

# Integrated modelling of stormwater treatment systems uptake

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## Abstract

Nature-based solutions provide a variety of benefits in growing cities, ranging from stormwater treatment to amenity provision such as aesthetics. However, the decision-making process involved in the installation of such green infrastructure is not straightforward, as much uncertainty around the location, size, costs and benefits impedes systematic decision-making. We developed a model to simulate decision rules used by local municipalities to install nature-based stormwater treatment systems, namely constructed wetlands, ponds/basins and raingardens. The model was used to test twenty-four scenarios of policy-making, by combining four asset selection, two location selection and three budget constraint decision rules. Based on the case study of a local municipality in Metropolitan Melbourne, Australia, the modelled uptake of stormwater treatment systems was compared with attributes of real-world systems for the simulation period. Results show that the actual budgeted funding is not reliable to predict

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systems' uptake and that policy-makers are more likely to plan expenditures based on installation costs. The model was able to replicate the cumulative treatment capacity and the location of systems. As such, it offers a novel approach to investigate the impact of using different decision rules to provide environmental services considering biophysical and economic factors.

*Keywords: agent-based modelling, cost-benefit analysis, exploratory modelling, urban water management, water infrastructure planning, water sensitive urban design*

## 1. Introduction

Nature-based solutions, also known as Water Sensitive Urban Design (WSUD) in Australia, Low Impact Development (LID) systems in the USA, or Sponge City technologies in China, have the potential to offset the negative impacts of urbanisation by providing a range of benefits, from stormwater treatment and harvesting to heat mitigation and recreational opportunities in a cost-effective and flexible way (Moore and Hunt 2012; Raymond et al. 2017). In the long term, this so-called 'green' infrastructure, is often more effective to enhance urban resilience than grey infrastructure (Dong et al. 2017). Consequently, environmental services and benefits provided by these solutions are increasingly considered and integrated into policy-making and urban planning guidelines (Woodruff and BenDor 2016; Nordin et al. 2017). However, many uncertainties remain regarding the decision-making underlying the installation of nature-based stormwater treatment solutions, such as the economic evaluation of environmental benefits, the various costs of systems over time, the most suitable location and types of systems needed to provide different services, etc. (Roy et al. 2008; O'Donnell et al. 2017).

Previous models focussed on the optimal design and locations of nature-based solutions to achieve better biophysical performance of the systems. These include EPA-SUSTAIN (Lee et al. 2012), UrbanBEATS (Bach et al. 2015), Soil and Water Assessment Tool (SWAT) (Mtibaa et

al. 2018) and other spatially explicit models (Zhang and Chui 2018). Although policy-makers may use decision support systems to inform their decision, they are unlikely to systematically follow the recommendations of such tools and make their decision solely based on biophysical performance of such solutions. A few other models have tested strategies that include economic variables. They usually focussed on the optimisation (using techniques such as genetic algorithms) of one or multiple benefits within a budget constraint (Chen et al. 2015). One limitation of these models is that they often assume perfect knowledge and decision-making capacity of the agencies. In practice, however, policy-makers may have limited knowledge on costs and benefits and a varying degree of commitment or capacity (Morison and Brown 2010). Therefore, practitioners tend to base their decisions on more accessible strategies, such as simple cost-effectiveness, cost-benefits analyses or multi-criteria decision analysis (MCDA) (Holz et al. 2004; Furlong et al. 2017a). Given the incomplete information available to practitioners, multiple stakeholders involved and the dynamic environment, the installation of stormwater treatment systems is complex. Such a complex problem can be investigated with an exploratory model (Bankes 1993; Rauch et al. 2017), in which the decision-making of stakeholders can be simulated autonomously considering this incomplete information.

Agent-based modelling offers a flexible approach to integrate socio-demographic dynamics with biophysical models and facilitates the exploration of the decision-making process, or decision rules (An 2012) in a bounded rational setting. Such models have been developed to explore the uptake of private technologies, such as water appliances (Chu et al. 2009; Galán et al. 2009) or rainwater tanks (Schwarz and Ernst 2009; Castonguay et al. 2018) in the water sector, energy-efficient vehicles (Querini and Benetto 2014; Silvia and Krause 2016) in the transport sector, and household-scale energy supply technologies (Sopha et al. 2013; Palmer et al. 2015) in the energy sector. With the exception of Montalto et al. (2013) and Lu et al. (2013), the simulation of

green infrastructure uptake has so far been overlooked and has yet to be compared to uptake in real-world cases.

Existing models mostly investigate the decisions of households and high-level policy-makers such as state government. Local government is seldom considered as an agent in such models, even though they are an important decision-maker in urban water sector and play an important role in the adoption of green infrastructure. In the Australian context, local governments, or city councils, are responsible for small-scale stormwater infrastructure, i.e., infrastructure servicing catchments of area less than 60 hectares (Eggleton et al. 2012). Similarly, municipalities are the main planning actors for stormwater management, green infrastructure adoption and the provision of environmental services in European countries (Ellis and Lundy 2016; Nordin et al. 2017) and the United States (Flynn and Davidson 2016; Woodruff and BenDor 2016).

Given the limitations of existing models in simulating the decision-making process of municipal councils for the uptake of nature-based solutions, the aim of this paper is to develop and apply an agent-based model that can simulate the uptake of decentralised WSUD assets for stormwater pollution management. The current version of the model investigates the placement of raingardens, sedimentation ponds and constructed wetlands, commonly installed in Australian cities to minimise the environmental impacts of urban development (Ahammed 2017; Kuller et al. 2018). With the application of the model, the specific objectives of the paper are to:

- Investigate four economic decision rules that could drive councils to install nature-based stormwater treatment technologies, using different budget constraints and technical spatial suitability; and
- Evaluate the performance of the model by comparing model results with attributes of existing systems in a council of the Melbourne metropolitan region on stormwater treatment capacity, the number of WSUD systems, and their location over the 2005-2012 period.



With this model, the paper addresses some of the knowledge gaps related to the decision-making of WSUD systems installation by exploring the role of engineering and economic rules in their adoption, and by evaluating the performance of the model against the actual data on WSUD adoption.

## 2. Model development

The model aims to investigate the decision-making process of policy-makers for the placement of WSUD technologies with biophysical (system design, location suitability, total nitrogen (TN) removal) and economic components (budget, system costs, economic value of TN removal). Socio-political considerations, which may impact on decision-making (Kuller et al. 2018) are outside the scope of this paper but could be added as additional factors of location suitability.

The model takes the form of a simplified agent-based model that focusses on the decision-making of one agent: the city or municipal council. City councils are responsible for small-scale stormwater infrastructure, i.e., infrastructure that services catchments of area less than 60 hectares (Eggleton et al. 2012), and therefore the model investigates the decision-making of this agent. This model is part of a tool (under development) that includes the simulation of the behaviour of other agents involved in urban water management, i.e., households, developers and state government (Castonguay et al. 2018).

### 2.1. Model structure

The model builds on two existing software: UrbanBEATS (Bach et al. 2015; Bach et al. 2018), which assesses technology selection, design and locations for different WSUD systems, and Dynamind (Urich et al. 2012; Urich and Rauch 2014), which tests decision rules and WSUD systems placement at parcel scale. Figure 1 shows the model flowchart across the two

environments. To explore different types of decision-making processes, several options, or decision rules, are customisable in the model including (see Section 2.3 for details):

- **Location selection rules (L):** The evaluation of land parcels is prioritised by the council agent according to design and location suitability of WSUD systems. Two different rules were tested (see Section 2.3.1 for details).
- **Budget measure rules (B):** Budget measures are defined as the different measures of funding allocated to the placement of WSUD systems. Three different measures of budget constraints were tested (see Section 2.3.2).
- **WSUD selection rules (S):** Decision rules are developed to select the most suitable WSUD system and size for each parcel. Our model explores four different combinations with the above **P** and **B** rules (see Section 2.3.3).

