, type and size of WSUD assets for an entire metropolitan region may underlie this scarcity. However, this information is crucial in WSUD planning and applications. To understand how the complex urban context impacts the current practice of WSUD planning, the present study aims to characterise WSUD composition (i.e. choice of technology type) and distribution in relation to the urban context for metropolitan Melbourne (Australia). More specifically, we focus on:

(1) exploring Melbourne’s current WSUD inventory in terms of types, land uptake and service area,

(2) investigating relationships between WSUD location and the urban context in terms of biophysical, socio-economic and urban form factors,

(3) assessing to what extent the current practice aligns with WSUD planning best practice as informed by local and current national guidelines

We hypothesise that biophysical factors consistently and strongly drive location choices for WSUD, as they can prohibit their implementation. We would also expect WSUD to be often present in relatively flat areas (as prescribed by design guidelines, e.g. Melbourne Water, 2005) and close to waterways (as WSUD in Melbourne is traditionally driven by the water authority, which is in charge of the larger urban waterways: Brown and Clarke, 2007). Furthermore, we hypothesise socio-economic factors to be weakly related to the locations of WSUD. While socio-economic factors aren’t prohibitive to implementation of WSUD, they can decrease its feasibility (CRCWSC, 2014). In contrast, urban form factors are expected to significantly relate to the locations of WSUD. For example, areas of high-intensity land-uses (e.g. commercial centres, high density residential) are space constrained and should therefore include smaller WSUD assets.

To the author’s knowledge, this is the first systematic analysis of a geo-located WSUD dataset, using one of the most extensive and complete inventories currently available. Furthermore, for the first time the relationship between a wide variety of spatially variable factors are compared to WSUD placement. In doing so, it increases our understanding on how the complex urban context impacts the current practice of WSUD planning. Lessons from this study are vital to move WSUD planning away from opportunistic practices.

2 Methodology

2.1 Data collection and preparation

Melbourne is a rapidly growing city and currently houses 4.5 million residents, making it the second largest city in Australia. It is a sprawled city (i.e. ‘low-density expansion of large urban areas, under market conditions, mainly into the surrounding agricultural areas’ - EEA, 2006: page 6), similar to others across the country (Coffee et al., 2016; McLoughlin, 1991), North America and, increasingly, also Europe (Batty et al., 2003). It was selected as our case study for its comparatively large experience with the implementation of WSUD (Ferguson et al., 2013) and the availability of a unique, georeferenced, metropolitan-wide WSUD asset database.

2.1.1 WSUD data acquisition and pre-processing

Melbourne Water, the local water authority, undertook an extensive mapping study of all WSUD assets in 2012, which was collated into a spatial database. The database only includes assets that are primarily built as stormwater management structures, thereby excluding other structures that have an impact on stormwater management (sometimes referred to as ‘passive systems’, such as lawns and ponds). The assets in the database are managed by different parties, including the local water authority (for assets with a catchment of over 60 hectares – Melbourne Water, 2017), local government and private parties. The scattered nature of management responsibilities is reflected in the scattered nature of data on the distribution of WSUD assets. Although the database contains significant imperfections in terms of accuracy and completeness, this database is one of the most extensive spatial databases of decentralised stormwater infrastructure in the world, and was therefore used in our study. In total, 2,018 WSUD assets were compiled (as a GIS point shapefile), including information about type, geolocation, address, year of construction, size (area) and asset ownership.

Although many additional WSUD assets have since been constructed (Melbourne Water, 2013), no further updates were made to this database. Therefore, we adopted the base year for our analysis as 2012 (i.e. the most recent year included in the database).

Two of the most crucial shortcomings of the raw database were: incorrect geo-locations and missing data on asset sizes. To remove these inaccuracies and complete the information, we invested considerable effort in verifying the entries and infilling the missing data into the original database. Missing information was sourced through contacting local councils, retrieving satellite imagery and conducting numerous site visits. Thus, the fraction of WSUD assets without size information was reduced to under 10%. All remaining missing system sizes were subsequently estimated, using median system sizes based on type and general location (classified as inner city, middle suburbs and outer suburbs) according to Buxton and Tieman (2005).

After cleaning, the database contained complete and verified information on 2,051 WSUD assets from 5 WSUD types: *(1) Box/Pit*, including planter box rain gardens and tree pits, *(2) Rain gardens*, including all other types of rain gardens and bio-retention systems, *(3) Swales*, vegetated drainage ditches, *(4) Ponds & Lakes*, containing all constructed open water bodies and *(5) Wetlands*, containing all constructed wetland systems.

2.1.2 Collection of urban biophysical, socio-economic and urban form data

We collected data on biophysical, socio-economic and urban form as our independent variables. The selection of these variables (summarised in Table 1) was based on availability and relevance. The included biophysical factors, surface slope and distance from natural waterways, are regularly considered in design (Melbourne Water, 2005; Woods Ballard et al., 2007) and suitability analyses of WSUD (e.g. Jin et al., 2006; Lee et al., 2012).

Socio-economic factors such as environmental awareness and related acceptance (e.g. Sharma et al., 2012; Thompson and Maginn, 2012; Wong and Brown, 2009), and education level (e.g. Chiesura, 2004; Lovell and Taylor, 2013; Mell, 2009) have been identified by the scientific literature as potentially impactful. IRSAD and IER are census-based indicators measuring aspects of socio-economic advantage and disadvantage, developed by the Australian Bureau of Statistics (ABS, 2013). While the former provides a rank of overall socio-economic advantage and disadvantage, the latter focuses on the financial aspect of relative advantage/disadvantage. Detailed information on these indicators can be found in ABS (2013). We included a 'heat vulnerability index' (Loughnan et al., 2012) in our analysis, considering the mitigating effects of WSUD on urban heat islands (e.g. Ahern, 2013; Bolund and Hunhammar, 1999; Lovell and Taylor, 2013). Scarcity of indicator data posed a barrier to the inclusion of socio-economic factors. To overcome this barrier, the use of proxy variables, describing phenomena which cannot be directly measured or for which data cannot be obtained, is common practice in social sciences (e.g. Montgomery et al., 2000). We represented 'environmental awareness' and 'sense of community' with the proxies 'first preference votes for The Greens in federal elections' and 'people engaging in voluntary work for a local organisation or group', respectively (see Table 1). Despite the inherent limitations related to the use of proxies, direct measurement of these indicators fell outside the scope of this study.

