

## Characterising a city for integrated performance assessment of water infrastructure in the DAnCE4Water model

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### ABSTRACT

DAnCE4Water is a strategic planning tool that simulates the dynamics of both urban development and societal systems with respect to the integrated water infrastructure. The Biophysical Module's *building block routine* creates a conceptual description of the urban form and integrated water infrastructure allowing its performance to be efficiently modelled. A prototype of this routine is presented using a hypothetical case study of a mixed residential land use block. Common urban planning parameters (derived from planning documents) and demographic information (from census data) are used to establish urban form geometry in the model and assess opportunities for lot-scale Water Sensitive Urban Design (WSUD) based on conceptual design curves and social inputs. The ability of the model to aggregate fine-scale information to a coarse resolution that allows its efficient performance assessment was tested. Initial results showed only minor differences between the two methods, attributed to slight inaccuracies in scaling of road areas. Simulations demonstrate the interaction between urban density, the environment and opportunities for WSUD. This biophysical component will not only aid DAnCE4Water in the assessment of adaptation strategies for urban water systems, but also become a powerful standalone exploratory tool.

### KEYWORDS

DAnCE4Water, strategic planning, residential density, urban form, WSUD, water sensitive

### INTRODUCTION

Population growth, rapid urbanisation and changing climate have been acknowledged as significant challenges. Although adaptation has become a keyword in planning and policy-making, the question of 'how' remains unanswered. Part of the reason for this is the lack of decision-support tools that provide assistance to allow key stakeholders to engage in effective participatory planning. Doubts on the predictability of the uncertain future with our current modelling approaches have been expressed both by urban and water system modellers (Beck, 1997; Batty, 2010). Beck (1997), however, asserts that we can reduce the uncertainty in our decisions by enhancing our understanding of system dynamics. A viable method is the exploratory modelling approach (Banks, 1993). An example is the use of virtual case studies to provide a generic assessment of our system. It has already been shown effective for studying water supply and sewerage systems (Sitzenfrei et al., 2010; Urich et al., 2010).

*PREPARED enabling change*, a project of the 7<sup>th</sup> European Framework Programme, aims to deliver a tool that embodies the synergies between social, urban and water systems modelling. DAnCE4Water (*Dynamic Adaptation for enabling City Evolution for Water*) is an strategic

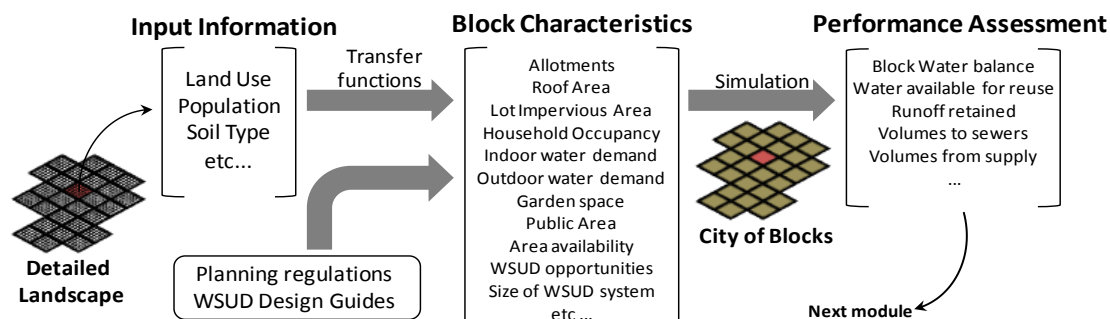
planning tool that simulates the dynamics of both urban development (Urich et al., 2011) and the societal system (De Haan et al., 2011; Ferguson et al., 2011) with respect to the integrated water infrastructure. Users specify an input scenario or “thought experiment” together with existing information about the urban infrastructure. The output is a collection of consequential and hypothetical narratives of what future development of the city could look like within defined constraints. The model is to be developed and tested on the city of Melbourne, Australia. A central component of DANCE4Water that helps achieve the link between the three major systems (i.e. urban form, societal and water systems) is the Biophysical Module; in particular, the *building block routine*. Its function is to process the information of the urban environment and transform it into a form that: 1) allows placement of urban water infrastructure (comprising central- and decentralised systems) and 2) allows its performance to be more efficiently assessed.

