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A planning algorithm for quantifying decentralised water management opportunities in urban environments

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ABSTRACT

With global change bringing about greater challenges for the resilient planning and management of urban water infrastructure, research has been invested in the development of a strategic planning tool, DAnCE4Water. The tool models how urban and societal changes impact the development of centralised and decentralised (distributed) water infrastructure. An algorithm for rigorous assessment of suitable decentralised stormwater management options in the model is presented and tested on a local Melbourne catchment. Following detailed spatial representation algorithms (defined by planning rules), the model assesses numerous stormwater options to meet water quality targets at a variety of spatial scales. A multi-criteria assessment algorithm is used to find top-ranking solutions (which meet a specific treatment performance for a user-defined percentage of catchment imperviousness). A toolbox of five stormwater technologies (infiltration systems, surface wetlands, bioretention systems, ponds and swales) is featured. Parameters that set the algorithm's flexibility to develop possible management options are assessed and evaluated. Results are expressed in terms of 'utilisation', which characterises the frequency of use of different technologies across the top-ranking options (bioretention being the most versatile). Initial results highlight the importance of selecting a suitable spatial resolution and providing the model with enough flexibility for coming up with different technology combinations. The generic nature of the model enables its application to other urban areas (e.g. different catchments, local municipal regions or entire cities).

Key words | DAnCE4Water, stormwater management, strategic planning, Water Sensitive Urban Design (WSUD)

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INTRODUCTION

Urban water management has significantly evolved in the last decade towards more integration, greater diversity of technologies (central and decentralised) and more decision-factors, such as social, economic, and environmental (Rauch *et al.* 2005; Brown *et al.* 2009). Planning and management of water infrastructure, however, needs to become more resilient in light of growing population, rapid urban expansion and unpredictable climate. The use of models in planning and design is becoming more widespread and uptake of integrated urban water models in practice is slowly underway (Bach *et al.* submitted). Despite this progress, we lack tools that can support growing interdisciplinary collaboration in planning urban water systems as well as model complex urban dynamics and its relationship with water infrastructure.

The expansion of central water supply and sewer systems within a growing urban environment has been the subject of recent modelling research (Sitzenfrei *et al.* 2010; Urich *et al.* 2011). Unpublished work analysing Melbourne's centralised systems also reveals significant correlation of network growth with urban expansion and changing demographics. Rozos *et al.* (2011) coupled the Urban Water Optioneering Tool (UWOT) with a cellular automata land use model to investigate the impact of decentralised management over time. Model outputs from their study depict changes in runoff, wastewater volumes and potable water demand over time for conventional and innovative water management approaches. These modelling studies, however, do not account for the feedback that centralised and/or decentralised water management poses on urban

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growth, planning and implementation of future water infrastructure.

DAnCE4Water (Dynamic Adaptation for enabling City Evolution for Water) is a strategic planning tool that models the evolution in water infrastructure over time by considering both the feedback between urban growth and society on water infrastructure planning and the impact that new infrastructure has on future development (Rauch *et al.* 2012). It comprises three modules: Societal Transition Module (STM) (focussing on societal dynamics and reported in detail by De Haan *et al.* (2012)), Urban Development Module (UDM) (modelling dynamic changes of cities, see Urich *et al.* (2012)) and Biophysical Module (BPM) (planning and adapting urban water infrastructure). The model receives input scenarios (e.g. policy experiments, exploratory experiments, 'what-if' questions) and encourages stakeholders to partake in participatory modelling. The focus of this paper is on the BPM, which is responsible for the spatial representation, planning, design and implementation of urban water infrastructure. The BPM uses the information provided by scenario and other modules on urban demographics and societal system to implement suitable infrastructure and adapt them in response to significant perturbations in the broader urban environment. Each run of the BPM follows five key steps: (1) receiving input maps; (2) discretising the region; (3) determining urban form; (4) placing and adapting infrastructure; and (5) assessing performance (see Figure 1).

