Towards Water Sensitive Urban Precincts: Modelling Stormwater Management Opportunities

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ABSTRACT

Water sensitive urban design is a contemporary approach to the planning and designing of urban environments that are 'sensitive' to the issues of water sustainability, resilience and environmental protection. For example, harvesting, treatment and use of stormwater to support green infrastructure embedded in the urban form can help protect waterways from excessive pollution and ecosystem degradation while reducing excess urban heat. Modelling tools can support strategic planning and conceptual design of new urban development as well as the re-development of existing urban areas. To address the above challenge, a modelling toolkit is being developed by the Cooperative Research Centre for Water Sensitive Cities, which integrates new research into stormwater management and green infrastructure. This paper presents the application of the modelling toolkit to identify and assess stormwater management opportunities for an urban greenfield development in Melbourne, Australia. The results show that the model was able to assess stormwater management opportunities under the constraints imposed by the different scenarios, and the analysis of the results suggested that a more integrated urban stormwater management approach is needed to achieve better environmental outcomes.

KEYWORDS

Stormwater management, WSC modelling toolkit, sustainable urban environment benefits

INTRODUCTION

Over the last decade major cities and towns in Australia have experienced prolonged drought and extreme heat events, followed in 2010 and 2011 by some of the biggest floods on record resulting in considerable economic losses. Furthermore, the longer duration of heat waves trends are intensified by the effects of increased urbanization and higher urban densities(e.g. Alexander and Arblaster, 2009). Human health and human thermal comfort are negatively impacted by the increase in occurrence and duration of extremes heat(e.g. Loughnan *et al.*, 2010). Not less critical are the negative impacts of urbanization on urban stream hydrologyand water quality(e.g. Hatt *et al.*, 2004).

The adoption of Water Sensitive Urban Design (WSUD) has shown great potential in creating more sustainable and liveable cities and towns. For example, excess urban heat can be mitigated by green infrastructures supported by stormwater (Wong *et al.*, 2013). Stormwater management and in particular, stormwater treatment and harvesting, can contribute to both water supply and environmental flow objectives(Mitchell *et al.*, 2007). The use of fit-for-purpose stormwater to augment traditional water supplies also helps to restore natural flows and water quality conditions and also to minimise the pollution impacts associated with urban areas.

Conceptual models are powerful tools to aid the planning, design and performance of different stormwater management strategies.There is a range of models that addresses most of the current challenges individually such as MUSIC(eWater, 2013) for the design of stormwater management technologies and CityDrain3(Burger *et al.*, 2010)for integrated urban water cycle management among many others (Bach *et al.*, 2014). Yet, neither the combination of strategic planning and conceptual design of water sensitive urban design technologies with different environmental responses (e.g. load reduction, microclimate enhancement, stream health) nor the synergy between the different benefits or impacts of different stormwater management strategies in urban environments have been addressed. To address these shortcomings, a modelling tool is being developed by the Cooperative Research Centre (CRC) for Water Sensitive Cities, which integrates new research into stormwater management and green infrastructure. This paper presents the tool’s rationale and its application to identify and assess stormwater management opportunities for an urban greenfield development in Melbourne, Australia.

METHODS

Model Overview

The Water Sensitive Cities (WSC) Modelling Toolkit (beta version) integrates new research into: stormwater management within the urban form, stormwater treatment and harvesting, stream health, and urban microclimate. It has been developed support catchment-/regional-scale planning and conceptual design of water sensitive cities through: (1) scenario generation and simulation, and (2) scenario assessment. Outputs from the scenario assessment process will enable future refinement of the considered options for the site.

Scenario generation and simulation.Core of the scenario generation and simulation component of the toolkit is the Urban Biophysical Environments and Technologies Simulator (UrbanBEATS) (Bach, 2012). UrbanBEATS (Figure 1-top) is a planning-support model, which integrated urban planning, geospatial analysis, holistic evaluation and WSUD stormwater system design to generate a large number of technological options (i.e. conceptual layouts of decentralised water management initiatives at the lot, streetscape and regional scales). Conceptual designs of WSUD technologies are created based on typical design parameters (e.g. 0.4 m depth for rain gardens; 72 hours of detention time for wetlands). These designs are only indicative and are not meant to replace the need for further detailed design. Suitability of technologies in specific urban locations is determined based on urban planning constraints and the availability of space defined by the user-defined planning regulations (see e.g. Bach, 2012). Top-ranking solutions are selected from the generated options based on a user-defined scenario (e.g. stormwater management objectives) and holistic evaluation of different WSUD technologies (using a multi-criteria scoring framework). Outputs from the scenario assessment module include a series of possible options for each WSUD scenario, which are subsequently used as inputs to the scenario assessment modules.

