WSUD

water e-journal
Online Journal of the Australian Water Association
ISSN 2206-1991
Volume 2 No 4 2017
https://doi.org/10.21139/wej.2017.031

OPTIMISATION OF WATER SENSITIVE URBAN DESIGN PRACTICES USING EVOLUTIONARY ALGORITHMS

THE DEVELOPMENT AND APPLICATION OF A FRAMEWORK TO INCORPORATE WSUD INTO AN OPTIMISATION PROCESS

C McPhail, S Vial, R van der Pennen, B Heidrich, Prof. A Simpson, Dr. J Cantone

ABSTRACT

Population growth and urban consolidation have resulted in a movement away from the natural landscape, creating a greater proportion of impervious area, and an increase in urban stormwater runoff. The increase in stormwater runoff has typically been handled using traditional drainage infrastructure such as pipes, pits and detention basins. An alternative is Water Sensitive Urban Design (WSUD), which has been shown to counteract the effects of increased runoff by decreasing the proportion of impervious area and utilising natural retention/detention. This research utilised evolutionary algorithms as a means of identifying, at the lot scale, the most efficient combinations of WSUD practices (rain gardens, bio-retention cells, rainwater tanks, etc.) to meet designated hydrologic objectives at the catchment scale. Furthermore, an optimisation step was included to determine, and explore, the trade-offs between WSUD practices and traditional drainage infrastructure. A case study on the proposed South Campus Research Park at the University of Illinois Urbana-Champaign (UIUC) was selected to determine the optimal combination of traditional and WSUD infrastructure to meet flooding, freeboard and peak flow criteria at minimum cost. The optimisation results showed that for a variety of rainfall average recurrence intervals (ARIs) it is cheaper to use a combination of traditional drainage infrastructure and WSUD rather than to only use the traditional drainage infrastructure.

KEY WORDS

WSUD, Water Sensitive Urban Design, Stormwater, Optimisation, SWMM

INTRODUCTION

Increased urbanisation will continually occur due to population growth resulting in an increase in impervious area. This affects the magnitude of stormwater runoff in terms of both volume and peak. Due to the environmental and flood concerns associated with traditional stormwater management, Water Sensitive Urban Design (WSUD) techniques have emerged. WSUD refers to decentralised measures that control stormwater by altering hydrological runoff and by recreating natural landscaped features. These practices typically reduce runoff by applying detention or retention where the rain falls, and encouraging infiltration.

Alternatively, traditional drainage infrastructure aims to convey water to an outlet as quickly as possible where detention or retention may be applied at a centralised location. Some WSUD practices including green roofs, rain gardens, bio-retention cells, permeable pavement, rainwater tanks, infiltration trenches and vegetative swales are applied at the lot scale but their effects can be seen at the catchment scale.

The following questions arise when considering the integration of WSUD and traditional stormwater management. What is the optimal combination of large scale detention storage and rainwater tanks at the residential lot scale? What other combinations of traditional drainage infrastructure and WSUD can be considered? This research aims to improve the understanding of the hydrologic impacts of WSUD at the watershed scale and to develop a tool that can be used to determine optimal combinations of WSUD and traditional stormwater management techniques.

The research objectives are presented below:

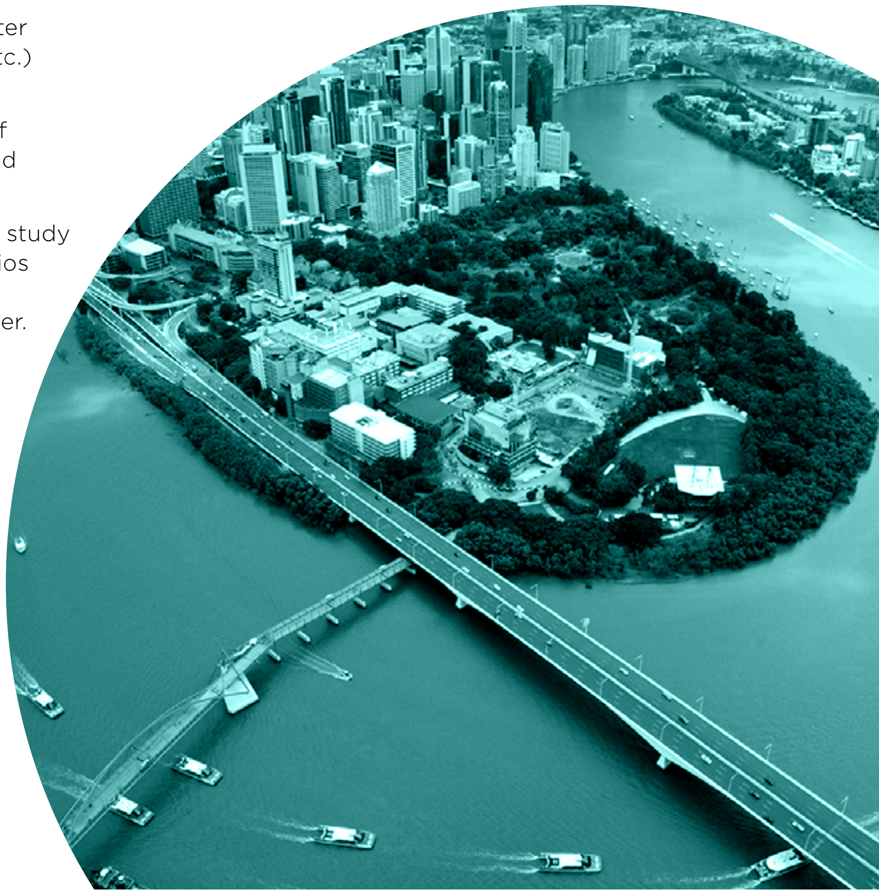
1. To improve understanding of the catchment-wide hydrologic impacts of various Water Sensitive Urban Design (WSUD) techniques (e.g. rainwater tanks, permeable pavement and green roofs etc.) implemented at the lot scale.
2. To develop a framework for the optimisation of stormwater collection systems using WSUD and traditional drainage infrastructure.
3. To apply the optimisation framework to a case study to determine and assess minimum cost scenarios and to better understand how WSUD and traditional drainage infrastructure work together.

