


Modelling a 'business case' for blue-green infrastructure: lessons from the Water Sensitive Cities Toolkit

Kefeng Zhang^{a,*}, Ana Deletic^a, Cintia B. S. Dotto^b, Ross Allen^c
and Peter M. Bach^{d,e,f} 

^a School of Civil and Environmental Engineering, Water Research Centre, UNSW Sydney, High St, Kensington, NSW 2052, Australia

^b City of Melbourne, Council House 2, 240 Little Collins Street, VIC 3000, Australia

^c Three Seeds Agency, 2 Collins Street, Melbourne, VIC 3000, Australia

^d Swiss Federal Institute of Aquatic Science & Technology (Eawag), Überlandstrasse 133, Dübendorf, Switzerland

^e Institute of Environmental Engineering, ETH Zürich, 8093 Zürich, Switzerland

^f Department of Civil Engineering, Monash Infrastructure Research Institute, Monash University, Clayton, VIC 3800, Australia

*Corresponding author. E-mail: kefeng.zhang@unsw.edu.au

Abstract

Stormwater management through Blue-Green Infrastructure (BGI) delivers multiple benefits across urban environments. However, current integrated modelling tools fail to provide a simplified way of assessing these benefits. In this study, we reflected upon the development of an interdisciplinary BGI planning-support tool, known as the Water Sensitive Cities Toolkit (the WSC Toolkit) and offer guidance for effective tool development going forward. Based on interdisciplinary research, the WSC Toolkit incorporates a suite of independent sub-modules but can be connected together to provide integrated assessment, allowing evidence-based quantification of multiple benefits associated with BGI, e.g., stormwater treatment and harvesting, stream hydrology, erosion, minor flooding, urban microclimate, etc. Distinguished from other larger complex models, the WSC Toolkit was characterised by its simplicity, modularity and extensibility, providing scenario-based integrated assessment of these benefits. Through case studies, we demonstrated how the WSC Toolkit can be used to support improved decision-making towards maximising the benefits of BGI. We also showed how it can act as a platform for practical application of latest research outcomes and meanwhile encouraging interdisciplinary collaboration. We reflect upon five key lessons that could guide future researchers in developing effective integrated assessment tools, particularly within highly interdisciplinary fields such as BGI.

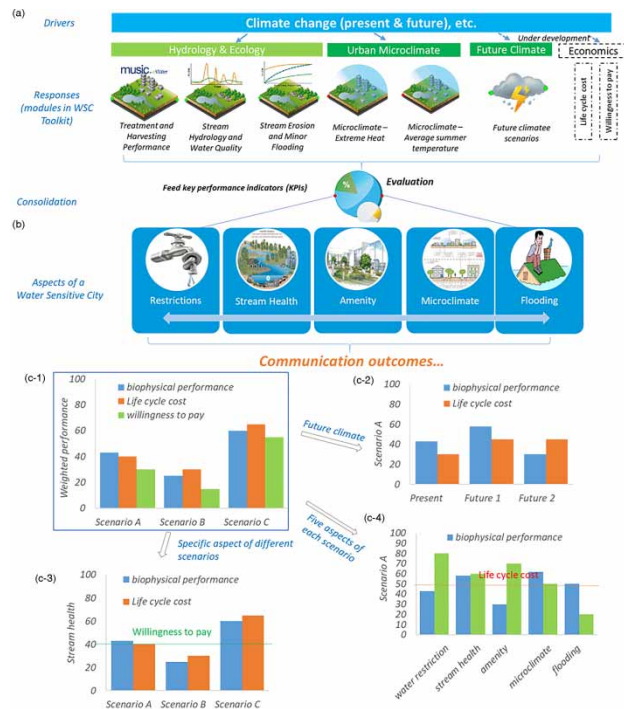
Key words: collaborative decision making, integrated assessment, modelling, stormwater management, Sponge City, Water Sensitive Cities

Highlights

- Multiple benefits of BGI recognised, but lack tools that bridge science and practice.
- Reflections on initial journey towards building the WSC Toolkit for assessing the benefits.
- It supports collaborative decision making & communication among stakeholders.
- Diverse case studies and testing build confidence and trust in new models.
- Lessons to guide future development of effective interdisciplinary integrated assessment tools.

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Graphical Abstract



INTRODUCTION

Urban stormwater runoff volume and pollution has increased significantly over the last decades due to the increase in impervious areas (Arnold & Gibbons 1996; Zgheib *et al.* 2012). This has led to adverse impacts on stream hydrology (Booth & Jackson 1997), and the deterioration of water quality in receiving water bodies (Jeng *et al.* 2005). Urban areas across Australia have also experienced prolonged drought for more than a decade, followed by some of the largest floods on record in 2010 and 2011, which caused considerable financial losses (Hughes & McMichael 2011). Beyond the urban water system, effects of urbanization and higher urban densities have also negatively impacted the health and wellbeing of urban spaces through the urban heat island (UHI) effect (Coutts *et al.* 2007; Alexander & Arblaster 2009). Threats to human health and human thermal comfort have prompted planners and researchers to rethink the design of urban neighbourhoods (Loughnan *et al.* 2010).

Urban stormwater treatment and harvesting through Blue-Green Infrastructure – BGI (commonly referred to in Australia as Water Sensitive Urban Design – WSUD and elsewhere as Low Impact Development – LID, Sustainable Urban Drainage System – SUDS, Sponge City – SC) (Ghofrani *et al.* 2017; Oral *et al.* 2020)) presents significant opportunities for harnessing stormwater as a resource for use in cities, while simultaneously protecting waterways from excessive pollution and ecosystem degradation and improving urban amenity (Wong *et al.* 2013). BGI stormwater technologies (e.g. biofilters and wetland) can efficiently remove sediments, nutrients, heavy metals, micropollutants and microorganisms in stormwater (Zhang *et al.* 2014; Persaud *et al.* 2019). Meanwhile, the fit-for-purpose use of stormwater to augment traditional water supplies helps to restore natural flows and water quality conditions and also to minimize the pollution impacts associated with urban areas (Fletcher *et al.* 2007; Mitchell *et al.* 2007; Zhang *et al.* 2020). In addition, BGI are also able to mitigate excessive urban heat by retaining water in the urban landscape and promoting increased evapotranspiration, which results in a reduction of local temperatures (Coutts *et al.* 2013b; Gunawardena *et al.* 2017; Broadbent *et al.* 2018).

Although the benefits of BGI may appear obvious, their uptake remains limited and a ‘business case’ for these systems can only be established through provision of quantitative evidence, with which a suitable economic assessment (e.g. cost-benefit analysis) or decision analysis framework (e.g. multi-criteria decision analysis) can subsequently be applied. Nevertheless, quantifying the multiple benefits associated with BGI towards building Water Sensitive Cities (Wong & Brown 2009) is not straightforward, as the nature of environmental and urban stormwater management is complex and diverse, involving multiple disciplines across economics, urban climatology, environmental sciences, ecology and engineering (Brown *et al.* 2015). An interdisciplinary approach is required to make significant real-world impact in practical applications of industry needs and problems (Elsevier 2015), and to tackle grand, global challenges (Ledford 2015). Brown *et al.* (2015) shared their successful experience of how to successfully catalyse interdisciplinary collaboration to deliver sustainable water management strategies of a water sensitive city. In particular, the development of integrated models as vehicles for communicating interdisciplinary research could be a promising approach to promote multidisciplinary collaboration. Integrated models help connect researchers, policy makers, and industry practitioners, providing a shared mission for all collaborators trying to make a real-world impact through their work, as well as enabling quicker transfer of latest knowledge into practice (Bach *et al.* 2014).