Finally, urban form factors describe artificial planning and urban landscape characteristics such as land use and location of assets. They were expressed either in relation to the general city structure or in relation to nearby features such as streets. A water-centric land-use classification detailed by Bach et al. (2015) was used for this analysis. As urban form changes with distance to the centre in a sprawling city such as Melbourne (Galster et al., 2001; McLoughlin, 1991), this factor was also investigated. Special attention was given to the presence (relative quantity and size) of WSUD in 'streetscapes', as a crucial subtype of the urban landscape. These are all public open spaces around roads and streets, which hold a special position because of their prominence in people's day-to-day experience of the city. As urban form factors are primarily concerned with WSUD appearance and integration in the landscape (including characteristics such as shape and size), we focussed our analysis on WSUD land uptake: the amount of space taken up by an asset and its distribution across land uses, rather than the asset's service provision.

INSERT TABLE 1

2.1.3 WSUD data preparation

We distinguished between two types of urban factors data: (1) spatially explicit data, which included biophysical and urban form factors and (2) non-spatially explicit data, which contained all socio-economic factors. The second type of data cannot be directly spatially analysed (due to its aggregated nature). Therefore, we defined a metric that aggregates WSUD data over a geographic unit (suburbs): *Relative WSUD* (RW). RW is dimensionless, and represents the fraction of a geographic unit's impervious surface stormwater runoff that is serviced by WSUD. RW typically varies between 0 (no impervious area serviced by WSUD) and 1 (all impervious areas serviced by WSUD). RW values occasionally exceed 1, as WSUD can treat upstream areas outside the geographic unit under consideration. RW allowed us to normalise the WSUD data set against varying rainfall pattern, asset type and connected impervious area. It was calculated as follows:

$$RW_j = \sum_{i=1}^{n} \frac{A_i}{\theta_i(e_j A_j) \times \alpha_{ij}} \qquad (equation\ 1)$$

where RW_j is Relative WSUD in geographic unit j (in our case suburb), θ_i indicates WSUD size relative to serviced impervious area, A_i is the area of WSUD asset i, α_{ij} the adjustment factor for technology i, used to adjust for differences between rainfall patterns and geography of geographic unit j (in some cases derived from a function, see equation 2), e_j is the impervious fraction of geographic unit j, A_j is the area of geographic unit j, n is the number of assets in geographic unit j. Metropolitan Melbourne is divided into four rainfall regions, defined by α_{ij}:

$$\alpha_{ij} = \beta_{tj}(MAR_j) \times \gamma_{tj} \qquad (equation\ 2)$$

where β_{tj} and γ_{tj} are adjustment factors depending on WSUD type t and geographic unit j (the reader is referred to chapter 2 of 'WSUD engineering procedures' for the values of β_{tj} and γ_{tj} - (Melbourne Water, 2005)), and MAR_j is the mean annual rainfall in geographic unit j (Melbourne Water, 2005).

2.2 Data analysis

2.2.1 Spatial analysis

All the spatial analyses were performed using the ESRI spatial software ArcMap. We analysed biophysical and urban form factors by overlaying the WSUD database with these datasets. We then compared the results to Melbourne's 'typical' (median) values, which were obtained using a Monte Carlo method. In total, 200,000 random points (approx. 100 x the number of WSUD assets) were sampled across our spatial domain to determine a 'typical' distribution of slope and waterway distance. As convergence occurred for both factors, we deemed the sample size to be sufficiently large. The distance to the geographic centre of Melbourne was calculated using the geographic centre (centroid) of the four inner-city councils as our datum. We identified this point using the definition of inner-city councils proposed by Buxton and Tieman (2005).

For 'Land use', the number and land uptake of WSUD assets were analysed per land-use category to determine trends in the distribution of WSUD. Streetscapes, as a subtype of urban landscapes, received additional attention in our analysis. We statistically compared the abundance of streetscapes to the abundance (land uptake and serviced area) of WSUD located in streetscapes to see if WSUD was overrepresented.

2.2.2 Statistical analyses

We conducted three stages of statistical analyses on the socio-economic factors to examine potential interrelationships with WSUD planning:

Simple correlation analysis

We determined correlations and cross-correlations using a correlation matrix in the statistical software SPSS. The normality assumption could not be verified, as a third of suburbs had an RW value of 0. Therefore, we used the Spearman's rho correlation coefficient, which is the non-parametric version of the standard Pearson correlation coefficient, and can overcome the issue of non-normally distributed data sets (Myers et al., 2010).

Evaluating relationships

We applied three techniques to further investigate relationships, as strong cross-correlations between nearly all factors were initially found. This pointed to a single factor that drove all cross-correlations and, thus, required normalisation. Exploratory spatial regression, stepwise regression and Principle Component Analysis (PCA) were performed on the data. We organised our data against four different definitions of the metropolitan region boundaries to account for the effect of Melbourne's unsymmetrical sprawl (Beed, 1981; Department of Infrastructure, 1998): (1) all urban and peri-urban suburbs, (2) exclusion of suburbs of 'rural' councils, (3) elimination of suburbs with a population density of under 500 p/km^2 and (4) elimination of 'fringe' suburbs, further than 30km from the geographic urban centre (as defined previously).

Exploratory spatial regression is the process of generating several regression models that include one, two, or up to any number of factors (Rosenshein and Scott, 2011). This iterative process consecutively eliminates the worst performing factor in terms of explanatory power (% of explored models in which the factor was selected) and consistency (tendency towards either a positive or negative relationship to the dependent variable). This method was applied using ArcMap's 'exploratory regression tool', to select the best performing proxy for factors that can be represented by several proxies (e.g. the fraction of people with a bachelor degree outperformed school diploma and postgraduate degree as a proxy for education level). Furthermore, it showed that there was little gain in including more than one factor in the regression model, pointing towards a single variable driving all cross-correlations.