Work to date has primarily focussed on the representation of urban form; in particular, residential districts as they are known to constitute a large proportion of a city (Stone, 2004) and are highly variable in parameters, such as imperviousness (Arnold and Gibbons, 1996). The works of both Alberti (1999) and Stone (2004) highlight a significant influence of urban form and planning regulations on the environment. A fine level of detail is needed in the *building block routine* as the information required to place and assess performance of water infrastructure cannot otherwise be accurately obtained. The challenge is to then aggregate this fine-scale information to a coarser resolution (at which performance of the integrated system is to be modelled) without losing accuracy. An initial prototype that can analyse residential blocks of mixed densities and assess opportunities for the implementation of water sensitive urban design (WSUD) was developed. The following paper will present the current version of the prototype under development using a hypothetical case study.

## MATERIALS & METHODS

### *Concept Overview and Case Study*

*Building blocks* are cells in the city grid containing information about urban form, demographics and urban water infrastructure. The Biophysical Model receives detailed geographic input (as shown in Figure 1). Simple transfer functions and user-defined planning regulations are used to swiftly calculate water-related characteristics (e.g. impervious areas, available space) for each land use within each block. If the model determines that it is feasible to place WSUD technologies in various areas of the block (a decision based on social and technological factors), it will also write this information to the array of block characteristics.



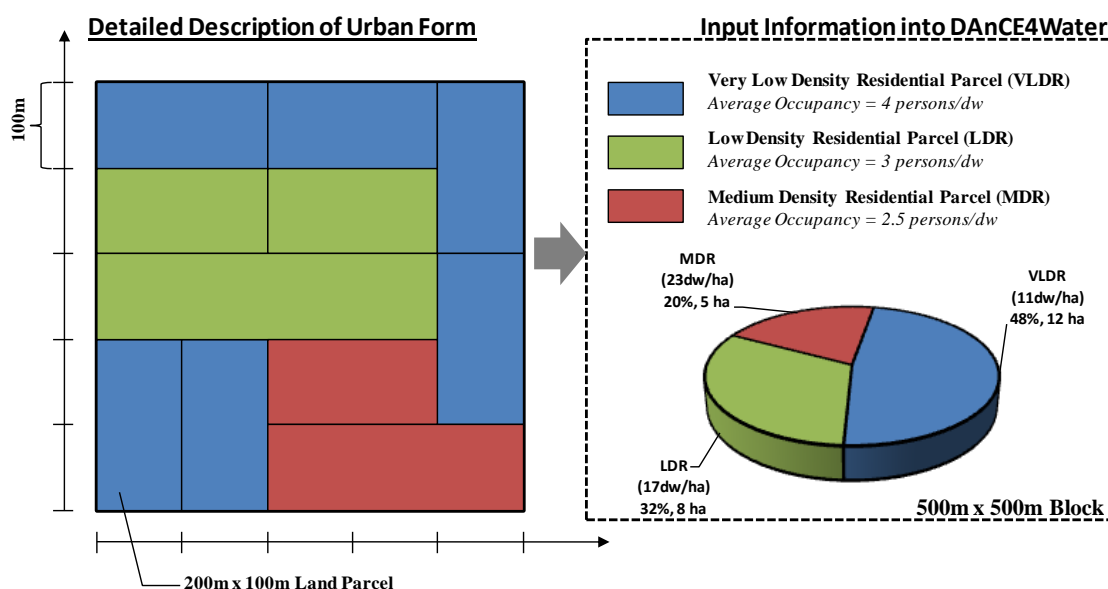
**Figure 1.** Flowchart of DANCE4Water’s Biophysical Module

Due to the size and complexity of simulations in the model, fine-scale block characteristics need to be aggregated to a coarse resolution that allows quick, yet reliable performance assessment. Performance assessment will output a number of indicators that become inputs to

other modules in DANCE4Water. The developed approach is general and can be applied to any possible combination of land use and lot, street and even small scale precinct application of WSUD technologies (the larger precinct scale WSUD application requires a separate approach that is currently under development). The approach is explained in detail using a simple case of the implementation of stormwater infiltration systems as the key stormwater management measure within an urban residential area.