LITERATURE REVIEW

Traditionally, a network of pipes and pits have been used as a collection system to transfer stormwater from individual lots or streets and transport it to an outlet, detention basin or treatment plant (Liu et al., 2014). Such systems are known as centralised systems because the majority of the detention, retention or treatment of runoff occurs at one centralised location (Damodaram et al., 2010).

These centralised systems may result in increased runoff and pollutant loads that can have many negative effects on the receiving water bodies (Lerer et al., 2015) including a decrease in river water quality (Ruth, 2003), reduction in eco-hydrological diversity (Booth and Jackson, 1997) and can cause stress in stream hydrology (Beighley et al., 2009).

In contrast, a decentralised system implements smaller retention and treatment practices in multiple locations leading to reduced runoff (Han and Mun, 2011) and may include WSUD practices (Liu et al., 2014). Common practices used as a part of WSUD include permeable pavement which has improved infiltration and groundwater recharge (Dietz and Clausen, 2008), green roofs which potentially reduce runoff by up to 50% (Liu et al., 2014) and bio-retention cells which retain water and remove pollutants (Kramer, 2013). Other common practices also include rain gardens, rainwater tanks, infiltration trenches and vegetative swales. The use of these practices to control stormwater at the source, rather than at the outlet of stormwater collection systems, can help reduce the need for larger facilities (U.S. EPA, 2000, Cohen et al., 2011) and can help achieve stormwater runoff and pollutant levels that are equal to those for the pre-development site (Dietz and Clausen, 2008).



The simulations by Cohen et al. (2011) showed that WSUD applied to each lot allows the use of stormwater pipes with smaller diameters.

Common modelling packages capable of modelling WSUD include the EPA Storm Water Management Model (SWMM) and MUSIC by eWater, ACT, Australia. Both are able to model quality and quantity of water. SWMM can be used to assess the performance of WSUD features at a lot, neighbourhood or regional scale (Phillips et al., 2006) and for both short- and long-term simulations (Rossman, 2010). Optimisation of stormwater management systems requires a model to simulate the catchment for various storm events, and an optimisation algorithm that is used to make decisions for the catchment model (Liong et al., 1995). An evolutionary algorithm may be used for optimising these systems and mimics the behaviour of natural selection to find the best solution (Diogo et al., 2000). The major benefit of evolutionary algorithms is that they do not require as much information as other algorithms (e.g. gradient-based searching requires a smooth differentiable cost-function) and thus solve problems that often cannot be solved by numerical techniques (Fogel, 2000).

An optimisation framework built using SWMM was analysed by Guoshun et al. (2013). Their aim was to undertake a multi-objective optimisation in order to determine a cost effective WSUD design. This design was concerned with the WSUD practices only and did not optimise them as an integrated system with traditional drainage techniques. It was determined that the most important decision for minimising cost was the location of the WSUD features.

The literature shows that there are gaps in knowledge for the creation of an optimisation framework with SWMM and the optimisation of both traditional infrastructure and WSUD together. Furthermore, the majority of research has focused on centralised WSUD practices such as constructed wetlands rather than lot-scale practices such as green roofs or bio-retention cells.

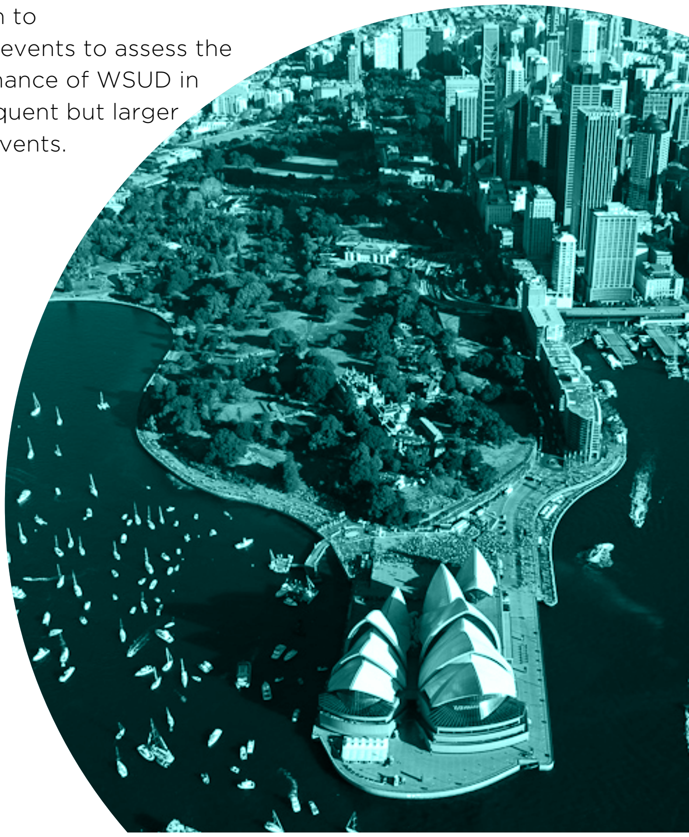
METHODOLOGY

In order to improve the understanding of the hydrologic impact of implementing WSUD techniques, decisions and design criteria were formulated within the Optimizer™ Water Collection Systems (WCS) software from Optimatics, South Australia. A new optimisation decision alters the type of WSUD technique and the size of the WSUD technique.