To improve our confidence in the analysis, we cross-checked these findings through stepwise regression and Principle Component Analysis (PCA), using the statistical software SPSS. In our analysis, each suburb average represented one data point. Stepwise regression is an automated process that includes and excludes predictors based on the t-statistic of their estimated coefficients (Draper and Smith, 2014). PCA is a technique for dimension reduction developed by Hotelling (1933), where the eigenvectors of all factors are projected on a lower, and in our case 2-dimensional frame. The eigenvectors that are most aligned with the dependent variable (RW) and with the highest eigenvalue (i.e. longest vectors) have the highest predictive power. Both analyses confirmed the existence of a single dominating variable.

<u>Correlation analysis of data subsets</u>

We normalised our dataset for *distance to centre* as a potential single dominating variable, representing the relative location of a region in the metropolitan area. We used the second definition of the metropolitan boundaries described earlier in this paragraph: eliminating regional councils. We divided Melbourne into spatial ‘rings’, based on *distance to centre*. The number of rings was determined through stepwise addition of classes in the symbology field of the shapefile within ArcMap, until all correlations between RW and *distance to centre* were removed. We used Jenks natural breaks classification method, which seeks to minimise variance within classes while maximising it between them (Jenks, 1967). Five rings (as opposed to the three rings used by Buxton and Tieman (2005)) were found to be the minimum necessary to remove the influence of the *distance to centre* with RW. Rings were given the following names from low to high *distance to centre*: (a) central (b) inner suburbs (c) middle suburbs (d) outer suburbs (e) fringe.

To investigate the relationships between each factor and RW, we repeated the simple correlation analysis for each ring individually, following the data normalisation and division into subsets, based on the five selected rings of Metropolitan Melbourne.

3 Results & Discussion

3.1 Descriptive statistics

The distribution, number, land uptake and service area of the various WSUD assets in the Melbourne metropolitan area are shown in Figure 1. Comparisons between system numbers, sizes and serviced area revealed their level of ‘compactness’; rain gardens represent 30% of the number of WSUD assets, 17.3% of service area but only 8.4% of the total land uptake by WSUD in Melbourne, reflecting their compact size. In contrast, wetlands have a 26.9% share in number, 65.5% share in service area and 62.9% share in land uptake. This compactness illustrates how various WSUD assets are suited for dense inner-city areas (rain gardens) or sprawling suburbia (wetlands).

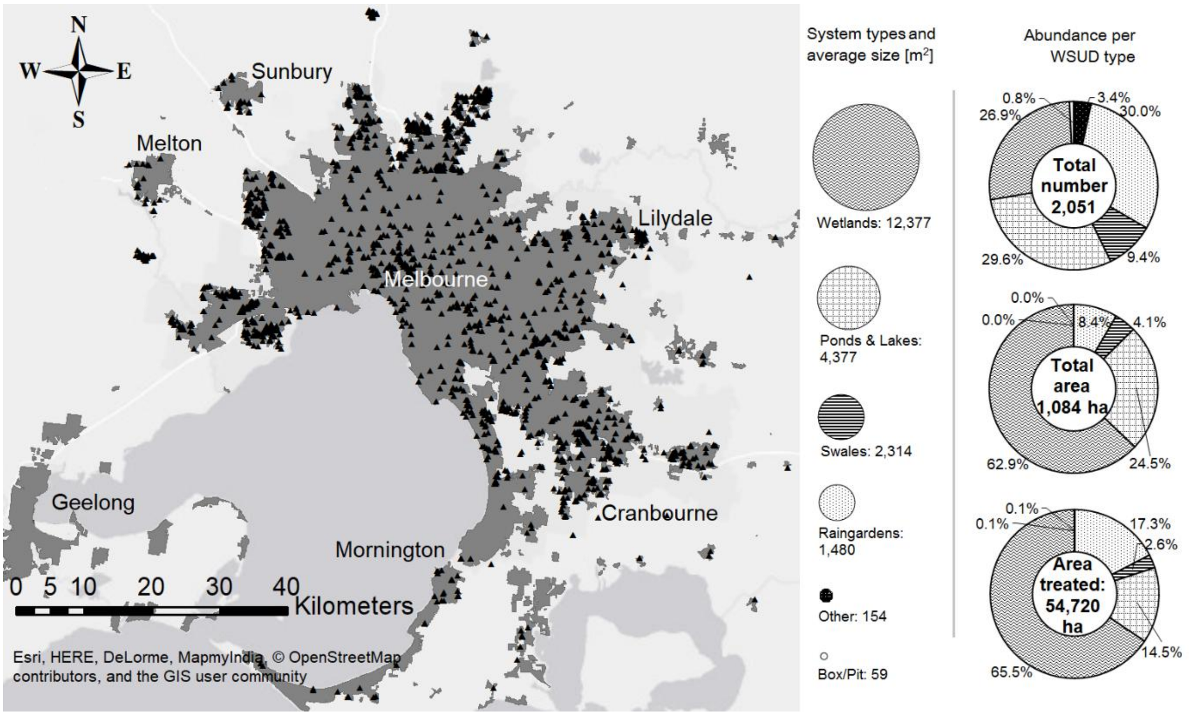

Figure 1 Spatial and typological distribution of WSUD in Melbourne; green rhomboids on the map represent locations of WSUD assets in 2012.

3.2 Biophysical factors

In line with our hypothesis, the observed patterns of WSUD placement suggest an important role for biophysical factors in the location choice for WSUD. WSUD is typically placed on lower slopes (median < 1%), and rarely on slopes above 5 % (Figure 2), in accordance with design guidelines (Melbourne Water, 2005). While guidelines for placement near waterways are absent, WSUD is placed close to natural waterways – often at the outlet of stormwater drainage systems, capturing and treating runoff from impervious areas in the catchment to protect waterway health (Walsh et al., 2005). This placement towards the end of catchments is unfortunate, as source control within catchments is shown to be more effective than 'end-of-pipe' solutions for pollution control (e.g. Bressy et al., 2012; Walsh et al., 2005) as well as for flood management (Urich et al., 2013).

