Modelling Interactions Between Lot-Scale Decentralised Water Infrastructure and Urban Form – a Case Study on Infiltration Systems

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Abstract Modelling the design and implementation of urban water infrastructure (particularly decentralised systems) for strategic planning and policymaking requires detailed information of the spatial environment and quantitative knowledge of social preferences. Currently available models, however, mostly use land use, population and impervious cover data without much regard for detailed urban form or society. This study develops an algorithm for determining urban form from minimal spatial data input by incorporating local planning regulations. The interaction between urban form and implementation of lot-scale infiltration systems under different social, biophysical and climate constraints is then investigated, firstly by looking at how this varies in different residential land uses and subsequently in a case study of a typical Melbourne residential subdivision of mixed land uses. Feasibility of infiltration and its downstream impact (runoff volume, frequency and pollution) were assessed for a range of social preferences (quantified as allowable garden space) and climate scenarios (30 % increase/decrease in rainfall and evapotranspiration). Performance indicators were determined through long-term simulation with the MUSIC software. Results show how different biophysical, planning, social and climate conditions affect infiltration feasibility as well as system performance. High infiltrating soils, for example, allow smaller, well-performing and socially less-imposing systems. Low infiltrating soils lead to larger system sizes, occupy much of the allotment's garden space, but nevertheless provide the benefit of runoff frequency reduction. Overall, climate impact was not significant except for areas with poorly infiltrating soils. Joint consideration of social, planning, climate and water management aspects potentially allows more efficient policymaking, as an array of system configurations can be tested against different multi-faceted scenarios. Such models can help facilitate better participatory planning and policymaking.

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1 Introduction

Pollution of natural waterways, degradation of downstream ecology, threats to a secure water supply and sanitation are examples of significant challenges posed by urbanisation, population growth and a changing climate (Vlachos and Braga 2001). Sustainable water management has evolved to embrace the inherent complexity of our water systems and manage multiple objectives in an integrated and interdisciplinary manner (Vlachos and Braga 2001; Mitchell 2004; Brown et al. 2009). Although adaptation to major challenges (e.g. climate change or urbanisation) has become a keyword in sustainable planning and policy-making, we still lack the knowledge and adequate tools to address how this should be accomplished. The use of models can allow rigorous testing or 'exploration' of different opportunities as well as facilitate participatory planning (see e.g. Bankes 1993; Goosen et al. 2007). Despite significant progress in integrated modelling, there are nevertheless many knowledge gaps within the interactions between the different urban water components (e.g. Rauch et al. 2002; Mitchell et al. 2007).

One particular example is the relationship between decentralised water management, urban planning and social impact. Water Sensitive Urban Design (WSUD) such as infiltration measures or constructed wetlands, has not only been advocated as an effective mitigation tool against the negative effects of urbanisation on downstream ecosystems, but also for supporting stormwater harvesting, delivering micro-climate benefits and amenity values to our cities (Wong et al. 2012) as well as a way of bringing back urban water to the community (Brown et al. 2009). WSUD design focuses on employing best management practices to treat impervious area runoff. Their design and implementation consider setback (i.e. required additional free space around the system to allow for maintenance access or protect nearby building foundations), local soil and groundwater requirements (Melbourne Water 2005). Apart from biophysical considerations, implementation of any technology must additionally consider social and institutional aspects, including the responsibilities assigned to maintaining and operating these systems once in place (Harvey et al. 2009) as well as people's perception and preference of these systems (i.e. degrees to which they recognise the multiple benefits of these systems). The latter has been subject of recent research (Dobbie and Green 2013), which demonstrated how human perception of such systems differs from their technical design objectives. Considering this issue was encouraged if communication and better management of these assets is to be achieved (Dobbie and Green 2013). Whilst the technical components of WSUD technologies are frequently considered in models such as MUSIC (eWater 2011), SWMM (Rossman 2004) and City Water Balance (Last 2010), little attention is given to planning, urban design and social aspects. As such, there is limited understanding on interactions between water infrastructure, urban form, people preference, all of which limit our capacity to build informative models for planning and policymaking (in particular for decentralised water infrastructure).

Integrating these aspects into our models is difficult as existing tools do not feature adequate spatial information about the urban form (seen here as the appearance of the urban environment, considering street widths, lot sizes, frontage, roof and garden areas) and demographics in catchments. Information is needed on how the public is organised within the existing urban environment (e.g. housing arrangements, recreation space, existing amenity) if their preferences can be taken into account. Yet, spatial representation lacks emphasis in models, despite a well-developed understanding of the environmental impact of

different urban forms and patterns (Alberti 1999; Pauleit and Duhme 2000; Stone 2004; Liu et al. 2012). At the city scale, Alberti (1999) reviewed how urban patterns (e.g. centralisation of a city or density) influence a diversity of environmental factors (e.g. energy, climate, air pollution, water pollution, urban heat islands), suggesting the need for more empirical studies to refine this knowledge. Such a study can be found in Pauleit and Duhme (2000), who conducted detailed spatial analysis of an urban area in Munich to assess the impact on local hydrology. Their analysis showed how different covers and urban unit types (e.g. building types, construction sites, and fields) resulted in differing opportunities for reducing stormwater runoff (through infiltration or rainwater harvesting). Using this detailed quantitative output, detrimental land covers (e.g. roads, multi-story blocks) could be located and mitigation strategies designed. Liu et al. (2012) show how impervious fraction and land use are insufficient for accurately predicting environmental impact and designing appropriate treatment systems. They highlight the need to consider more detailed urban form. Stone (2004) addresses this by illustrating the variability of imperviousness in different residential forms, governed by specific planning constraints. Overall, the consensus is that environmental quality and performance differ across urban forms/patterns and that these should be more actively considered in modelling (Liu et al. 2012) and management (Alberti 1999). Unfortunately, such detail, although required for the design and implementation of WSUD systems, is not readily available in our existing urban water models despite being crucial for assessing feasibility of alternative technological solutions.

