Can we model the implementation of water sensitive urban design in evolving cities?

Peter Marcus Bach, David T. Mccarthy and Ana Deletic

ABSTRACT

This study showcases the dynamic simulation capabilities of the Urban Biophysical Environments And Technologies Simulator (UrbanBEATS) on a Melbourne catchment. UrbanBEATS simulates the planning, design and implementation of water sensitive urban design (WSUD) infrastructure in urban environments. It considers explicitly the interaction between urban and water infrastructure planning through time. The model generates a large number of realizations of different WSUD interventions and their evolution through time based on a user-defined scenario. UrbanBEATS' dynamics was tested for the first time on a historical case study of Scotchman's Creek catchment and was trained using historical data (e.g. planning documents, narratives, urban development and societal information) to adequately reproduce patterns of uptake of specific WSUD technologies. The trained model was also used to explore the implications of more stringent future water management objectives. Results highlighted the challenges of meeting this legislation and the opportunities that can be created through the mix of multiple spatial scales.

Key words | dynamic modelling, exploratory modelling, historical planning, infrastructure evolution, strategic planning, urban form

Peter Marcus Bach (corresponding author)
David T. Mccarthy
Ana Deletic
Monash Water for Liveability,
Department of Civil Engineering,
Monash University,
Clayton,
VIC 3800,
Australia
and
Cooperative Research Centre (CRC) for Water
   Sensitive Cities,
Monash University,
Clayton,
VIC 3800,
Australia
E-mail: peterbach@gmail.com

INTRODUCTION

Green water infrastructure, in particular, water sensitive urban design (WSUD) has been gaining increasing attention in the modelling literature in recent years (Makropoulos *et al.* 2008; Lee *et al.* 2012). Their planning and design is a complex task, requiring consideration of scale, system type, urban form and social factors. Recent WSUD models such as UWOT (Makropoulos *et al.* 2008) and SUSTAIN (Lee *et al.* 2012) have provided users a means of exploring their design and placement in urban environments. All of these consider a wide range of technical and holistic factors for identifying suitable locations and/or technologies, which can meet different water quantity and quality objectives. Their shortcomings, however, include a lack of consideration of landscape integration, in particular interactions with urban form, which governs the feasibility of 'on-the-ground' WSUD implementation (Wong 2005). Furthermore, none of the existing models is capable of modelling dynamic changes in WSUD infrastructure. Such features are important if models of this nature are to be used in exploring future sustainable and adaptive strategies (see, for example, McIntosh *et al.* 2007). Previous research has modelled the

evolution of centralized infrastructure (Urich *et al.* 2013), but to the authors' knowledge no existing work has been found on modelling the evolution of WSUD infrastructure through time. Understanding how to adapt and plan around existing WSUD infrastructure to address changes in the urban environment (e.g. changing policy, climate and/or land use) is crucial. As such, there is a need for an integrated model that will allow planners to explore different storylines or 'narratives' of how WSUD infrastructure could change through time.

Recent work has led to the development of the Urban Biophysical Environments And Technologies Simulator (UrbanBEATS), a planning-support model for exploring design and placement of WSUD infrastructure (Bach 2014a, b). UrbanBEATS differs from other existing tools in that it specifically considers interactions between urban planning (which defines urban form), WSUD (both technical design and landscape integration) and the urban environment (land use, demographics and biophysical constraints) in a spatially and temporally explicit, yet simplistic, conceptual manner. Previous work has demonstrated the

urban and technology planning concepts of the model on single static snapshots of urban environments (Bach *et al.* 2013a, b). This paper aims to show the potential of Urban-BEATS' dynamic simulation capabilities in supporting future strategic planning and policy-making for WSUD stormwater infrastructure. For the first time, we test the model's performance in reproducing historical patterns of WSUD infrastructure implementation for a local suburban area in Melbourne, Australia.

METHODS

General model overview

UrbanBEATS integrates urban planning and water management with urban form and the biophysical environment to generate thousands of possible WSUD management interventions for a user-defined future masterplan or present urban environment. The model comprises two modules: (1) Urban Planning and (2) WSUD Planning modules.