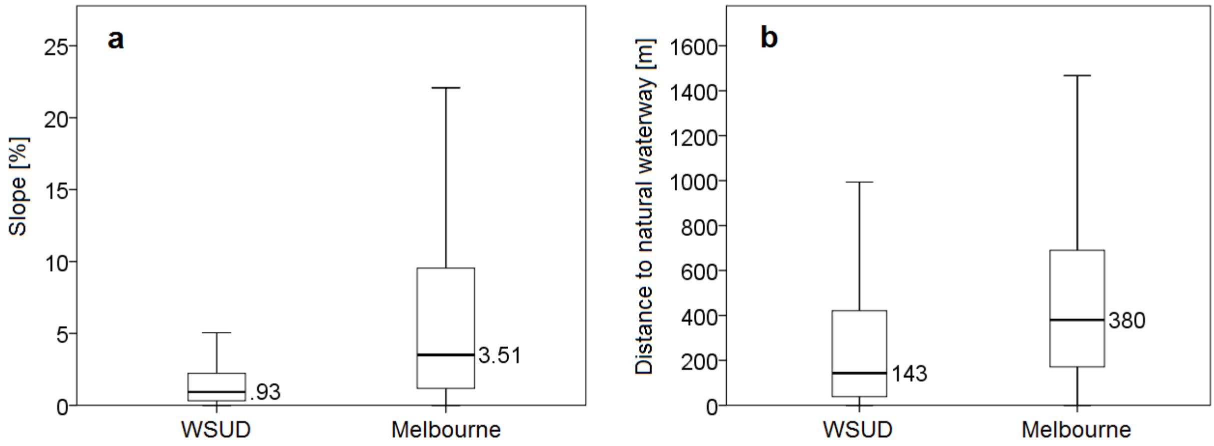

Figure 2 Relation between the (a) slope and (b) distance to natural waterways of WSUD locations, compared to randomly selected Melbourne locations.

3.3 Socio-Economic factors

Against our hypothesis, all but two socio-economic factors were highly and inversely correlated to RW (except for *Index of Economic Resources* - IER which is proportional to RW) (Figure 3a). Exceptions are *Index of Relative Socio-Economic Advantage and Disadvantage* (IRSAD) and *Heat Vulnerability*, where no correlations were observed (Figure 3a). As nearly all factors were cross-correlated, we used stepwise regression (Figure 3b), exploratory spatial regression (Figure 3c) and PCA (Figure A.1, Appendix 1) to investigate relationships. All these techniques pointed towards just two strong predictors for RW: *distance to centre* and *age of development*, which are highly correlated to each other (Figure 3b). As these factors were strong predictors for all socio-economic factors as well, normalisation was required.

Results show that the predictive strength of *distance to centre* and *age of development* depends on the definition of the metropolitan boundary, as Melbourne's sprawl is asymmetrical and historically occurred in south-easterly direction, along major railway lines and highways (Beed, 1981; Department of Infrastructure, 1998) (Figure 4i). During

Melbourne's expansion, the metropolitan area encapsulated existing settlements along its fringes. Therefore, *distance to centre* performs best when the metropolitan boundary is defined to exclude 'fringe' and 'shire' councils along the urban periphery (i.e. an attempt to symmetrise sprawl – Figure 3b,c). The performance of *age of development* is more robust against changes in the definition of the metropolitan boundary, but slightly weaker overall.

Five 'urban ring' subsets of data were acquired after normalisation for *distance to centre* (Figure 4h), as described in Section 2.2.2. Following normalisation, we found that nearly all correlations between socio-economic factors and RW were eliminated (Table 2). Only in the fringe ring did some correlations remain, potentially caused by the distortion of Melbourne's unsymmetrical sprawl pattern. Several circumstances may explain the relationship between RW and *distance to centre*. Further from the dense inner city, decreasing urban densities remove space constraints. Cities sprawl from their centre through consecutive addition of urban developments in their fringes, leading to older and more established areas close to the centre (Department of Infrastructure, 1998). Retrofitting in older established areas is more challenging and costly due to a fixed urban context. Therefore, system placement is preferred in less established areas further from the centre. Furthermore, Melbourne's planning regulations prescribe all new greenfield developments to implement WSUD (DPCD, 2016), while requirements for WSUD implementation in infill developments are only present in a small number of jurisdictions. Finally, higher RW in fringe areas aligns with recent insights on stream health protection, prioritising protection of pristine peri-urban catchments (Urrutiaguer et al., 2012).

a **Spearman's rho correlations**

		RW	Age of Development	Distance to Centre	Population Density	House Price	Education Level	Environmental Awareness	Sense of Community	Heat Vulnerability	IRSAD	IER
RW	Correlation Coefficient	1.000	-.271**	.317**	-.239**	-.242**	-.199**	-.258**	-.246**	-.098	-.065	.155**
	Sig. (2-tailed)	.	.000	.000	.000	.000	.000	.000	.000	.080	.249	.006
	N	317	283	317	317	305	317	317	317	317	317	317
Age of Development	Correlation Coefficient		1.000	-.747**	.561**	.692**	.704**	.689**	.578**	.149*	.314**	-.271**
	Sig. (2-tailed)		.	.000	.000	.000	.000	.000	.000	.012	.000	.000
	N		283	283	283	277	283	283	283	283	283	283
Distance to Centre	Correlation Coefficient			1.000	-.623**	-.711**	-.798**	-.760**	-.479**	-.110*	-.329**	.325**
	Sig. (2-tailed)			.	.000	.000	.000	.000	.000	.050	.000	.000
	N			317	317	305	317	317	317	317	317	317
Population Density	Correlation Coefficient				1.000	.518**	.590**	.501**	.361**	.227**	.152**	-.298**
	Sig. (2-tailed)				.	.000	.000	.000	.000	.000	.007	.000
	N				317	305	317	317	317	317	317	317
House Price	Correlation Coefficient					1.000	.915**	.613**	.842**	.060	.763**	.198**
	Sig. (2-tailed)					.	.000	.000	.000	.293	.000	.000
	N					305	305	305	305	305	305	305
Education Level	Correlation Coefficient						1.000	.707**	.782**	.029	.709**	.054
	Sig. (2-tailed)						.	.000	.000	.605	.000	.338
	N						317	317	317	317	317	317
Environmental Awareness	Correlation Coefficient							1.000	.530**	.005	.370**	-.183**
	Sig. (2-tailed)							.	.000	.924	.000	.001
	N							317	317	317	317	317
Sense of Community	Correlation Coefficient								1.000	-.057	.756**	.289**
	Sig. (2-tailed)								.	.308	.000	.000
	N								317	317	317	317
Heat Vulnerability	Correlation Coefficient									1.000	-.186**	-.241**
	Sig. (2-tailed)									.	.001	.000
	N									317	317	317
IRSAD	Correlation Coefficient										1.000	.656**
	Sig. (2-tailed)										.	.000
	N										317	317
IER	Correlation Coefficient											1.000
	Sig. (2-tailed)											.
	N											317