### Input Information

The hypothetical case study (in Figure 2) is a 500m x 500m block containing residential parcels of three different population densities (indicated here as an average occupancy and dwelling density). The perimeter of each parcel (i.e. rectangle) within the block represents the street network (a clarification is provided in Figure 3). Planning regulation and WSUD design inputs are defined in Table 1. This case study block will be simulated on three different soil types (sand, sandy clay and medium clay). The block will be modelled as a whole (the *Aggregation* approach) and compared for accuracy with an alternative method of simulating each individual land parcel first and adding the outputs together (the *Summation* approach).



**Figure 2.** Layout of Case Study Block (including land use and population density inputs)

**Table 1.** Urban planning and Infiltration system design input parameter values

ALLOTMENT PLANNING PARAMETERS	ALLOTMENT FRONTAGE PARAMETERS
<ul style="list-style-type: none"> <li>• Maximum site impervious cover = 80%</li> <li>• Front setback distance = 4m</li> <li>• Side/Rear setback distance = 1m</li> <li>• Number of carports = 1</li> <li>• Garage included = YES</li> <li>• Minimum driveway width = 2.6m</li> <li>• Patio area = 2m<sup>2</sup></li> <li>• Average floor space per person = 84m<sup>2</sup></li> </ul>	<ul style="list-style-type: none"> <li>• Front road lane width = 5m</li> <li>• Nature strip width = 3m</li> <li>• Footpath width = 2m</li> <li>• Driveway access width = 2.6m</li> </ul>
	WATER MANAGEMENT, SOCIAL PARAMETERS
	<ul style="list-style-type: none"> <li>• Best management target for flow reduction = 90%*</li> <li>• Sacrificial garden space for WSUD (as % of total) = 30%*</li> </ul>
SOIL INFORMATION	INFILTRATION SYSTEM DESIGN
Infiltration rates for: <ul style="list-style-type: none"> <li>• Sandy soil = 360mm/hr</li> <li>• Sandy clay = 36mm/hr</li> <li>• Medium clay = 3.6mm/hr</li> </ul>	Sizing Requirements for different soil types: <ul style="list-style-type: none"> <li>• Sandy soil: 0.4% surface area*, 1m setback dist.**</li> <li>• Sandy clay: 2.0% surface area*, 2m setback dist.**</li> <li>• Medium clay: 6.4% surface area*, 4m setback dist.**</li> </ul>

\*As percent of catchment impervious area. Requirement corresponds to achieving best practice of retaining at least 90% of lot runoff; system has a 1m depth with a media porosity of 0.35. Infiltration from sidewalls assumed to take place and approximated using simplified triangular hydrostatic pressure distribution.