The agent, i.e., the city council, evaluates the suitability of parcels individually and decides whether or not to install which type and size of WSUD system. Once a system has been installed on a parcel, the attributes of the parcel (e.g. suitability and the proportion of catchment effective impervious area (EIA) that has been treated by a WSUD asset installed in the simulations) are updated for the next simulation step, in this case a year. The agent evaluates parcels until the annual budget has been exhausted. A description of the model following the Overview, Design concepts, and Details (ODD) protocol, based on Grimm et al. (2010), is presented in Supplementary data, Table S.1.

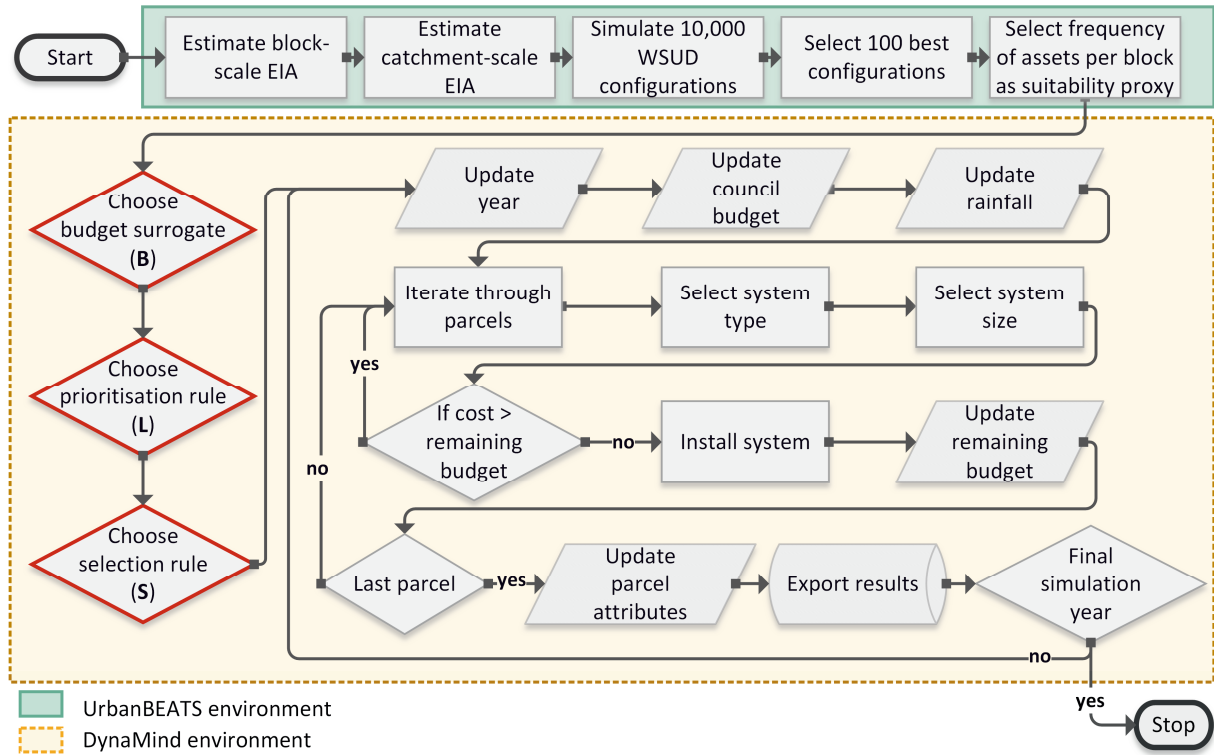


Figure 1: Flowchart of the model across UrbanBEATS and DynaMind environments. Red rhombus boxes show the configuration of location selection (L), budget measure (B) and selection rules (S).

## 2.2. Design and location suitability

The first part of the model assesses the design and location suitability for different WSUD systems using the UrbanBEATS software (Bach et al. 2015; Bach et al. 2018). This sub-model requires spatial inputs (rasters of elevation, soil types, population and zoning) at a 10 m resolution to enable the extraction of impervious area on grid cells or blocks of 500 m in resolution (for the complete description of the process of imperviousness estimation at block scale, please refer to Bach et al. (2018)). The effective impervious fraction, i.e., the fraction of total impervious surfaces that are directly connected to a drainage system, was set to 0.9 in UrbanBEATS, which represents the upper end value of the fraction range, based on MUSIC

Guidelines (Melbourne Water 2018). Water flow paths are created from elevation data to delineate sub-catchments using the D8 method on the coarse grid according to O'Callaghan and Mark (1984). This information is then used to estimate catchment-scale EIA, defined as the sum of EIA of all upstream blocks. The catchment EIA is later used to determine the size requirement for each WSUD asset to achieve a given target of pollution removal.

In the current model version, the types of systems assessed are raingardens, constructed wetlands and sedimentation ponds. To determine the suitability at block scale of each WSUD type, Monte Carlo simulations are run in UrbanBEATS to create 10 000 randomly generated layouts of WSUD assets, based on scales of treatment, objective of TN removal (in this case 45%) and available area, following the procedure described by Bach et al. (2013). The selected scales of treatment were street, neighbourhood and basin scales, whereas lot-scale systems were not considered as they are considered in the model as privately-owned systems, e.g., rainwater tanks. Out of the 10 000 layouts, the 100 best performing, i.e., the layouts that achieve the highest TN removal, were selected and the frequency of WSUD assets for each type of WSUD and each block was used as a proxy for suitability. This number of simulations was chosen to have a large enough sample (100 layouts) to differentiate frequencies of WSUD assets. Once block suitability for each system type and catchment EIA have been modelled, these attributes are written on parcels within each block (for the spatial representation of block- and catchment scale EIA, and the translation of attributes from blocks to parcels, see Figure S.2 in Supplementary data).

## 2.3. Decision rules

The decision-making process of the city council agent is based on decision rules that comprise a combination of location selection methods of parcels (**L**), budget measures (**B**) and selection rules for WSUD placement (**S**), as presented in Table 1.

### 2.3.1. Location selection

The suitability maps from UrbanBEATS simulations are used to inform the council agent on the best locations for the placement of systems. The agent has two options:

- **L1: Random location** – the agent evaluates parcels in a random order. In practice, decision-makers may not have access to information around the suitability of parcels and the location choice may rather be influenced by related projects, such as road or drainage works (Urrutiaguer et al. 2010) .
- **L2: Optimised location** – the agent evaluates parcels by order of decreasing technical and spatial suitability, as per UrbanBEATS results, assuming that the city council prioritises the most suitable system on most suitable parcels.

### 2.3.2. Budget measures

The model uses a budget constraint or ‘budget measure’ to limit the funding available for the investment on WSUD systems. The three budget measures are:

- **B1: Council allocation** – most city councils have a section on integrated water management or WSUD in their annual budgeted capital works. The allocated amount to WSUD in official annual budgets is therefore used as the first budget measure.
- **B2: Net installation costs** – the second budget measure consists of using the aggregated installation costs of observed systems for the simulation period. Funding for

WSUD systems, especially smaller and street-scale systems such as raingardens or swales, may originate from other budget sections, e.g. drainage or road works, or even from other organisations, e.g. water utility or state government.