c

	Distance to Centre~		Age of Development~	
	Position	*% Significant*	*Position*	*% Significant*
All metro suburbs	2	28	1	88
No Rural Councils	1	100	2	47
No pop. Dens. <500	3	45	1	84
No fringe areas	1	96	2	55

b

	Distance to Centre			Age of Development			*Cross Correlation*
	p-value	*Corr. Coeff.*	*Stepwise^ Regression R^2*	*p-value*	*Corr. Coeff.*	*Stepwise^ Regression R^2*	
All metro suburbs	0.739	0.016	x	<0.0005	-0.208	0.061	-0.744
No Rural Councils	<0.0005	0.317	0.104	<0.0005	-0.271	x	-0.747
No pop. Dens. <500	<0.0005	0.300	x	<0.0005	-0.248	0.070	-0.744
No fringe areas	<0.0005	0.288	0.074	0.002	-0.193	x	-0.734

Figure 3 Correlation matrix between RW and all socio-economic factors per suburb, excluding rural councils and (a) comparative performance to predict RW for variables: *distance to centre* and *age of development* through correlation and stepwise regression (b) as well as exploratory regression (c).
Shaded cells indicate (a) highly significant correlations between RW and the socio-economic variables, (b,c) outperformance over the other variable
*Correlation is significant at the 0.05 level (2-tailed). **Correlation is significant at the 0.01 level (2-tailed).
^All four stepwise regressions resulted in a single factor to be selected for the optimal model.

~'Position' indicates the relative strength of the factor compared to the 8 factors used in this exploratory regression, whereas '% Significance' indicates the percentages of trials in which this factor was identified a significant contribution to the predictive model. In all trials the direction of the relation n was consistent (positive for *distance to centre* and negative for *age of development*).

INSERT TABLE 2

These results suggest a tendency for WSUD to be located in communities of relatively low house prices, environmental awareness, sense of community and education level as well as high economic resources, as they tend to be located further from the centre (note: such a city structure is typical for Australian cities; however, this could be different in other parts of the world). Such tendency is most likely unintentional, given the emphasis on physical factors and hydrology in the planning practice (Schifman et al., 2017). A potential lack of understanding and appreciation for WSUD, resulting from low environmental awareness and education levels, may cause a lack of acceptance and intentional and unintentional maltreatment of these assets, jeopardising their operation (Chaffin et al., 2016; Sharma et al., 2012). This highlights the need for investment in human, social and cultural capital through education campaigns about the function and benefit of green infrastructure, to support the uptake and acceptance of WSUD practices among residents. Such investments were proven highly effective for the uptake of rain gardens and rain tanks (Green et al., 2012), and were shown to dramatically increase people's acceptance (Mathey et al., 2015). At the same time, WSUD has the potential to educate communities about the importance of urban water and stream protection, increase a sense of community by serving as a public open space (Dobbie and Green, 2013; Rijke et al., 2008) and increase property prices through their amenity value (Mahan et al., 2000).

Our results indicate that socio-economic factors are currently not considered in location planning directly. The disregard of most socio-economic factors may be caused by a lack of knowledge and awareness among planning practitioners. This presumption is reinforced by the low representation of socio-economic criteria in WSUD guidelines and regulations.