Costs for WSUD techniques have been obtained from the literature and used as a basis for identifying the least cost combinations of WSUD techniques that satisfy environmental and technical design criteria. The newly developed decision and design criteria were used in Optimizer WCS to assess the impact of alternative combinations of WSUD techniques and traditional drainage infrastructure.

Model development

The US EPA's SWMM computer program was selected for the hydrologic modelling. This program was used primarily because of the ability of Optimizer WCS to link with SWMM. Additionally, SWMM is able to model WSUD practices and when running simulations a relatively high temporal resolution is available (sub-hourly). The model is also one of the most widely utilised models for stormwater system assessment and is freely available without commercial restrictions. A range of ARI rainfall events were selected prior to optimisation. From the literature, WSUD is known to be useful for small rainfall events but for large events the impact on reducing peak flows to predevelopment conditions is less apparent. Hence, larger ARI rainfall events should be used in addition to smaller events to assess the performance of WSUD in less frequent but larger storm events.



Simulations

To assess the potential benefits of using WSUD, predevelopment hydrographs were obtained for the rainfall durations and ARIs to find the critical storm duration for the events simulated. This critical storm duration is the equivalent of the time of concentration for the catchment, which is the time taken for runoff from the furthest point of the catchment to reach the catchment outlet. This value gives the maximum peak flow and can be used as a design criteria for the optimisation of post-development models. When considering the application of WSUD to a post-development scenario, a number of constraints were taken into account as certain types of WSUD practices can only be applied to specific types of development. For example, a green roof can only be applied to a roof and not a driveway. The development types within each sub-catchment were assessed and possible WSUD practices were then identified for each of the development types.

Optimisation formulation

A number of WSUD practices can be created in SWMM with parameters being defined in the model. These practices were applied to each sub-catchment by setting an area of cover, the amount of impervious area treated and the saturation level. To create an optimisation framework that would complement this model, Optimizer was utilised. Optimizer software currently allows traditional drainage infrastructure to be optimised but does not have the ability to optimise WSUD. As a result, JavaScript decisions needed to be written and imported into Optimizer. This software allows for custom JavaScript decisions to be imported into the optimisation framework without requiring any linking to the algorithms.

The decision variables for stormwater systems have commonly included conduit sizes, the weir crest heights and detention storage sizes, and now include WSUD decisions. For the JavaScript to work when imported into Optimizer, the software requires three main functions; encode, decode and cost. The encode function creates an array of potential options, while the decode function alters the SWMM model based on the solutions generated by the encode function. The cost functions then give a cost to the selected option. Changes to the SWMM model via the decode function are made by the use of JavaScript keywords and functions recognised by Optimizer, hence allowing the alterations.

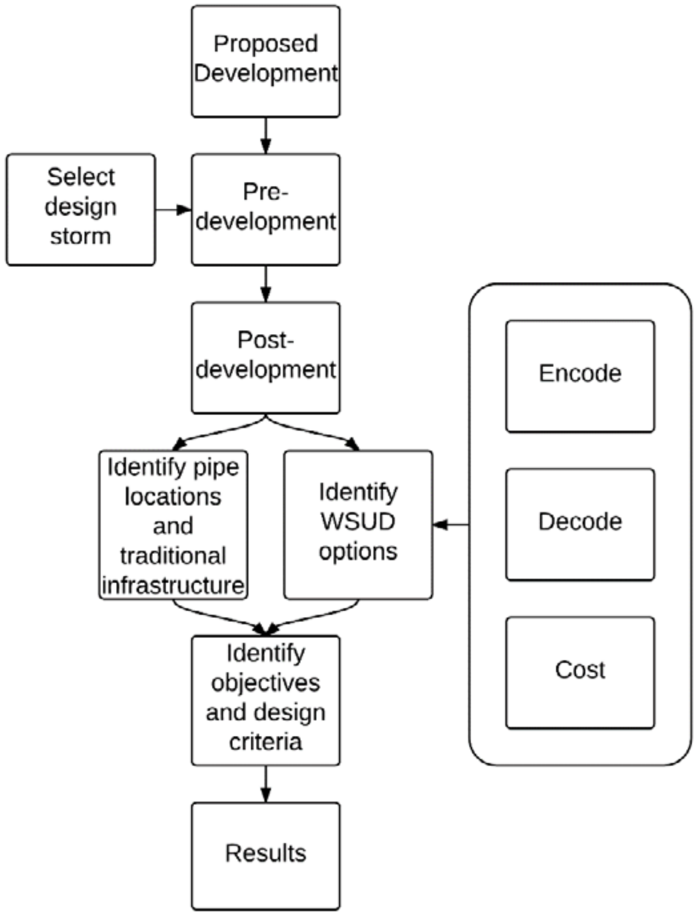


Figure 1. Generic framework for application of optimisation to a combination of WSUD.

Along with the WSUD decisions, optimisation decisions, objectives and design criteria, an optimisation framework was created within the Optimizer software. Design criteria are used to satisfy the technical or environmental constraints (e.g. flooding restrictions, minimum freeboard, conduit size, impervious area etc.) and may result in a penalty if not met for one of the optimisation constraints. Figure 1 shows the generic framework of the optimisation and can be applied to any proposed development.