The Urban Planning module uses four basic input maps of land use, population, elevation and soil as well as parameters of planning regulations to stochastically reconstruct an abstraction of the urban form in a grid-based representation. Each grid cell, known as a *Block*, serves as a geospatial database of biophysical, planning and urban form information for the particular area of the region. The module is driven by the demographic and land use data as well as user-defined planning rules (e.g. setbacks in residential areas, building size restrictions, parking provisions in commercial areas, road reserve cross-section and open space encumbrances). Key concepts of the Urban Planning module are described further in Bach *et al.* (2013a) and details on calibrating urban form in the model can be found in Bach (2014a).

The WSUD Planning module assesses existing systems, and designs and implements new WSUD infrastructure from information about the modelled urban environment. These processes are guided by user-defined water management objectives (e.g. runoff, pollution reduction, water recycling) and urban planning requirements (see, for example, Bach *et al.* 2013a). Each management objective comprises *target* (e.g. pollutant load reduction) and *service level* (e.g. percentage of impervious area over which targets are to be met). Technologies are sized using a database of performance curves, which were generated from long-term simulations with the MUSIC model (eWater 2011). Opportunity for new technologies is assessed by searching the case study region at all spatial scales for feasible locations for implementing WSUD infrastructure and running a Monte Carlo procedure to generate thousands of different technological layouts combining these different options. A multi-criteria scoring is used to reduce the thousands of combinations to a small number of 'favourable' solutions, which provide adequate service, meet legislative targets and utilize technologies that score highly among the multiple criteria (further details can be found in Bach *et al.* (2013b)).

Modelling dynamics

The execution of Urban Planning followed by WSUD Planning modules is referred to as a *model cycle*. UrbanBEATS' dynamic simulation mode involves the repetition of two alternating model cycles (Figure 1; top): (1) Planning Cycle, which uses masterplan data to design new and adapt existing WSUD infrastructure to suit current water management targets; and (2) Implementation Cycle, which takes a selected planned configuration of WSUD systems and implements them into the 'present state' urban environment (of that respective time period) based on the amount of 'on-the-ground' development. The dynamic simulation repeats this process through time (illustrated in Figure 1; bottom) at variable periods in time (referred to as 'milestones'), which are of historical significance to the case study (e.g. newly prescribed targets) as defined by the input narrative. This is intended to replicate the real-world process of designing and implementing infrastructure and revising the designs over time due to unforeseen events or the availability of new information in the planning process.

In addition to the methods already described previously in the general overview, the Planning Cycle also performs a retrofit action on existing WSUD infrastructure. Performance of each existing system in the map is assessed using the appropriate design curves. The decline in performance is described as a deficit in the service provided by the system. Based on this deficit and the current user-defined scenario, the model uses a decision-tree to undertake one of three possible actions for each existing WSUD system: (1) *keep* (the system is unchanged and continues occupying its current location); (2) *upgrade* (the system design is changed and additional space is sought in the area to accommodate this change); or (3) *decommission* (the system is removed from the map, which releases occupied land for new technologies). *Implementation* of technologies is governed by a set of decision rules that check the amount of urban development that has taken place at a given point in time (when compared to the masterplan), the spatial scale
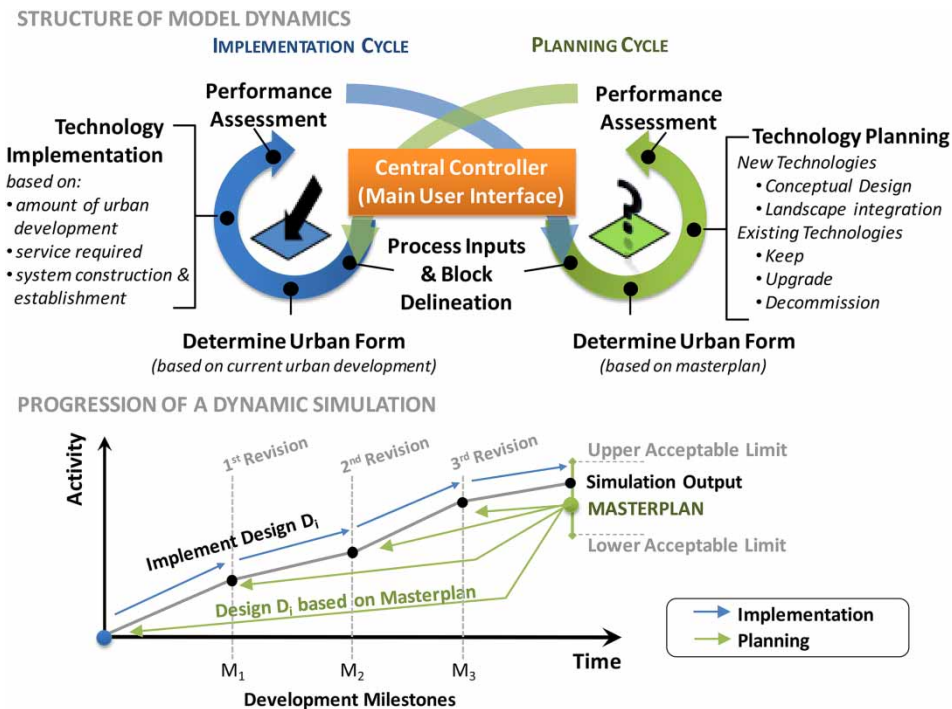
Figure 1 | Structure of UrbanBEATS' model dynamics (top) and illustration of the progression of a dynamic simulation (bottom).