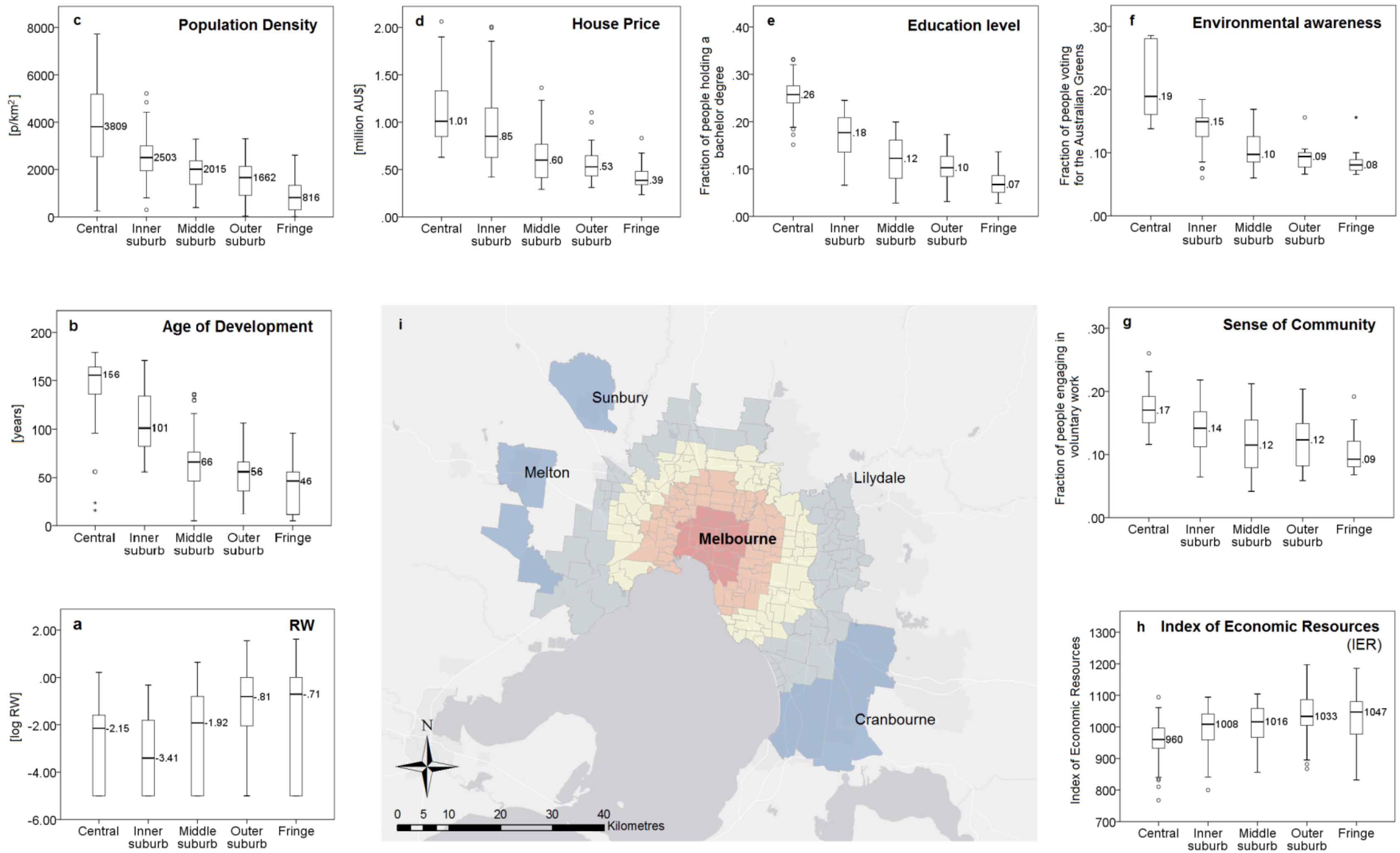

Figure 4 (a): Relationship between *distance to centre* and RW, (b-h): Relation between the significantly correlating socio-economic factors and *distance to centre* and (i): Map of central-inner-middle-outer-fringe rings.

3.4 Urban form factors

Figure 5 shows that larger WSUD assets tend to be placed further from the city centre, confirming the “design bulls-eye” suggested by Charlesworth (2010). Rain gardens have the most even distribution, pointing to their versatility and flexibility. Very small assets, such as box rain gardens and tree pits, tend to be placed in inner-city areas (Figure 5). Large assets such as ponds, lakes and wetlands are predominantly placed in outer suburbs and fringe areas. Swales sit between these extremes, with the majority of assets situated in middle and outer suburbs.

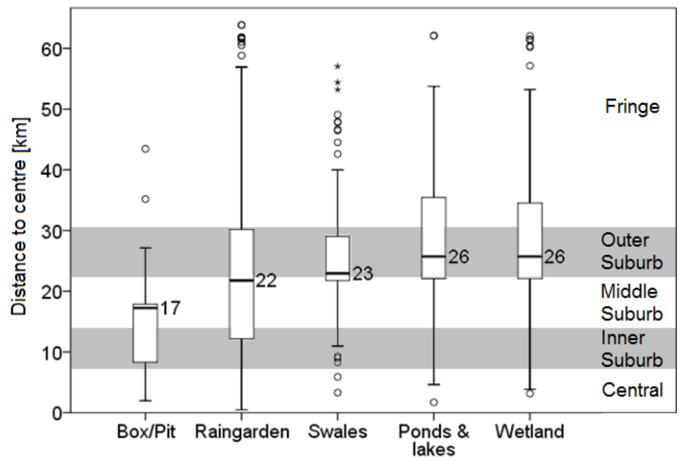

Figure 5 Distribution of WSUD types and their *distance to centre*, sorted by increasing system mean size.

Figure 6a shows the distribution of WSUD in terms of frequency (y-axis) and the total land uptake (x-axis) among different land-use types. It shows us that land uses of high density and public exposure such as ‘mixed high-density residential & commercial’, ‘low density trade’ and ‘high density residential’ have a high density of very small assets. The exception is ‘mixed trade & industry’ where density is low, but system sizes are large. Relatively open and predominantly publicly owned land uses such as ‘floodway’ and ‘service and utility’ have many large assets. The exception is ‘reserves’ where fewer WSUD assets are placed. Some land uses that might benefit most from the educational and amenity benefits of WSUD, i.e. ‘education’ and ‘health and community’ (schools, hospitals, libraries etc.) have a low occurrence of assets.

Streetscapes received special attention in our analysis. Quality of streets is at the core of urban productivity, sustainability, quality of life and social inclusion (UN Habitat, 2013). They form a major part of all impervious surfaces in the city and are typically publicly owned. Figure 6b shows a heavy overrepresentation of WSUD in Melbourne streetscapes, with over 21% of all assets representing nearly 15% of serviced area in this urban landscape, which represents only 6% of Melbourne area. Assets are relatively small, illustrated by the difference between the share in number (21%) and land uptake (9%) of assets. Anecdotal evidence from municipal planning practitioners suggests that opportunistic planning practices may explain the overrepresentation of WSUD in streetscapes, as councils tend to utilise street renewal and roadworks to co-implement assets (e.g. Allan, personal communication, 1 September 2015; Innes, personal communication, 23 October 2015).

These findings are generally in line with our hypothesis. Although urban form factors are not always as prohibitive as some biophysical factors, they are still well understood and thoroughly considered in current urban planning practice.