This study presents an algorithm of the BPM for the rigorous planning and assessment of suitable decentralised Water Sensitive Urban Design (WSUD) options in a local urban catchment in Melbourne, Australia (up to Step 4 in Figure 1). Flexibility and sensitivity of the algorithm are assessed. Furthermore, the paper also introduces a 'utilisation' metric that can help quantify the 'opportunity', 'feasibility' or 'level of adoption' of different WSUD technologies in urban catchments. This metric is useful for communicating results back to users and broader stakeholders and informing other parts of the DAnCE4Water model. The concept is broadly applicable to other modelling exercises.

METHODOLOGY

Data set

Geographic data (raster grids of land use, population, soil infiltration, elevation) were sourced for a local urban catchment in Melbourne's south-eastern suburbs. Soil infiltration rates were estimated from a soil classification map using

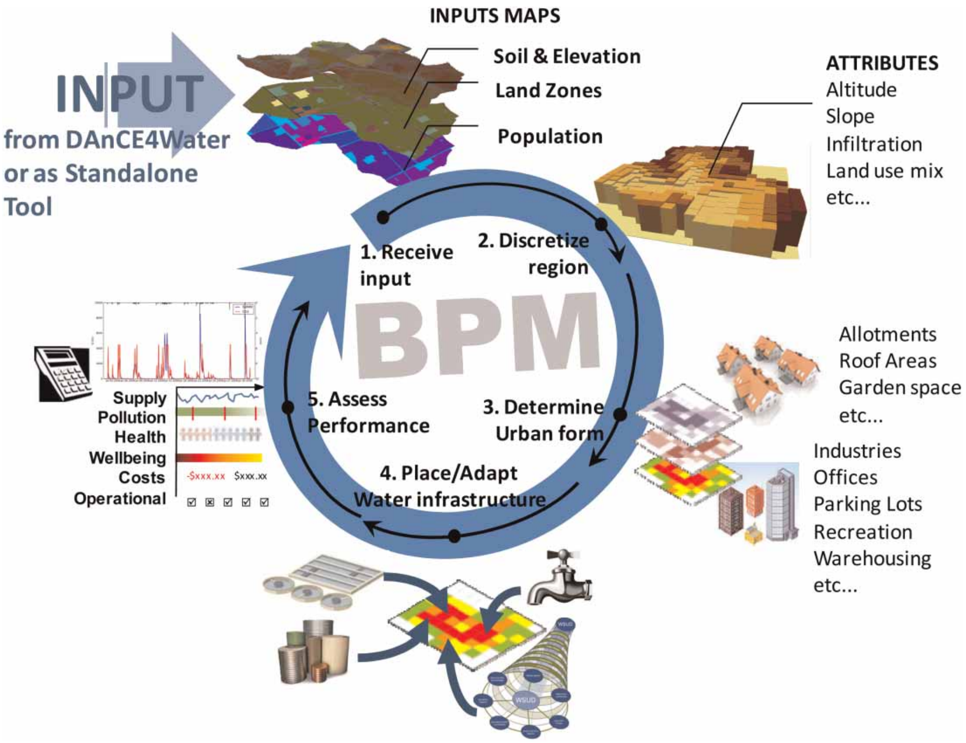

Figure 1 | Overview of DAnCE4Water's Biophysical Module.

typical values derived from WSUD guidelines (Melbourne Water 2005), but can also be calculated if existing soil properties are available and spatially explicit. The study area, Scotchman's Creek catchment, is primarily a residential catchment with local pockets of other land uses including larger areas of open space. The catchment has undergone significant urban development of varying urban densities. As such, it is ideal for investigating different scales of water management and of a reasonable spatial area for testing model algorithms. Note that this study will only focus on water management in residential districts. Adjacent open spaces will serve as hosts for neighbourhood and sub-basin-scale water management. Implementations at this scale can include flood water storage and/or a water quality control for parts or all of the upstream catchment.