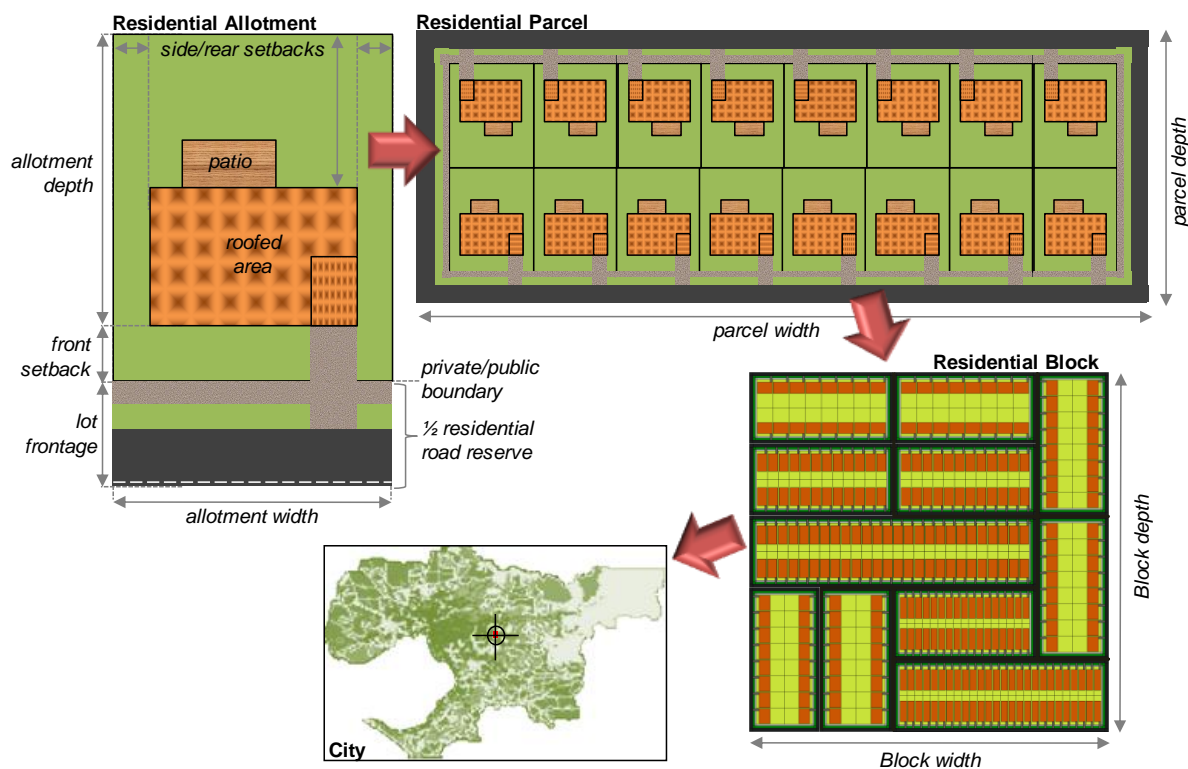
\*\*Setback distances obtained from Melbourne Water (2005), specified for a range of soil types

### Block Characteristics

After defining the inputs, the *building block routine* then follows four key steps to fill the vector of block characteristics. These are described in detail in the next two sections, but can be summarised as follows:

- (1) Transform the input information into a more detailed geometric description of urban form using local urban planning rules.
- (2) Derive relevant biophysical information required to characterise the integrated water system from geometry and demography.
- (3) Use conceptual design rules and social inputs fed by the user (or other modules) to populate as much of the block as possible with water sensitive technologies at different scales (lot, street, precinct – this paper only focuses on the lot scale)
- (4) Scale finer details (Figure 3) up to the appropriate spatial resolution, at which performance will be assessed (here, this corresponds to a 500m x 500m catchment).

Once these four steps have been completed, the outputs are transferred to a performance assessment component. For this study, ‘performance assessment’ focuses only on simulating rainfall runoff and the impact of lot-scale infiltration on block hydrology.



**Figure 3.** Spatial definitions used in DAnCE4Water

*Step 1: Characterising Residential Districts.* Four different spatial levels are defined in Figure 3; allotment, parcel, block and city. In the first step, urban planning rules (from Table 1) are applied to each land use to evaluate the detailed geometry (at the lot-scale). Total area of the land use is subdivided into number of allotments and allotment frontage (road lane, nature strip and footpath). As no information about quantity and size of parcels in a block is provided to the model (land use percentages will instead be derived from an input raster), the algorithm at the moment assumes that each land use class is a long parcel of 100m depth bounded by frontage (like the example in Figure 3). Setback rules, roof area, on-site parking and other descriptors listed in Table 1 are applied to a single lot (lots in a residential density

are assumed to be identical). The representation of allotment driveways (public and private) is similar to the method presented by Stone (2004).