at which the technology is being implemented and the user-defined scenario on how water management service should be provided during development.

Case study description and data set

The objective of this case study was to assess how well the model can reproduce the actual implementation of WSUD within the catchment over the last two decades. We used Scotchman's Creek catchment (Figure 2) – a 10 km² area in Melbourne's south-eastern suburbs, containing a mix of land uses of varying densities. The catchment was used in previous studies (Bach *et al.* 2013b) and is therefore a familiar test bed for UrbanBEATS. Digital elevation and soil maps, which are considered static model inputs, were prepared for the catchment. Additionally, historical land use and population data were obtained through the interpretation of aerial imagery, old census records and application of urban modelling (the details of which are beyond the scope of this study, but model outputs were validated against aerial imagery).

There is a lot of deep uncertainty surrounding the historical development of WSUD in the catchment since historical planning documents could not be found for the specific area. It is not feasible to capture the political climate of the last 40 years and the tacit knowledge of the decision-

makers themselves in simple model algorithms. It is partly due to this reason that UrbanBEATS adopts an exploratory rather than a predictive approach, the former of which has been regarded as useful for undertaking robust decision-making and dealing with such uncertainties (see, for example, Lempert & Collins 2007). For the historical case study, it was decided to use the present-day catchment as the *masterplan* for the simulation with the intention that the model should reproduce WSUD infrastructure 'as it was delivered'. WSUD infrastructure for model training was obtained from an asset database created by the metropolitan water authority, Melbourne Water. Construction dates provided for each of the systems allowed the data to be split into the four key historical time periods for comparison with model results. Design data obtained for the WSUD infrastructure were unfortunately incomplete due to various circumstances (lost data, confidentiality, ongoing projects, etc.).

Key historical milestones related to WSUD were identified from the literature (Ferguson *et al.* 2013) and the catchment's time-stamped data. These include the implementation of the first WSUD systems (1990), publication of best practice environmental management (BPEM) targets for Victoria (1999), the emergence of biofiltration technology (2004), and stormwater management regulations introduced in Victoria (2006). These milestones
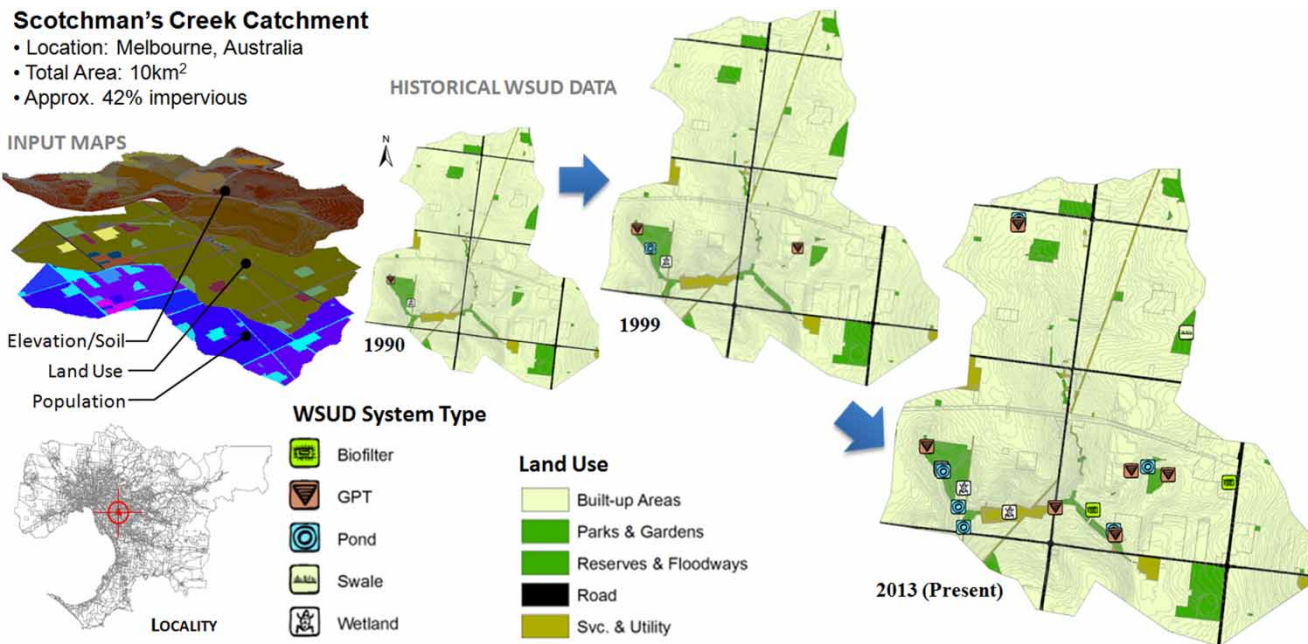
Figure 2 | Scotchman's Creek case study, catchment and historical timeline of WSUD implementation.