Spatial representation algorithms

Geographic input data (10 m × 10 m rasters) are processed and aggregated to a coarse grid of *building blocks* (resolution determined by modelling aims, user preference and computational capacity – ranging from 100 × 100 m to 1 km × 1 km). Each *block* contains detailed information about the local area of the catchment and can be regarded as a neighbourhood within the region. This information is added to or updated in each *block* as the simulation progresses, from areal proportions of different *land use*, *total population* and *average soil infiltration rate* (calculated for each individual *block* from finer resolution input raster data) to *total residential allotments*, *local street widths*, *water demand* or *number of streetscape WSUD systems* (in later steps). The architectural detail of the urban form is necessary for the planning of WSUD systems and is obtained from rules set by planning schemes and building regulations for the region – here the *Planning Provisions for Victoria* (DPCD 2006). An insight into how these rules are incorporated into an algorithm is provided in a previous study (Bach *et al.* 2011). The algorithm for residential districts has since been improved and tested on real-world data. To account for the variability of urban forms across the study area, some planning parameters (e.g. site setbacks, nature strip and footpath widths) are specified as ranges (as prescribed by local planning documents) and are stochastically varied from *block* to *block*.

The model also relates each individual *block* to its neighbours and the larger drainage basin by delineating flow paths using a well-known method (O'Callaghan & Mark 1984). This information provides detail about the sub-basin structure of the input map, which sets the boundary conditions for decentralised system design and water management targets. The algorithm is applied at the *block* resolution under the assumptions that: (1) drainage infrastructure is generally constructed to follow the natural contours; and (2) the level of accuracy obtained from this method is sufficient for the high level water infrastructure planning exercise that follows (i.e. for assessing flood mitigation solutions, for example, this method needs to be replaced with a more accurate method for determining flow directions based on finer resolution digital elevation data).

Planning of WSUD options

The WSUD planning algorithm is illustrated in Figure 2 for a single catchment (or 'basin' as is referred to in the model) consisting of 18 *blocks*. The whole process comprises three steps: (1) Assess WSUD Opportunities; (2) Construct Basin Management Options; and (3) Evaluate and Rank Options. WSUD implementation is considered at four different scales: within each *block*, lot-, street- and neighbourhood-scale systems are assessed and larger systems at the sub-basin scale may service several *blocks* along the same flow path. Design is based upon simple WSUD system sizing curves (which are fed into the model and can be easily replaced) and can either be sourced from published literature or created using tools such as the Model for Urban Stormwater Improvement Conceptualisation (MUSIC) (eWater 2011) and local climate data. Design also considers space for system maintenance, setbacks, safety and amenity prescribed by state-of-the-art.

Assessment of opportunities for WSUD implementation

Assessment of possible opportunities is first carried out separately for all four scales. Available space (from spatial algorithms) is compared with required system size to meet required water management targets (e.g. pollution or hydrological targets) using the local design curves. A user-defined number of system types are checked at each scale within each *block* and each *sub-basin* of *blocks* (illustrated in Figure 2). Lot-scale systems are designed to service all onsite impervious area of the lot. However, the degree of lot scale implementation within a block is allowed to vary between none and all houses in the block (at a user-defined increment). Remaining untreated areas are considered at the next immediate scale (i.e. streetscape, etc.). Systems considered at street, neighbourhood and sub-basin scales service varying portions of the remaining untreated impervious area (e.g. 0 to 100% at user-defined increments). Sub-basin scale design uses information on flow directions (red arrows in Figure 2) to identify all upstream *blocks*