- **B3: Net present costs** – the third measure consists of the sum of net present costs of actual systems for the simulation period, in order to better consider the variation in maintenance and operation costs across system types.

*Table 1: Decision rules (location selection, budget measures and WSUD system selection) used in the decision-making process of the city council agent in the simulations.*

Model scenario	Description
<b>Location selection (L)</b>	
L1: Random location	Parcels are selected randomly
L2: Optimised location	Parcels are prioritised according to their suitability as per UrbanBEATS results
<b>Budget measures (B)</b>	
B1: Council allocation	Allocation for capital works in annual council budgets for the simulation period
B2: Net installation costs	Aggregation of installation costs of actual systems for the simulation period
B3: Net present costs	Aggregation of net present costs of actual systems for the simulation period
<b>Selection rule for WSUD placement (S)</b>	
S1: Suitability	Select type and size of WSUD with highest suitability according to treatment target
S2: Suitability, maximising area	Select type and size of WSUD with highest suitability according to budget
S3: Benefit-cost ratio	Select type and size of WSUD with highest benefit-cost ratio according to treatment target
S4: Cost-effectiveness	Select type and size of WSUD with lowest cost according to treatment target

### 2.3.3. Selection rule for WSUD placement

City councils may use different decisions to invest in WSUD systems depending on a number of factors such as commitment, capacity and available knowledge (Morison and Brown 2011). The model tests four investment decision rules that can be applied by councils. For all decision rules, the agent first assesses the minimum requirements of land parcels before investing in a WSUD system, i.e., minimum area and land use for each type of system. The four decision rules are:

- **S1: Suitability** – the agent selects the most suitable system for the parcel, based on UrbanBEATS results. The size of the selected system is determined based on *Best Practice Environmental Management Guidelines* (BPEMG), i.e., aiming at 45% reduction in TN annual loads (Victorian Stormwater Committee 1999).
- **S2: Suitability, maximising area** – the agent selects the most suitable system for the parcel based on UrbanBEATS results but limits the size of the system based on the available budget. For this rule, the agent can consider systems that treat a greater area than that required by BPEMG. Policy-makers may prefer to invest on a project that exceeds BPEMG target rather than to divide the investment into multiple and less suitable projects (A. West, pers. comm., July 14, 2017).
- **S3: Benefit-cost ratio** – the agent selects the system that provides the highest net present value, by comparing the net present benefit of each system with their net present cost. Even though the use of benefit-cost ratio in decision-making is not systematic, it is occasionally used in practice to decide upon the most suitable WSUD system (Holz et al. 2004; Furlong et al. 2017b). The assessment of TN removal benefit and different costs are presented in the next section.
- **S4: Cost-effectiveness** – the agent selects the type of system that achieves the TN removal target at the lowest cost, to represent a decision-making based on cost-

effectiveness. Cost-effectiveness analysis facilitates the comparison of options to policy-makers without the need to evaluate their economic benefits (Hatt et al. 2006; Department of Planning and Local Government 2010) and is commonly used by municipal councils to compare projects (A. West, pers. comm., July 14, 2017).

#### 2.4. Benefit and costs assessment of WSUD systems

The quantity of TN removed  $TN_{p,w,y}$  [kg/year] by each type of WSUD system  $w$  for each parcel  $p$  and at year  $y$  is estimated using the Simple Method (Schueler 1987):

$$TN_{p,w,y} = R_{p,y} \times C \times A_{p,w} \quad (1)$$

where  $R_{p,y}$  is the annual runoff [m] at parcel  $p$  and at year  $y$ ,  $C$  is the estimated TN concentration [kg/m<sup>3</sup>] and  $A_{p,w}$  is the extent of catchment EIA [m<sup>2</sup>] treated by a WSUD system  $w$  for a given parcel  $p$ .  $C$  is estimated at 0.0021 kg/m<sup>3</sup> based on typical concentrations of urban runoff in Melbourne (eWater 2013).  $A_{p,w}$  is estimated from the area converted to a WSUD system on a parcel ( $a_{p,w}$ ) and the required area for each system type  $w$  to achieve the target of TN reduction  $TNR$ , in this case 45%, measured as the proportion of the impervious catchment and based on MUSIC simulations (Francey 2005). The result is then adjusted with a factor for each asset type  $w$  ( $AF_w$ ) to account for differences in hydrologic regions across the Melbourne metropolitan area (1.6, 1.1 and 1.2 for ponds, raingardens and wetlands, respectively) (Francey 2005):

$$A_{p,w} = \begin{cases} \frac{a_{p,w}}{0.0016e^{6.134 TNR}} AF_w, & w=\text{wetland} \\ \frac{a_{p,w}}{0.0011e^{8.249 TNR}} AF_w, & w=\text{raingarden} \\ \frac{a_{p,w}}{0.000661e^{7.578 TNR}} AF_w, & w=\text{pond} \end{cases} \quad (2)$$

The annual runoff ( $R_{p,y}$ ) is calculated as:



$$R_{p,y} = P_{p,y} \times F \times Rv_p \quad (3)$$

250 where  $P_{p,y}$  is the annual rainfall [m] for parcel  $p$  at year  $y$ ,  $F$  is the fraction of annual rainfall  
 251 events that produces runoff (estimated at 0.9 for urban areas based on Schueler (1987)) and  
 252  $Rv_p$  is the runoff coefficient for each parcel  $p$ . Schueler (1987) recommends the use of the  
 253 following equation to determine the runoff coefficient:

$$Rv = 0.05 + 0.9/la \quad (4)$$

254 where  $la$  is the impervious fraction. As the EIA was used to estimate the treated area  $A_{p,w}$ , i.e.,  
 255 assuming that all impervious areas are directly connected to a drainage system and impervious  
 256 fraction is equal to 1, the coefficient  $Rv_p$  was rounded to 1.  
 257 The monetary benefit of stormwater treatment  $B_{p,w,y}$  [AU\$] on a parcel  $p$  where a WSUD system  
 258  $w$  has been installed at year  $y$  is assessed considering a stormwater offset rate:

$$B_{p,w,y} = O_y \times TN_{p,w,y} \quad (5)$$

259 Where  $O_y$  is the stormwater offset rate, determined by the regional water utility based on the  
 260 “levelised costs” of constructed wetlands [AU\$/kg of TN removed], and set for year  $y$ . To  
 261 compare benefits and costs over time, the benefits are then discounted ( $NPB_{p,w,y}$ ) [AU\$] with a  
 262 discount factor  $d_{n,w}$  over the lifespan of each system  $t_w$ :

$$d_{n,w} = \forall n \in \{1, \dots, t_w\}: \frac{1}{1 + r^n} \quad (6)$$

$$NPB_{p,w,y} = \sum_{n=1}^{t_w} B_{p,w,y} \times d_{n,w} \quad (7)$$

The lifespan of each system type was taken from eWater (2013) but may vary widely depending on various factors such as adequate maintenance and renewal. Therefore, simulations were run with sampling from a uniform distribution from a range of lifespans suggested by eWater (2013).