Scenario assessment.The scenario assessment modules (Figure 1-bottom) are used to evaluate different stormwater management strategies in terms of: treatment/harvesting performance; stream health benefits (hydrologic and geomorphic); minor flooding impacts; and, urban heat reduction. The rationale of each of these modules is briefly described below:

1. ***Treatment/ harvesting performance*** – the WSC model links dynamically to MUSIC (Model for Urban Stormwater Improvement Conceptualisation by eWater, 2013),

which was developed for Australian climate conditions and currently underpins the decision-making process in urban water management, policies and regulation. MUSIC is a simplified conceptual stormwater model that simulates continuous stormwater flows, pollution generation and the hydrodynamics of WSUD systems.

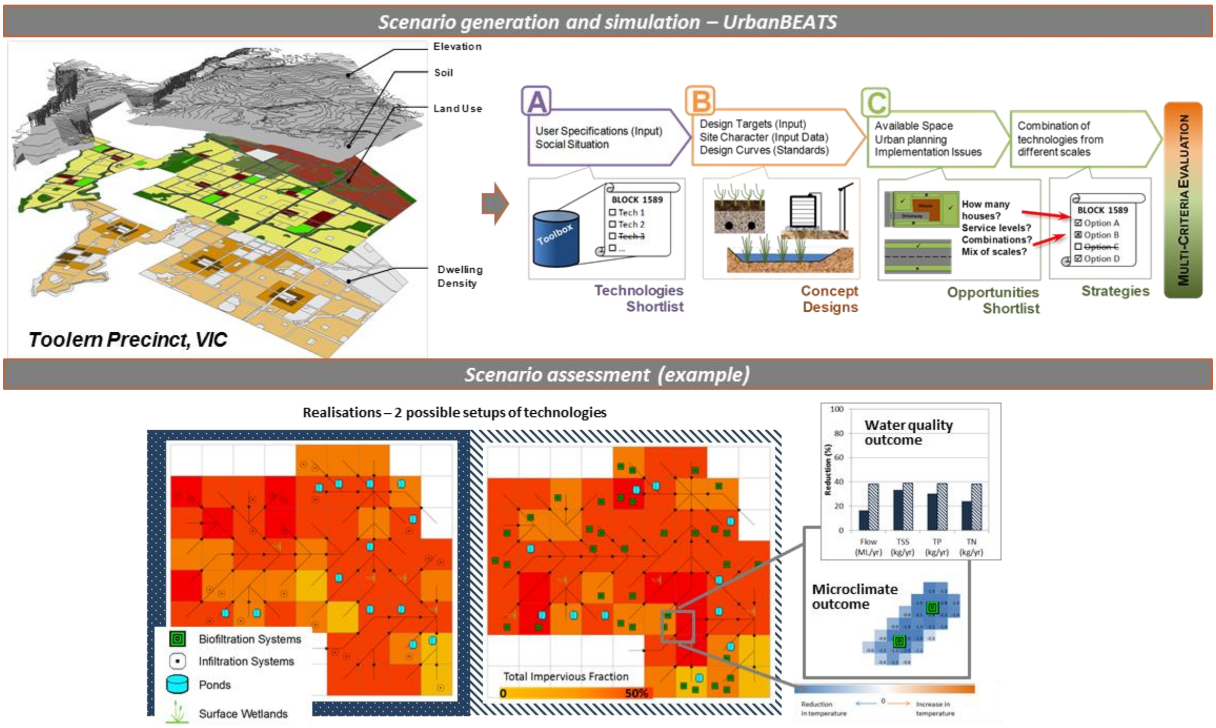

Figure 1. Representation of the scenario generation and simulation and scenario assessment components of the WSC modelling toolkit.