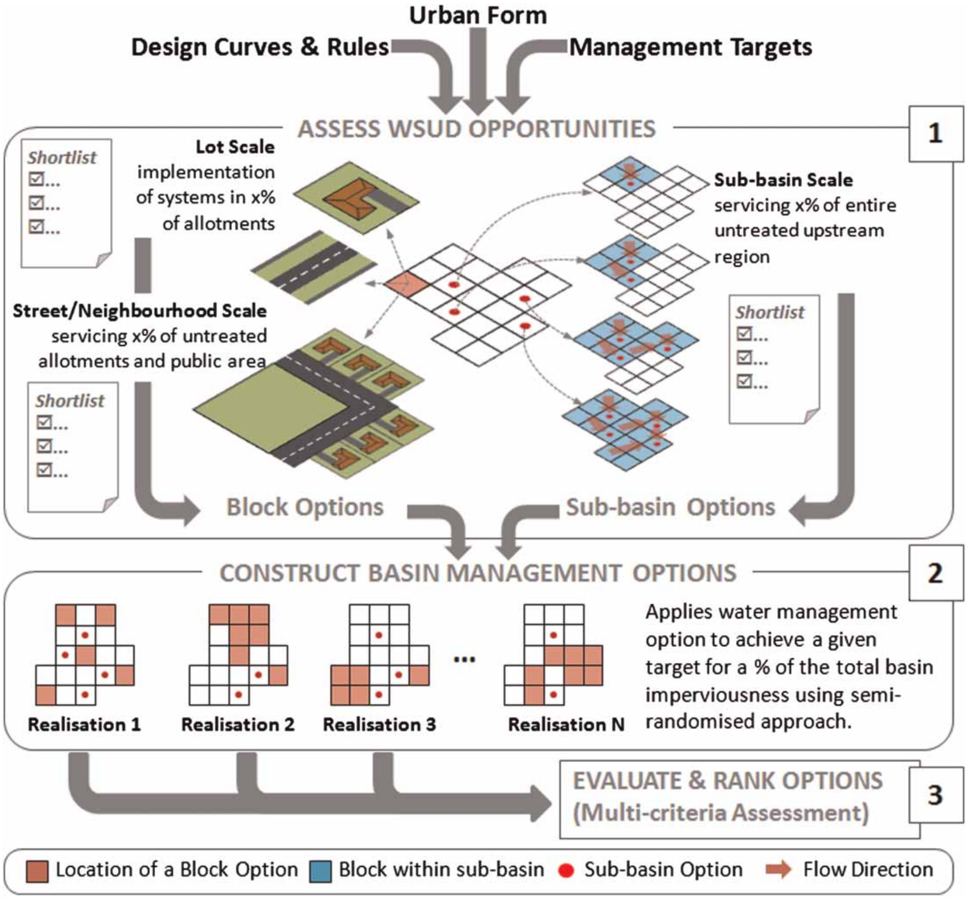

Figure 2 | Planning algorithm for assessing decentralised water management options in a single basin.

(blue-shaded *blocks* in Figure 2) and their untreated impervious areas draining to possible design locations (red dots in Figure 2). The outcome of this first step is a wide range of system designs to treat different amounts of impervious areas in the sub-basin at different scales. This step creates a list of possible system designs for each scale.

Construction of WSUD options

Using the substantial list of management options established previously, the second step (Construction of WSUD Options) uses a partly systematic, partly randomised approach to piece together combinations of systems into management options for each basin in the region. Lot-, street- and neighbourhood-scale opportunities are first systematically combined to provide a myriad of *within-block* options (a maximum of one technology is used at each scale in each configuration). Each of these local options is scored using a multi-criteria assessment framework (explained in the next section). All scored options are sorted into distinct bins representing the overall degree of local treatment they provide. The top scoring 5% of options in each bin are retained while the rest are discarded, leaving a reduced number of highly effective local management options.

The randomised approach is used to construct possible system configurations for the entire basin ('basin management options' in Figure 2). It assumes that each design has an equal likelihood of being selected, but adjusts the list of possible system designs if necessary to prevent 'over-design' for the entire basin (by removing options that treat more impervious area than what has been left over by other systems further upstream). Starting at the most upstream location, a possible sub-basin-scale system ('none' is also an option) is randomly selected from the list of possible system designs. Top ranking *within-block* options (from randomly chosen bins) are subsequently chosen to infill the additional untreated impervious area ('none' once again being an option). The list of possibilities at each position in the basin is adjusted to account for the already serviced areas. The algorithm proceeds to the downstream-most location of the basin. The process is repeated 1,000 times to produce an array of different options that will treat 'none' to 'all' of the impervious area in the catchment.