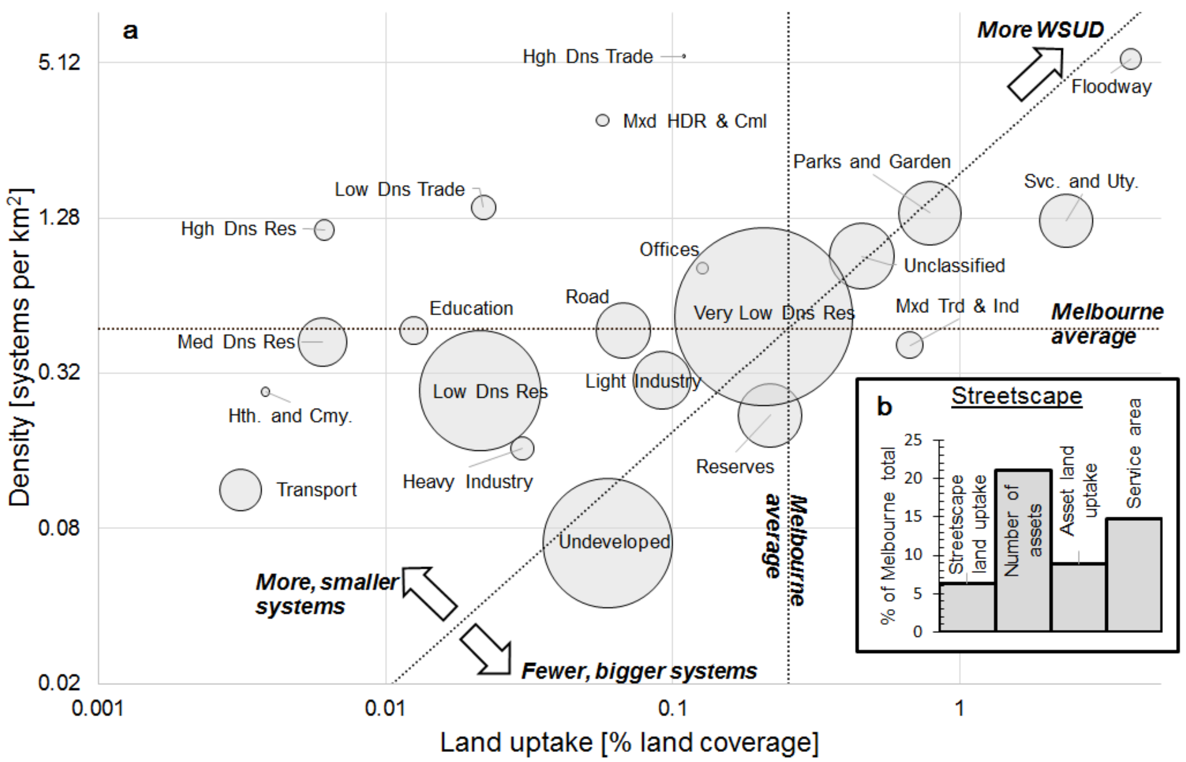

Figure 6 (a) Prominence of WSUD among land-use types in terms of system count (vertical axis) and size (horizontal axis). Each circle represents a land-use type, circle size represents the area of that land-use type in Melbourne. The horizontal and vertical lines represent the average density and land uptake of assets, while the diagonal is the iso-size line at the average system size in Melbourne. (b) Prominence of WSUD in streetscapes.

The results of this paper reflect the relatively ad-hoc WSUD planning practices in Melbourne in which certain biophysical and urban form factors are considered, whilst socio-economic factors are largely overlooked. This has, unintentionally, led to an uneven distribution of WSUD systems and their attributed benefits across the Melbourne Metropolitan area. In turn, this results in reduced effectiveness (i.e. optimising benefits and co-benefits).

To prevent these undesirable outcomes, strategic WSUD planning practices and tools should be employed, rigorously considering all aspects of the specific urban context, actively involving all relevant stakeholders, and remaining adaptive to an uncertain and ever-changing reality. Such tools and methods are increasingly being adopted by sustainable urban water management practitioners and include, but are not limited to: planning simulators (e.g. SUSTAIN-EPA: Lee et al., 2012) , (spatial) multi-criteria decision analysis (e.g. Fronteira et al., 2014), adaptive governance (e.g. Schifman et al., 2017), participatory approaches to promote social and cultural learning (e.g. Shuster W.D. et al., 2008) and experimentation (e.g. Chaffin et al., 2016; Farrelly and Brown, 2011).

4 Conclusion

This is the first study to systematically investigate the relationships between WSUD distribution and biophysical, socio-economic and urban form factors for a greater metropolitan region. We used one of the most extensive and complete spatial WSUD databases in the world. Despite its status as ‘front-runner’, the asset data for Melbourne are still imperfect and needs significant levels of engagement. Nevertheless, clear trends could be observed. Numerically, rain gardens, ponds, lakes and wetlands are equally abundant, while wetlands overwhelmingly account for the greatest land-uptake with two-thirds of the WSUD total.

The manifestation of WSUD as an integrated part of the urban landscape is reflected by its reciprocal relation with the urban context, as highlighted by our study results. Strong relationships between WSUD distribution and biophysical, socio-economic and urban form factors were revealed. Constraints from biophysical factors as well as urban form underpin WSUD placement; however, socio-economic factors are disregarded. Biophysical circumstances can prohibit WSUD placement, while socio-economic factors seem to have a more accidental, potentially unintended effect. Urban areas that may highly benefit from WSUD may thus be overlooked. Intrinsically interwoven, these three aspects constitute the physical and social fabric of city scapes, which build the stage for WSUD integration.

Melbourne’s current policy and guideline frameworks do not prevent ad-hoc and opportunistic planning practices to dictate WSUD placement. Ad-hoc planning does not promote equitable distribution of WSUD. In Melbourne it has led to the overrepresentation of WSUD in communities with low environmental awareness, low education levels and low sense of community, as a result of the specific urban structure.

To make WSUD successful, it is critical for urban planners to start incorporating a wide variety of biophysical, socio-economic and urban form factors in their decision-making. Currently, we lack understanding of the urban context in relation to WSUD placement, restricting our capacity to increase strategic approaches. This study is a first attempt to address this gap, but increased efforts from government and water authorities/utilities to create and maintain high quality asset inventories are called for. Therefore, recent trends towards more strategic and integrated planning for WSUD are encouraging and have the potential to significantly improve the outcomes of water quality, flood safety and amenity for urban communities.

Future research should focus on replication of this work in comparable urban landscapes with WSUD found across Australia and North America, such as the green champion city of Portland in the USA (Netusil et al., 2014), as well as for those in Europe and Asia, where urban growth is governed by different patterns. Including other/more factors is important, as our study is limited and doesn’t include important variables such as land. The outcomes of this and future studies should be used to raise awareness among urban planners about the outcomes of their current processes. They call for the development and application of practice guidelines, strategic approaches and planning support systems that enable integration of a broader set of criteria in addition to biophysical design parameters.

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Table of Tables

Table 1 Factors selected for the spatial analysis of WSUD.