are strongly related to key historical events in Melbourne's urban water management narrative presented by Ferguson *et al.* (2013). Scotchman's Creek's adoption of WSUD has been mostly large-scale. Figure 2 depicts the actual evolution of WSUD infrastructure in Scotchman's Creek catchment. Most systems are concentrated in the south near the catchment outlet. Apart from rainwater tanks (which were implemented primarily for potable water substitution and were not available in the data set), no other small-scale technologies were present in the catchment. Numerous gross pollutant traps (GPTs) are scattered across the catchment – a technology, which was not considered during the initial development of UrbanBEATS due to its low performance in removing key pollutant types.

Model setup, training and performance

UrbanBEATS' dynamic simulation requires consideration of several different inputs: (a) dynamic timeline, (b) delineation and urban form, (c) technology planning and (d) technology implementation inputs.

Dynamic timeline

To simulate the historical development of WSUD within the catchment, one pre-WSUD time period (1972), four key dates (1990, 1999, 2004 and 2006) and the present day (2013 at the

time of this study) were selected as milestones. UrbanBEATS was set to run both planning and implementation cycles for each of the six different time periods. The first time period (1972) was used to establish some basic urban form, which was updated in subsequent years (no WSUD infrastructure was present yet). Training of the model was carried out across the milestones 1990, 1999, 2004 and 2006 based on the collected data, while possible future implications (explained below) were explored in the 2013 milestone. Technology planning parameters were adjusted by trial and error across all milestones (it was also ensured that parameter values were within realistic ranges). Five realizations of the full-dynamic simulation were subsequently generated and compared with observed data.

Delineation and urban form

The catchment was modelled using 200 m × 200 m blocks, the choice of which was heavily influenced by the high concentration of WSUD systems in the southern part of the catchment and concerns about model accuracy in using a coarse block size. Key urban planning parameters for different land uses were obtained from planning guidelines across Melbourne (e.g. DPCD 2006), state-wide regulations and previous calibration (Bach *et al.* 2013b). Parameter ranges were kept constant throughout the simulation, since few historical planning data were available that could be used

to refine these inputs across time. Detailed model setup and calibration of urban form can be found in another study (Bach 2014a).

Technology planning inputs

Four technology types (wetlands, ponds, swales and biofilters) were enabled as options in the model based on the historical narrative (see Table 1). Typical design configurations were chosen for each technology. For simplicity, the same design was used throughout the whole simulation. Target and service levels (provided in Table 1) were identified by analysing the available WSUD data and the historical documents. A multi-criteria scoring matrix was required for each milestone. The relative scores for the social criterion for each technology were defined based on previous social research (Ferguson *et al.* 2013) and are shown in Figure 3.

Scores from other criteria were kept constant as per Bach *et al.* (2013b). All sub-scores were normalized before tallying a total score for each layout. For retrofit, no decommissioning of technologies was permitted in the simulation to match historical context. Changes to individual WSUD systems were required if the performance deficit was greater than 40% over time (the parameter choice is arbitrary but unlikely to be sensitive as the water management targets did not significantly change throughout time).