To evaluate the benefit-cost ratio of each option and to estimate budget measure **B3: Net present costs**, the net present benefits are compared with net present costs. The costs of different systems are based on life cycle cost (LCC) studies and include construction, annual maintenance, annualised renewal and decommissioning costs. Construction costs  $CC_{a,w}$  [AU\$] and annual maintenance costs  $MC_{a,w}$  [AU\$] of WSUD type  $w$  and of area  $a$  are determined based on Parsons Brinckerhof (2013) LCC review and analysis:

$$CC_{a,w} = \begin{cases} 1911a_w^{0.6435}, & w=\text{wetland} \\ 6023.1a_w^{0.54}, & w=\text{raingarden} \\ 685.1a_w^{0.7893}, & w=\text{pond} \end{cases} \quad (8)$$

$$MC_{a,w} = \begin{cases} 1289.7a_w^{0.206}, & w=\text{wetland} \\ 199.19a_w^{0.449}, & w=\text{raingarden} \\ 185.4a_w^{0.478}, & w=\text{pond} \end{cases} \quad (9)$$

Stormwater treatment systems need to be renewed periodically in order to ensure an optimal operation and pollution removal. An annualised renewal cost ( $RC_w$ ) [AU\$] is estimated based on a review of renewal costs compiled by eWater (2013):

$$RC_{a,w} = \begin{cases} 0.0052CC_{a,w}, & w=\text{wetland} \\ 0.02CC_{a,w}, & w=\text{raingarden} \\ 0.014CC_{a,w}, & w=\text{pond} \end{cases} \quad (10)$$

The cost associated with the decommission of each system  $DC_{a,w}$  [AU\$], occurring at the end of its lifespan, is also estimated from eWater (2013):

$$DC_{a,w} = \begin{cases} 0.42CC_{a,w}, & w=\text{wetland} \\ 0.39CC_{a,w}, & w=\text{raingarden} \\ 0.38CC_{a,w}, & w=\text{pond} \end{cases} \quad (11)$$

277 Finally, to estimate the budget measure **B3: Net present costs** and to assess **S3: Benefit-cost**  
 278 **ratio** and **S4: Cost-effectiveness** selection rules, the net present cost of each system ( $NPC_{a,w}$ )  
 279 [AU\$] is estimated by discounting  $MC_{a,w}$  and  $RC_w$  over the lifespan of each system type  $t_w$ , and  
 280  $DC_{a,w}$  for the last year of each system's lifespan:

$$NPC_{a,w} = CC_{a,w} + \sum_{n=1}^{t_w} (d_n \times MC_{a,w} + d_n \times RC_w) + DC_w \times d_{t,w} \quad (12)$$

281 It was assumed that no compensation or additional costs for retrofitting were required for the  
 282 installation of systems.

283

## 284 2.5. Model output

285 The model produces spatial layers in SpatialLite format for each year of the simulation. The  
 286 attributes of installed WSUD systems are included within the parcel layers (e.g., installation  
 287 year, size, type and treatment capacity). Other important output data are blocks and flow paths,  
 288 which are first created from UrbanBEATS simulations and then updated in DynaMind  
 289 simulations. Blocks and flow paths are used to modify the treated catchment impervious area  
 290 after a WSUD system has been installed on a parcel. Aggregated information for the whole case  
 291 study (e.g., cumulative treatment capacity and cumulative number of WSUD systems) are  
 292 contained in a council layer (for a representation of spatial layers and the parameters contained  
 293 in each of these layer, see Figure and Table S.2 in Supplementary Data).

### 3. Model application

#### 3.1. Case study: WSUD uptake in Kingston council

The model was applied with all twenty-four combinations (two location, three budget measures, four selection rules) in the Kingston local government area (Figure 2a), located within the Melbourne metropolitan area, to explore the range of results from the possible decision-making processes. The municipality has an area of 91 km<sup>2</sup> and a population of approximately 150,000 as of 2016. The city has a long coastline along Port Phillip Bay and thus pollution removal is a major water management objective for the council (AECOM 2012). A simulation period from 2005 to 2012 was selected, as it encompassed many relevant local planning milestones. For instance, the Kingston's Open Space Strategy was reviewed in 2005 and 2012 and the Kingston's Integrated Water Cycle Strategy was initiated in 2012. Moreover, model results are compared with attributes of existing WSUD systems from a database, which was last updated in 2012.

The annual budget of the city council allocated to WSUD in capital works for each year of the simulation was used to determine the first budget measure (**B1**). The installation costs and net present costs of existing systems installed between 2005 and 2012 were aggregated to estimate the second and third budget measures (**B2** and **B3**) (Figure 3).

Population and zoning maps from 2011-2012 (the end of the simulation period) were used since urban development was not simulated (Table 2). It was assumed that the placement of systems has been planned considering population and land use projections for 2012, the start of the city's Integrated Water Cycle Strategy. Annual rainfall from two rainfall stations across the case study area were obtained from the Bureau of Meteorology (BOM) and used to simulate runoff (the location of rain stations and their respective annual rainfall are displayed on Figure S.3 of Supplementary Data).

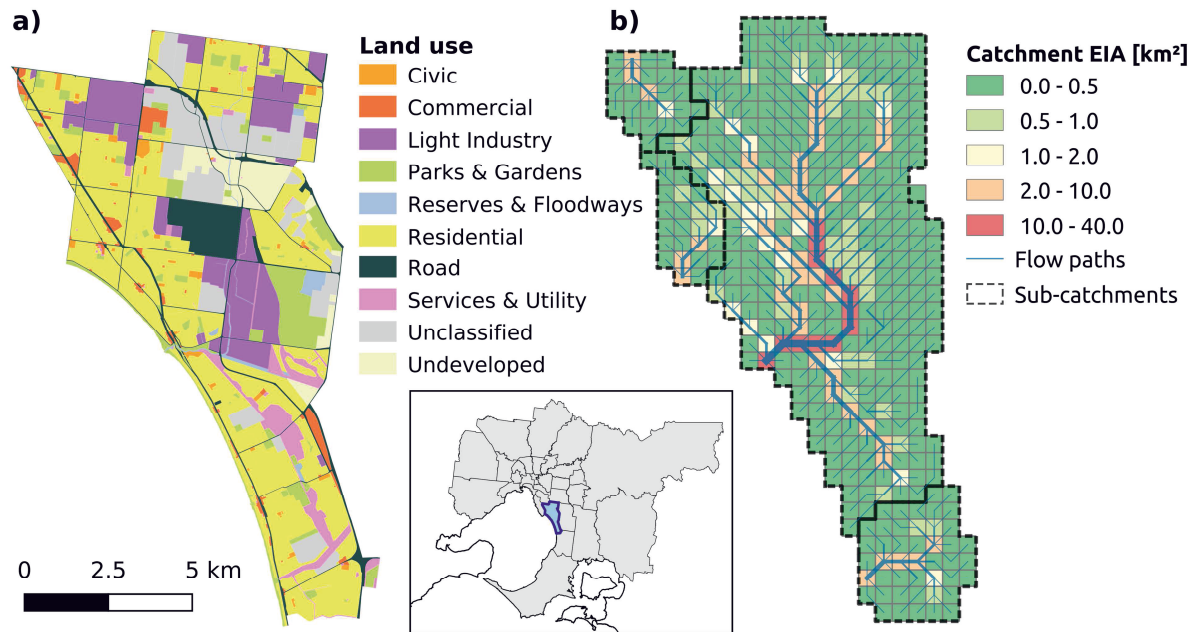


Figure 2: Case study area of Kingston city located within the Melbourne metropolitan area with land use (a), and catchment effective impervious area measured at block level (500m) and sub-catchments (b).