A range of optimisation scenarios were run to assess the performance of different combinations of WSUD and traditional drainage infrastructure.

These optimised scenarios were compared to determine which options produced the lowest cost and best performance. The different ARI rainfall events were also assessed to view performance under both regular and extreme rainfall events. This permitted an evaluation of the reduction in peak flow rates against the predevelopment conditions.

Case Study – PROPOSED SOUTH CAMPUS RESEARCH PARK at the University of Illinois (Urbana-Champaign)

Background

The proposed South Campus Research Park at University of Illinois Urbana-Champaign (UIUC) campus was used as a case study for this research. This is a greenfield site that has a proposed development plan shown in Figure 2. The total area of the catchment is 9.96 hectares.

Figure 2. Plan of the proposed South Campus Research Park, University of Illinois.

As shown in Figure 2, there are a variety of land uses in the current plan. This site is ideal to simulate and optimise using WSUD as each WSUD practice can be applied to sections of the proposed development areas.

Simulations

The pre- and post-development scenarios were simulated in SWMM for the University of Illinois campus. ARI rainfall events of 1 in 5 and 1 in 100 years were used. These simulations were run for storm durations of 10, 30, 50 and 80 minutes for both ARIs. Storm events were generated using data provided by the Illinois State Water Survey. These simulations were conducted to find the time of concentration for the different scenarios which would be used for the optimisation. The predevelopment scenario was modelled in SWMM assuming the impervious portion of the catchment to be 10% based on aerial imagery. To model the post-development scenario, the proposed South Campus Research Park was modelled in SWMM and a large detention storage was included at the downstream end to reduce the peak flows of the system. The infrastructure was sized using best engineering judgment and trial and error. A separate model was created without detention basins. Simulations were conducted for both traditional drainage infrastructure scenarios (with and without detention storage).

A number of further scenarios were simulated where WSUD was applied in conjunction with traditional drainage infrastructure (post-development) scenario. Six different WSUD scenarios were simulated for the two ARI rainfall events for different storm durations (10, 30, 50 and 80 minutes). These simulations were run to increase the understanding of the hydrologic potential of WSUD and also find the time of concentration for the model to be used in the optimisation process. As mentioned previously each WSUD practice could only be applied to particular land-use types (see Table 1).

Table 1. The applicability of WSUD practices to each development.

Land use	Potential applicability of WSUD techniques						
	PP	RG	GR	BRC	RB	IT	VS
Drive	✔						
Parking	✔	✔		✔		✔	✔
Walk	✔						
Buildings			✔		✔*		
Other		✔		✔		✔	✔

Note: PP = permeable pavement, RG = raingarden, GR = green roof, BRC = bio-retention cell, RB = rainwater tank, IT = infiltration trench, VS = vegetative swale.

The results obtained from the simulations run in SWMM can be seen in Table 2 below along with the corresponding storm duration.

Table 2. SWMM simulation results.

	5 year ARI		100 year ARI	
	Peak Flow (L/s)	Storm Duration (min)	Peak Flow (L/s)	Storm Duration (min)
Pre-development	458	10	1262	10
Traditional (No Detention)	1855	30	3087	10
Traditional (Detention)	1228	30	3133	30

The initial simulations with the addition of WSUD found that the peak flow in the majority of cases occurred for the 30 minute design storm for both rainfall ARIs. Of the six initial WSUD scenario simulations, only one scenario was able to reduce the peak flow to that of the pre-development flow for both ARI rainfall events. This scenario used green roofs for all buildings, permeable pavement wherever possible, rain gardens and bio-retention cells. A 30 minute storm duration produced the highest flows for the majority of scenarios and hence was chosen for use in optimisation.

Optimisation Formulation

Based on a review of the literature, it was determined that for this case study the WSUD optimisation decision would alter the area used for each WSUD type in a sub-catchment. This was selected as it determined how much WSUD is applied to the catchment and where, as opposed to other parameters such as berm height or soil depth. Each land-use in each sub-catchment was allocated a variety of WSUD options. These options resulted in varying areas of each sub-catchment being subjected to various WSUD types.

The JavaScript decisions were written such that each WSUD type may only be applied to the appropriate areas within a sub-catchment. Each type of WSUD can cover a certain area, hence a range of percentages of cover is written into the decisions dependant on the WSUD type. This is with the exception of rainwater tanks that are sized based on volume rather than area, and bio-retention cells or rain gardens which are restricted to smaller areas. The decisions were also written so as to allow for a variety of WSUD options in each sub-catchment. The optimisation objective chosen was to minimise the total capital cost of the storm water infrastructure system. There were also three design constraints:

1. There must be no flooding at any of the nodes.
2. The freeboard should be more than 3 feet.
3. The peak flow from the catchment outlet has to be equal or less than the predevelopment critical peak flow.

Cost penalties were applied to guide the optimisation algorithm away from solutions where these design criteria were not satisfied.

It was identified that conduit diameters could range between 1 to 12 ft. and the depths ranged from 5 to 12.5 ft. For the detention storage options, a variety of volumes between 0.5 and 20 million gallons were used. These were converted to cubic feet and the corresponding cost was calculated. For the sizing of the detention storage a linear regression was used to determine a relationship between the volume and cost. The corresponding equation used was $C = 10.237 \times V$, where C is the cost (AUD) of the storage and V is the volume of water (cubic feet) detained by the weir. Costs for each WSUD practice needed to be determined in order to ensure the most cost effective design is chosen. Cost data to be included in the optimisation was found using a variety of sources (see Table 3) (Daley, 2007).