Modelling studies frequently use basic characteristics (e.g. land use/land cover distribution, population density) to describe the urban environment (e.g. Arnold and Gibbons 1996; Ravagnani et al. 2009; Ty et al. 2012). These are useful in assessing basic interactions between water management and the environment, but are limiting when attempting to simulate effects of adaptation strategies. Some studies extend this by investigating relationships between landscape metrics (e.g. landscape fragmentation, diversity and the descriptive statistics related to these) and environmental impact (Amiri and Nakane 2009; Schwarz 2010). These, however, are often unable to capture unique local features in the spatial environment, which are crucial to planning water infrastructure at a range of different scales. In an effort to improve detail in spatial representation, impervious fraction has additionally been considered, quantified through empirical relationships with land use/land cover (Arnold and Gibbons 1996; Ravagnani et al. 2009; Sitzenfrei et al. 2010). Ravagnani et al. (2009) acknowledge that although fairly accurate estimates of impervious cover can be obtained using existing empirical relationships, a greater source of inaccuracy in their assessment was the absence of more detailed information about the urban environment (e.g. connectivity of contributing impervious areas). Liu et al. (2012), show that solely using impervious cover and land use as indicators for water management can be misleading and that more detailed urban form needs to be taken into account if better results are to be obtained. In short, the current lack of detail in representing urban form in water systems modelling limits accurate modelling of local-scale processes (e.g. infrastructure placement in local streets or houses), which influence the global picture of the urban environment.

In light of the key research gaps that have been identified above, a study was designed with the aim of developing a model that simulates the interactions between urban form, people's preferences, and the planning of WSUD. This aim will be addressed by achieving two objectives:

- Objective 1: To develop a numerical model for characterising urban form, as well as planning (designing and placing) and assessing WSUD systems to meet required stormwater management targets;

- • Objective 2: To test the above model and explore interactions between urban form, people's preference and WSUD design for:

  - a) number of homogeneous residential parcels (e.g. low to medium density residential land use);
  - b) a sub-division block with mixed residential land uses.

The proposed model accomplishes detailed spatial representation of urban form using minimal data inputs and quantitatively defines people's preferences, thereby allowing planners to explore possible design strategies or policies. We intend to apply this model to an entire city (using spatially explicit data that can be represented as a grid of sub-regions or city 'blocks') and link it with well-known water system models. However, for the convenience of this understanding the methods, typical templates of residential urban forms and a simple case study of a typical residential sub-division of Melbourne, Australia will be used (Objective 2). The concepts are demonstrated using infiltration systems at the lot scale to manage stormwater runoff under different social, biophysical and climate scenarios only. However, the model is being extended to other decentralised stormwater infrastructure (e.g. raintanks, wetlands, bioretention, etc.) and other spatial scales such as the streetscape (i.e. the area beyond the lot comprising nature strips, footpath and local streets) and broader neighbourhood (encompassing local parks and larger open spaces).

2 Materials and Methods

2.1 Proposed Model for Urban Form and WSUD Planning

Figure 1 provides an overview of the general concept, which comprises three key steps to transform a detailed geographic map of biophysical and demographic data into a conceptual representation of urban form with possible water infrastructure:

- • Step 1: Characterising residential urban form
- • Step 2: Assessing opportunities for WSUD
- • Step 3: Aggregating information for further analysis

2.1.1 Step 1. Characterising Residential Urban Form

In this step, geographic information (land-use, population, soil type) and locally sourced land regulations are converted into characteristics which describe the urban form. The concept builds upon knowledge from Stone (2004), who investigates the relationship between local land regulations and residential imperviousness. Land regulations or 'planning rules' provide basic geometric and architectural design restrictions that are influenced by neighbourhood character and regional policies (Gurran 2011). They provide a set of parameters that can be used to determine urban form (exactly or at least within a range of numbers) down to the lot scale and can be user-defined to suit specific urban areas.

Firstly, the 'city' is subdivided into a number of square 'blocks' of a defined size and land use mix (defined by the user according to the size of the case study and input data). Each block is characterised by a number of 'parcels', which, in this example, contain residential allotments, roads, nature strips and footpaths. The number of dwellings in the block is defined by a density metric derived from the population map (dwelling or population density). As no information about quantity and size of parcels in a block is provided, the model assumes that each land use class is a long rectangular parcel of 100 m depth bounded
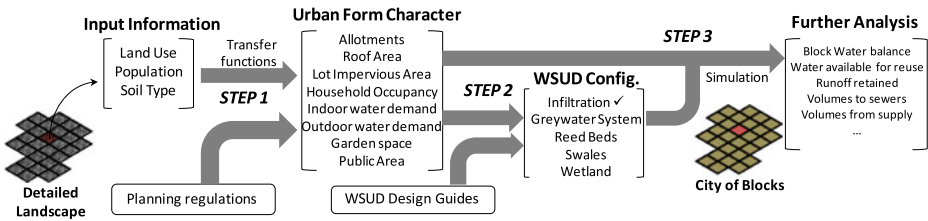
Fig. 1 General urban form and water infrastructure planning modelling process

by frontage ('Residential Parcel' in Fig. 2). Total parcel area of the land use is subdivided into number of allotments (using population and density data) and allotment frontage (road lane, nature strip and footpath).

To calculate detailed information, we use the input set of 'planning rules', such as those for Metropolitan Melbourne presented in Table 1 (left column). Within a parcel, all allotments are modelled as identical. The typology of a fully-/semi- detached dwelling is adopted ('Residential Allotment' in Fig. 2). Setback rules, roof area, on-site parking and other descriptors listed in Table 1 are applied to a single lot. The representation of allotment driveways (public and private) is similar to the method presented by Stone (2004) (Fig. 2). Building footprint is defined by occupancy and floor-space requirement, the latter of which can be sourced from local census data (e.g. 84 m^2/person for Melbourne, Table 1).

Once the geometry has been defined, water-related parameters (e.g. imperviousness, connectivity of impervious area to drainage) are determined. For simplicity, all impervious areas are assumed to be effective (meaning they all contribute to runoff during rainfall), which is considered a "worst-case" scenario approach when sizing WSUD systems. Total allotment impervious area therefore is calculated as the sum of roof, driveway, and patio areas.