There are a variety of existing models for communicating the diversity and complexity of the BGI scholarship to practice and supporting the planning thereof (Lerer *et al.* 2015; Kuller *et al.* 2017). However, use and adoption of such tools in practice are minimal due to mismatches in meeting industry conventions and user expectations (Kuller *et al.* 2018) and the general utility of such tools at the science-policy interface (Chong *et al.* 2017) that can influence the level of involvement of stakeholders. Outstanding challenges for building interdisciplinary support tools still exist. Firstly, facilitating knowledge transfer is considerably difficult, especially when coordinating researchers from various backgrounds. Moreover, generalisation and education of the knowledge to the broader urban water and planning sectors is another challenge, particularly when audiences communicate with different technical languages. Guidance document and demonstration projects may become useful means of communication between the different stakeholders. Models, however, can provide an automation and systematic approach to applying the science in an experimental local context, e.g. planning-support, testing and evaluating policy options, exploratory modelling and participatory modelling (Voinov & Bousquet 2010).

Historically, there are examples of successful development of integrated urban water models from research to practice and mainstream. For example, the Storm Water Management Model (SWMM) is the most widely used hydrology and hydraulic water quality simulation model for planning analysis and design related to stormwater management (Rossman 2010). The development of SWMM (over the last 50 years) involved a large development team including researchers, government agencies, and private sectors and so on with different background. Guidance documentation, reports and demonstration projects were produced during development phase and feedback was collected to refine the model, which contributed the success and widespread use of SWMM. MUSIC (the Model for Urban Stormwater Improvement Conceptualisation, by eWater (2014)) is another example. It is widely used in Australia for the conceptual design of urban drainage systems with emphasis on BGI to meet the best management practice. MUSIC is a product from the Cooperative Research Centre for Catchment Hydrology (CRCCH) research program, which originally had the clear goal of packaging many of its research findings into a user-friendly, integrated tool to predict various aspects of urban catchment hydrology, e.g. stormwater quality and quantity, the performance BGI (Wong *et al.* 2002). Development, communication and adoption strategy plans were made to facilitate the communication between research team, industrial stakeholders and end-users, and provide focussed discussion, comments and improvements for better delivery of catchment solutions. These all show a good example of bringing a wide range of multidisciplinary skills to promote the procedure of transferring the research into practice. There are also some other examples of integrated urban water models, such as MOUSE, InfoWorks and STORM, which also have their capabilities and strengths in different aspects,

e.g. diverse uses, spatial and temporal resolution, catchment and drainage networks, contaminants and types of BGI solutions (Elliott & Trowsdale 2007; Obropta & Kardos 2007).

Despite leading examples and an emergence of many alternative tools from the scholarship (see (Lerer *et al.* 2015; Kuller *et al.* 2017)), common pitfalls remain. Firstly, in addition to being complex, existing BGI models also do not simulate the diversity of multiple benefits beyond a single discipline. This is compounded by lack of user-friendliness and the required transdisciplinary expert knowledge, which is in contrast to the aforementioned examples of stormwater management models usually adopted within a single disciplinary domain. Secondly, BGI models do not directly simulate how well BGI provide ecosystem services, which are actually one of their key purposes (Elliott & Trowsdale 2007) and additional effort is required to quantify these. For example, many models focus solely on urban water engineering aspects but fail to assess other societal benefits such as local microclimate improvement associated with distributed stormwater management (Wong *et al.* 2013). Thirdly, given BGI's interdisciplinary nature, a more diverse audience of stakeholders is involved. Not only engineers (for urban drainage model development), but also social scientists, climatologists, economists who can provide the research basis for assessing relevant benefits should be involved. Finally, in large, interdisciplinary research programs, an overarching modelling toolbox may not always be the initially intended primary output. One needs to therefore ask the question if and how research outcomes should be packaged if the need for a modelling toolbox eventually arises.

In this paper, we reflect upon the early development of an interdisciplinary planning-support tool, known as the Water Sensitive Cities Toolkit (WSC Toolkit) and offer guidance for effective tool development going forward. The WSC Toolkit provides evidence-based quantification of multiple benefits associated with BGI based on the interdisciplinary research outcomes from within the CRC for Water Sensitive Cities (CRCWSC), a nine-year program, which brought together an interdisciplinary and multi-national team of researchers. Our reflection is scoped around four key areas:

- **Conceptualising** a usable software that encapsulates and communicates the interdisciplinary nature and approach to BGI planning
- **Execution** and development of the toolkit alongside ongoing research and practice including decisions around model complexity vs. communicating key research outcomes
- **Demonstration** of the toolkit's application, involvement and co-development with stakeholders at a national level
- **Key lessons learnt** around model development, design and communication.

While there are many papers on lessons learnt from model development (e.g. Burger *et al.* 2016), the novelty of this paper lies in the interdisciplinary context under which we built the WSC Toolkit. The lessons in this paper reflect the early years of the tool's development from its conception in 2012 up to 2017. By no means do we conclude that the tool embodies a 'perfect' model for BGI planning but has provided valuable lessons that any model developer can adopt. In fact, since 2017, the WSC Toolkit has been integrated into other ongoing tools developed by the CRCWSC and rebranded. Our intended purpose of this discussion is to provide suitable guidance to modellers and practitioners who work at this interdisciplinary and science-practice interface and support the future development of effective and usable tools for BGI.

CONCEPTUALISING THE WSC TOOLKIT

Defining the aims of the WSC toolkit

The initial concept for the WSC Toolkit arose after much deliberation within a work package of the research program labelled as 'Integration and demonstration through urban design', intended to make research outputs accessible to the CRCWSC's large group of industry stakeholders. By harnessing the

momentum of a number of ongoing modelling projects at the time (Rauch *et al.* 2017; Bach *et al.* 2020), producing an accessible piece of modelling software as a vehicle for applying cutting-edge research was seen as a favourable option, especially in the early years of the CRCWSC. As such, to distinguish itself from other larger complex models, several fundamental modelling aims were defined for the WSC Toolkit including:

- **A tool for integrated assessment.** Given the early stages of many research projects, proper model ‘integration’ would not be possible given existing knowledge gaps about system interactions and would lead to unintended and potentially ‘wrong’ outcomes (e.g. studies have discussed the intricacies of integration in-depth (Voinov & Shugart 2013; Bach *et al.* 2014)). As such, the ethos was to create a tool that was not about linking all the processes of different aspects, but rather to link all results/benefits and provide a holistic picture for integrated assessment for guidance and decision-making.
- **Simplicity** referred to a tool for the layperson. At the time, there were plenty of detailed models available (e.g. MUSIC, SWMM), but only few that would serve a purpose in the initial planning stages of BGI. As such, to support discussion among multiple stakeholders, it was more effective to develop a tool that can perform an initial rapid screening of BGI solutions and can be easily used by a wide range of end-users rather than modellers, e.g., governments (to support development of regional or local water strategies), water utilities (to support water servicing strategies), as well as consultants (to support water-sensitive strategic planning and urban development).
- **Modularity and extensibility.** In order to adapt to the increasing complexity of research and management/changing of development teams that often occur within large nine-year research programs, we aimed to develop a modular tool in terms of software design and extensibility (i.e., a ‘plug-n-play’ architecture) so that future refinement of existing research and new research outcomes could be readily incorporated. In its initial years, science around aspects such as the impact of BGI on urban microclimate or economics were still in their infancy and had not yet produced detailed models encompassing all variables and processes.
- **Scenario-based assessment.** In order to align with the ‘endgame’ of supporting decision-making, current industry approaches to assessing BGI options in urban precincts and the overarching CRCWSC agenda, scenario-based assessment (where a ‘do-nothing’ option would be compared to ‘water sensitive alternatives’) was found to be most effective in communicating the ‘business case’ for BGI. This type of language was already prevalent in Australian integrated urban water management and it was favourable to adopt this familiar style of thinking.