Table 3. Cost of WSUD practices.

WSUD Practice	Cost
Permeable pavement (asphalt)	$3 per square ft.
Pervious pavement	$15 per square ft.
Bio-retention (curb contained)	$40 per square ft.
Bio-retention (basin with underdrain)	$10 per square ft.
Rain garden (curb contained)	$20 per square ft.
Rain garden (basin with underdrain)	$5 per square ft.
Rain water tank (above ground)	$10 per cubic ft.
Green roof	$20 per square ft.

The case study specific WSUD JavaScript options for the Optimizer software included:

- The applicable WSUD for each land-use.
- The possible area that each WSUD practice could cover. WSUD was given options of covering 5% to 95% of the total possible area using 5% increments.
- Rainwater tanks were given a variety of options between 5 and 250 ft^3 for each building.
- Bio-retention cells and rain gardens in parking areas were restricted to between 5% and 10% of the parking area using 1% increments. It is unrealistic for these to exceed 10% of the car park because of the loss of car parking space.
- The maximum area a WSUD practice or combination of practices could take up of a particular land-use was set at 95%.

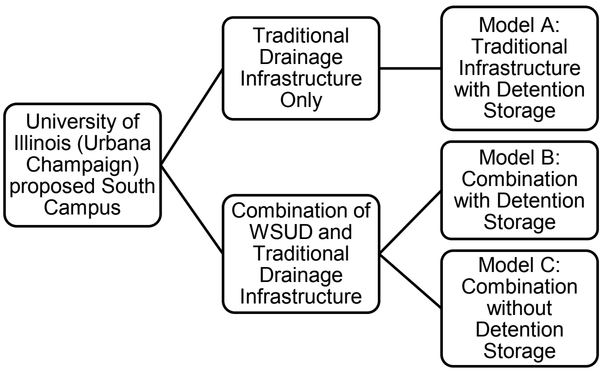


Figure 3. Optimisation runs conducted for the case study.

The models A, B and C, outlined in Figure 3 were each run for a 5 year and 100 year rainfall ARI event resulting in a total of six optimisation runs. Each model was optimised for 100,000 evaluations in Optimizer.

RESULTS AND DISCUSSION

Optimisation of 1 in 5 Year ARI Storms

Models A, B and C (see descriptions in Figure 3) were optimised for the 1 in 5 year rainfall ARI storm event. Table 4 provides a summary of the costs.

Table 4. Summary of costs in US Dollars for the optimised models with a 1 in 5 year rainfall ARI.

Cost ($)	Model A	Model B	Model C
WSUD	-	82,897	138,190
Conduits	876,332	509,758	557,420
Storage	93,705	68,150	-
Total	970,037	660,805	695,610

Model A had a relatively large cost for the conduits. Additionally, the storage cost was also higher than the other model with detention storage (Model B). The solution for Model A was able to satisfy all design criteria (the peak flow at the outlet was 456 L/s compared to the predevelopment flow of 458 L/s).

The addition of WSUD reduced runoff from each sub-catchment and thus smaller conduits may be used. The result of this is a lower cost for conduits for Model B as indicated in Table 4. Very small areas of the site were subjected to WSUD techniques in Model B and the majority of this was in the form of permeable pavement in most drive, walk and parking areas. The peak flow of 364 L/s was less than the predevelopment flow of 458 L/s and all other design criteria were satisfied. The considerable difference between these flows is due to the flooding design criteria. When some WSUD features were removed from this optimised solution, flooding occurred at some nodes.

As with Model B, Model C is able to use smaller conduits due to the use of WSUD. The cost of conduits was slightly higher than Model B, however, the cost was much lower than the cost for Model A. More WSUD is used because it is the only means of reducing the peak flow without the provision of detention storage. The amount of WSUD varied between 5% and 10% for most paved areas and several of the buildings also included rainwater tanks of varying sizes.

It should be noted that the majority of WSUD practices were concentrated at the downstream end of the catchment suggesting that it is more cost effective to reduce the flow from downstream catchments rather than the upstream catchments. The peak flow of 436 L/s was less than the predevelopment flow of 458 L/s.

Optimisation of 1 in 100 year ARI storms

Similarly to the 1 in 5 year rainfall ARI, Models A, B and C (see descriptions in Figure 3) were optimised for the 1 in 100 year rainfall ARI and the results are summarised in Table 5.

Table 5. Summary of costs in US dollars for the optimised models with a 1 in 100 year rainfall ARI.

Cost ($)	Model A	Model B	Model C
WSUD	-	188,595	326,232
Conduit	631,882	654,732	868,429
Storage	938,190	133,745	-
Total	1,570,072	977,072	1,194,661

For the 1 in 100 year rainfall ARI all design criteria were met in Model A with the peak discharge at the outlet being 1229 L/s compared to the peak discharge of the predevelopment model of 1262 L/s. In Model B between 10 and 35% of most paved areas were used for permeable pavement. Again, the increased amount of WSUD allowed for a greatly reduced storage size. This is because both WSUD and detention storage are capable of reducing the peak flow and with this case study it was found more cost effective to utilise the WSUD. Most WSUD was located at the downstream subcatchments. The peak flow was 1062 L/s compared to the predevelopment model of 1262 L/s and all design criteria were met. Again, the absence of detention storage must be balanced by an increase in WSUD for Model C. The permeable pavement covered 5 to 30% of most paved areas and large rainwater tanks were used at most buildings. The WSUD techniques were more evenly spread throughout the catchment when compared to the 1 in 5 year ARI storm. The design criteria were satisfied including the peak flow criteria with 1133 L/s for Model C compared to 1262 L/s for the predevelopment scenario. Figure 4 shows the locations of each type of WSUD throughout Model C.