2. ***Stream health, hydrology and water quality***–this module assesses how well different stormwater interventions mimic processes of stream hydrology and water quality in natural catchments (i.e. zero impervious areas) by reducing runoff and increasing baseflows. Four indicators, of direct ecological relevance to streams, were adapted from the Little Stringybark Creek project(Little Stringybark Creek, 2012):
   - *Number of runoff days per year:*an indicator of stream disturbance and typically very low in natural catchments.
   - *Total volume reduction:*how well stormwater management initiatives reduce runoff from urbanised areas, i.e. the difference between the excess volumes generated from urbanization and volumes used/lost from WSUD interventions.
   - *Proportion of filtered volume:*how stormwater management restores natural stream flows. In summary, the aim is to filter water, which enters the stream during the most frequent events.
   - *Water quality:* indication of how well different WSUD interventions achieve pollution concentration targets that are beneficial to the streams.
3. ***Stream health – stream erosion index (SEI)***–this module evaluates the impact of various stormwater management interventions on the geomorphic form of the streams by calculating the Stream Erosion Index (SEI) before and after WSUD interventions. SEI is computed as the ratio between the stream erosion potential of the post developed catchment; we refer to$SEI_{urbanised}$(before WSUD intervention) and SEI_{WSUD}(after WSUD intervention):

$$SEI_{(Urbanised\ \ or\ WSUD)} = \frac{\sum\left(Q_{post} - \frac{Q_2}{2}\right)}{\sum\left(Q_{pre} - \frac{Q_2}{2}\right)}$$

where Q_{post} is the flow rate from (i) urbanised areas when calculating $SEI_{urbanised}$, and (ii) post-WSUD catchment for SEI_{WSUD}; and, Q_2 is the 2 year AverageRecurrence Interval (ARI) peak discharge from the natural catchment.The Department of Environment and Climate Change (DECC) has defined the flow surrogate threshold as 50% of the 2 ARI peak discharge from the catchment (Q_2). Coupled to the WSC modelling toolkit, MUSIC is used to compute the flow series and a partial frequency analysis is used to determine Q_2. A few studies, which tested the adequacy of SEI objectives and values, suggested that best practice SEI to be set at 2 and a stretch target of 1(Brookes and Wong, 2009).

4. ***Minor flooding impact***– this module evaluates the potential of the different stormwater management options to reduce minor flooding in urban areas, mainly in terms of managing the largest, most frequent events (e.g. rainfall events up to the 3 month for water quality management). It is based on the work ofE2DESIGNLAB (2013), which showed the use of partial series analysis to quantify the minor flood benefits from WSUD. It uses the same method described for the SEI above.
5. ***Microclimate impacts***– this module (still in its early stages of development)assesses the impacts of green areas/infrastructures on the urban microclimate. Specifically, it aims to identify their cooling effects on the urban environment. This module is based on the work from Coutts and Harris (2012) and Nury *et al.* (2012), in which remote sensing was used to capture spatial variations in land surface characteristics and Land Surface Temperature (LST). It utilises relationships between LST and different land covers (e.g. impervious areas, grass, tree, wetlands) in a 30 m resolution.

Case study

*Study site.*In this study, the WSC modelling toolkit is used to investigate stormwater management opportunities for Toolern, a 24 km^2 outer urban greenfield development (representative maps are presented in Figure 1 - top left corner) in the west of Melbourne, Australia. The average annual rainfall volume is around 450 mm. The development is mostly residential (44%) with mixed densities.Further information about the site and data can be found inBach *et al.* (in preparation).

Scenario generation and simulation. The model setup consisted in defining the main parameters necessary for the scenario generation stage of the model, which refer mostly to urban planning and technology design information. The setup of such parameters, informedby the precinct structure plan(PSP by GAA, 2011), was presented by Bach *et al.* (in preparation), in which the authors also simulated a scenario to reproduce the PSP specifications. Due to space constraints, we guide the reader to Bach *et al.* (in preparation) for a complete description about the choice and values of model parameters.

In terms of technologies, the PSP previews mostly basin-based technologies (e.g. surface wetlands and ponds) at neighborhood and sub-basin scales instead of filter-based technologies (e.g. bioretention and infiltration systems) at allotment or street scales. It also states that most of the harvested water will be directed to a reservoir on the south-west of the site. In this study, the different scenarios were generated aiming to change features that would potentially impact mainly on stream health hydrology, water quality and geomorphology aspects. In addition, the simulation scenarios were developed to consider technologies mostly for stormwater pollution management. Stormwater harvesting option in the model is under development.