Overall toolkit concept design

Figure 1 illustrates the concept of the WSC Toolkit that resulted from modelling aims. The benefits/responses of implementing stormwater managements across various aspects including hydrology, ecology, society (microclimate), as well as economics can all be assessed independently via different modules (Figure 1(a)). Results can then be linked together by an evaluation module to give integrated assessment across five important biophysical performance aspects of water sensitive cities (Figure 1(b)), which are well informed by all the research conducted within CRCWSC (Wong *et al.* 2013). Outputs with different levels of details can then be communicated with end-users in a straightforward way. For example, the overall biophysical performance, life cycle costs and community preferences (i.e. willingness to pay) for different stormwater management scenarios can be plotted together to allow an overall comparison (Figure 1(c-1)). A favourable scenario (or an optimum) based on the overall comparison then can be further inspected with regards to different biophysical performance aspects (Figure 1(c-4)) or considering future climate conditions (Figure 1(c-2)); in addition, if a specific aspect of biophysical performance is concerned (e.g. stream health – a suburb with a waterway that suffers significant stream erosion), these scenarios can then be compared with regards to the concerned issue (Figure 1(c-3)).

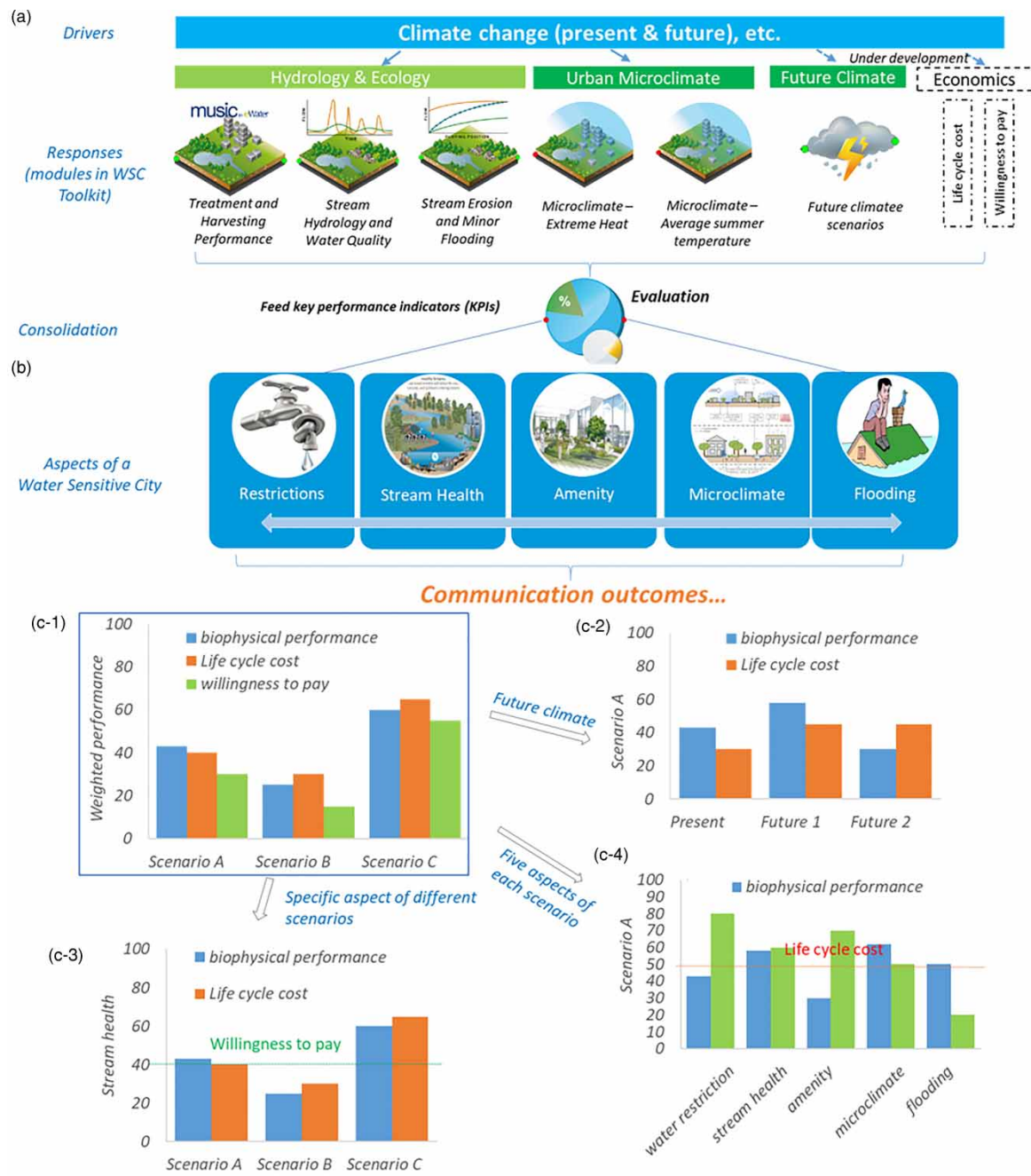


Figure 1 | Concept of WSC Toolkit Design.

Reviewing this concept with industry stakeholders reinforced the alignment of the modelling approach with different end-users and that, even without direct consultation of experts, a level of confidence and trust that the tool encapsulated the interdisciplinary nature of BGI and urban stormwater management could be created.

EXECUTION AND OVERVIEW OF KEY MODEL CONCEPTS

Design strategies

Design of assessment modules (e.g. responses in Figure 1(a)) involved three main steps: (1) identifying key research highlights from respective projects within the program that can be operationalised,

(2) selecting and conceptualising suitable models and performance indicators that will enable the research outcomes to be adopted in practice and (3) programming, testing and demonstrating the assessment modules against existing data sets and standards within the toolkit's architecture (Figure 1). Within the scope of this paper, we discuss how we conceptualised four areas of research within the toolkit, all at different stages of their research and development: hydrology and ecology, urban microclimate, future climate and economics. A combination of approaches included:

- leveraging existing industry standard packages such as MUSIC (eWater 2014) to undertake initial hydrologic simulation followed by evaluation using new research outcomes,
- starting with simplified empirical approaches to urban heat (e.g. Coutts *et al.* 2016) to build understanding and confidence in industry stakeholders about newer concepts
- developing large accessible climate data sets that forgo the need to run complex climate models, yet provide a comparable and consistent baseline for comparing BGI scenarios (the impact of future climate on BGI is analysed in Zhang *et al.* (2019)), and,
- distilling complex economic research outcomes in favour of highly uncertain empirical relationships.

We briefly describe the underlying concepts for each of the four domains of assessment.

Hydrology and ecology

Treatment and harvesting performance

Extensive research on stormwater management and harvesting has already been conducted resulting in many stormwater models such as SWMM (Rossman 2010) and MUSIC (eWater 2014). MUSIC is extensively used for assessing the stormwater quality treatment and harvesting performance of BGI interventions, more commonly referred to in stormwater systems as WSUD. As such, rather than rebuilding existing hydrologic models, we leveraged the availability and prevalence of MUSIC in Australian stormwater practice and used its command line functionality within the WSC Toolkit. Output from MUSIC (i.e. hydro- and pollutographs) could then be used directly to provide information on stormwater management benefits, e.g. load reduction of total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN) as well as the amount of reused water. By including MUSIC's performance indicators, we can form a more complete picture of stormwater management benefits when combined with the WSC Toolkit's other modules.

Stream hydrology and water quality

This sub-module was designed to assess 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 base flows. Based on the work on restoration of creek hydrology conducted by Walsh *et al.* (2012) in Little Stringybark Creek catchment (Melbourne, Australia), four indicators, of direct ecological relevance to streams were recommended:

- **Number of runoff days per year:** an indicator of stream disturbance and typically very low in natural catchments. A runoff day is defined using Equation (1):

$$Q_{\text{peak-daily}} > 3 * Q_{\text{baseflow}} \quad (1)$$

where $Q_{\text{peak-daily}}$ is the peak flow of the day, [m^3/s]; Q_{baseflow} is the median daily base flow of the natural catchment, [m^3/s].

- **Proportion of total volume reduction (VR%)**: indicates how well stormwater management initiatives reduce runoff from urbanised areas, defined as the difference between the excess volumes generated from urbanisation and volumes used/lost from BGI interventions. VR% is calculated using Equation (2).

$$VR\% = \frac{V_{\text{reused}} + V_{\text{evap}} + V_{\text{infil(optional)}}}{RD * EIA} \times 100 \quad (2)$$

where V_{reused} , V_{evap} , and V_{infil} are the annual total volume of water reused, evapotranspired, and infiltrated, respectively [m^3]. RD is mean annual rainfall depth [m]. EIA is effective impervious area [m^2] of the study catchment.