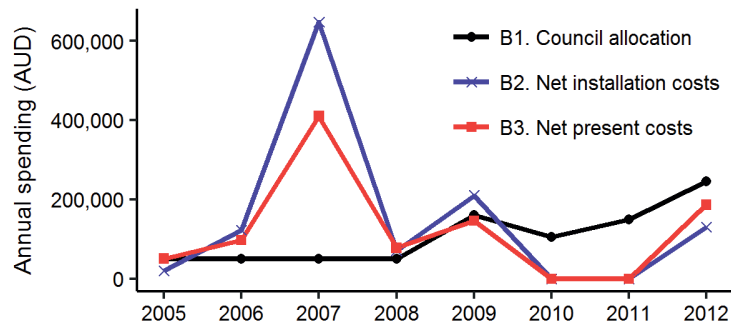


Figure 3: Annual spending for WSUD systems within city of Kingston according to the three tested budget measures (see Table 1).

Table 2: Spatial input parameters to produce suitability maps from UrbanBEATS software and for the installation of WSUD systems in DynaMind software.

Software	Input data	Temporal coverage	Source
UrbanBEATS	Population	2011	ABS <sup>1</sup>
	Zoning	2011	DELWL2
	Soil type	2016	DELWP
	Elevation	1985	DELWP
DynaMind	Land use	2006	DELWP
	Planning overlays	2005-2012	DELWP
	Building footprints	2015	DELWP
	Rainfall	2005-2012	BOM
	Existing WSUD systems	2005-2012	Kingston City council

<sup>1</sup>Australian Bureau of Statistics

<sup>2</sup>Department of Environment, Land, Water & Planning

In 2005, the water utility Melbourne Water initiated the Stormwater Offset Scheme to provide a market for TN removal. This program offers the option to developers to achieve best practice objectives for TN removal (45% reduction of typical annual load) within their development or pay an offset to the water utility (Brown and Clarke 2007). The price was determined based on the “levelised cost” of constructing regional wetlands to remove one kg of TN (RossRakesh et al. 2006) and is reviewed annually. The offset rate ranged from 800 to 2225 AU\$/kg TN for the simulation period (A. Hardy, pers. comm., August 8 2017). The discount rate used in the simulation is 6% for low risk band projects, which include water infrastructure projects (Partnerships Victoria 2003).

### 3.2. Comparison between simulated and actual WSUD uptake

Model results were compared to the attributes of observed systems installed during the simulation period and the fitness of model results was evaluated with the Nash-Sutcliffe model

coefficient of efficiency ( $E$ ) (Nash and Sutcliffe 1970). Since the model focusses exclusively on the decision-making of the city council, systems installed by developers and the water utility were omitted for the comparison. The dataset of observed systems includes their geographic location, the type of systems and their size. Equation 2 was used to estimate the treated area of existing systems for comparison with model results.

The spatial comparison of modelled and actual systems was conducted with density estimation and interpolated stormwater treatment capacity. The density of modelled systems is measured with the two-dimensional kernel density estimation method, with the bandwidth selection following Silverman's rule of thumb (Venables and Ripley 2002, p.127, equation 5.5). The predicted treatment capacity was interpolated with the treatment capacity and location of each modelled system with the inverse distance weighting method (IDW), and cross-validated with the leave-one-out method with three inverse distance power (IDP) factors (i.e., 1, 2 and 5).

### 3.3. Uncertainty assessment

Due to the uncertainty related to several parameters, a range was selected for sampling from uniform distributions (Table 3). For instance, because some parcels have a drainage area greater than 0.8 km<sup>2</sup> in the case study area, simulations were run with a uniform distribution for the block-scale EIA and rainfall parameters ( $\pm 20\%$ ) to address the uncertainty pertaining to runoff and TN removal.

In total, 500 simulations were carried out for each of the twenty-four model combinations (500 simulation runs were considered sufficient to reach a convergence of treatment capacity, displayed in Figure S.4 of Supplementary Data).

Table 3: Range for parameters sampling for uncertainty assessment.

Parameter	Unit	Source	Range
Block-scale EIA	m <sup>2</sup>	UrbanBEATS simulations	± 20%
Rainfall	m	BOM	± 20%
Discount rate	%	Partnerships Victoria (2003)	[4-8]
Construction cost	AU\$	Parsons Brinckerhof (2013)	± 20%
Maintenance cost	AU\$	Parsons Brinckerhof (2013)	± 20%
Raingarden lifespan	Years	eWater (2013)	[25-50]
Wetland lifespan	Years	eWater (2013)	[40-60]
Pond lifespan	Years	eWater (2013)	[40-60]

The range of results was then compared with attributes of existing systems (cumulative treatment capacity, cumulative number of systems, location of systems and spatial distribution of stormwater treatment).

## 4. Results and discussion

### 4.1. WSUD uptake as a function of budget measures

#### 4.1.1. Stormwater treatment capacity

In this section, the aggregated treatment capacity from the model after 500 simulations is compared with the treatment capacity of actual systems. Figure 4 shows the range of modelled treatment capacity for the two location rules, the four system selection rules and the three budget measures as per Table 1.

For **B1** simulations, a large discrepancy could be observed at year 2007, where actual treatment capacity was considerably larger than modelled treatment capacity. The model underestimated treatment capacity until the end of the simulation. Simulations using aggregated installation costs as the budget measure (**B2**) showed more accurate modelled treatment



capacity compared to **B1** simulations, as evidenced by higher  $E$  values for all scenarios (all between 0.59 and 0.99). The important increase in 2007 was observable for all cases. **S3** and **S4** had a larger uncertainty than **S1** and **S2** simulations, despite high  $E$  values, due to the sampling range of costs parameters, i.e., lifespans, installation costs, maintenance costs and discount rate for cost-benefit ratio and cost-effectiveness assessments. Finally, Figure 4 shows modelled and actual treatment capacity with net present costs as the budget measure (**B3**), assuming that policy-makers fully consider all costs. Model results showed a similar trend but underestimated observed treatment capacity. The uncertainty of results was larger than **B1** but lower than **B2** simulations.