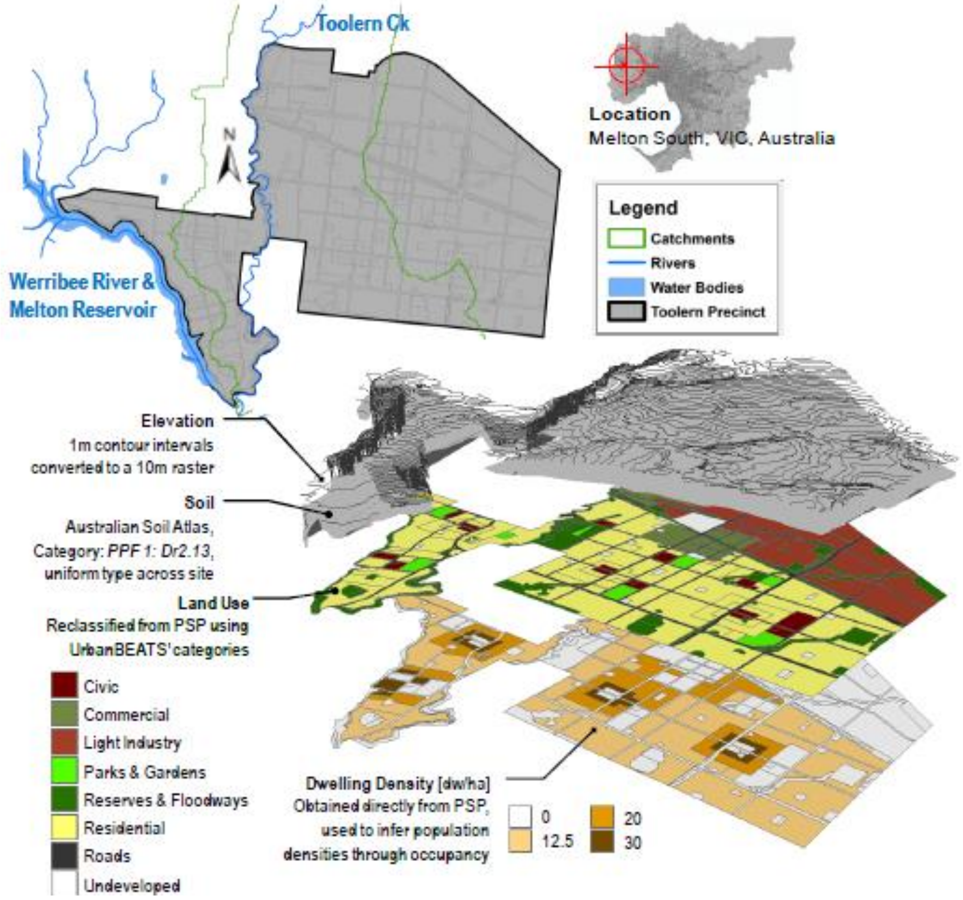

Figure 2. Toolern Precinct Location, existing infrastructure and surrounding biophysical features (left) and input maps for Toolern precinct (right) (Source: Bach *et al.* in preparation).

The Multi-Criteria Scoring Matrix for WSUD Technologies was used based on project themes, metrics and indicators (based on data gathered during a stakeholder engagement workshop), in which the technical, environmental, economic and social had 2, 4, 3 and 7 descriptive metrics, respectively. In addition these metrics were tuned in the model to meet the equivalent stakeholder weightings of 20%, 30%, 10% and 40% for technical, environmental, economic and social metrics respectively. See Bach*et al.*, in preparation for detailed description.

A number of stormwater management scenarios were investigated and compared with a base case scenario based on the proposed master plan of the development (except for the harvesting option).The setup of different scenarios was designed to cover a range of factors that were expected to impact on the model outcomes. However, only some of them and their results were likely to represent real projects. For example, for consistency, it was necessary to have a scenario where all the systems were lined and another opposite scenario where all systems are unlined (the change in this variable is of importance, for example, to reduce runoff volumes). While, this can be the case for biorention systems, it is not the desired case for infiltration systems in which, lined systems would not make sense. As such, only the realistic scenarios were considered, and the changing variables are summarised in Table 1.

The base case scenario considered that all the roofs were directly connected to the drainage system (0% disconnection). The combination disconnected scenario differs from the base case scenario for the fact that 100% of the roofs were disconnected from the drainage system, while in the combination semi-disconnected, the amount of roofs disconnected from the drainage system varies and was represented by a number randomly sampled between 0% and 100% for each of the 500 by 500 m block.

The base case scenario had 100% of the areas of parks or green space available for the implementation of stormwater management technologies, while the combination green space for WSUD - min had only 25% of the same area was available. 25% was determined through a number of model runs, in which this factor was varied to definethe minimum amount of greenarea that should be available for stormwater management in orderto achieve the objectives set in the PSP.

Table 1. Summary of key model input parameter values for the different scenarios.