Evaluation and choice of WSUD options

To decide upon a final water management option, the model runs the second pass multi-criteria assessment for each combination to narrow down the 1,000 designs to a few candidates. Four criteria are considered: technical, environmental, economic and social. In each criterion, individual technologies are ranked to a number of metrics on a scale from 0 to 5 depending upon expert opinion. A scoring matrix was adapted from the DayWater Multi-Criteria Comparator (Ellis *et al.* 2008) for the selected WSUD technologies (bioretention scores were derived from a combination of similar systems). The framework is one of few existing multi-criteria assessments specific to WSUD technologies and is informed by expert opinion. Future work will develop a unique framework that more closely relates to the contexts, in which DAnCE4Water will be used and that will incorporate more recent knowledge about the perceptions of WSUD.

The multi-criteria scores apply only to individual technologies, and these have to be combined to determine an overall score for each management option. As such, sub-scores are weighted according to the imperviousness that each system serves. These are added to determine criterion and total scores using a weighted-sum model (Triantaphyllou 2000). The final options are reduced to a number of top-ranked alternatives (here the Top Ten). In a dynamic DAnCE4Water simulation, one of these 10 options is chosen based on weighted probabilities for implementation at the current time period. For the current study, the variability of these 10 options is explored.

Simulation scenarios and sensitivity testing

The planning algorithm was tested on Scotchman's Creek Catchment (Figure 3), which is a rather typical 1,000 ha residential area of Melbourne (average imperviousness of approx. 40%). Pollution management targets for system design were set to meet Total Suspended Solids, Total Nitrogen and Total Phosphorus load reductions of 80, 30 and 30% respectively. Table 1 summarises five different types of WSUD technologies (biofilters/bioretention, infiltration systems, ponds/basins, swales and surface wetlands) featured at different spatial scales in the simulation, their maximum allowable size (to prevent unrealistic design outcomes) and their criteria sub-scores for the scoring matrix used. When calculating the total score, each sub-score is weighted against its criterion weight. The different weightings for the four criteria are user-defined and should reflect their relative importance in the opinion of the users or stakeholders on a scale from 1 (least important) to 10 (most important). For simplicity, this study assumes equal weighting among criteria.

The model outputs a spreadsheet containing details of a complete water management strategy (i.e. location, system size, scale, etc.) for each of the top ranked options. In

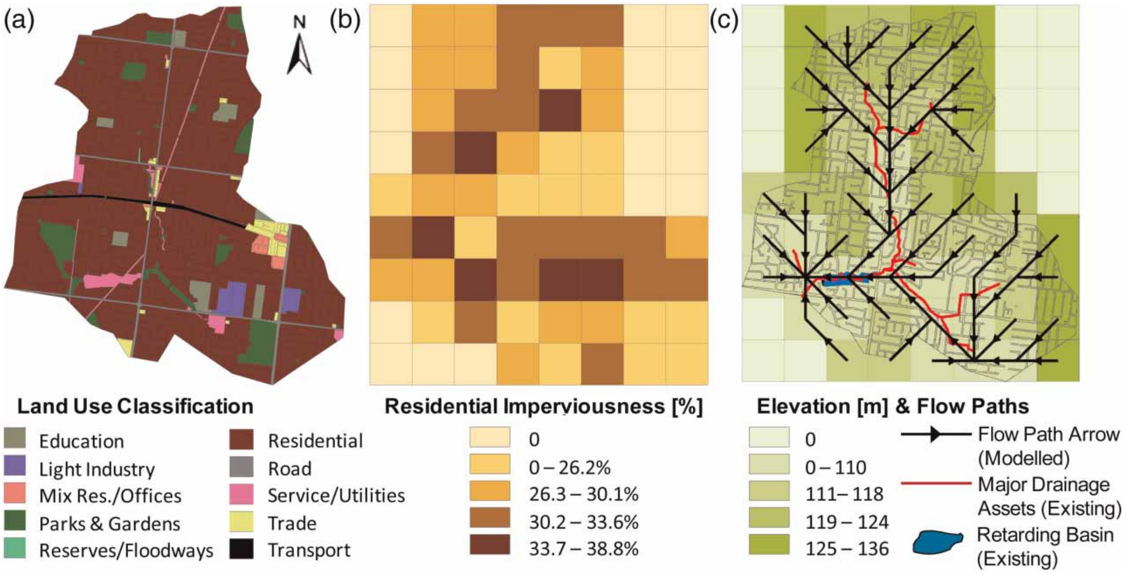

Figure 3 | Scotchman's Creek Catchment simulation for 500 m building block size, (a) land use input data, (b) residential total imperviousness and (c) elevation showing modelled flow paths and actual major drainage assets.