Comparison of optimal solutions

The solution using only traditional drainage infrastructure (Model A) used larger pipe diameters than the two other solutions that combined the traditional drainage infrastructure with WSUD techniques (Models B and C). This is to be expected because the WSUD reduces surface runoff and thus smaller pipes can be used. As expected, Model A requires a greater amount of storage to reduce the peak flow. This is because there are no WSUD techniques provided to detain the runoff and thus reduce the peak flow in that plan. The quantity of WSUD treatment varies greatly between Models B and C. The model without storage (Model C) requires much more WSUD treatment because this is the only way the peak flow can be reduced. Combined infrastructure with storage (Model B) can reduce the peak flow through detention. For that reason, it is possible to reduce the amount of WSUD treatment. All solutions used permeable pavement as the primary type of WSUD treatment in conjunction with rainwater tanks. Some of the solutions used rain gardens or green roofs in small quantities.

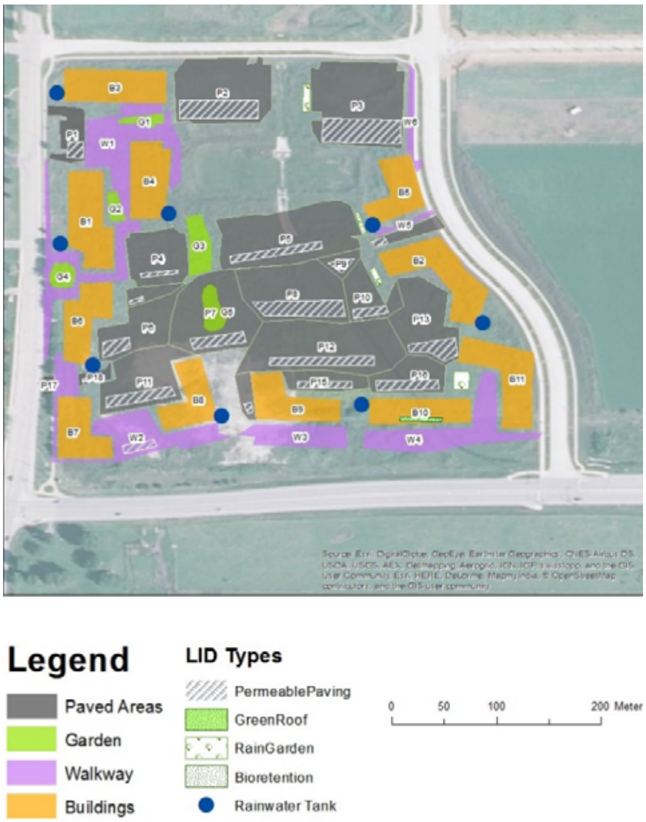


Figure 4. WSUD locations for the optimised Model C (1 in 100 year storm).

The permeable pavement and rainwater tanks were spread almost evenly throughout the catchment, however, there was a slight tendency for higher proportions of WSUD treatment in the downstream areas. This shows that a trade-off has been made during optimisation and that permeable pavement and rainwater tanks proved to be the most effective when considering cost and in their function of decreasing runoff. The costs of the WSUD options are shown in Table 3.

The review of literature showed that it is often a planning requirement that the peak flow of a developed site be kept below the peak flow of the predevelopment catchment. A comparison of the peak flows can be seen in Figure 5 and it shows that the predevelopment flows are the baseline that all solutions are compared to.

The difference in the peak flows of the models in Figure 5 is also shown below in the hydrographs in Figure 6. Both Figure 5 and Figure 6 show that the peak flow for the optimised solutions remained below that of the predevelopment flows despite the impact that increased impervious cover has on peak flow (Figure 5). It can also be seen in Figure 6 that the inclusion of detention storage (Models A and B) prolongs the duration of higher flows. See Table 6 for a summary of all costs.

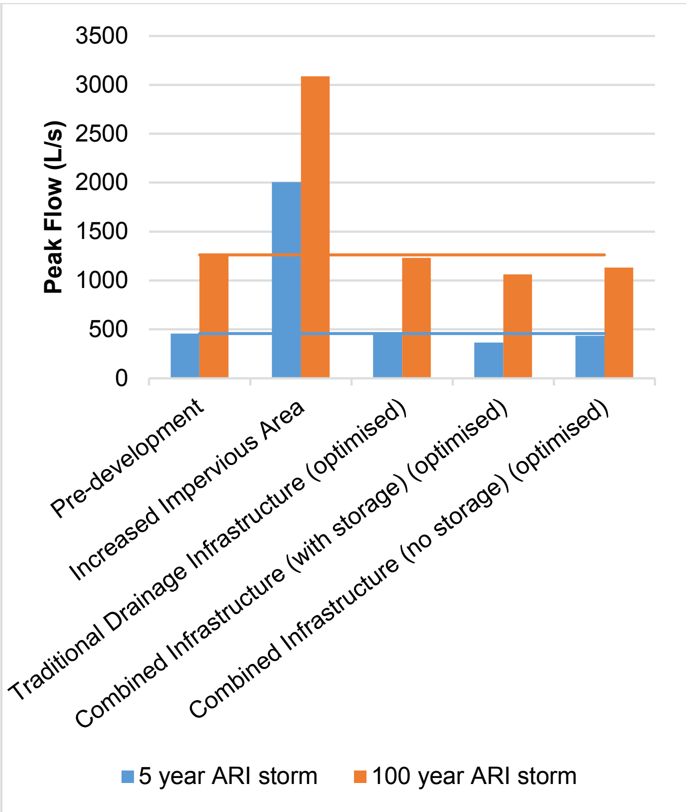


Figure 5. A comparison of the peak flows for the pre- and post-development models.