2.1.2 Step 2. Assessing Opportunities for WSUD Placement

Once the 'blocks' are adequately characterised, data on different land covers and other characteristics are used to assess the feasibility of different WSUD options ('WSUD Config' in Fig. 1). For example, the design and placement of an infiltration system considers not only local soil conditions (available from input map of soil type), hydrology and catchment imperviousness, but also setback distances from nearby structures and available space required to achieve best practice, as per local technical guidelines (Table 1, right). In a similar manner, constructed wetland design focuses not only on required surface area for treatment, but also local soil conditions, distance from groundwater table and a buffer area for landscaping and safety around their perimeter. Based on user-defined targets for best management practice, the surface area of a WSUD technology (as a percentage of the catchment's impervious area) is determined from sizing curves (or design lookup tables) already available to practice; in Australian practice every region has sizing curves for WSUD design that are based on prescribed load reduction targets for solids and nutrients (e.g. Victorian Stormwater Committee 2006; Queensland Government 2010). However, if unavailable, the sizing curves that relate performance of WSUD systems to their size can be created using detailed modelling software such as SWMM (Rossman 2004) or MUSIC (eWater 2011). The total system footprint (surface area and additional space requirements, for landscaping etc.), is then calculated. For the system to be feasible at the lot scale, there needs to be enough available surface area (garden space) for the system taking into account:
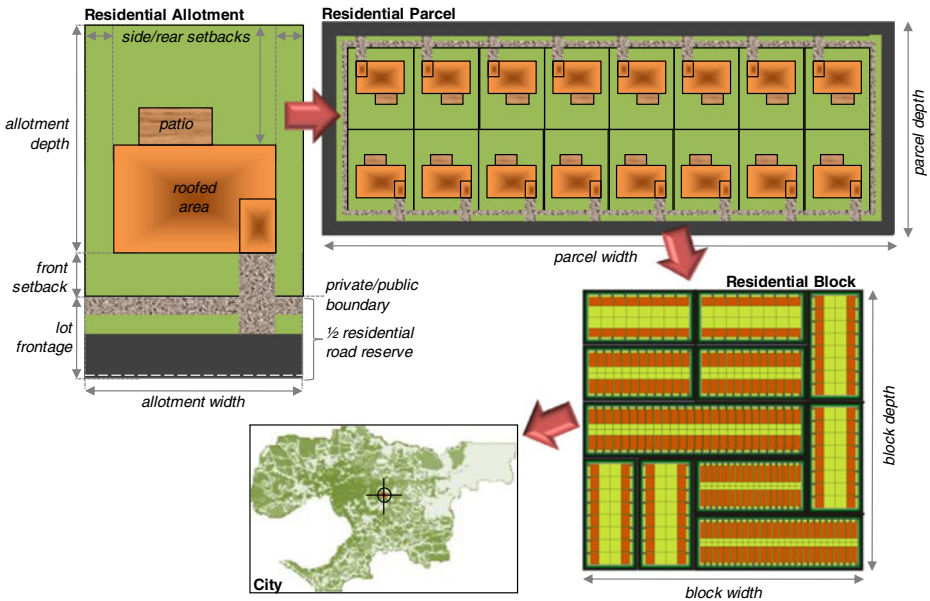
Fig. 2 Representing residential urban form at different spatial scales

Table 1 Melbourne urban planning rules (left) and infiltration system design input parameter values (right)

Allotment and streetscape planning parameters*		Infiltration system design*	
Description	Value	Soil type	Design requirements
Maximum site impervious cover	80 %		
Front setback distance	4 m	Sandy soil:	0.4 % surface area[**],
Side/Rear setback distance	1 m	(360 mm/hr)	1 m setback dist.[***]
Number of carports	1		
Garage included	YES	Sandy clay:	2.0 % surface area[**],
Minimum driveway width	2.6 m	(36 mm/hr)	2 m setback dist.[***]
Patio area	2 m^2		
Average floor space per person	84 m^2	Medium clay:	6.4 % surface area[**],
Front road lane width	5 m	(3.6 mm/hr)	4 m setback dist.[***]
Nature strip width	3 m		
Footpath width	2 m		
Driveway access width	2.6 m		

* Planning information obtained from: (DPCD 2006; Victorian Building Commission 2006), WSUD design information obtained from: (Melbourne Water 2005), average floor space per person obtained from Australian Census Data (ABS 2012)

**Systems surface area expressed as percentage of catchment impervious area. Requirement corresponds to achieving best practice of retaining at least 90 % of lot runoff; system has a 1 m depth with media porosity of 0.35

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

(1) additional space requirements (setbacks or buffers) and (2) the proportion of garden that residents are willing to devote to this practice. If both conditions are met, the model implements the WSUD system in every lot of that residential parcel. The algorithm allows for introduction of other similar feasibility criteria specified by the user (e.g. economic factors, proximity to groundwater table, etc.).

2.1.3 Step 3. Aggregating Information for Further Analysis

The final step aggregates information from all land parcels to the block level and prepares data for consequent WSUD performance assessment, using available modelling tools such as MUSIC (eWater 2011) or SWMM (Rossman 2004). This step is important for two reasons: (1) it prepares the data in a way that allows for efficient long-term performance simulation and (2) by aggregating information across all spatial scales; the model can be easily linked with other simulation software. At present the model prepares data for easy integration with the Australian software MUSIC.

To avoid modelling each individual allotment and each individual infiltration system, we assessed the feasibility of simplifying a MUSIC performance assessment model of the block. All impervious areas that are 'served' by some form of WSUD system (i.e. their runoff is treated by the system) were grouped separately from those that are not. Similarly, the individual WSUD technologies within each lot are aggregated to one single WSUD system of equivalent size (one for each type e.g. total area of infiltration systems, wetlands, bioretention present in the block). This simplified, aggregated model comprising served and unserved impervious areas and an equivalent WSUD technology was compared with a non-aggregated model in MUSIC where each lot and WSUD system is modelled individually. The difference between simplified and fine-grained models only showed minimal discrepancies of at most 2 % in total runoff volumes. This exercise showed that loss of fine-scale information through aggregation generally has minimal influence on the accuracy of global system performance, particularly because the model uses a conceptualised representation of the catchment. It allows us to run more efficient and rigorous performance analyses using longer time series data to better understand the behaviour of our decentralised water management strategy, which is what the following case studies adopt.