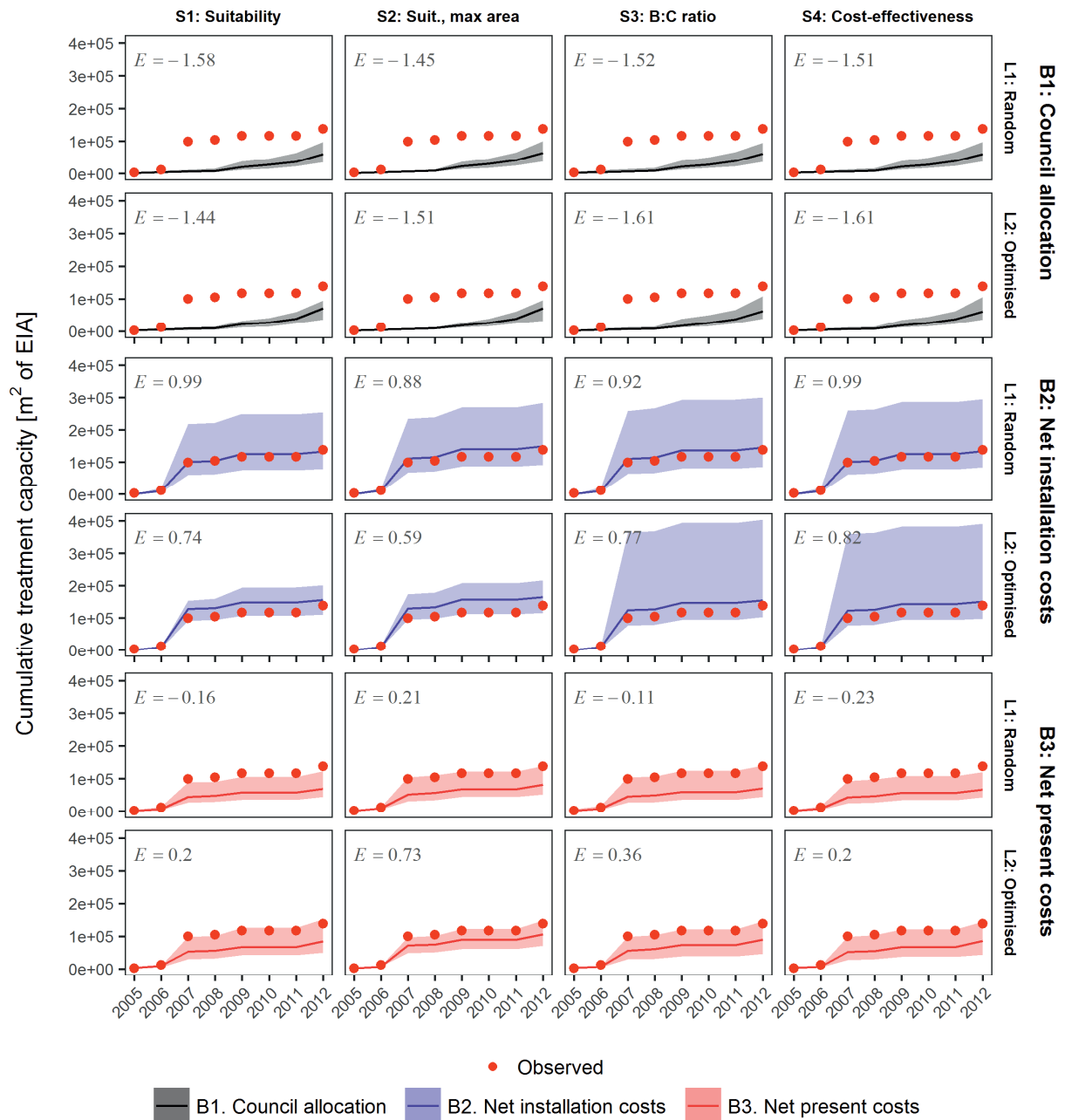


Figure 4: Simulated treatment capacity according to the three budget measures, two location and four system selection rules. Shaded areas represent values between 5<sup>th</sup> and 95<sup>th</sup> percentiles and the solid line represent the median treatment capacity after 500 simulations. Red points show the observed treatment capacity.

The **B1** model version with allocated budget by city councils in capital works was the least accurate model version. This is mainly due to a large raingarden installed in 2007 which did not appear in the annual budget. City councils may not list all systems in the capital works section on WSUD assets and therefore using funding allocated by councils for the installation of WSUD systems in their annual budget was not reliable to accurately predict treatment capacity. The **B2** model version with installation costs as budget measure was able to replicate the observed treatment capacity for all rules. The **B3** simulations were slightly less accurate (consistently under-predicting the uptake) with only one scenario with an *E* value above 0.7, but with very small uncertainties.

Although the median values of modelled treatment capacity for rules **S3** and **S4** were able to reproduce actual values, especially for **L1** scenario, the uncertainty was the largest among all model variations. Again, this can be explained with the range for sampling of costs parameters (discount rate, installation costs and maintenance costs), as well as lifespans of the three system types for the analysis of benefit-cost ratio and cost-effectiveness. The median treatment capacity for **L2** location and **S1** and **S2** selection rules overestimated the observed treatment capacity, which could indicate that councils may have considered not only installation costs but also some additional costs, e.g. for operation and maintenance.

Although observed treatment capacity fell within the range of most decision rules for **B3** budget measure, this model version underestimated treatment capacity. This can be due to the high maintenance and renewal costs of raingardens (the only observed system type installed), which drives the spending from this budget measure down. Limited information is available on renewal and decommissioning costs of WSUD systems and thus policy-makers are unlikely to systematically consider these costs in their budget. Policy-makers are more likely to take decisions based on more reliable and available data such as installation costs, which can be seen in **B2** simulations, and annual maintenance costs.

Decision rules **S1** and especially **S2** had lower uncertainty range across the three budget measures. As no costs or benefit were considered in these decision rules, the uncertainty in costs and lifespans parameters did not affect the results. Conversely, decision rules **S3** and **S4** had the potential to provide greater treatment capacity but show a larger uncertainty.

#### 4.1.2. Number and types of WSUD systems

The cumulative number and types of WSUD systems showed a similar pattern to treatment capacity. With **B1: Council allocation** budget, model results under-predicted the number of systems for most of the years, whereas **B3: Net present costs** budget predicted a lower number for all model variations, and both scenarios show low *E* values for installed raingardens (Figure 5).

**B2: Installation costs** simulations were again more effective in predicting the right number of systems. All simulations fit the observed data and display high *E* values (0.75-0.93), showing a larger number of raingardens installed, compared to ponds and constructed wetlands, in accordance with actual systems. However, location rule **L2: Optimised** more accurately replicated the types of systems installed (i.e., only raingardens), whereas some ponds and wetlands were installed in **L1: Random** simulations, particularly for selection rules **S3: Benefit-cost ratio** and **S4: Cost-effectiveness**. This can be explained by the lower costs and greater benefit-cost ratio for larger pond and wetland systems compared to raingardens when considering costs and benefit for the selection of systems and disregarding location suitability. The simulated count and type of systems were consistent with the simulated treatment capacity, as budget measure **B2** was more effective in replicating the attributes of actual WSUD assets.