Traditional infrastructure (the most common form of stormwater management) produces the greatest cost for both storm events as shown in Table 6. Furthermore the traditional infrastructure only solution does not have any of the other benefits associated with WSUD as discussed in the review of literature. Table 6 shows that the use of combined WSUD techniques and traditional infrastructure (Models B and C) had similar costs both with storage (Model B) and without storage (Model C) for the 1 in 5 year storm. To achieve the design criteria the solution without storage was required to use more WSUD techniques and larger conduits because none of the water could be retained.

When considering a larger storm such as the 1 in 100 year event the difference between the two combined infrastructure solutions is greater than for the 1 in 5 year event (see Table 6). Both are still significantly lower in cost than the solution that uses only traditional infrastructure. The model that incorporates storage is a lower cost solution for both ARIs.

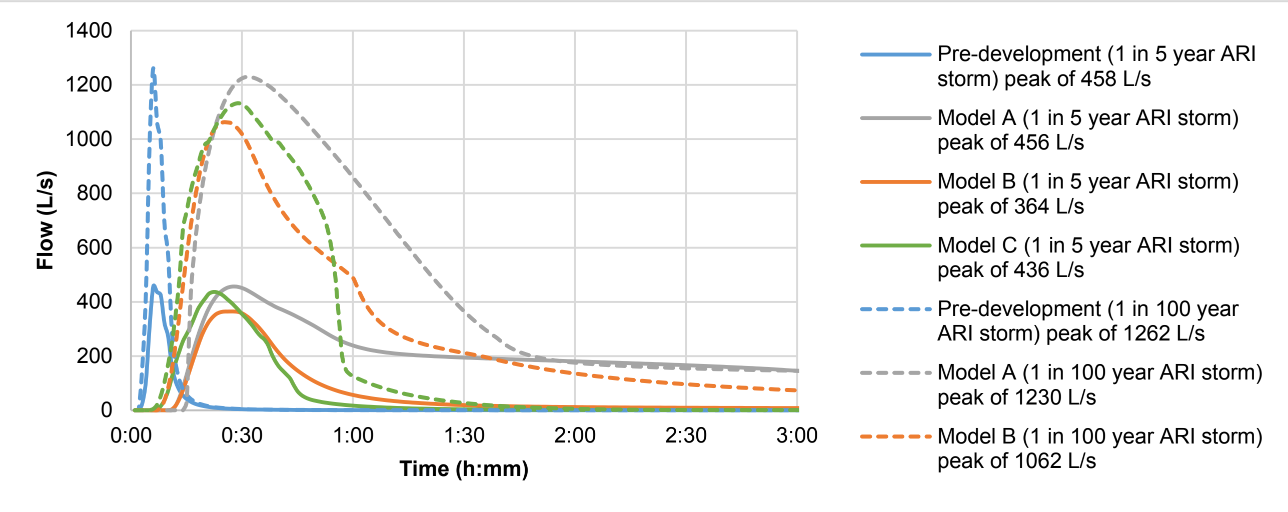


Figure 6. A comparison of the predevelopment and optimised solution hydrographs.

Table 6: Cost comparison for optimised solutions.

ARI	Cost ($)	Model A	Model B	Model C
1 in 5 year storm	WSUD	-	82,897	138,190
	Conduit	876,332	509,758	557,420
	Storage	93,705	68,150	-
	Total	970,037	660,805	695,610
1 in 100 year storm	WSUD	-	188,595	326,232
	Conduit	631,882	654,732	868,429
	Storage	938,190	133,745	-
	Total	1,570,072	977,072	1,194,661

CONCLUSIONS

This research has shown that the optimisation of a combination of Water Sensitive Urban Design (WSUD) practices and traditional drainage infrastructure is an effective method of designing stormwater systems. A case study has shown that for a variety of rainfall ARIs that it is more cost effective to use a combination of traditional drainage infrastructure and WSUD than to only use the traditional drainage infrastructure alone. When the optimisation framework was applied at the University of Illinois to the proposed South Campus Research Park it was found that a combination of both WSUD and traditional drainage infrastructure gave the lowest cost solution. It was also found that the combined infrastructure with detention storage was lower in capital cost than the combined infrastructure without detention storage, however, both were significantly lower in capital cost than the scenario with only traditional drainage infrastructure. For the 1 in 5 year rainfall event the combined infrastructure with and without storage cost $660,800 and $695,600 respectively compared to the solution with only traditional infrastructure that cost $970,000. Similarly for the 1 in 100 year storm the cost of the combined infrastructure with and without storage was $977,100 and $1,194,700 respectively while the traditional infrastructure cost $1,570,100.