2.2 Model Testing for Placement of Infiltration Systems in Melbourne, Australia

Melbourne planning rules, listed in Table 1-left, were derived from several Australian urban planning documents (e.g. Victorian Planning Provisions, Building Regulations, and Building Code of Australia). The average floor space per person was obtained directly from census data from the Australian Bureau of Statistics (ABS 2012). Although a range of values were identified for each parameter (e.g. front setbacks could vary between 4 m and 9 m), one consistent set was chosen for all residential land uses. It was preferable to avoid dealing with possible parameter sensitivity issues at this stage as the number of interactions being investigated is already significant.

For this study, infiltration systems were selected, since their interaction with given planning regulations is significant. Their size requirements (surface areas expressed in terms of the impervious catchment area), as well as other design rules (presented in Table 1) were sourced from local WSUD guidelines (Melbourne Water 2005). The model was initially tested by placing infiltration systems in parcels of homogeneous land use and subsequently into a mixed land use block, as explained below.

2.2.1 Infiltration Systems and Homogeneous Land Use Parcels

This section addresses the first Objective 2(a), which has two purposes: testing and validating the urban form algorithm and exploring the interactions between people preference (i.e. allowed use of garden space) and technical feasibility of infiltration systems, individual residential land uses (i.e. densities) and local soil conditions. The outputs of the model comprised performance curves of the infiltration systems efficiency (percent of runoff reduction) as function of the system size (expressed as a percentage of available garden space). These were obtained by simulating the hydrologic performance of different infiltration system sizes under various climates (using a 10-year rainfall time-series) for different catchment configurations defined by the residential land uses and soil types.

Three net densities were selected: Very Low Density (VLDR, 11 dwellings per hectare), Low Density (LDR, 17 dw/ha) and Medium Density (MDR, 23dw/ha), each having average occupancies of 4, 3 and 2.5 persons per dwelling, respectively. Note that 'density' is an ambiguous term (Bamford 2007) and that these values do not follow any pre-defined framework, but rather were chosen arbitrarily to reflect a range of significantly different dwelling arrangements found in Melbourne. Planning and WSUD design information for infiltration systems from Table 1 (with exception of the required system size as these were varied to produce enough data for the performance curves) were applied to a typical allotment for each of these three densities on three different soil types: sandy (360 mm/hr), sandy clay (36 mm/hr) and medium clay (3.6 mm/hr). Infiltration rate influences design requirements for infiltration measures including setbacks required from the system to nearby foundations and pavements (Melbourne Water 2005). The required system area therefore comprises the effective surface area responsible for infiltrating stormwater plus additional space to meet setback requirements.

Deriving infiltration system performance required long-term hydrologic simulation. As such, data on Melbourne's climate over 10 years from 1959 to 1969 was sourced at a 6-minute time step (annual average rainfall – 614 mm/yr). These years were chosen as their average represents the long term average rainfall in Melbourne (annual rainfall of 655 mm). The MUSIC software was used to set up a model from the aggregated spatial information (as discussed in Step 3). Recommended rainfall-runoff and water quality parameters for Melbourne (eWater 2011) were used. Other parameters were selected based on resulting infiltration system design, urban surface cover across the residential parcel and local soil conditions.

Three climate conditions were tested: base case (no change in climate), a wetter future climate (+30 % rainfall, -30 % evapotranspiration) and a drier future climate (-30 % rainfall, +30 % evapotranspiration). The authors acknowledge that this approach is very simplistic, and thus does not capture the intricate dynamics illustrated in the climate change literature. In fact, using existing scaling techniques that rely on statistical probabilities (Arnbjerg-Nielsen 2011) or deriving data sets through downscaling of global and regional climate models (see, e.g. Ty et al. 2012) have resulted in climate patterns that better represent predicted changes. However, as climate was not the focal point of this investigation, the simplistic method was determined as sufficiently suitable for making basic inferences about potential impacts and assessing interactions with other factors.

2.2.2 Infiltration Systems and Mixed Residential Land Use Block

Objective 2(b) is addressed in this case study by testing the model in a more realistic and larger spatial context. A semi-hypothetical case study (Fig. 3) was developed based on a typical residential subdivision found in Melbourne. The area is a 500 m×500 m block

containing residential parcels of three different population densities, as specified in Fig. 3 (20 %, 48 %, and 32 % of the block containing VLDR, LDR and LDR land uses, respectively). Once again, planning regulations and WSUD design parameters from Table 1 were applied (this time using the specified size required for infiltration systems to retain 90 % runoff).

The same biophysical conditions (three soil types) were simulated for four different household preferences towards implementation of infiltration systems: residents were willing to allow 15 %, 30 %, 50 % and 80 % of their garden space (i.e. of the available space for WSUD on each individual allotment for each residential land use) for the construction of infiltration systems. The hydrological performance of these 12 combinations is subsequently assessed in the similar way as for the homogeneous land use case using MUSIC for the three climate conditions: base case, wet future, dry future (resulting in a total of 36 scenarios). In aggregating the information for the mixed land-use case, the whole residential block was subdivided into two urban sub-catchments: areas treated by infiltration systems and remaining untreated areas. Additionally, an equivalent pre-developed forested catchment model (100 % pervious) of the same residential block area was set up to better assess urbanization and mitigation impacts.

Performance of the system in this case study was expressed in terms of three indicator groups:

(1) total annual pollutant loads for total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP),
(2) total annual runoff volumes, and
(3) runoff frequency, as well as *retention capacity* (RC), both calculated on a daily time step. RC (expressed here as a percentage instead of fraction) is defined as (Walsh et al. 2009):

$$RC = \left[1 - \max\left(\frac{R_t - R_n}{R_u - R_n}, 0 \right) \right] \times 100\% \qquad (1)$$

where:

R_t annual runoff frequency from treated surfaces [days/yr]
R_n annual runoff frequency from surfaces in a pre-developed state (i.e. forested catchment) [days/yr]
R_u annual runoff frequency from untreated surfaces [days/yr]