Technology implementation inputs

In Melbourne, it is common for WSUD technologies to be built prior to or during construction of new areas (Leinster 2006). As such, implementation of WSUD was set to occur if developed land exceeded 30% of the total area (this was once again an arbitrary choice and, since most of the

Table 1 | Overview of milestones in historical timeline and key dynamic modelling aspects

Year	Narrative	Key aspects for model setup
1972	Initial state of the catchment, no technologies present	• Only delineation of Blocks and calculation of urban form within the catchment
1990	Demonstration of wetlands and ponds in the catchment	• Enabled Wetlands, Ponds and Swales in the technology toolbox • Management of total suspended solids (TSS) pollution in catchment only (approximately 10% load reduction)[a] • Servicing only 1% of the basin impervious area[a]
1999	First best practice environment management (BPEM) targets published	• Management of TSS, total nitrogen (TN) and total phosphorus (TP) pollution to reduce 80%, 45% and 45% of loads, respectively • Servicing only 10% of basin impervious area[a]
2004	Biofiltration technology becomes mainstream	• Enabled Biofiltration Systems in the technology toolbox • Using the same targets and service as 1999
2006	Pollution management regulations passed and integrated into planning scheme	• Same pollution management targets as per 1999 • Servicing 25% of basin impervious area
Present (2013)	Testing the implications of a revised set of BPEM targets for stormwater management in urban areas	• Increased pollution management targets to 85% TSS, 50% TP and 50% TN reduction • Introduced runoff reduction target of 20% volume reduction • Service requirement increased to 100% as the new BPEM

[a]These values were obtained through trial and error as there were no prescribed targets by the State Environmental Planning Policies (SEPP) in 1990, but the model relies on these for the planning of technologies. Setting target and service to a low value will produce a very low number of technologies to be implemented in the catchment.
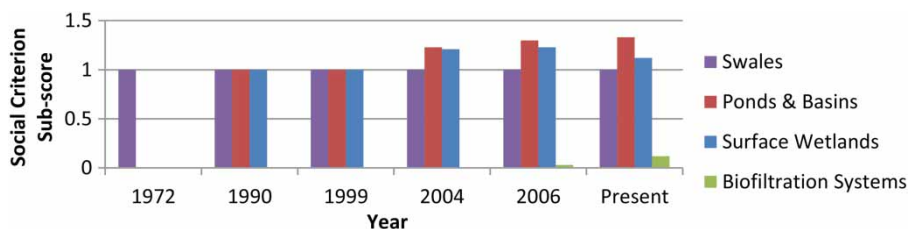
Figure 3 | Social criterion scores for model multi-criteria assessment for individual technologies across time.

catchment had already been developed, was likely to be insensitive). Larger-scale systems were allowed to be constructed even if the land has not yet been zoned (i.e. was 'undeveloped' in the input land use map).

Model performance

Model performance was assessed in three ways: (1) visual inspection of selected locations and technologies, (2) comparing typical sizes of ponds and wetlands and (3) assessing how well the model reproduces *technological uptake*. As a surrogate for uptake, we use a metric known as *selection frequency*, which is defined as the frequency of occurrence of a particular technology counted based on the number of times; it is selected by the model (e.g. in how many blocks and at how many scales the technology type was selected). Selection frequencies were calculated for the three prevalent technologies within the catchment over time: ponds and basins, constructed wetlands and biofilters.

RESULTS AND DISCUSSION

Figure 4 shows one example output of a model realization for the year 2006 compared with the observed data. Note that although the model appears to place a large quantity of systems across the map (e.g. the chain of ponds in adjacent blocks in the west), they should be reasonably interpreted as one large equivalent system since the grid representation will affect the distribution of impervious area and available space for WSUD infrastructure. The dark grey (orange in online version of paper) boxes indicate specific locations where modelled and observed data match. The only

exception is the use of GPTs, which the model appears to compensate for through the use of additional wetlands. There are also specific areas where the model did not choose to place any technologies despite their presence in the observed data. Instead, the model selected a variety of alternative locations in the catchment. This relates to the stochastic nature of the model: Figure 4 shows only one possible realization of a number of different alternatives. Box plots in Figure 4 show that the observed surface areas of basin systems (ponds and wetlands) are similar to the equivalent surface areas of modelled systems (analysis of the data showed that there were six times as many systems placed by the model, but with surface areas, which were on average six times smaller than the actual size). The model also tends to place larger systems in some cases. This can be due to either (1) an attempt to compensate for the absence of GPTs or (2) the result of using present-day design approaches to design systems of the past (that may not have considered issues accounted for in current state-of-the-art).