- **Proportion of filtered volume (FV%)**: a measure of how stormwater management restores natural stream flows based on the aim of filtering water, which enters the stream during the most frequent storm events

$$FV\% = \frac{(V_{\text{exfil}} + V_{\text{infil}} + V_{\text{overflow}})(< 3 Q_{\text{baseflow}})}{RD * EIA} \quad (3)$$

where V_{exfil} and V_{overflow} are the annual total volume of water ex-filtrated and overflowed, respectively [m^3].

- **Water Quality**: indication of how well WSUD stormwater systems achieve pollution concentration targets that are beneficial to the streams (as opposed to annual loads). Median concentrations of TSS, TP and TN across the 6-min performance data are estimated using MUSIC.

As these four indicators are readily estimated using output hydrographs from MUSIC, it was yet another reason for the direct reliance on MUSIC in the WSC Toolkit.

Stream erosion and flooding

The impact of various WSUD interventions on the geomorphic form of the streams by calculation of the Stream Erosion Index (SEI) before and after intervention is the third aspect of the hydrology and ecology group of modules (Brookes & Wong 2009). SEI is computed as the ratio between the stream erosion potential of the post developed catchment; we refer to $SEI_{\text{urbanised}}$ (before intervention) and SEI_{WSUD} (after intervention) (Equation (4)):

$$SEI_{(\text{Urbanised or WSUD})} = \frac{\sum \left(Q_{\text{post}} - \frac{Q_2}{2} \right)}{\sum \left(Q_{\text{pre}} - \frac{Q_2}{2} \right)} \quad (4)$$

where Q_{post} is the flow rate [m^3/s] from (i) urbanised catchment when calculating $SEI_{\text{urbanised}}$, and (ii) post intervention through WSUD measures for SEI_{WSUD} ; and, Q_2 is the 2-year Average Recurrence Interval (ARI) peak discharge [m^3/s] from the natural (pre-developed) catchment. Half of the Q_2 flow defines the critical shear stress conditions as corresponding to a 'channel forming flow' (Brookes & Wong 2009). As with other indicators, MUSIC outputs were once again used to compute the flow series and to conduct a partial frequency analysis is used to determine Q_2 according to the method described in Australia Rainfall and Runoff (AR&R) (Pilgrim 2001).

The potential of the different stormwater management options to reduce minor flooding in urban areas is also estimated, mainly in terms of managing the largest, most frequent events (e.g. rainfall events up to the 3-month for water quality management). Same partial frequency analysis was used

to estimate the probability of occurrence of flood events (ARI of up to 10 years) for understanding minor flooding benefits, similar methods were also used by [E2Designlab \(2013\)](#).

Urban microclimate

The assessment of urban microclimate (specifically urban heat) is often difficult, e.g. processing high resolution airborne thermal infrared remote sensing data (e.g. [Coutts *et al.* 2016](#)), Landsat data mapping (e.g. [Aniello *et al.* 1995](#)) or running highly complex computational models based on Computational Fluid Dynamics (CFD) ([Nice *et al.* 2018](#)). However, these methods only require acquisition of high-quality data that are sometimes also expensive, but also the methods themselves are complicated beyond the use of the layperson. Development of the urban heat mitigation science for BGI is an ongoing topic within the CRCWSC, beginning with the establishment of empirical relationships between BGI and land surface temperature ([Coutts *et al.* 2013a, 2013b](#)) and leading, later on, to the development of a fast model for urban heat mitigation assessment through BGI ([Broadbent *et al.* 2019](#)).

The initial representation of urban heat mitigation in the WSC Toolkit was a simple empirical mapping exercise based on investigations that captured spatial variations in land surface characteristics and physical Land Surface Temperature (LST) available under several CRCWSC projects (B3.1 Cities as Water Supply Catchment: Green Cities and Microclimate and B3.2 The Design of the public realm to enhance urban microclimates – both led by [Tapper \(2016a, 2016b\)](#)). A large monitoring program of LST using airborne remote sensing (30 m resolution) between 12 pm and 2pm within the City of Phillip Bay (Melbourne, Australia) on 26th February 2012 was performed by [Coutts & Harris \(2013\)](#) and [Nury *et al.* \(2012\)](#); the results indicated that different land covers (e.g. dry or irrigated grass, roof, concrete, tree, road and water) had distinctly correlated LST distributions (see [Figure 2](#)).

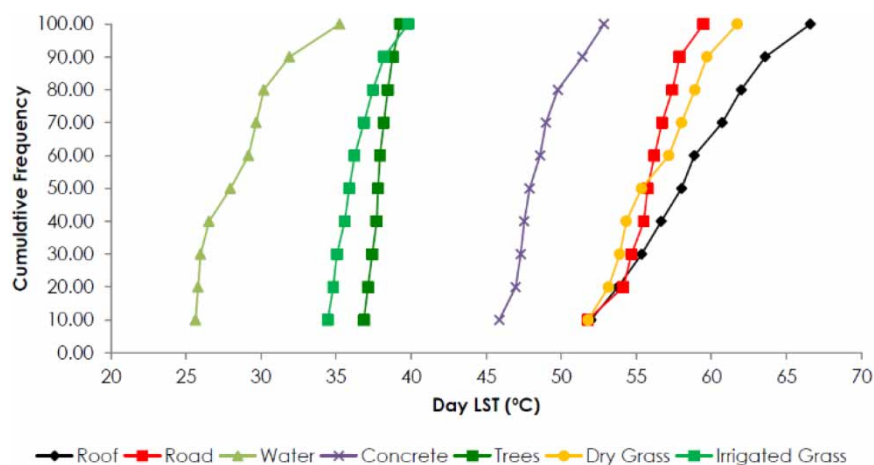


Figure 2 | Daytime Land Surface Temperature data from Port Philip Bay on extreme heat day in 2012 (data from [Harris & Coutts \(2013\)](#)).

These LST distributions of different land covers were then adopted and implemented in the WSC Toolkit as an initial means of demonstrating, on the one hand, the variations in LST across a cityscape and, on the other hand, the impact that BGI can have on urban heat. Particular emphasis was placed on making this module interactive (using aerial imagery and a sandbox tool, allowing users to freely place BGI interventions across their case study). Each BGI intervention was assumed to alter the surface land cover and consequently its temperature and was thus represented as one of the existing land

surface covers in [Figure 2](#) (e.g. irrigated grass, water and/or trees). This would later be replaced by more robust modelling tools that simulate the energy balance and convert surface to air temperatures such as TARGET ([Broadbent *et al.* 2019](#)), which has since been underway.

Future climate

Assessment of the uncertainty of the benefits associated with stormwater management in future climate usually require high spatial and temporal resolution rainfall projections, which are rarely available. Hence it was decided to work closely with climate scientists on the CRCWSC project (B1.1 Cities as Water Supply Catchment: Urban rainfall in a changing climate – led by [Deletic \(2016\)](#)) to develop a Multiplicative Cascade Model for prediction of high-resolution space-time simulations of rainfall projections. With the successfully development of the model ([Raut *et al.* 2018](#)), future projections of 6-min and 1 km resolution rainfall downscaled from ensemble of 8 different General Circulate Models (GCMs) at various sites across four cities (i.e. Melbourne, Adelaide, Sydney and Brisbane) in Australia were generated to form large data sets. Given the complexity of setting up such models, the access to future climate prediction data was instead preferred as it: (1) forwent the need to simulate future climate (allowing faster setup and evaluation of BGI scenarios), encouraging users to run their scenarios using an ensemble of future rainfall datasets rather than choose a single best model, (2) provided a consistent basis for multiple users to compare future climate impacts of their interventions, (3) maintained the tool's modularity, allowing developers and researchers to roll out updates to these data if necessary in future. More information on the data set and its impact on BGI interventions is provided by [Zhang *et al.* \(2019\)](#).