The choice of TSS, TN and TP is based on best management practices in Australia, which places primary focus on these pollutants (Wong 2005). RC is a metric that relates pre-development runoff frequency with post-development runoff frequency before and after the application of treatment measures (Walsh et al. 2009) and ranges from zero (no improvement) to 100 % (pre-developed state). Walsh et al. (2009) interpret retention capacities of unity (i.e. 100 %) as an impervious surface from which runoff reaches downstream environments no more frequently than the pre-urban state. It is useful for illustrating the effects of infiltration measures in this example, but cannot exceed a value of one as it will mean that the frequency of runoff is lower than pre-developed state (i.e. we are not allowing enough water into the receiving stream). As such, runoff frequencies of treated areas were additionally calculated to indicate the degree to which receiving environments downstream are starved because too much water is being retained.
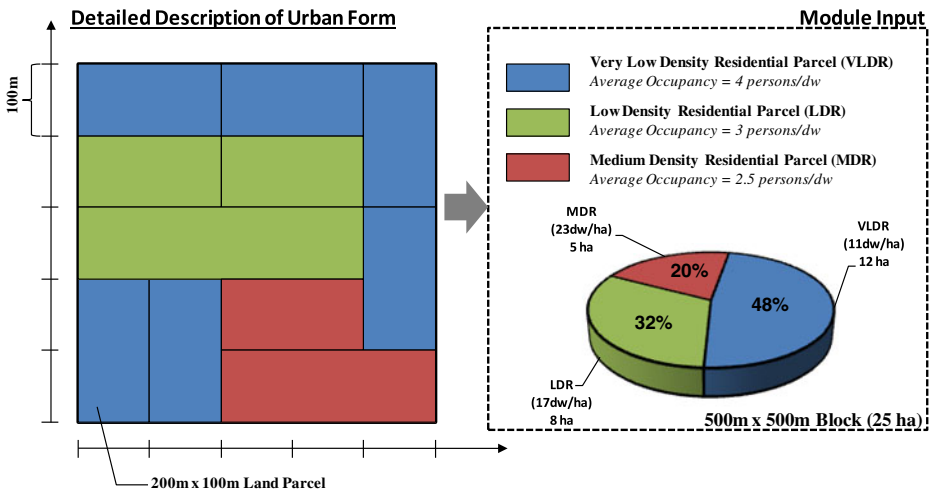
Fig. 3 Layout of Semi-hypothetical residential case study block

3 Results &Discussion

3.1 Infiltration Systems and Homogeneous Land-Use Parcels

Table 2 presents a breakdown of urban form on a typical allotment in each residential density, calculated from the modelling results of the first case study. Total impervious fractions for these three densities vary from as low as 42 % to almost 60 %. One would expect to observe this trend since higher densities generally should result in higher imperviousness due to the higher levels of building construction. Despite these simplistic results, one advantage of this modelling approach is the additional site cover breakdown acquired. The model not only reports on key parameters required for water management, but also on how their values arise. For instance, it can be seen that the primary determinant of the impervious fraction is the floor space, which was calculated based on dwelling occupancy. For this configuration of planning rules and the chosen densities, roof areas are seen as the key contributor to impervious areas at the lot scale in all cases, suggesting a possible focus for water managers in selecting effective management strategies. The contribution to impervious area by other site elements on the other hand is minimal.

Even though results from the model appear realistic, values of impervious fractions should nevertheless be compared with literature (see Table 3 for a summary of values). In their modelling of storage behaviour relationships of recycling schemes, Mitchell et al. (2005) used impervious fractions of 42 % and 70 % for 'traditional' sub-urban and 'high density' residential land uses in Melbourne, respectively. Modelled values are within this range. Stone's (2004) mean impervious fraction measured around 32 % (with increasing trend) for lot sizes less than 1,000 m^2 – the same trend is observed in the model results. The Melbourne Water guidelines (Melbourne Water 2010) specify ranges of impervious fraction for different residential zones based allotment size. Results are consistent (e.g. 40–0 % imperviousness suggested for 800–4,000 m^2 allotments, comparable to the modelled value of 50 % and 50–70 % imperviousness for 500–800 m^2 allotments compared to 56 %). These comparisons are, however, made cautiously as Stone (2004) shows that allotment size is not necessarily the strongest determinant for impervious cover. The model under predicts a value of 62 % for medium density residential, whereas guidelines suggest 70 % to 80 % (lot size of

Table 2 Summary of urban form results for different residential densities

Net Density*	VLDR (11dw/ha)	LDR (17dw/ha)	MDR (23dw/ha)
Average allotment size [m^2]	908	589	436
Floor space (excluding garage) [m^2]	336	252	210
Patio and driveway areas [m^2]	12	12	12
On-site parking area (carport + garage) [m^2]	34	34	34
Impervious area for typical allotment [m^2]	382	298	256
Available lot space for WSUD [m^2]	526	291	180
Average allotment imperviousness	42 %	51 %	59 %
Residential parcel imperviousness	50 %	56 %	62 %

*The equivalent gross densities for these three values are 8dw/ha for VLDR, 12dw/ha for LDR and 17dw/ha for MDR and were estimated based on a residential parcel of 200 m×100 m (as shown in Fig. 2) using the frontage information specified in Table 1

350–500 m^2). This discrepancy is explained by the difference in selected occupancy compared with what most likely occurs in MDR zones in Melbourne. This is, however, an exercise of model calibration to specific urban forms around Melbourne and is therefore not of direct interest in this study. Overall, the similarity of modelled impervious areas show that the model algorithm can provide realistic results.

Performance curves of infiltration system, as function of the required system footprint (given as a percentage of available lot space), are shown in Fig. 4. Whilst the surface area of infiltration measures designed to meet best management practices does not significantly increase with stricter targets, the additional space required to integrate them into the urban form will often limit their application (seen by the much larger surface area requirements for low infiltrating soils and higher densities). Even though this space is usually available on the lot scale, it can occupy up to more than half of its garden space (e.g. in the case of medium clay soil for 17dw/ha or sandy clay soil for 23dw/ha). Although WSUD systems can be regarded as multi-functional assets (providing amenity as well as water services), it is perceived that the utilised land that could otherwise be used for recreation, buildings and other forms of infrastructure, is lost. From a planner's perspective, the implementation represents a trade-off between achieving stormwater management at the expense of afore-mentioned uses for that land. From the local residents' perspective, this represents a sacrifice of personal space and time (in cases where the household is responsible for maintaining the system) for aiding the broader environment and community. These two perspectives are often difficult to quantitatively define. As such, introduction of a household preference variable in this study can aid modellers in representing the degree to which people are accepting WSUD systems. A recent study on the receptivity of green infrastructure showed how such preferences (potentially quantifiable through household surveys) can be incorporated into models of biophysical processes (Sun and Hall 2013).