Table 1 | Chosen scales for WSUD technologies, maximum areas for design and criteria sub-scores

	Spatial Scales[a]					Un-weighted Criteria Sub-scores[b]			
Technology	**L**	**S**	**N**	**SB**	**Max. System Area [m^2]**	**Technical**	**Environ.**	**Economic**	**Social**
Biofilters/Bioretentions (BF)	✓	✓	✓	✓	5,000	3.60	3.60	4.50	3.50
Infiltration Systems (IS)	✓	✓	✓	–	5,000	2.80	3.00	2.50	2.50
Ponds & Basins (PB)	–	–	✓	✓	10,000	3.40	2.60	3.50	3.50
Swales (SW)[c]	–	✓	–	–	600	3.00	3.80	4.00	2.75
Surface Wetlands (WSUR)	–	–	✓	✓	10,000	3.40	3.20	2.50	4.00

[a] *L* = Lot, *S* = Street, *N* = Neighbourhood, SB = Sub-basin.

[b] The scores range from 0 to 5 and represent the average score across all metrics in that criteria group.

[c] Swale implementation is also limited by a minimum nature strip width requirement of 2 m.

order to assess not only this large volume of results in an efficient manner but also the sensitivity of different model parameters, a metric that could provide an overview of water management in the catchment was required. 'Utilisation' of each technology type (e.g. bioretention, surface wetlands, etc.) was defined as the impervious area that it treats relative to the total catchment impervious area treated by WSUD for that option and is calculated as:

$$U_i = \frac{A_{i\_\text{treated}}}{\sum_i^n A_{i\_\text{treated}}} \qquad (1)$$

U_i is the utilisation for a particular technology i [ ], A_{i_treated} is the total impervious area treated by technology i among n technologies in the catchment [m^2].

Discussion will focus on the sensitivity of model outputs for variations in: (1) size of blocks, using 500 m and 1 km resolutions; and (2) the increment set for application of systems at each scale using increments of 10, 25 and 50% (e.g. if the increment is 25%, this means that a WSUD system can either be 'implemented in' or 'implemented to treat' 25, 50, 75, or 100% of 'houses' or 'all impervious area', respectively). Note that for each of the three increment options tested (10, 25, 50%) the same respective increment value was used across all scales (i.e. if the increment was 25%, each scale assessed WSUD systems that address 10, 20, 30, up to 100% of the impervious area and houses).

RESULTS AND DISCUSSION

Spatial data output

The model writes the information contained in each building block as a shape file output, which can be viewed in any geographic information system (GIS) program. Figures 3(b) and 3(c) show maps of imperviousness and elevation with flow paths for Scotchman's Creek catchment for 500 m × 500 m building block size. The original data are shown alongside (in Figure 3(a)). Areas of high residential imperviousness are primarily located in the southern parts of the catchment. Drainage paths merge along the road running through the centre of the catchment (see Figure 3(c)) and progress towards the south-western region ('Parks & Garden' and 'Services & Utility' land uses patches in Figure 3(a)). The output was validated by comparing modelled flow paths with a map of the major drainage infrastructure obtained from the water authority. Despite applying a simple method to a coarse resolution of 500 m × 500 m, both modelled and actual flow directions were similar.

WSUD options and utilisation of various technology types

It was found that systems were quite spatially distributed across the Scotchman's Creek catchment with the highest concentration near the outlet in the south. The present state of Scotchman's Creek catchment features several lot-scale systems as well as a series of larger wetlands in its southern region. Although these were not taken into the count in the model, outputs suggested placing ponds and wetlands in these same areas in most of its options, thereby supporting the algorithm's validity. The northern, upstream-most region of the catchment was also found to contain very low to no implementation of technologies, possibly due to its fairly dense urban form.