Economics

The economic valuation of BGI has been a topic of interest worldwide ([Bagstad *et al.* 2013](#); [Pandit *et al.* 2013](#); [Ashley *et al.* 2018](#); [Gunawardena *et al.* 2020](#); [Langergraber *et al.* 2020](#)). For the WSC Toolkit and in conjunction with the ongoing research within the CRCWSC program at the time on the willingness to pay (WTP) for the benefits of BGI ([Gangadharan 2016](#)), several options for quantification were available. On the one hand, life cycle costing (LCC) ([Gluch & Baumann 2004](#)) is well-integrated into the MUSIC model ([eWater 2014](#)) and one option that could be leveraged. On the other hand, new outcomes from research on the non-tangible benefits including considerations of key socio-economic factors such as community income, education, and psychological factors such as personal experiences and preconceptions through surveys conducted across Australia were emerging. Although the economics were not extensively considered during the development phase of the WSC Toolkit that this reflective paper is based on, its importance was recognised in the development of other modules and guided the selection of performance indicators from which monetary values could later be derived.

Software implementation

The WSC Toolkit and all the aforementioned modules including the integration with MUSIC was built into a simple user interface (see [Figure 3](#)). User interface design focussed heavily on presenting the tool's overarching concept ([Figure 1](#)) in a quick, visual, and accessible manner. The core engine was built using C++, which interfaced with Python modules. A modular software architecture and data management structure was assembled. Large data sets (e.g. future rainfall predictions or aerial imagery) are input to the model using industry-standard file formats (e.g. netCDF and GeoTIFF respectively). Outputs were written as .csv or image files, easily accessible and read by standard text and image-processing software. This ensured that users could readily post-process model results

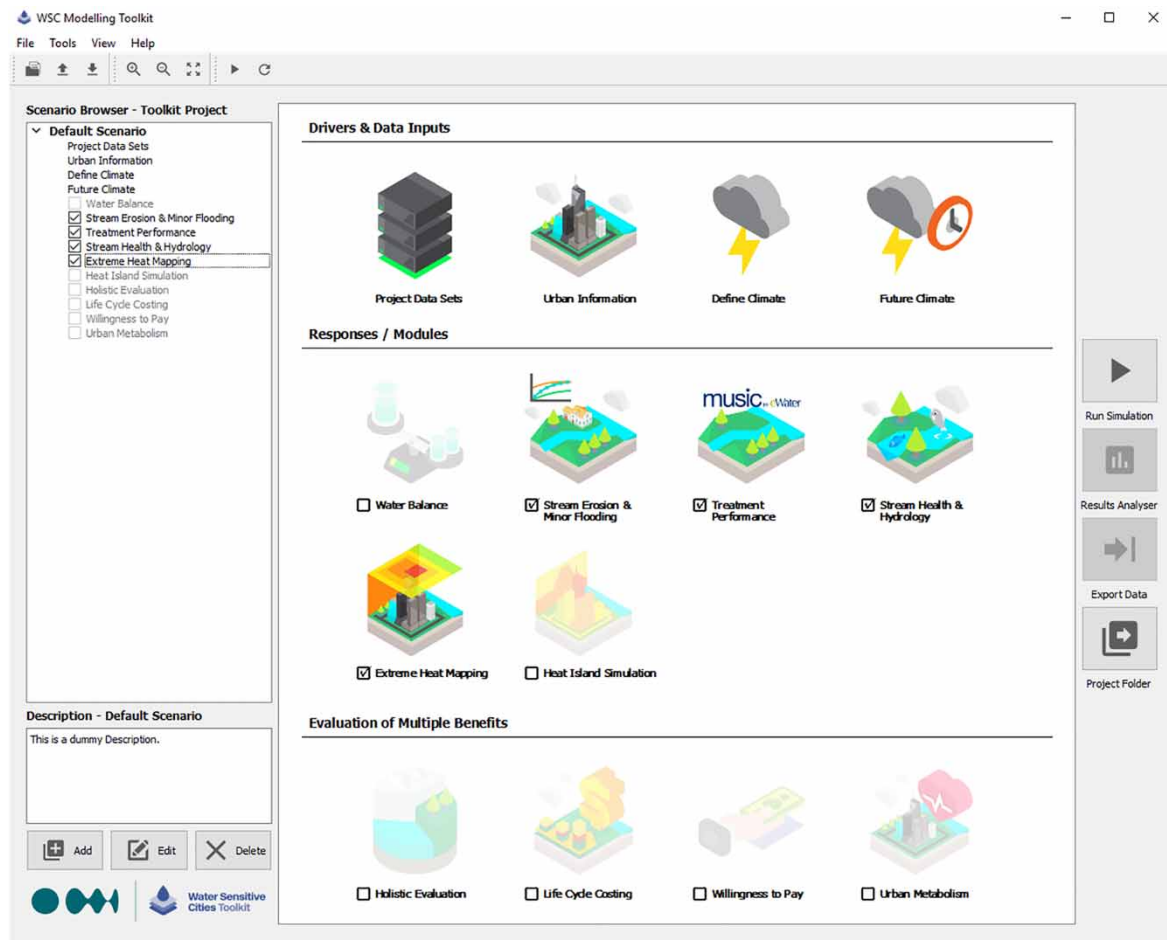


Figure 3 | Screenshot of the WSC Toolkit Software Implementation.

and communicate these effortlessly. As MUSIC is a licensed software, its simulation engine could not be packaged with the WSC Toolkit to beta testers. However, given its outreach across Australia and the time resource required to re-develop its key functionality, this trade-off had to be accepted.

DEMONSTRATION AND APPLICATION

The development of WSC Toolkit saw the frequent opportunity to leverage case studies and contacts in the Australian urban water sector to test and demonstrate its potential. This opportunity was also a means of disseminating ongoing research outcomes, building an interested and confident audience, establishing trust and validating the user experience design.

Integrated assessment of the Toolern Precinct

Integrated assessment across various aspects allows in-depth comparison between different potential scenarios. A case study was conducted on the Toolern Precinct, Melbourne, Australia (24 km² urban greenfield development) to investigate stormwater management benefits, with emphasis on the hydrology and ecology aspects. The case study was chosen for its familiarity, having recently (at the time) been subject of an integrated water management plan and serving as a case study in parallel modelling research (Bach *et al.* 2020). Five different scenarios were developed for a sub-catchment of the Toolern Precinct with 11,600 m² of total residential roof area, 3,450 m² of total road area and

1,950 m² of commercial impervious area: (1) lined bioretention systems, (2) lined bioretention systems with rainwater tanks (for harvesting and reuse), (3) unlined bioretention systems (4) constructed wetlands, and (5) stormwater ponds. These systems contained in each scenario are widely used for stormwater management and hence through this study it was interesting to see their differences in the benefits of various aspects they can provide, thus proper decisions made under specific conditions. Details of the catchment properties and configurations of the treatment systems are given in Table S1 of the Supporting material. A 'no stormwater treatment' scenario was also included in the simulation for comparison. Further information about the Toolern Precinct can be found in [Bach et al. \(2020\)](#).

A summary of all the simulation results for the five proposed stormwater management scenarios and 'no management' control are presented for Toolern Precinct in [Table 1](#). In terms of treatment performance, it can be easily seen that, although scenarios with ponds and wetlands had around 13–49% lower pollutant loads reduction, they were more than twice as effective in reducing runoff volume due to greater system area and storage capacity (resulting in detention of stormwater and higher evapo-transpiration) compared to bioretention systems without harvesting. Unlined bioretention systems allow exfiltration loss and hence can reduce ~2.3 time more runoff volume than lined systems. Rainwater tanks exhibited additional benefits in reducing runoff volume, since the captured rainwater (3.2 ML/year) can be used for irrigation to reduce potable water supply. This simultaneously contributed to a higher reduction of pollutant loads, as was also proven in other studies ([Zhang et al. 2020](#)).