The decline or possible improvement of system performance under different climatic conditions is another consideration. Curves for favourable conditions in Fig. 4 (i.e. 360 mm/hr sandy soil or 11dw/ha low density), for example, show that performance can vary as much as ±10 % depending on likely future climate, although the rainfall inputs varied ±30 %. This estimate is naturally fraught in much uncertainty due to the method used to model this climate as well as the large uncertainties generally encountered in predicting climate change impacts (e.g. Ashley et al. 2005; Wilby et al. 2006). Therefore it can be concluded that results are not highly sensitive to possible changes in climate.

Table 3 Summary of literature values of impervious frakctions for residential land uses

Source	Impervious fraction	Description
Mitchell et al. (2005)	42 %	Traditional sub-urban residential
	70 %	Traditional high-density residential
Stone (2004)	32 %	Mean value for lot sizes <1,000 m^2
Melbourne Water (2010)	40 % – 50 %	For 800 m^2 – 4,000 m^2 lot sizes
	50 % – 70 %	For 500 m^2 – 800 m^2 lot sizes
	70 % – 80 %	For 350 m^2 – 500 m^2 lot sizes

Infiltration systems generally present themselves as a feasible opportunity for lot-scale stormwater management, taking up as little as <10 % of available lot space even in moderate density (17dw/ha) and sandy clay (36 mm/hr) environments. Future upgrades of these systems to comply with more stringent legislation (e.g. an increase in required runoff retention) or wetter climate would only require minimal additional space of approximately less than 5 %. For worse soil conditions or greater densities, feasibility declines as expected. Whilst, technically, the system should still comply with legislation, they are likely to encounter social, economic and other objections beyond the scope of this modelling exercise.

3.2 Infiltration Systems and Mixed Residential Land Use Block: Planning Results

Applying the urban form algorithm to the mixed land use block case study resulted in 298 allotments in total of which 104 were VLDR, 106 LDR, and 88 MDR land use. As the previous application showed, it is possible to implement these systems in all blocks, as long as there is sufficient space (based on planning and design rules and people preferences). This would treat a total impervious area of 9.4 ha, which represents 70 % of all impervious surfaces (13.5 ha) in the residential block; the remaining 30 % being comprised of non-allotment-related impervious areas (roads, footpaths, etc.) which are not considered for treatment in this example.

However, for some combinations of soil type and household preference, not all lots were capable of incorporating an infiltration system; the results for these scenarios are shown in Table 4. Lower soil hydraulic conductivities combined and higher imperviousness levels requires larger infiltration system footprints and, hence, implementation could be limited depending on the available space (i.e. land-use) and residents' preferences (i.e. how much of the available open space of their gardens can be allocated to treatment systems). An order of magnitude decrease in soil infiltration rate, for example, results in up to four times the required system size due to setback requirements. As such, it can be speculated that additional space requirements for infiltration systems will very likely be more significant than for other technologies, such as wetlands (where a smaller clearance/buffer zone around the water body must be established) or raintanks (where foundation must be adequate to carry the imposed load and enough headroom and access must be provided to access the tank for maintenance).

The results demonstrate the feasibility of infiltration systems in a mixed residential land use block, highlighting the challenges encountered in applying uniform rules and legislation across a diversity of urban forms. For example, residents in higher density areas may be required to provide more garden space as a penalty for the increased imperviousness or conversely disconnect the existing impervious areas from downstream drainage. Alternatively, an offset scheme similar to an existing example in Melbourne (RossRakesh et al. 2006) can be tested,
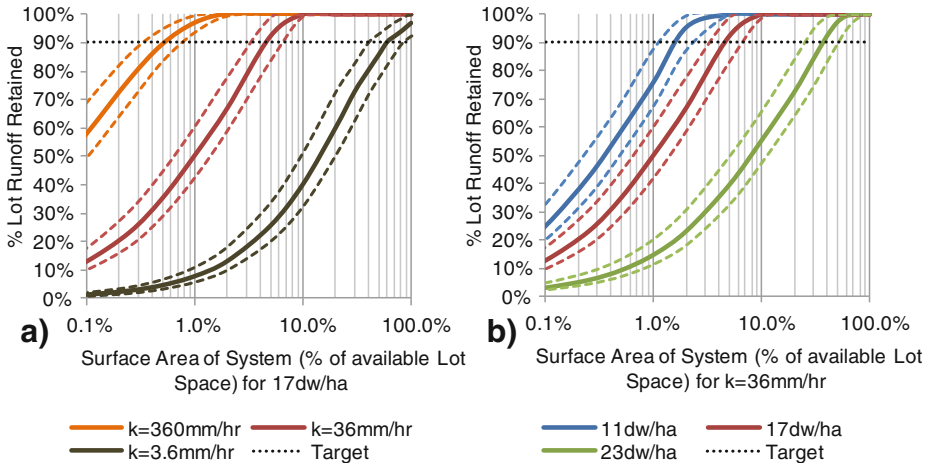
Fig. 4 Relationships between urban density, soil type and garden space required for infiltration systems: for Low Density Residential (LDR) development and all tested soil types (*left*), and sandy soils (k=36 mm/h) and all tested urban densities (*right*): *coloured dashed lines* show results for rainfall and evapotranspiration scaled inversely to each other by ±30 %, while the selected management target of 90 % lot runoff reduction is highlighted by the *black dotted line*

where targets for runoff reduction can be relaxed and instead an economic cost is imposed to allow for the construction of downstream mitigation measures.

3.3 Infiltration Systems and Mixed Residential Land Use Block: Performance Results

Total runoff volumes, TSS, TN and TP pollutant loads are shown in Figure for each scenario alongside the pre-developed level (orange bars indicate the changes due to the two climate scenarios). The levels of runoff and pollution resulting from no treatment are shown for the different climate scenario ('Untreated'lines). Some scenarios re-produced these levels of emission,as infiltration systems were not feasible for these cases and therefore could not improve existing hydrologic impact (e.g. 36 and 3.6 mm/hr soils on as little as 15 % maximum allowable garden space).