Category	**Parameter** **Value for the scenario**	**Scenario**					
		Base case (PSP based)	Basin-based systems	Filter-based systems	Combination semi-disconnected	Combination disconnected	Combination green space for WSUD-min
		Value for the scenario					
Urban Planning	Residential Planning Parameters						
	Downpipe disconnection from roofs (%)	100	100	100	U[0 100]*	100	0
	Other Planning Parameters						
	Park areas green space %	100	100	100	100	100	25
Technology Design	Bioretention Systems	Unlined	n/a	Unlined	Unlined	Unlined	Unlined
	Infiltration Systems	Unlined	n/a	Unlined	Unlined	Unlined	Unlined
	Ponds & Basins	Unlined	Unlined	n/a	Unlined	Unlined	Unlined
	Surface Constructed Wetlands	Lined	Lined	n/a	Lined	Lined	Lined

* number randomly sampled between 0% and 100% for each of the 500 by 500 m block

*Scenario assessment.*The scenario assessment modules also have parameters to be setup before the simulation. They are described below (and were not changed for the different scenarios because they are related to targets):

- ***Treatmentperformance:*** it was derived from the PSP that 40% of the runoff from impervious area should be treated (details in Bach *et al.*, in preparation) to achieve the water quality management reduction targets. These targets were used according to current Best Practice Management (Victorian Stormwater Committee, 1999), in which reductions of Total Suspended Solids (TSS) loads of 80%, Total Nitrogen (TN) loads of 45% and Total Phosphorus (TP) loads of 45% are specified.
- ***Stream health, hydrology and water quality:*** the targets regarding the desired water quality improvement, to assure a significant benefit to the streams, were used according to the Little Stringybark Creek (2012) project, which specifies targets of TSS, TN and TN and TP median concentration of 20, 0.60 and 0.05 mg/L, respectively and a number of runoff days per year equal to 12.
- ***Microclimate impacts:*** the microclimate module was run to provide some preliminary insights about the difference in Land Surface Temperatures between impervious areas and areas with green infrastructure as suggested in the PSP.

RESULTS AND DISCUSSION

Scenario generation and simulation

As expected, the results regarding the spatial representation of the study site were in accordance with the ones found by Bach *et al.*, in preparation. The model reproduced 4 sub-basins within the site (as also divided in the PSP), with the total impervious fractions ranging from 0% to 85% for industrial zones, and from 40% to 70% for residential zones). The remaining variables related to the spatial representation of the catchment are not described here (please refer to Bach *et al.*, in preparation for detailed explanation and illustration of the results). This paper focusses on the final results obtained by the scenario generation and simulation stage (i.e. the different setup of stormwater management interventions obtained with the different scenarios) and on the main impacts of such interventions on the different aspects of the environment (scenario assessment stage).

A number of scenarios were run to determine the minimum amount of green areas that should be available for stormwater management and it was found that values lower than 25% would not allow the 40% service level (i.e. proportion of runoff from impervious area to be treated) in all 4 sub-basins (Figure 3 a).

The analysis of the 3 top ranked realisations for all the scenarios and sub-basins revealed that basin-based technologies were preferred over the filter-based ones within the simulations. Wetlands achieved a proportion of 100% treatment of the serviced area in the top ranked realization of the base case and basin-based systems scenarios. This is probably due to the fact the model was run for a single objective of stormwater pollution management (and not runoff reduction) and also because surface wetlands presented a total higher score in the MCA scoring matrix than the other considered technologies (Bach *et al.*, in preparation).The scenarios in which only filter-based technologies were allowed did not produce any results probably due to the low infiltration rates of soil on-site.

Scenario assessment

The analysis of the 3 top ranked realisations for all the scenarios and sub-basins achieved the pollutant load reductions at the service level of 40%. TheStream health – hydrology and water quality indicators did not drastically changed between scenarios. The frequency of runoff is directly related to the levels of imperviousness in a catchment(Fletcher *et al.*, 2011). As such the number of runoff days per year was sensitive to the scenarios in which the proportion of roofs disconnected was varied. It was found to be between106 and 110 for the base case, 95and 99 for the combination semi-disconnected and 80 for combination disconnected. Reason for such high values is that ponds and wetlands do not perform well in reducing the amount of runoff (opposite to raintanks, for example that capture the water before the runoff generation). A larger proportion of roof runoff disconnection from the drainage system also improved the proportion of filtered flow (i.e. treated flows - larger than the baseflow from a natural catchment); however, this proportion improved from only 3% to 6%, fromthe base case to combination disconnected, respectively. These are very little benefits; these values could be significant decreased if we aimed to treat a larger portion of the total runoff. In addition, the trade-off of benefits within scenarios was not evident; it is suggested that a more multi-objective analysis should be carried out in the future.