As for stream hydrology and water quality, differences between scenarios can similarly be observed, with the harvesting scenario (bioretention + rainwater tank) reducing the most runoff volume and

Table 1 | Results of WSC Toolkit simulation on stormwater management benefits

Benefit	Indicators	No treatment	Lined Bioretention	Lined Bioretention + harvesting	Unlined Bioretention	Wetland	Pond	Ideal values
Treatment performance	Volume reduction (%) ^a	0	7	43	16	26	27	–
	TSS reduction (%)	0	93	96	93	71	78	85 ^b
	TP reduction (%)	0	71	82	73	66	67	45 ^b
	TN reduction (%)	0	68	80	70	52	45	45 ^b
Water captured	Water supplied (ML/year)	0	0	3.2	0	0	0	–
Stream hydrology and water quality	Number of runoff days per year	97	136	106	322	355	355	–
	Proportion of runoff volume reduction (%)	0	5.6	34.6	5.6	6.7	5.3	–
	Proportion of filtered volume (%)	0	0.1	0.1	0.0	0.0	0.0	78/93 ^c
	Water Quality – TSS (mg/L)	201.5	2.6	2.3	2.4	6.0	12.1	20 ^d
	Water Quality – TP (mg/L)	0.41	0.11	0.11	0.11	0.06	0.09	0.05 ^d
	Water Quality – TN (mg/L)	2.86	0.6	0.6	0.6	1.1	1.4	0.60 ^d
	Stream Erosion Index (SEI)	4.1	2.1	1.4	2.0	1.2	0.8	2/1 ^e
Stream erosion and minor flooding	3 month ARI peak flow reduction	0	38	63	38	64	70	–
	2 year ARI peak flow reduction	0	20	30	20	32	44	–
	Stream Erosion Index (SEI)	4.1	2.1	1.4	2.0	1.2	0.8	2/1 ^e

^aFor the Volume reduction in the Treatment Performance, it only applies to the treatment system (considering in and out), meanwhile exfiltration loss is considered.

^bFrom BPEM (VSC 1999).

^c78 – catchment with pasture vegetation and 93 – catchment with forest vegetation: these were derived according to the model by [Zhang et al. \(2001\)](#).

^dvalues suggested by [Walsh et al. \(2012\)](#) for stream health.

^e[Brookes & Wong \(2009\)](#) suggested that the 'best practice' SEI that should be achieved is 2 with a stretch target of 1.

pond treatment scenario providing relatively poorer water quality. Notably, the number of runoff days calculated for all management scenarios were higher than the urbanised catchment (with no treatment) (Table 1); this is because stormwater systems not only attenuate daily peak flows but also increase flow durations through slow release. None of the proposed scenarios showed remarkable increase in the proportion of filtered volume as only flow rates lower than three times median daily base flow are counted as filtered volume (Equation (3)). Nevertheless, further treatment may be required to meet the TP and TN target values suggested by Walsh *et al.* (2012) to protect stream health (Table 1).

According to the estimation by WSC Toolkit (Table 1), all management scenarios are efficient in reducing the peak flows by 35–70% for the 3-month ARI (which is normally used as the design flow for stormwater quality improvement, VSC 1999) and 20%–45% for the 2-year ARI peak flow (used for waterway geomorphic protection) compared to the urbanised catchment (Table 1 and Figure 4). Ponds and wetlands were more effective (60–70% for 3-month ARI and 30–45% for 2-year ARI) than bioretention without harvesting scenarios (38% for 3-month ARI and 20% for 2-year ARI) in reducing the peak flows; harvesting and reuse of stormwater can again provide additional benefits in reducing peak flows (63% for 3-month ARI and 30% for 2-year ARI). SEI values were also reduced by all the scenarios, which all met the ‘best practice’ SEI value of 2 suggested by Brookes & Wong (2009), with pond being the best strategy (SEI = 1).

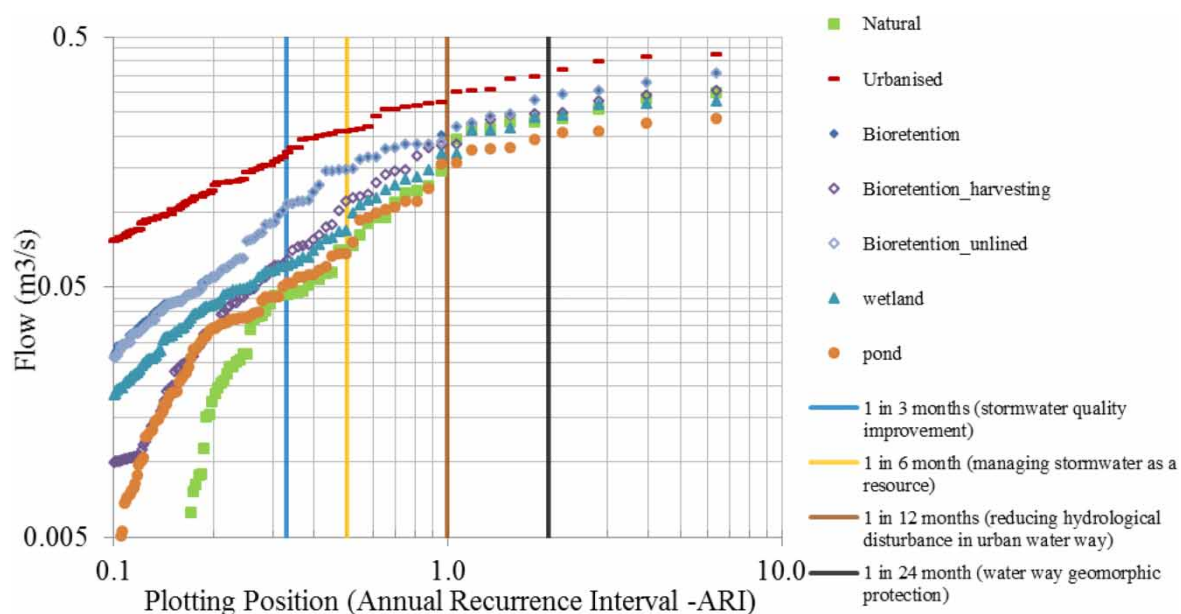


Figure 4 | Flood mitigation (Peak flow) of different scenarios.

Using the WSC Toolkit for estimating those benefits of various aspects, the quantitative comparisons between scenarios are possible, which further supports well-informed decision-making process. For example, if the most important objective of Toolern Precinct development is to protect local stream erosion, then the pond treatment scenario is optimum. Otherwise, if better treatment performance is sought, bioretention systems with stormwater harvesting is preferable. With this information, further integrated assessment can be conducted to link all these indicators to the five different aspects of Water Sensitive City to allow an overall evaluation as demonstrated in Figure 1.

Supporting a collaborative process

While the above application demonstrates the detailed assessment of the WSC Toolkit, it can also be used in a simpler way to support comprehensive collaborative process. CRCWSC ran several Research Synthesis workshops, which brought together many research areas and disciplines with government and private industry partners to develop practical ‘ideas’ for addressing specific industry-based challenges. For example, in the ‘Ideas for Aquarevo’ concept developed by the CRCWSC Research Synthesis workshop in 2014 (CRCWSC 2014), three broad themes were identified around which the ‘ideas’ should be developed: (1) urban planning and design, (2) BGI and (3) intelligent (water + energy) systems. The WSC Toolkit was supported by the blue-green infrastructure theme, which aimed to use water and vegetation to achieve multiple community benefits, including stormwater quality improvement, safe conveyance of floodwaters, and improved urban microclimate through mitigation of urban heat. In the synthesis workshop, the WSC Toolkit’s stream health module was applied to show stormwater management initiatives adopted at Marriott Waters (one of the focus area of Aquarevo site) and incorporated in the Aquarevo master plan (such as linear pond/wetland system). Results show stormwater management initiatives in reducing pollutant loads associated with residential area, while other indicators of stream health (e.g. number of runoff days) were not well managed by the adopted stormwater management measures. However, these other indicators were less relevant at this location given the highly modified and degraded condition of the receiving waters.