	Name	Description	Spatial unit*	Source**
Biophysical	Slope	Slope of the surface [%]	Location	VIC Data
	Topography	Distance to natural waterways [m]	Location	VIC Data
Socio-Economic	Age of development	Time since first development in an area [years]	Suburb	Melbourne Museum
	Population Density	Permanent residents from census [p/km^2]	Suburb	ABS
	House price	Median price of house sales in 2014 [AU$]	Suburb	DELWP
	Education Level	Proxy: People holding a bachelor degree [fraction]	Suburb	ABS
	Environmental Awareness	Proxy: First preference votes for 'The Greens' in 2002 and 2010 federal elections [fraction]	Electoral district	VEC
	Sense of Community	Proxy: People engaging in voluntary work for a local organisation or group [fraction]	Suburb	ABS
	Heat vulnerability	Ordinal index ranging from 1-10 (low-high vulnerability)	Postcode	Loughnan et al. (2012)
	IRSAD	Index of Relative Socio-economic Advantage and Disadvantage. Ordinal index with arbitrary scale.	Suburb	ABS
	IER	Index of Economic Resources. Relative indicator. Ordinal index with arbitrary scale	Suburb	ABS
Urban form	Land use	Two types of land-use classifications: by the Victorian government and adapted from Victorian zoning regulations.	Location	VIC Data; Bach et al. (2015)
	Distance to centre	Distance to Melbourne's geographic centre [km] (centroid of the four inner councils according to Buxton & Tieman (2005))	Suburb	Calculated

*The smallest spatial unit of the source data.
**VIC Data: government data repository for the state of Victoria, accessed through www.data.vic.gov.au. Melbourne Museum: unpublished dataset from May 2015. ABS: Australian Bureau of Statistics, census data 2011, accessed through www.abs.gov.au. DELWP: Victoria Department of Environment, Land, Water and Planning, accessed through www.delwp.vic.gov.au. VEC: Victorian Electoral Commission, accessed through www.vec.vic.gov.au.

Table 2 Normalisation for *distance to centre*: correlation coefficients between socio-economic factors and RW per urban ring

Factor	**Centre**		**Inner Suburbs**		**Middle Suburbs**		**Outer Suburbs**		**Fringe**	
	Corr. Coeff.	*p**	*Corr. Coeff.*	*p**	*Corr. Coeff.*	*p**	*Corr. Coeff.*	*p**	*Corr. Coeff.*	*p**
Age of development	-	-	-	-	-	-	-	0.01	-	-
Population Density	-	-	-	-	-	-	-	-	-	-
House Price	-	-	-	-	-	-	-	-	-	-
Education Level	-	-	-	-	-	-	-	-	-	-
Environmental Awareness	0.346	0.01	-	-	-	-	-	-	-0.318	0.043
Sense of Community	-	-	-	-	-	-	-0.405	0.001	-0.430	0.005
Heat Vulnerability	-	-	-	-	-	-	-	-	-	-
IRSAD	-	-	-	-	-	-	-	-	-	-
IER	-	-	-	-	-	-	-	-	-	-

*Only significant correlations (p-value of 0.05 or below) are shown in the table.

Appendix A

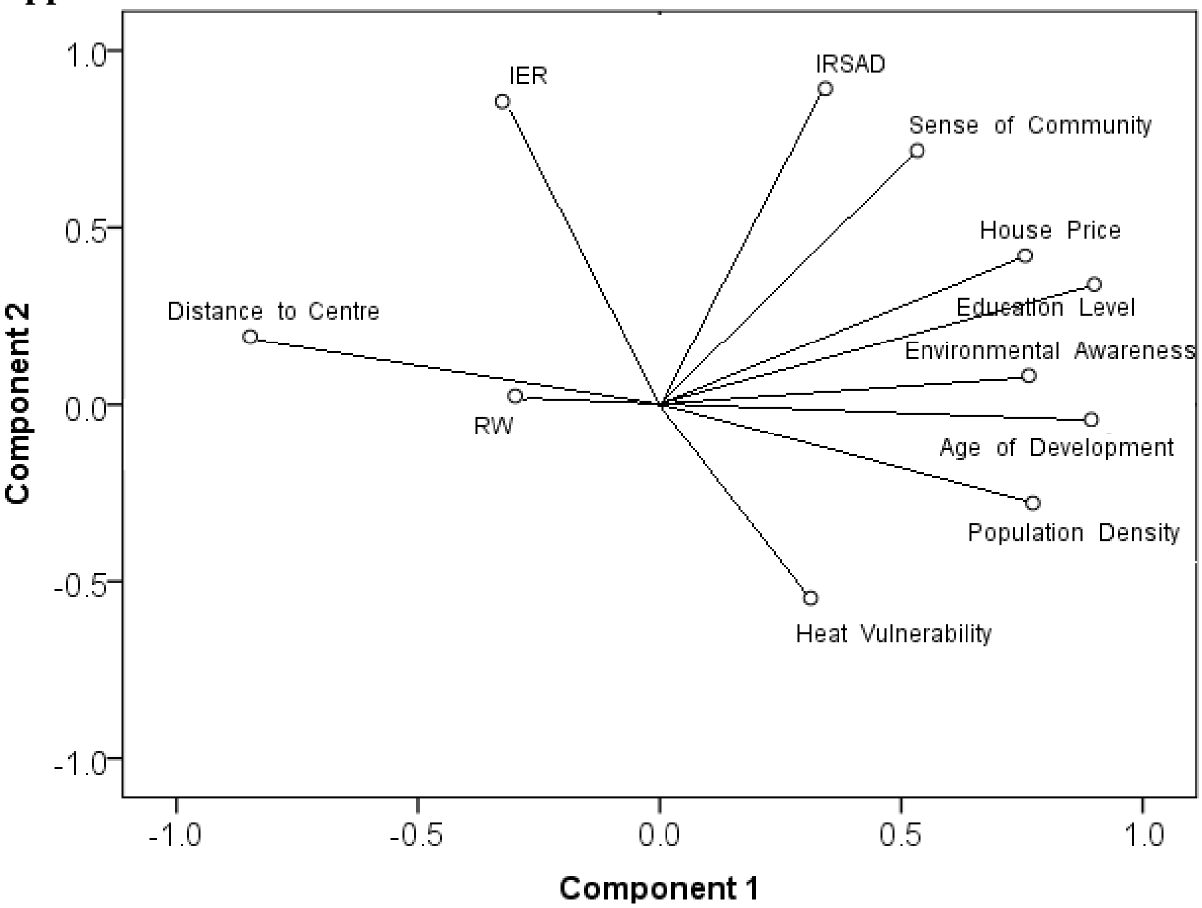

Figure A.1 Component plot in rotated space.