Figure 3 b shows the different ARI peak discharges for two simulated scenarios (including the results representing the natural and urbanised catchments): base case scenario, in which 100% of the green areas were set available for WSUD interventions, and the combination green space for WSUD - min, which had only 25% of the same area available. It can be seen that the simulated scenarios reduced the magnitude of the most frequent peak flow rates, and that as expected the amount of available green space for WSUD interventions played an important role. In the base case scenario, the reduction (compared to a urbanised catchment without any WSUD intervention) was up to 70% to the 3 months ARI, which contributes to stormwater quality improvement, and up to 60% to the 6 months ARI, which characterises the period in which we can start managing stormwater as a resource. The SEI index was not satisfactory in any of the scenarios, suggesting perhaps that stormwater harvesting and/or a large service level would improve the results.

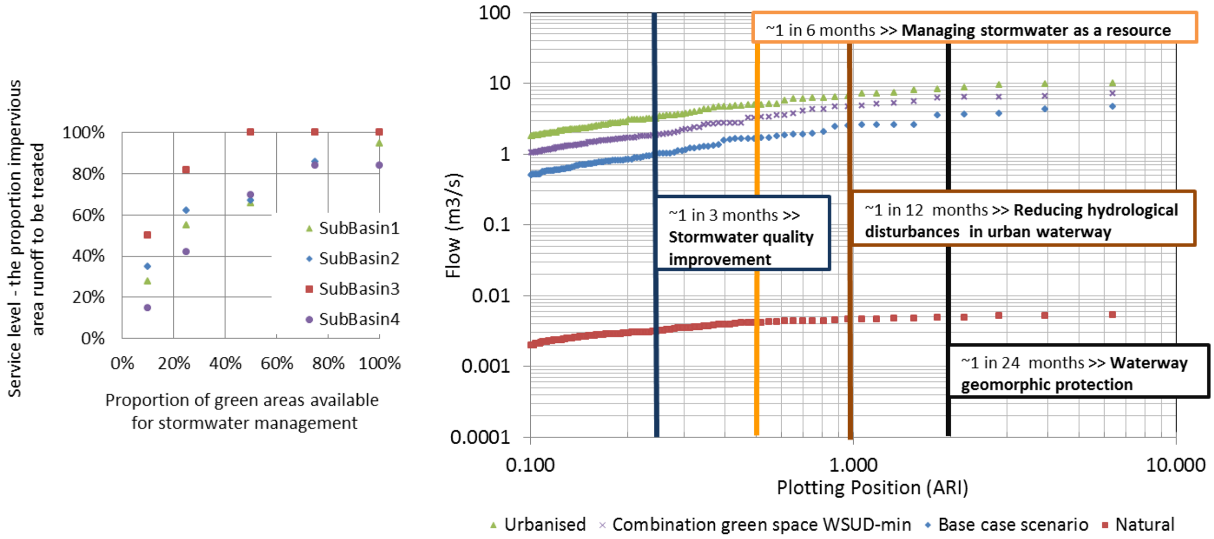
a) b)

Figure 3.a) Relationship between the proportion of green areas available for stormwater management and the service level (i.e. proportion of impervious area runoff to be treated); b) Example results from the minor flooding impacts module: the different ARI peak discharges for two simulated sample scenarios (including the results representing the natural and urbanised catchments).

In terms of microclimate, showed that the LSTin green areas and areas where WSUD interventions were implemented was around5°Clower than inthe impervious areas. These are very preliminary results as the model is still very limited due to a large number of assumptions. But it can already give insights on the potential of green infrastructure in reducing LST.

CONCLUSIONS

This paper introduced the Water Sensitive Cities modelling toolkit, a model for the strategic planning and conceptual design of stormwater management opportunities. This paper is the first attempt to showcase the application of the model to a case study. The model was able to assess stormwater management opportunities under the constraints imposed by the different scenarios. Results indicate that stormwater pollution management also reduce the frequency peak flows associated with the 3 month ARI.However, stormwater pollution management on its on is not able to achieve broader hydrologic and ecologic benefits.

Ongoing development of the modelling toolkit seeks to implement harvesting option in scenario generation stage, as well as improving the microclimate module. Future work is the development of aframework for quantifying non-monetary benefits of stormwater management initiatives.

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