Selection frequencies over time for three prevalent WSUD technologies are shown for modelled and observed values in Figure 5. It can be seen that observed and modelled selection frequencies do not match up in most cases. This is possibly explained by the absence of GPTs in the model. Results, however, highlight that the general patterns can be reproduced with careful training and more complete data. Ponds, for example, exhibit the initial increase in 'uptake' followed by a decline from 2006 onwards. Wetlands are widely used at first, but decline quite rapidly over time. Biofilters were not present until 2006, after which a gradual uptake followed. Furthermore, due to the difficulty in training the model for the year 1990, it is not surprising that in most cases a much larger mismatch between modelled and observed data can be
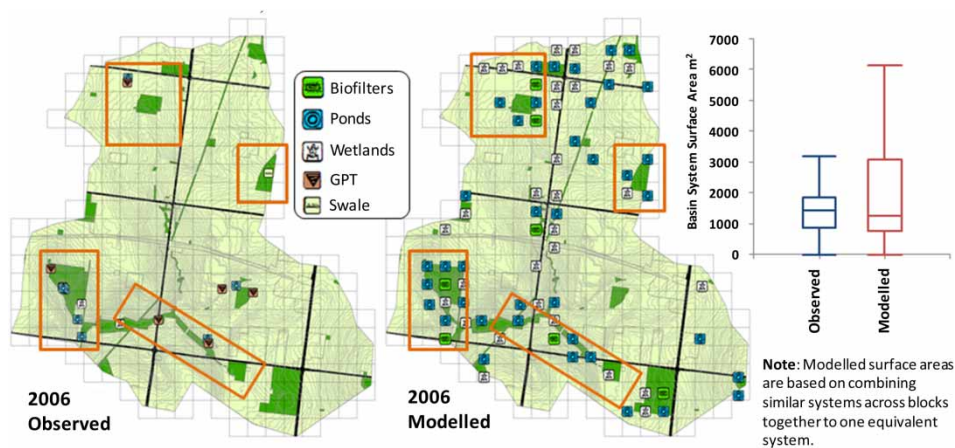
Figure 4 | Comparison of spatial placement of WSUD systems between observed and one realization using 200 m × 200 m blocks. The full colour version of this figure is available online at http://www.iwaponline.com/wst/toc.htm.
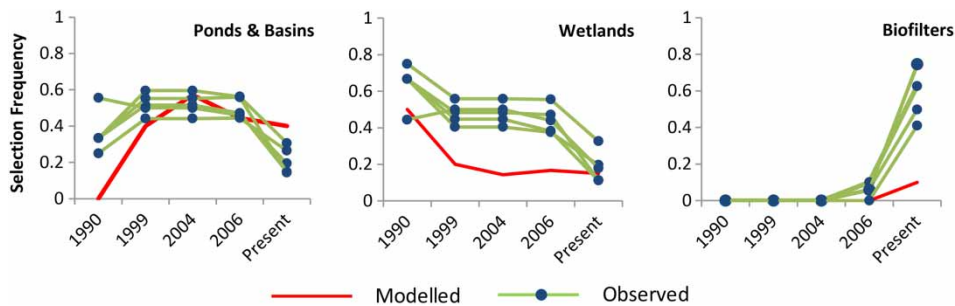
Figure 5 | Observed and modelled realizations of uptake for different WSUD technologies in Scotchman's Creek catchment using selection frequency metric as a surrogate.

seen. Many projects during this time period were demonstration projects, meaning that their targets and service levels would not have been defined by any prevailing legislation but instead by project-specific requirements.

The challenge of meeting more stringent BPEM standards was assessed. While there appears to be ample space in the catchment, it was found that achieving a 100% service level using only large-scale systems was difficult unless large investments were made to improve upon existing systems in the catchment. The model simulations indicated that plenty of opportunities exist at the lot and street scales (biofilters are particularly opportunistic as seen in Figure 5) in upstream areas. This is possible because Scotchman's Creek catchment's urban structure is well aligned with major drainage corridors. Although small-scale systems are currently not used within the catchment, they may become a necessity in future for effective water management. The application of widespread stormwater harvesting projects can also potentially aid in the reduction of runoff and pollution and represents a possible scenario that can be assessed in further work.