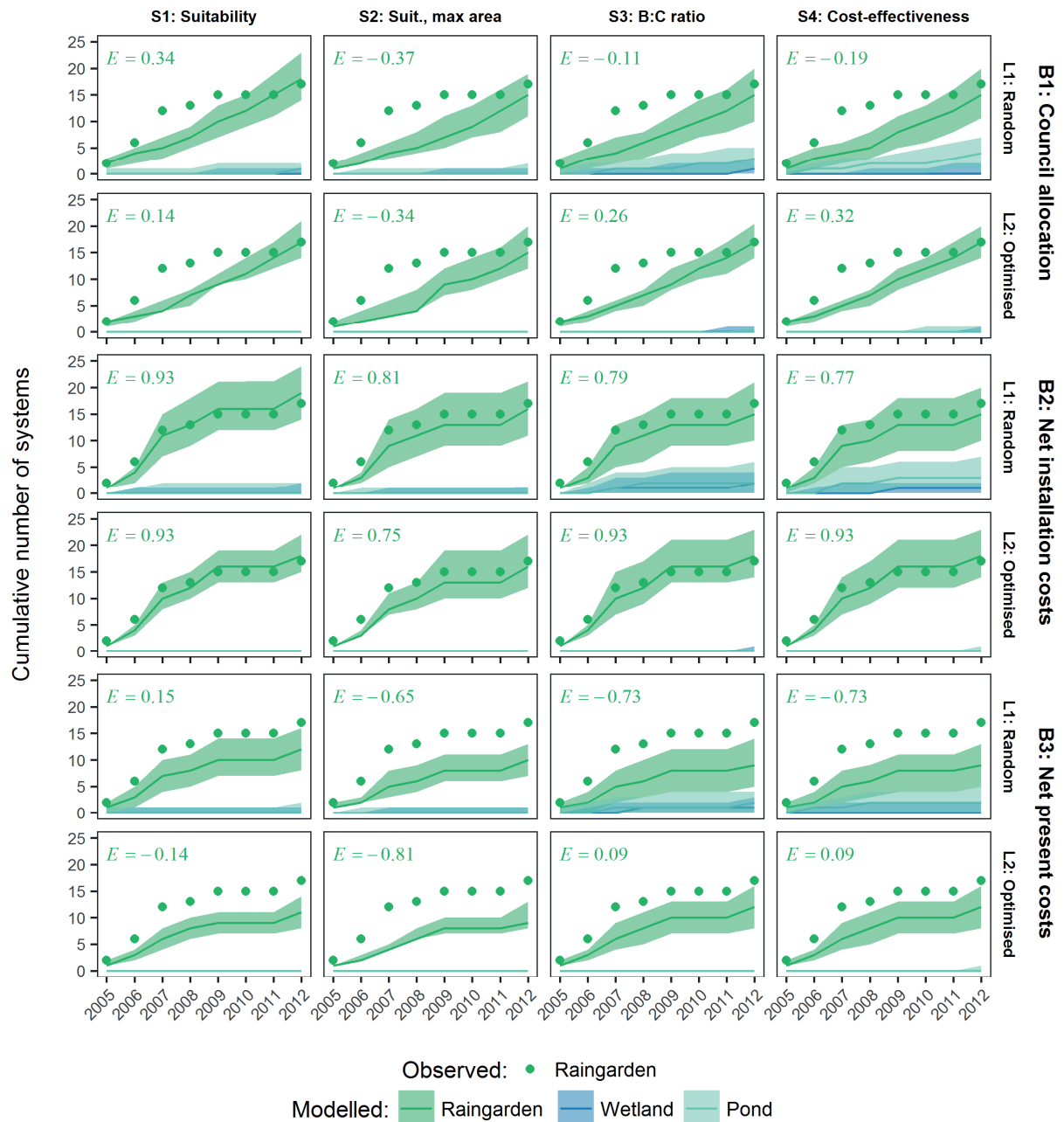


Figure 5: Simulated number of WSUD assets according to the three budget measures, two location and four system selection rules. Shaded areas represent values between 5<sup>th</sup> and 95<sup>th</sup> percentiles and the solid line represent the median number of systems after 500 simulations. Points show the observed number of systems. Nash-Sutcliffe efficiency (E) was measured to compare median count with observed count of raingardens.

## 4.2. Location of WSUD systems

The capacity of the model to replicate the location of WSUD assets and spatial distribution of treatment capacity was evaluated by looking at simulations from budget measure **B2: Installation costs**, which demonstrated a better fit to simulate WSUD uptake than **B1: Council allocation** and **B3: Net present costs**. Further, selection rules **S1: Suitability** and **S2: Suitability-maximisation** were chosen because of lower uncertainty of WSUD uptake than **S3: Benefit-cost ratio** and **S4: Cost-effectiveness** (results on remaining simulations are presented in Supplementary data, Figures S.5 and S.6).

Figure 6a shows the density of modelled WSUD assets (in this case only raingardens) over 500 simulations compared to the location of actual systems installed during the simulation period. Results with location **L1: Random**, for both selection rules **S1** and **S2**, showed a higher modelled density of systems along the coastline. However, the density spread on a much larger area than **L2: Optimised** results. Selection rule **S1** and location rule **L2** most accurately reproduced the location of systems in the western part of the council but presented a mismatch for the systems in the southern part. This mismatch, where modelled systems are seen further south than the actual assets, may be explained by existing treatment in the council southeast of Kingston city, which would reduce the suitability or need for treatment in the southern part of the council. If treatment occurs in the drainage system before entering the council area, the council will likely prioritise other sub-catchments in the study area. The southern part of the administrative area is a small sub-catchment within the council but part of a larger catchment that extends beyond the council area (see Figure 2b for the map of sub-catchments). To address this mismatch, the model could be applied on a catchment scale rather than administrative scale to fully consider pollution removal from WSUD systems installed upstream by neighbouring councils.

Results for selection rule **S2** and location rule **L2** showed a more precise but less accurate density which missed most of the observed systems. According to this model setting, in which the size of WSUD systems was maximised based on the available budget, the agent focussed on a smaller number of suitable areas and was less reliable to reproduce the location of systems than **S1**.

The interpolated treatment capacity of modelled WSUD systems using IDW compared with the treatment capacity of actual WSUD assets is shown in Figure 6b (the calibration of the IDW with different IDP factors is detailed in Supplementary data, Table S.7). Simulations with **L2** location rule showed less variations whereas **L1** simulations showed multiple hotspots across the council. These treatment capacity hotspots can be observed in the north-eastern part of the council where no actual systems have been installed, therefore incorrectly predicting higher treatment capacity. In the southern part of the city, simulations with location rule **L2** predicted a hotspot, in accordance with the higher density observed in Figure 6a.