'Utilisation' for each of the five technology types was calculated for the top 10 options out of the 1,000 realisations in each scenario and plotted against user-defined increment and block size (see Figure 4). For example, the model

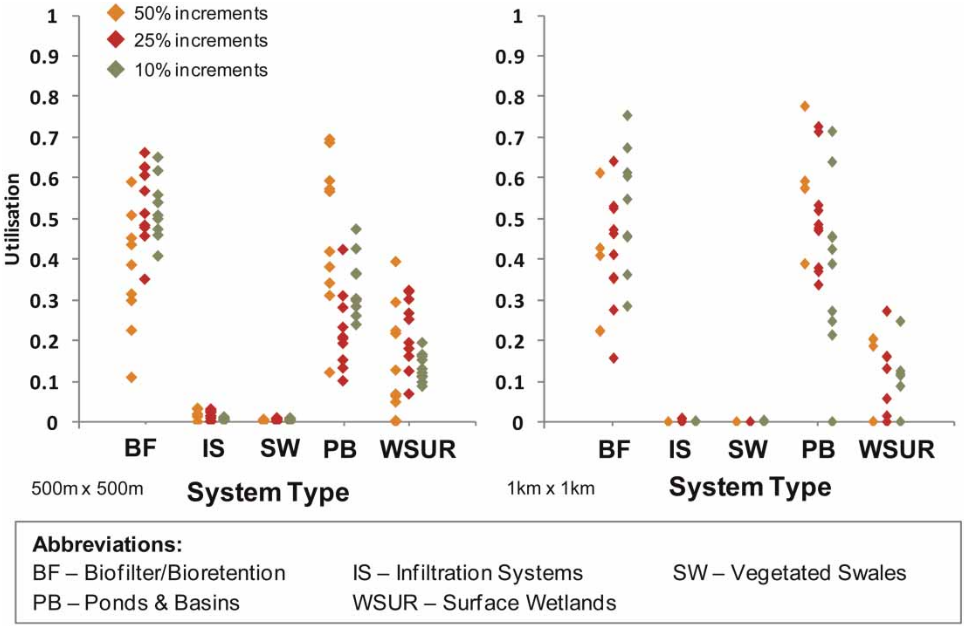

Figure 4 | Utilisation of different WSUD technologies in top-ranking options for Scotchman's Creek Catchment (at 10, 25 and 50% user-defined increments for 500 m × 500 m and 1 km × 1 km blocks).

suggests that 35 to 65% of the total impervious area to be treated can be serviced using bioretention systems (BF) when modelling the catchment using 500 m blocks and 25% increments. This spread, however, changes to 15 to 75% when modelling the catchment using 1 km blocks at the same increment, indicating sensitivity to block size. Additionally, Table 2 presents mean value and coefficient of variation of utilisation for each case. This metric was found to be useful as it provided an efficient way of condensing the large volume of model output and assessing sensitivity of key model parameters.

Trends shown in Figure 4 reveal that BF are relatively widespread in most of the top-ranking options (utilisation averaging around the 50% mark). This is partly due to the system's advantage of a small footprint, great flexibility and its widespread preference, evidenced in the four evaluation criteria. The use of infiltration (IS) was limited due to the additional nature strip width requirements (the planning algorithm varies this stochastically between 1 m and 3 m) and poor infiltration capacities in certain areas of the catchment, respectively. Swales (SW) were also not particularly prominent due to their large size in comparison

Table 2 | Mean and coefficient of variation of 'Utilisation' for each WSUD technology at different increments and block sizes

		500 m × 500 m Block Size			1000 m × 1000 m Block Size		
System		**50% incr.**	**25% incr.**	**10% incr.**	**50% incr.**	**25% incr.**	**10% incr.**
Biofilters/Bioretention	*μ*	0.370	0.536	0.525	0.379	0.418	0.550
	CV	37.8%	18.1%	13.8%	40.5%	33.4%	29.0%
Infiltration Systems	*μ*	0.016	0.016	0.070	0	0.003	0
	CV	83.2%	65.9%	43.4%	0.0%	155.1%	269.2%
Swales	*M*	0.002	0.005	0.004	0	0	0
	CV	133.9%	78.1%	78.3%	0.0%	0.0%	288.8%
Ponds & Basins	*μ*	0.468	0.224	0.331	0.562	0.500	0.380
	CV	39.4%	42.3%	22.5%	19.6%	26.5%	54.9%
Surface Wetlands	*M*	0.144	0.219	0.133	0.059	0.079	0.069
	CV	92.3%	39.7%	25.5%	160.6%	120.6%	121.4%