For this case study, parameters listed in Table 1 were informed by several Australian urban planning documents (e.g. Victorian Planning Provisions, Building Regulations, Building Code of Australia). Although a range of values was identified for each parameter (e.g. front setbacks could vary between 4 and 9m), one consistent set was chosen for all residential land uses. It was preferred to avoid dealing with possible parameter sensitivity issues at this early stage of model development. The final product will allow for these parameters to be varied across the city (either through defined relationships or a stochastic method). The average floor space per person was derived based on census data from the Australian Bureau of Statistics by dividing the average floor area by the average occupancy of residential dwellings for Melbourne.

*Step 2: Calculating biophysical information.* The second step involves the calculation of parameters required for water-related assessment (e.g. opportunities for WSUD, connections with centralised wastewater and water supply infrastructure, urban drainage). The private and public impervious areas were the main interest in this study and were calculated from geometry and assumed to fully contribute to runoff from the lots (a “worst-case” scenario approach in sizing infiltration systems).

*Step 3: Assessing Opportunities for WSUD.* The design and placement of an infiltration system considers not only local soil conditions, hydrology and catchment imperviousness, but also setback distances from nearby structures and available space required to achieve best practice (Melbourne Water, 2005). Furthermore, it is also a social issue at the lot-scale, as to whether residents are willing to sacrifice part of their garden to the establishment of these systems. Using available information calculated from the first two steps, the third step determines the available space in one allotment. Based on user-defined requirements for best management practice (here 90% flow retention – see Table 1), the surface area of the infiltration system (as a percentage of the catchment’s imperviousness) is determined from a lookup table. The required surface area of the system, including setback distances, is calculated. For an infiltration system to be feasible at the lot scale for a given soil type, there needs to: a) be enough available surface area (garden space) for the system and b) the required space should not exceed the proportion of garden that residents are willing to sacrifice (defined here as 30% of total garden area). If these two criteria are met, the system is installed in every lot of that residential parcel. Table 2 defines various required system surface areas and setback distances for the three soil types.

*Step 4: Aggregating information to block level.* The fourth and final step aggregates information from all land parcels to the block level. All impervious areas that are ‘served’ by some form of WSUD system (i.e. their runoff is treated by the system) are grouped separately from those that are not. If the system were for decentralised wastewater or water supply, populations being ‘served’ by these systems are considered instead. The equivalent size of WSUD technologies that are present in the block is calculated. For this example, the total surface area of infiltration system present in the block was calculated. This aggregation results in fewer catchments and systems to model and is therefore more computationally efficient. This is necessary, as DANCE4Water will eventually have to simulate the entire city of Melbourne, which at a 1km x 1km resolution would require 9,000 such blocks.

### Performance Assessment

The land parcel and residential block information were transferred to a simple performance assessment model. The Rainfall/Runoff component of the MOPUS model (McCarthy, 2008) was adopted. The rainfall runoff component defines an initial loss of 1mm for impervious surfaces and requires specification of a maximum pervious soil storage depth (kept as a constant of 100mm due to the hypothetical nature of the case study). No routing was assumed. The infiltration systems were modelled with a simple water balance. Infiltration was assumed to take place through the base and sidewalls of the system (pressure distribution along the sidewalls was approximated as triangular). Performance was assessed using a 6-minute rainfall and a daily potential evapotranspiration time-series of Melbourne for one year.

## RESULTS & DISCUSSION

### Comparison of Summation vs. Aggregation

Results from various simulations undertaken are presented below in Table 2. Total runoff volumes correspond to one year of simulation using the 6-min rainfall series (total annual rainfall of 655mm). Comparing *Summation* with *Aggregation* method reveals minor differences in volumes across all cases. Small dissimilarities in imperviousness show that the *Aggregation* method is a valid approach to scaling up the information without losing much accuracy. The reason for differences is due to the assumption made about representing land use inputs as long parcels (explained in Step 1 of the methodology). It resulted in slightly more allotments and less road reserve on-site. Nevertheless, this simple assumption may be accurate enough as percentages are not very different.