Additionally, the impact of BGI on local temperatures was also assessed using the microclimate impact module developed at that time (see Figure 5). Through implementing BGI initiatives in Aquarevo, land surface temperatures shifted towards cooler ranges due to the increase in open space areas (e.g. grass, trees, water, etc) and decrease in hard road surfaces. Since then, the microclimate module has been further developed and its application and demonstration are showcased in the next sections.

External and independent case studies

As part of ongoing research synthesis, the WSC Toolkit demonstrated its applicability as a support tool for stakeholder workshops. However, the litmus test of the model was its ability to work with ‘real-world’ data and case studies and for users to be able to use the tool independent of its developers. As such, we also conducted several external, independent case studies to test whether our proposed framework (Figure 1) was aligned with industry workflows.

We tested the WSC Toolkit’s urban microclimate module on the City of Unley in South Australia (see Figure 6(a)). Unley Council strives to create a more liveable, resilient and sustainable city for future generations. Urban heat is an ongoing challenge in South Australia. As such, BGI solutions were suggested for a particular downtown street (Leader Street) to improve the local amenity within the council’s busiest district.

The WSC Toolkit was set up using high-resolution aerial imagery, which was reclassified to an input land cover map using ArcMap’s supervised classification toolbox. Upon running the WSC Toolkit, its visual outputs could be used to engage with the local council to explore key hotspots around the council area. A detailed report on this investigation is documented elsewhere (Zhang *et al.* 2015). Using this heat map, the council could not only identify potential sites for BGI solutions to mitigate urban heat, but also test the effectiveness of street-scape tree pits and bioretention swales along Leader Street. Figure 6(b) demonstrates visually the impact that implementing and establishing these green assets had on local temperature reduction (up to 6 °C in LST during extreme hot summers). With this first, empirical version of the WSC Toolkit’s microclimate module, significant impact through demonstration and understanding of the science behind urban heat could already be established.

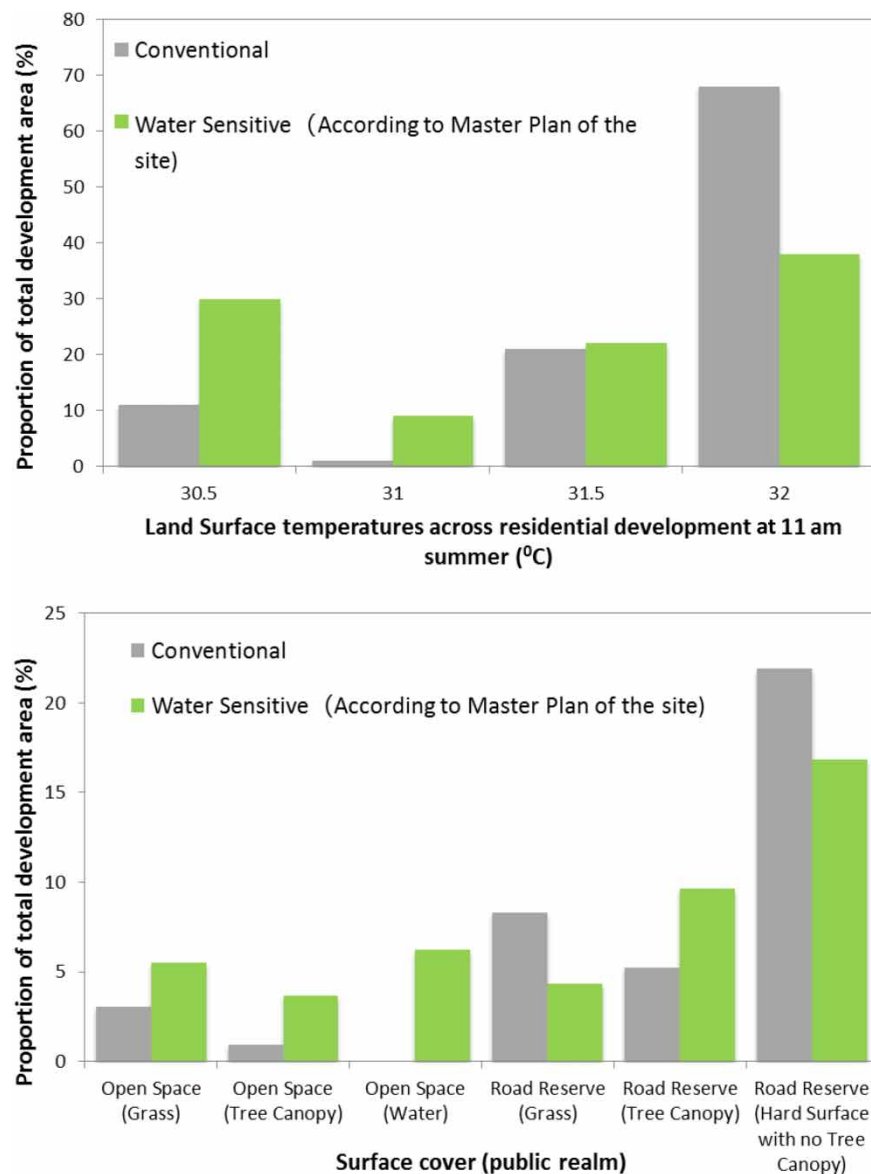


Figure 5 | Microclimate impact assessment on the Aquarevo case study modelled during the CRCWSC Research Synthesis workshop in 2014.

Further initiatives in South Australia began in 2017 and were led by *Natural Resources Adelaide*, who demonstrated leadership in applying the WSC Toolkit's urban microclimate module to a number of local street-scapes case studies within the City of Adelaide and the City of Mitcham. Independent validation of the tool's outputs with remotely sensed thermal imagery was also undertaken with consistency in LST patterns reinforcing the validity of our initial empirical approach. Through this exercise, stakeholders not only found use in understanding the impact of BGI on urban heat, but also identified the WSC Toolkit as a potentially useful tool for pre-screening the need to undertake expensive aerial thermal imagery surveys.

Building a confident and interested user base

By 2017, the WSC Toolkit had been applied to case studies within the states of Victoria (Toolern and Aquarevo) and South Australia (City of Unley) and independently by stakeholders (City of Mitcham and City of Adelaide). To promote the widespread potential of the WSC Toolkit, more active