This case study also highlighted the difficulty of conducting historical modelling studies in terms of data acquisition and uncertainty. Much of the data is either non-existent or too coarse for detailed modelling. This also made it difficult to conduct a rigorous quantitative evaluation of model performance. As such, improved methods for exploring the uncertainties associated with model results would greatly complement these dynamic algorithms, especially when real-world data are absent or fraught with inaccuracies. Improved exploratory methods are also particularly important in helping modellers deal with the deep uncertainties that surround the master planning and robust decision-making exercise (see, for example, Lempert & Collins 2007). For historical case studies, this can be partially addressed by using masterplans of 'how technology was delivered', but for future development scenarios more effort needs to be invested in how to best explore possible outcomes.

CONCLUSION

We showcased the first dynamic simulation capabilities of the UrbanBEATS in reproducing historical trends of the uptake of different WSUD technologies, and explored future challenges of revised water management policy in the catchment. While different model realizations do not exactly reproduce the uptake of different technologies in the catchment throughout history, similarities in the general locations, types and trends for each technology are promising. Further work on the model will involve refinements of its algorithms to account for a wider variety of factors, which can affect the implementation and evolution of WSUD systems as well as application of the model in a real-world planning context (where design and construction stages of a local development are simulated throughout time). In this case, an opportunity for stakeholders of a particular project to partake in the modelling exercise will allow for improvements to UrbanBEATS' overall design and its planning-support capabilities to be made.

ACKNOWLEDGEMENTS

REFERENCES

Bach, P. M. 2014a *UrbanBEATS – A Virtual Urban Water System Tool for Exploring Strategic Planning Scenarios*. PhD thesis, Monash University, Melbourne, Australia.

Bach, P. M. 2014b UrbanBEATS – An exploratory model for strategic planning of urban water infrastructure. http://www.urbanbeatsmodel.com (accessed 23 July 2013).

Bach, P. M., Deletic, A., Urich, C., Sitzenfrei, R., Kleidorfer, M., Rauch, W. & McCarthy, D. T. 2013a Modelling interactions between lot-scale decentralised water infrastructure and urban form – a case study on infiltration systems. *Water Resources Management* **27**, 4845–4863.

Bach, P. M., McCarthy, D. T., Urich, C., Sitzenfrei, R., Kleidorfer, M., Rauch, W. & Deletic, A. 2013b A planning algorithm for quantifying decentralised water management opportunities in urban environments. *Water Science and Technology* **68** (8), 1857–1865.

DPCD 2006 *Planning Scheme of Victoria*. Victorian Planning Provisions. Department of Planning and Community Development, Melbourne, Victoria, Australia.

eWater. 2011 *MUSIC by eWater, User Manual*. eWater, Melbourne, Australia.

Ferguson, B., Brown, R. R., Frantzeskaki, N., De Haan, F. J. & Deletic, A. 2013 The enabling institutional context for integrated water management: lessons from Melbourne. *Water Research* **47**, 7300–7314.

Lee, J. G., Selvakumar, A., Alvi, K., Riverson, J., Zhen, J. X., Shoemaker, L. & Lai, F.-H. 2012 A watershed-scale design optimization model for stormwater best management practices. *Environmental Modelling & Software* **37**, 6–18.

Leinster, S. 2006 Delivering the final product – establishing vegetated Water Sensitive Urban Design systems. *Australian Journal of Water Resources* **10** (3), 321–329.

Lempert, R. J. & Collins, M. T. 2007 Managing the risk of uncertain threshold responses: comparison of robust, optimum, and precautionary approaches. *Risk Analysis* **27** (4), 1009–1026.

Makropoulos, C. K., Natsis, K., Liu, S., Mittas, K. & Butler, D. 2008 Decision support for sustainable option selection in integrated urban water management. *Environmental Modelling & Software* **23**, 1448–1460.

Mcintosh, B. S., Seaton, R. A. F. & Jeffrey, P. 2007 Tools to think with? Towards understanding the use of computer-based support tools in policy relevant research. *Environmental Modelling & Software* **22**, 640–648.

Urich, C., Bach, P. M., Sitzenfrei, R., Kleidorfer, M., McCarthy, D. T., Deletic, A. & Rauch, W. 2013 Modelling cities and water infrastructure dynamics. *Engineering Sustainability* **166** (ES5), 301–308.

Wong, T. H. F. 2005 *Australian Runoff Quality*. Australia Engineers Australia, Sydney.