to wetlands (WSUR) and bioretention (for the same performance target). Utilisation values of ponds (PB) and surface wetlands were relatively similar, the latter being smaller. This is partly due to space constraints within the catchment with only several local pockets of open space available.

The influences of block size and increment choice on 'utilisation' are judged as quite sensitive. A larger block size and larger increment lead to significant variation in results. Using 1,000 m building blocks produces higher values of CV. A coarser resolution might not accurately reflect the variability in urban form (as the planning algorithm only runs at the block-level) and consequently overshadows otherwise opportunistic systems such as infiltration and swales (see Figure 4). This suggests that the 1,000 m resolution might be too coarse to produce any useful results for this particular size of case study. Further work is needed to determine the optimal block size for a given catchment size that should include modelling of the performance of the WSUD options. Selecting a block size that is too fine (e.g. 100 m), however, will significantly increase the simulation times, while output trends are likely not to differ from what can already be observed for 500 m blocks in Figure 4 (unless they become more pronounced). Nevertheless, further testing is required to understand the trade-offs between block size, computational efficiency and the quality of model results.

Decreases in CV and scatter of points are observed with decreasing increment (Table 2). This convergence can possibly be interpreted as a typical or recommended level of 'utilisation' for each system type if they are to be used in conjunction with each other in this particular catchment. Not surprisingly, smaller increments lead to a larger variety of designs from which the model can sample when developing management options. It should be noted that the scenarios presented in Table 2 were for options that meet the given target for the entire basin (e.g. a case of a new development where WSUD is regulated and the given pollution targets must be met for the entire development). The distribution of systems across the catchment will become far more limited if the targets are to be met at only a fraction of the basin (e.g. a retrofitting case).

Implications for planning and model limitations

The paper has presented only a small snapshot of a substantial collection of output provided by the model. Each combination output file is spatially explicit in that it indicates systems implemented in each building block at each scale. Values of 'utilisation' presented earlier provide a general indication of feasibility of different water management technologies for the catchment. Scotchman's Creek catchment's urban form, for example, favours larger end-of-pipe solutions with an array of lot-scale systems widely used upstream. Among these solutions, bioretention and ponds/basins are the two predominant types of systems used. Translation of such results into practical measures, however, will require a greater number of simulations as well as a participatory setting where inputs are provided by various experts. Furthermore, the model currently disregards existing systems implemented in the catchment. Even though there were similarities between actual and modelled implementation, the model will need to account for what already exists in the catchment if it is to be applied in a more realistic context.

CONCLUSION

This study has presented the initial results of a planning algorithm for decentralised water management options that forms part of DAnCE4Water's Biophysical Module. The approach considers a variety of scales and technologies and uses detailed urban planning information to determine urban form and opportunities for various water management measures. A semi-randomised approach is used to piece together a plethora of management options, each of which is evaluated in a multi-criteria context. Results, expressed in terms of 'utilisation', indicate differing levels of opportunities for five different systems for managing water quality in residential areas and open spaces of Scotchman's Creek catchment. The catchment's urban form was found to favour larger end-of-pipe solutions near its outlet as opposed to a more distributed configuration. The model's validity was shown by comparing actual systems and suggested options by the model algorithm.

Future work on the model will also encompass algorithms for non-residential zones and the addition of more decentralised technologies (for wastewater and water supply) to the existing toolbox. The model will also need to simulate implementation and modification of decentralised systems into the dynamic urban environment as the city, legislation and social paradigms change. These dynamics will also be one of the key connections between the biophysical and social systems in DAnCE4Water. Extensive testing on Scotchman's Creek catchment will continue, entailing the possibility of a second case study in future.

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