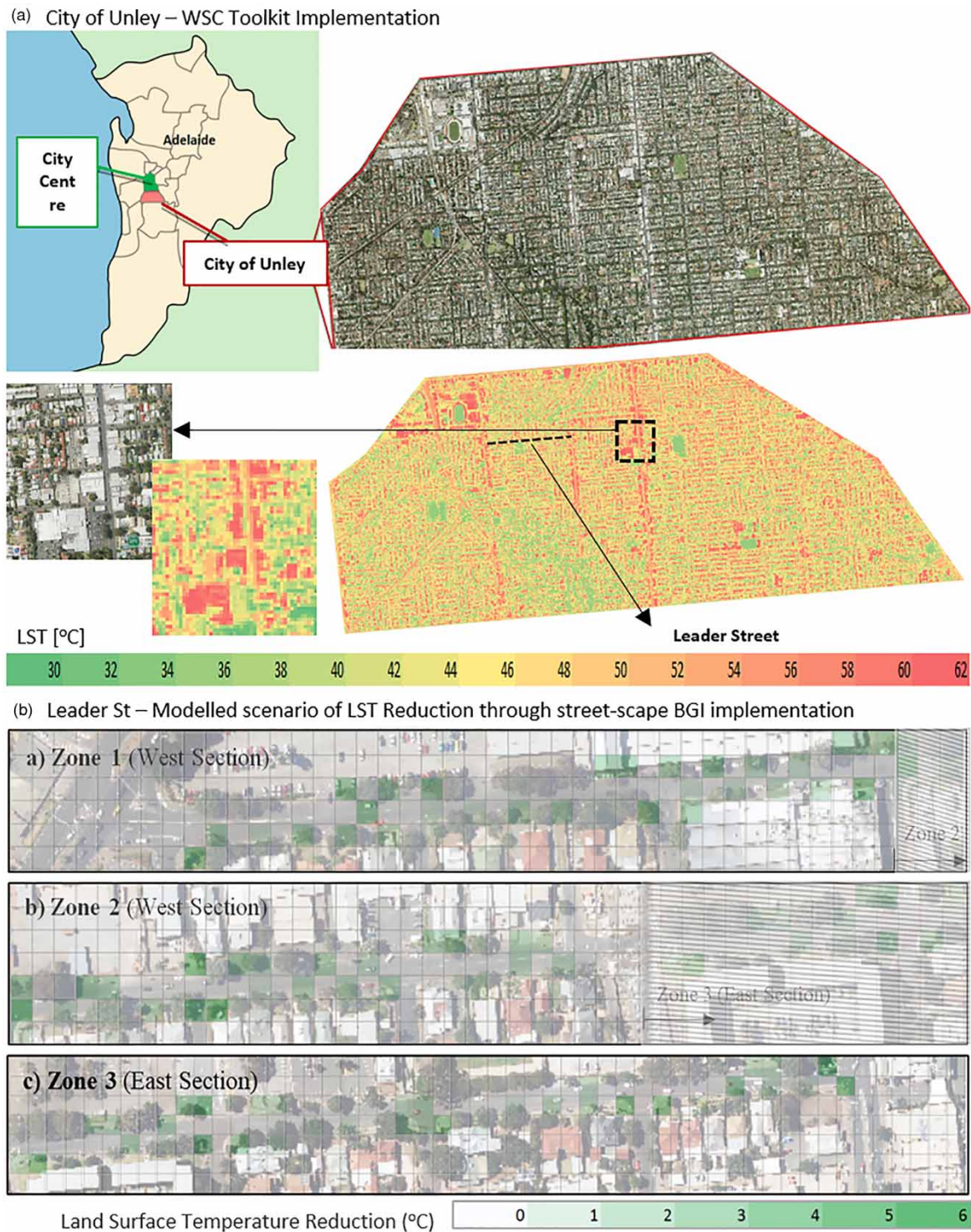


Figure 6 | Application of the WSC Toolkit Urban Microclimate Module to the City of Unley, South Australia showing aerial imagery, converted land surface temperature map and a zoom-in of the main commercial district.

engagement with users was sought through a series of national training workshops. Organisation and promotion of such workshops was aided by local industry champions and capacity building organisations within the water sector through the CRCWSC's network. Marketing was achieved through 'word-by-mouth', online articles and the attractiveness to work on a familiar, local case study during the session (e.g. we used two small rural developments in South Australia, a re-development case study in New South Wales and a future master plan in Queensland).

By this stage, a usable interface had been developed and a good foundational understanding on the multiple benefits of BGI had been established. Each training workshop lasted up to a full day and, depending on location, adopted a local case study to demonstrate, in particular, the tool's novel capabilities such as the urban microclimate module. Workshops were 'hands-on' and 'interactive' (see Figure 7), where hypothetical planning and design of BGI for the respective case studies were undertaken and participants could present their own ideas not only 'on paper', but through the use of the WSC Toolkit.



Figure 7 | National training workshops for the WSC Toolkit using local case studies and engaging local stakeholders in collaborative discussions on the importance of BGI in mitigating urban heat.

The workshops also served as a co-design exercise for the WSC Toolkit development team, where feedback on user friendliness was obtained and request for features were collected and implemented shortly before the next workshop. This 'do as we develop' approach was effective as it allowed us to shape the user experience according to stakeholder expectations and preferences, resulting in a more intuitive software. The impact of these training sessions was felt nationally and revisited months later in news articles (CRCWSC 2017b) and a national conference (CRCWSC 2017a).

KEY LESSONS LEARNT

Through the efforts of the development team and the engagement of industry partners, significant momentum and interest in the WSC Toolkit could be forged through the many demonstrations. We reflect upon five key lessons that we feel can guide future researchers in developing effective integrated assessment tools, particularly within highly interdisciplinary fields such as Blue-Green Infrastructure.

Lesson 1: never sacrifice a clearly defined modelling aim and a clear understanding of how the model is to be used even if the initial development may seem vague. Even if the model at first appears broad and even if the intended output emphasises a software product that, in part, relies on already existing tools, a novel and clear modelling aim can always be defined that allows selection and development of a well-rounded tool. Through the context of the CRCWSC research program, the model had a key target audience and a purpose – rather than replacing existing models, it served to complement if not enhance existing tools. Furthermore, it was an important learning and collaborative experience that would bring together stakeholders and researchers regardless of the outcome.

Lesson 2: Be clear about whether it is an integrated model or a model for integrated assessment. In this particular context, it was clear that the tool had to incorporate a large number of models across disciplines. However, it was not always necessary (if at all) to link every sub-model with each other. A clearly defined endgame or key outputs will indicate whether you are integrating models for the sake of integrating or whether the 'big picture' comes from the discussion with stakeholders that different outputs will facilitate. In other words, we could answer the question of whether we are telling a story

from multiple perspectives (i.e. integrated assessment) or whether we are intending to tell a complex story (i.e. integrated modelling).

Lesson 3: Even if the tool comprises multiple models, balance complexity and consider your user base. Adding complexity can sometimes risk losing your audience, therefore, the question is whether model ‘complexification’ is really necessary. Furthermore, complexity in model outputs and complexity in model algorithms are two separate considerations. This lesson was particularly significant during stakeholder engagement on the urban microclimate module, where keeping it simple at the start created interest and developed understanding in participating stakeholders. Visual outputs that are easily communicated was highly effective over detailed graphs of land surface temperatures. Overall, we found that stakeholders were generally not welcoming of the ‘black-box’ style of model communication. Therefore transparent and honest communication of model capabilities and limitations was also important.

Lesson 4: Engage with stakeholders and practitioners early in the process and, especially in interdisciplinary projects, incorporate a wide range of stakeholders. Through this, modellers can ascertain whether their aims and assumptions align with stakeholder needs before any significant work is undertaken. This helps prioritisation of key needs and expectation management of all involved parties. Early engagement also allows researchers to gain better insight not only into the available data of ‘real-world scenarios’ and its quality used by stakeholders, but also the general thought processes and ‘tricks of the trade’ with which effective communication of model output can be designed.

Lesson 5: Build flexible software, clearly defined framework to guide the model development and balance visual appeal with well-rounded science. This ensures that if leadership on model development should change over the course of its development, well-structured frameworks are in place. Resources for model development in research are often scarce and should be best optimised through effective and flexible software architecture. Finally, a picture paints more than a thousand words and visualisations are incredibly effective communication tools (as seen frequently in the use of the urban microclimate module). However, visualisations should never jeopardise the core scientific merit nor hide the key scientific flaws and limitations behind the model. Be transparent when communicating visual information to stakeholders.

CONCLUSIONS

In this paper, we presented the WSC Toolkit – a tool used for evidence-based quantification of multiple benefits associated with Blue-Green Infrastructure (BGI) based on the interdisciplinary research outcomes. Reflections on the early years of the tool’s development from its conception in 2012 up to 2017 and guidance for effective tool development going forward were presented. The application of the WSC Toolkit on various case studies was also presented to show how the tool can be used to support improved decision-making, serve as a vehicle for demonstrating new understanding of multi-functional BGI and engage in discussions towards operationalising the uptake of BGI, as well being a platform for practical application of latest research outcomes and meanwhile encouraging interdisciplinary collaboration.

To produce an accessible tool as a vehicle for applying cutting-edge research across multiple discipline, we aimed to develop a distinct software (not as a replacement, but rather to complement existing tools) that is simple, modular and extensible and for integrated assessment of the multiple benefits of BGI and scenario-based comparisons to inform decision making.

Based on a number of case studies and experience in training and demonstration, the application of WSC Toolkit showed how it can be used to support improved decision-making in BGI, as well as being a platform for practical application of latest research outcomes and meanwhile encouraging

interdisciplinary collaboration. Five key lessons learnt were presented to guide future researchers in developing effective integrated assessment tools, particularly within highly interdisciplinary fields such as Blue-Green Infrastructure.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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