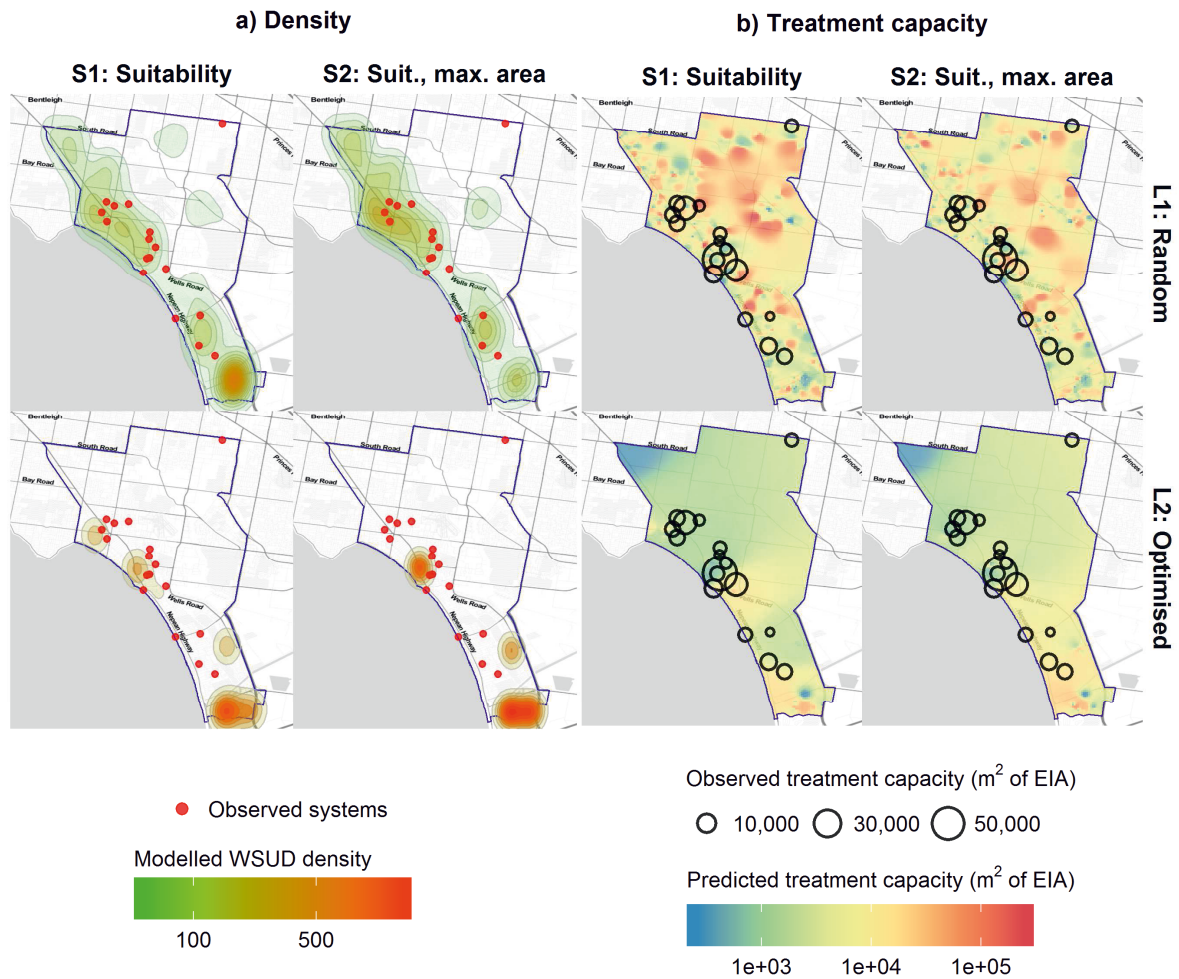


Figure 6: Comparison of modelled and actual systems' location density for city of Kingston using two-dimensional kernel density estimation (a) and interpolated treatment capacity (using and IDP of 5) (b) for budget measure **B2: Installation costs**, location **L1: Random** and **L2: Optimised** and selection rules **S1: Suitability** and **S2: Suitability-maximisation**.

However, as discussed above, this area is a small separate catchment and the city of Kingston may not have focussed on that area. Other management solutions in neighbouring council may explain the mismatch of treatment capacity. Both location and selection rules could not predict higher treatment capacity in the mid-western part of the council, as shown by actual systems.



### 4.3. Limitations of the model

The model combination using budget measure **B2: Installation costs**, selection rule **S1: Suitability** and location rule **L2: Optimised** was most effective in reproducing cumulative treatment capacity, the number and types of systems installed and the location of systems with the lowest uncertainty. The model was able to replicate the treatment capacity for the simulation period by considering some of the biophysical (suitable design and location rules) and economic (budget measures and selection rules) uncertainties. However, these are few of the uncertainties pertaining to the decision-making of stormwater management. Socio-political and governance uncertainties such as lack of knowledge and awareness, resistance to novel approaches and practices, changing legislation and political leadership are some of the additional factors affecting the decision-making process (O'Donnell et al. 2017) that are not considered in the model.

Furthermore, stormwater management is a complex problem that includes multiple stakeholders, e.g. state government, water utility, developers, and households. Our model only focusses on the decision-making process of the main agent for WSUD systems uptake, i.e., the municipal council, but other agents could be added to the model to represent the complex dynamics and interactions among stakeholders involved in stormwater management. For instance, stormwater treatment systems installed in adjacent municipalities or by developers within the municipality may have influenced the suitability assessment by the Kingston city council. Also, community receptivity and acceptance are likely to have impacted the location choice of installed systems. The performance of the model could be further improved by using a case study where administrative boundaries are more aligned with catchment boundaries, to improve pollution assessment while keeping the decision-making boundary. Including these factors and calibrating the effective impervious area have the potential to improve the capacity of the model to predict the spatial distribution of stormwater treatment capacity.

## 5. Conclusion

A new model was presented to simulate the decision-making process underlying the installation of WSUD systems by local governments. Key outcomes of this study were:

- The model was able to replicate the uptake of existing systems installed by the Kingston City council for the 2005-2012 period, by testing location rules, budget measures and WSUD selection rules.
- Modelling the uptake of WSUD assets with the actual allocated budget by the council for the simulation period proved to be ineffective to replicate the uptake of systems. Rather, the budget measure consisting of aggregated installations costs could replicate the uptake of the count and types of systems.
- Decision rules to select WSUD systems based on their optimal design and location were found to be more robust than selection rules based on costs and nitrogen removal benefit.

The model could provide insights to policy-makers on the anticipated environmental benefit of using certain rules for the selection of WSUD systems, selection of locations and budget constraints. Furthermore, this approach allows users to assess the robustness of different decision rules to achieve stormwater treatment targets and could be used as an exploratory modelling tool to test decision rules to improve stormwater management under different scenarios of urban development.

The model will be further extended to assess interactions of stakeholders in urban water systems. Besides local government, the model will include other relevant actors, namely households, the state government and developers, and assess the placement of both public and private WSUD assets, for example rainwater harvesting tanks (Castonguay et al. 2018). By

including the behaviour of other agents, the model will allow users to investigate the benefits of strategies and policy mechanisms to improve stormwater management with a holistic approach.

## Acknowledgement

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## Nomenclature

$y$	year
$p$	parcel
$a$	Area converted to a WSUD [m <sup>2</sup> ]
$w$	WSUD system (pond, raingarden or wetland)
$TN_{p,w,y}$	Total nitrogen removed by a WSUD system $w$ on parcel $p$ at year $y$ [kg]
$R_{p,y}$	Runoff for parcel $p$ at year $y$ [m]
$C$	TN concentration from runoff [kg/m <sup>3</sup> ]
$A_{p,w}$	Impervious catchment area treated by WSUD system $w$ for a given parcel $p$ [m <sup>2</sup> ].
$AF_w$	Adjustment factor to account for different hydrologic regions across Melbourne for WSUD system $w$
$TNR$	Targeted removal of TN [%]
$P_{p,y}$	Rainfall for parcel $p$ and year $y$ [m]
$F$	Fraction of annual rainfall events that produces runoff [%]
$Rv_p$	Runoff coefficient for each parcel $p$ [%]
$d_{n,w}$	Discount factor at year $n$ of the lifespan of WSUD system $w$
$t_w$	Lifespan of WSUD system $w$ [year]

$r$	Discount rate [%]
$NPB_{p,w,y}$	Net present benefit of TN removal for parcel $p$ provided by WSUD system $w$ at year $y$ [AU\$]
$B_{p,w,y}$	Economic value of TN removal benefit for parcel $p$ provided by WSUD system $w$ at year $y$ [AU\$]
$CC_{a,w}$	Construction cost of WSUD system $w$ of area $a$ [AU\$]
$MC_{a,w}$	Maintenance cost of WSUD system $w$ of area $a$ [AU\$]
$RC_{a,w}$	Annualised renewal cost of WSUD system $w$ of area $a$ [AU\$]
$DC_{a,w}$	Decommissioning cost of WSUD system $w$ of area $a$ [AU\$]
$NPC_{a,w}$	Net present value of cost of WSUD system $w$ of area $a$ [AU\$]
$O_y$	Stormwater offset rate at year $y$ [AU\$]

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- A model was developed to simulate the uptake of stormwater treatment systems.
- Location choice, budget measure and WSUD selection were assessed as decision rules.
- The model performance was evaluated in a suburb of Melbourne, Australia.
- The robustness of each decision rule was determined through uncertainty assessment.