**Table 2.** Comparison of Results for Residential Block Case Study

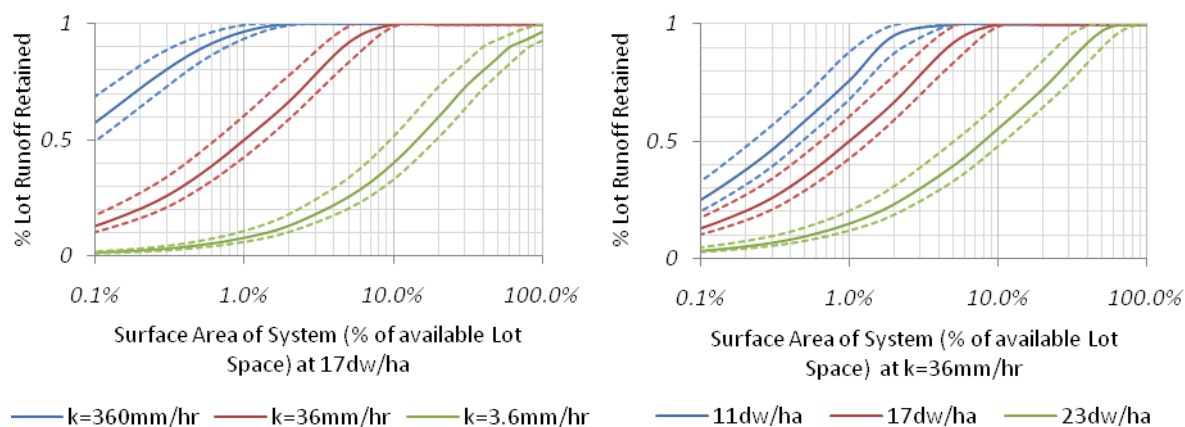
	Individual Parcels (Summation Method)	Block at once (Aggregation Method)
<b>BASE CASE SIMULATIONS (WITHOUT INFILTRATION SYSTEMS)</b>		
Total Block Runoff (without WSUD) [m <sup>3</sup> ]	92,729	90,914
Total catchment imperviousness	55%	54%
<b>WITH INFILTRATION SYSTEMS ON SANDY SOIL (k=360 mm/hr)</b>		
Land uses where Infiltration System Installed?	VLDR / LDR / MDR	VLDR / LDR / MDR
% of Allotments outfitted with WSUD*	100%	100%
% of impervious area served by WSUD	35%	38%
Total Runoff (with WSUD) [m <sup>3</sup> ]	48,915 (47% retained)	46,861 (48% retained)
Change in Evapotranspiration	+6%	+7%
<b>WITH INFILTRATION SYSTEMS ON SANDY CLAY SOIL (k=36 mm/hr)</b>		
Land uses where Infiltration System Installed?	VLDR / - / -	VLDR / - / -
% of Allotments outfitted with WSUD*	34%	34%
% of impervious area served by WSUD	15%	16%
Total Runoff (with WSUD) [m <sup>3</sup> ]	70,079 (24% retained)	66,578 (27% retained)
Change in Evapotranspiration	+20%	+22%
<b>WITH INFILTRATION SYSTEMS ON MEDIUM CLAY (k=3.6 mm/hr)**</b>		
Land uses where Infiltration System Installed?	- / - / -	- / - / -
<b>WITH INFILTRATION SYSTEMS ON MEDIUM CLAY (k=3.6 mm/hr) – Sacrificial garden space relaxed to 50%</b>		
Land uses where Infiltration System Installed?	VLDR / - / -	VLDR / - / -
% of Allotments outfitted with WSUD*	34%	34%
% of impervious area served by WSUD	15%	16%
Total Runoff (with WSUD) [m <sup>3</sup> ]	66,110 (29% retained)	62,004 (32% retained)
Change in Evapotranspiration	+42%	+45%

\*As WSUD was only assessed for the lot-scale, % of streets outfitted with WSUD would be 0% for all cases and was therefore not included in the table

\*\*As no infiltration systems could be installed due to exceeding the allowed social preference limit, an additional simulation was carried out where the 30% sacrificial garden space was relaxed to 50%. Systems therefore can be placed in VLDR areas.