The overall improvement in runoff volume, if all allotments are implemented with infiltration, would meet the 90 % reduction target at the lot scale. However, as no measures were implemented at the street scale, the effects of streetscape imperviousness on runoff volumes, frequencies and water quality are still quite significant. For all cases on 360 mm/hr soil (where infiltration systems were implemented in every lot), reductions in runoff volumes are still three times the pre-development level (30ML/yr over 10ML/yr) and pollutant loads are well above pre-development levels. Furthermore, even with implementation of infiltration systems, the beneficial effects could be cancelled by different future climate regimes. For example, the 36 mm/hr soil with 30 % available garden space scenario would produce flows and pollution equivalent to base climate untreated levels in a wetter climate (shown by the orange bar exceeding base untreated levels), despite implementation of infiltration systems. At the same time, a drier future climate can contribute to further reduction of negative downstream impacts, maintaining pre-development flows and pollution closer to pre-climate change state. The cyclic nature of climate and the contrasting impact this simple simulated strategy exerts, highlights the need for dynamic policies that may change depending on the situation (e.g. water restrictions in Australia or ambient water quality standards in streams across Europe). The multi-faceted

Table 4 Resulting lot-scale water management plans for semi-hypothetical residential block under different scenarios

	Infiltration rate [mm/hr]	Maximum Allowable Garden Space			
		15 % Garden Space	30 % Garden Space	50 % Garden Space	80 % Garden Space
Residential densities, where infiltration systems are feasible	360	All	All	All	All
	36	–	VLDR	VLDR & LDR	All
	3.6	–	–	VLDR	VLDR & LDR
Number of allotments with infiltration systems installed*	360	298	298	298	298
	36	0	104	210	298
	3.6	0	0	104	210
Total Area of infiltration systems in block [m^2]	360	375.54	375.54	375.54	375.54
	36	0	794.85	1426.91	1877.71
	3.6	0	0	2543.52	4566.11
Catchment imperviousness served by infiltration systems**	360	69.7 %	69.7 %	69.7 %	69.7 %
	36	0	29.5 %	53.0 %	69.7 %
	3.6	0	0	29.5 %	53.0 %

* Total number of allotments in the block has been calculated as 298 divided as 104 lots in very low, 106 lots in low and 88 lots in medium density residential areas

** Total catchment area: 25 ha with a total impervious fraction of 53.9 %, served imperviousness is calculated as treated impervious area divided by total impervious area

interpretation of results from such modelling exercises can contribute to dynamic policy development.

The impacts of the tested WSUD measures on stormwater discharge frequency are presented in Table 5. Whilst total development/block runoff frequency did not change because street areas are left untreated, different degrees of alteration can be observed for treated areas (i.e. ignoring those areas which are not treated) under different scenarios. The minimum achievable reduction in runoff frequencies for treated areas ranged from 1.3 % up to 6.9 %, which is comparable to the pre-development level runoff frequencies (2 %). The decreasing trend in frequency with decrease in infiltration rate sounds counterintuitive, but is reasonably explained by the significantly larger infiltration system size in order to meet the 90 % runoff reduction target. These can readily capture more rainfall events– primarily because their larger ponding zone greatly increases storage capacity – and prevent frequent overflows (the main process contributing to the calculation of runoff frequency from treated areas). RC values are generally within desirable magnitudes in cases where treatment can be applied (Table 5). Values of 100 % for some cases on 36 mm/hr and all cases on 3.6 mm/hr soil, however, need to be scrutinized with actual runoff frequency data. In fact, runoff frequencies lower than pre-developed levels were calculated for cases on 3.6 mm/hr soil in Table 5, suggesting that some level of "overtreatment" is occurring.

Absolute differences in runoff frequencies illustrate contrasting behaviour among soil types. Climate impact appears more pronounced on areas with high runoff frequencies, whereas the effects are not as sensitive in areas with low runoff frequencies (seen by the smaller variations in RCs on medium clay soil). In relation to other performance indicators, however, relative change in runoff frequencies are very similar across values in Table 5. This low sensitivity in the results suggest that as long as there is implementation of systems in the catchment, a change in climate appears to have no significant impact on runoff frequency

(in contrast to runoff volumes and pollution in Fig. 5). Two factors can explain this behaviour. Firstly, existing implementation provides storage to capture small rainfall events even if they do not reduce total runoff volume by the required target. Secondly, the model used linearly-scaled climate data. This means that no change in rainfall pattern (i.e. intensities, dry weather periods) has occurred and as long as existing storage capacity is high enough, increased rainfall volumes are likely to be captured. It is possible that using a different data set to represent a change in climate might not yield the same result.

Preference of the residents to install infiltration systems is very important; significant improvements in overall performance appear to lie between the 30 % and 50 % thresholds of maximum allowable garden space, which leaves a reasonable amount of amenity space for home-owners, particularly in larger allotments.

3.4 Discussion of Overall Interactions and Implications to Practice

The analysis has shown that effectiveness of water management is heavily dependent on urban planning and people preference, biophysical conditions (e.g. soil characteristics) and climate. It is well known that increased system sizes are required to achieve management targets on poorly infiltrating soils. Comparatively, infiltration measures have proven to be more efficient and socially less imposing (i.e. footprint required) on sandy soils and lower densities, able to greatly reduce runoff and pollution loads even in wetter and drier future climates because of their greater implementation. Ultimately, any policy or design decision made with the aid of models would require a much greater variety of options to choose from and an evaluation based on multiple factors – the exploratory modelling approach (Bankes 1993). This model provides this opportunity by giving users the ability to explore alternatives of achieving high treatment efficiencies, either by simulating change in urban form through specific statutory planning controls, simulating change in people's preferences or through the interplay between these factors. As such, variable design objectives or location-specific policies can be tested across a large spatial extent to understand not only the local impacts of certain strategic decisions, but also the global picture.