### ***Interactions between urban density, environment and WSUD***

This second part of the discussion looks into the practical implications of the results. The model quite prominently illustrates the dilemma between density, soil and availability of space in installing infiltration systems. Figure 4 more explicitly describes the feasibility of installing infiltration systems at the lot-scale. The graphs were created from simulations on a block of uniform land use. In both cases of higher density and lower infiltration rate, the feasibility of lot-scale infiltration systems is reduced. This is either because there is not enough available space for achieving best practice, or the space required exceeds what residents are willing to sacrifice (i.e. a social constraint). The situation becomes interesting if we consider possible changes to rainfall and evapotranspiration (shown in Figure 4 by the dashed lines). In a drier climate scenario, for example, infiltration becomes more opportune, whereas if future rainfall is likely to increase (while evapotranspiration decreases), the feasibility worsens.



**Figure 4.** Relationships between density, soil type and garden space required for infiltration systems (dashed lines show results for rainfall and evapotranspiration scaled by  $\pm 30\%$ )

A net increase in evapotranspiration is, however, observed with decreasing soil infiltration rate in Table 2 (provided the system could be installed). This is possibly explained by the longer retention of water in the system as a result of slower infiltration. Despite the difficulties of placing these systems in high density and low infiltration areas, findings from the simulations nevertheless show that infiltration systems could be a popular alternative in promoting evapotranspiration to mitigate urban heat island effects. The feasibility of these systems in such environments could be further improved through the addition of on-site storage for example. These advantages are examples of what DAnCE4Water will eventually incorporate into its WSUD assessment procedure and are the subject of future work.

### ***Further work on other land uses, scales and WSUD technologies***

Further work will explore suitable ways of identifying the amount of road reserve within the different residential densities to improve the model's scaling method. Two methods, in which this could possibly be accomplished, include: use of intersection densities as was trialled by Stone (2004), or defining typical percentages of road area as a function of population or dwelling density. The concept to date has solely focussed on the representation of residential districts containing detached or semi-detached dwellings. Apart from higher density residential districts, which require further work, DAnCE4Water features numerous other land classes including commercial, industrial, municipal and open space area that this concept will incorporate. The presented case study focussed only on stormwater infiltration systems at the lot scale. This is one technology of an entire suite of WSUD tools that address sustainable decentralised stormwater, wastewater and water supply. With additional land uses, the process

of identifying opportunities for WSUD at the lot, street and precinct scales (as well as combinations of systems) will become more complex. Water quantity, quality, reuse and urban amenity are to all be considered. An example of how reuse and urban amenity can come into play was provided previously.

## CONCLUSION & OUTLOOK

DAnCE4Water's Biophysical Module is an important feature for linking urban environment and the societal system with the integrated water infrastructure. This study has presented an initial trial of the module's building block prototype. The model uses local urban planning rules to derive necessary information that allows it to efficiently relate with the water system. These rules are what characterise the urban form of cities. They do not only ensure the model's widespread applicability, but also allow the users to explore how these forms may change in future scenarios when planning rules are modified. Once complete, the biophysical component will not only aid DAnCE4Water in the assessment of adaptation strategies for Melbourne's urban water system, but also become a powerful standalone exploratory tool by itself. Watershed managers and urban planners can use it to better understand interactions of the urban form, water infrastructure and climate. This study showed some examples of the interactions between density, WSUD opportunity and improvements to the local hydrology.

## ACKNOWLEDGEMENTS

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