Table 5 Runoff frequency and retention capacities of pre-developed, untreated and treated areas for semi-hypothetical residential block under different scenarios

| Climate scenario | Annual runoff frequencies | | | | Retention capacity – RC** | | |
| | Total block | Treated areas only* | | | | | |
		360 mm/hr	36 mm/hr	3.6 mm/hr	360 mm/hr	36 mm/hr	3.6 mm/hr
No scaling (Base Climate)	26.4 %	6.90 %	3.20 %	1.30 %	81.0 %	96.9 %	100 %
Wet (+30 % rain, -30 % evap.)	22.9 %	9.30 %	4.80 %	2.85 %	81.9 %	100 %	100 %
Dry (-30 % rain, +30 % evap.)	28.3 %	3.90 %	1.60 %	0.40 %	87.7 %	96.1 %	100 %

*Frequencies from treated areas are quoted. There was no change in total block runoff frequency because only lots were treated with infiltration measures. Streetscape areas were left untreated. Values were similar across all social scenarios (differing by ±0.1 %)

** Pre-developed runoff frequency was determined as 2 % of days for no climate scaling, 6 % of days for a 30 % increase in rain case and 0 % for the 30 % decrease in rain case
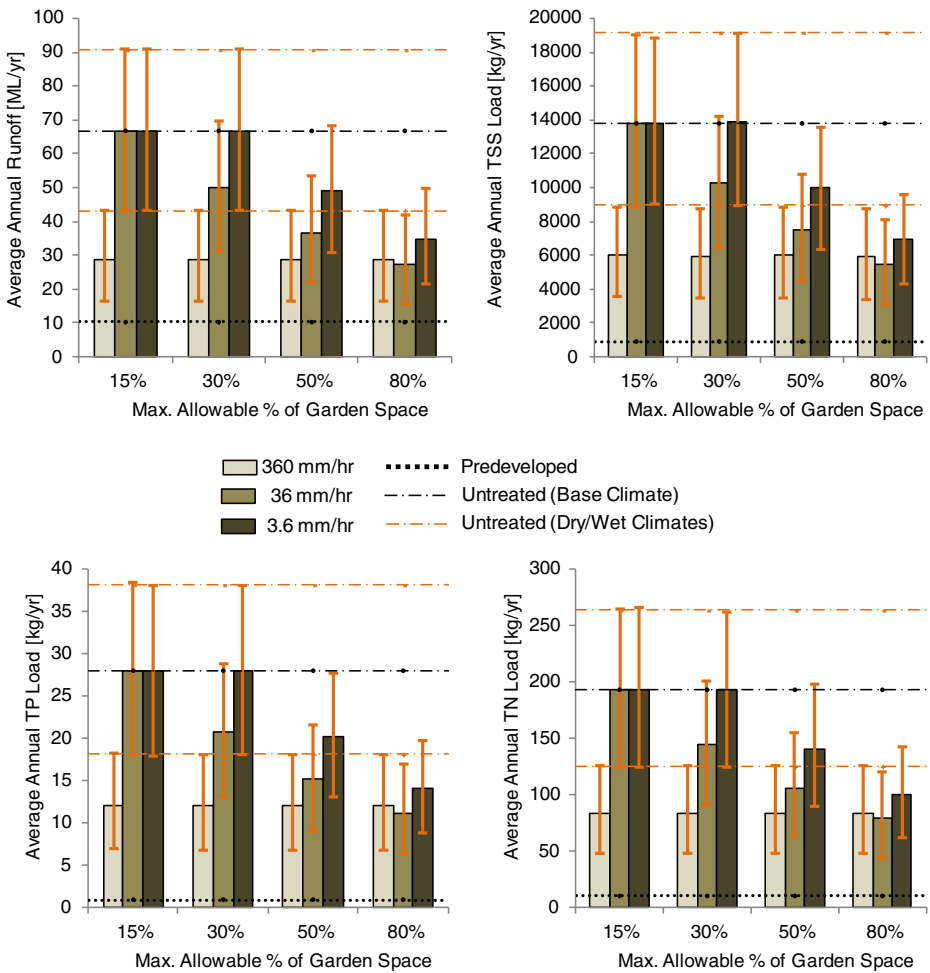
Fig. 5 Average annual runoff volumes, TSS, TP and TN pollutant loads for semi-hypothetical residential block under different scenarios compared with pre-developed and post-developed untreated states (orange bars show effects of climate change, upper bars for +30 % rain and -30 % evap. and lower bars for -30 % rain and +30 % evap. scenarios)

This study focussed on showcasing the methodology using just lot-scale infiltration measures in local dwellings, but the same method is generally applicable to other systems (e.g. wetlands, greywater tanks, bioretention), water management goals (e.g. pollution control or water recycling) and urban form typologies (e.g. high-density apartments, industrial estates, commercial shops). Additionally, a range of other social decision factors can be taken into account using this same framework (e.g. people's general preferences towards taking responsibility in managing local systems). The methodology can be applied to real-world data, but requires consideration of the variability in urban form. This variability is attributed to changes in land use controls through time, which have constrained development intensity both economically and aesthetically (Gurran 2011). The model can capture this if planning parameter values are stochastically and spatially varied (within representative ranges) across the simulated city. Finally, such a modelling exercise would greatly benefit

from a thoroughly prepared climate dataset that more accurately emulates predicted climate change impacts on the local conditions.

4 Conclusions

This investigation presented an algorithm for more detailed spatial representation of residential urban form for modelling planning and placement of WSUD and the interactions with social preferences and climate to be assessed. Key messages from the research show that:

- The use of planning rules in modelling urban form achieves more detailed spatial representation, allows for planning and implementation of WSUD and other water technologies to be modelled and can result in a richer understanding of environmental impact of different development types.
- Joint consideration of social, planning, climate and water management aspects can potentially allow more efficient policymaking as an array of system configurations and designs can be tested against different multi-faceted scenarios.
- The use of such modelling approaches in policy and decision-making can potentially improve communication between many stakeholders including the broader community.

The model produces a highly conceptualised and abstract representation of the urban environment and is not suited for detailed modelling of urban form. For developing planning strategies for local areas, however, the level of detail is seen as adequate and an improvement over existing approaches. Furthermore, the model uses parameters that can be informed by local legislation and data that is widely available and easily obtainable (e.g. land use, population, soil). Emergence of such models will enable users to explore a richer and greater number of planning scenarios.

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