There are several directions that could be taken to improve the understanding of combinations of WSUD and traditional stormwater infrastructure. The applicability of the method above to a variety of case studies will show that it is a viable alternative to traditional stormwater infrastructure. The inclusion of optimisation parameters such as berm height or soil depth may lead to more cost effective results. It is important for the stormwater industry that solutions are easily used by decision makers and the use of multi-objective optimisation would enable decision makers to choose from a variety of solutions. There are several other types of WSUD that may have been included and these may provide solutions that are able to better achieve optimisation objectives. It is also important to investigate the impact of multiple storm events over extended period simulations.

In some cases it is possible that repeated storms may diminish the retention and detention capabilities of the WSUD due to soil saturation.

ACKNOWLEDGMENTS

We would like to express sincere gratitude towards our supervisors Prof. Angus Simpson and Dr. Joshua Cantone. Their guidance, support, encouragement and expertise has been instrumental throughout the entirety of this project and contributed to its success. We would like to also thank Optimatics for allowing us the use of the Optimizer software, and in particular Ben Ernst and the Development Team who provided us with their time and support.

REFERENCES

BEIGHLEY, R. E., KARGAR, M. & HE, Y. 2009. Effects of impervious area estimation methods on simulated peak discharges. Journal of Hydrologic Engineering, 14, 388-398.

BOOTH, D. B. & JACKSON, C. R. 1997. Urbanization of Aquatic Systems: Degradation Thresholds, Stormwater Detection, and the Limits of Mitigation. Wiley Online Library.

COHEN, J. P., FIELD, R., TAFURI, A. N. & PORTS, M. A. 2011. Cost Comparison of Conventional Gray Combined Sewer Overflow Control Infrastructure versus a Green/Gray Combination. Journal of Irrigation and Drainage Engineering, 138, 534-540.

DALEY, R. M. 2007. Chicago Green Alley Handbook: An Action Guide to Create a Greener, Environmentally Sustainable Chicago, Chicago Department of Transportation.

DAMODARAM, C., GIACOMONI, M. H., PRAKASH KHEDUN, C., HOLMES, H., RYAN, A., SAOUR, W. & ZECHMAN, E. M. 2010. Simulation of combined best management practices and low impact development for sustainable stormwater management. Wiley Online Library.

DIETZ, M. E. & CLAUSEN, J. C. 2008. Stormwater runoff and export changes with development in a traditional and low impact subdivision. Journal of Environmental Management, 87, 560-566.

DIOGO, A. F., WALTERS, G. A., RIBEIRO DE SOUSA, E. & GRAVETO, V. M. 2000. Three-Dimensional Optimization of Urban Drainage Systems. Computer-Aided Civil and Infrastructure Engineering, 15, 409-425.

FOGEL, D. B. 2000. What is evolutionary computation? Spectrum, IEEE, 37, 26, 28-32.

GUOSHUN, Z., PATRICK, R. & YONG, T. 2013. Multi-objective optimization of low impact development designs in an urbanizing watershed. Open Journal of Optimization, 2013.

HAN, M. & MUN, J. 2011. Operational data of the Star City rainwater harvesting system and its role as a climate change adaptation and a social influence. Water Science & Technology, 63, 2796-2801.

KRAMER, M. G. 2013. Our Built and Natural Environments: A Technical Review of the Interactions Between Land Use, Transportation, and Environmental Quality. Second ed.: U.S. EPA,.

LERER, S. M., ARNBJERG-NIELSEN, K. & MIKKELSEN, P. S. 2015. A Mapping of Tools for Informing Water Sensitive Urban Design Planning Decisions—Questions, Aspects and Context Sensitivity. Water, 7, 993-1012.

LIONG, S.-Y., CHAN, W. T. & SHREERAM, J. 1995. Peak-flow forecasting with genetic algorithm and SWMM. Journal of Hydraulic Engineering, 121, 613-617.

LIU, W., CHEN, W. & PENG, C. 2014. Assessing the effectiveness of green infrastructures on urban flooding reduction: a community scale study. Ecological Modelling, 291, 6-14.

PHILLIPS, B. C., YU, S., ZHANG, S. & THOMPSON, G. 2006. Analysing the Performance of WSUD using XP-SWMM.

ROSSMAN, L. A. 2010. Storm Water Management Model User's Manual Version 5.0. Cincinnati, OH: Water Supply and Water Resources Division, National Risk Management Research Laboratory, U.S. EPA.

RUTH, O. 2003. The effects of de-icing in Helsinki urban streams, Southern Finland. Water Science & Technology, 48, 33-43.

U.S. EPA 2000. Low Impact Development (LID): a literature review. United States Environmental Protection Agency.

THE AUTHORS

Cameron McPhail is currently a PhD candidate at The University of Adelaide. He completed a Bachelor of Civil & Structural Engineering with honours in 2015 and has gained experience in water, stormwater and software engineering. Cameron's current research is looking to improved decision-making in long-term planning of water infrastructure under deep uncertainty.

Sean Vial is a Graduate Civil and Environmental Engineer at Southfront – a specialist consultancy in the field of stormwater management. He has completed a double degree in Civil and Environmental Engineering (Honours) with a Bachelor of Science. Sean has gained experience with Natural Resources Adelaide & Mount Lofty Ranges and SA Water. He has extensive knowledge of stormwater management, water sensitive urban design, geology and ecology.

Bonnie Heidrich graduated from a Bachelor of Civil and Environmental Engineering with honours in 2015. She has since been working as a consulting Stormwater Engineer at Southfront while also pursuing further study in Environmental Policy and Management at the University of Adelaide.

Rebecca van der Pennen graduated from The University of Adelaide with a degree in Civil, Structural and Environmental Engineering (Honours) at the end of 2016. Currently, Rebecca is travelling and working in the USA and will be working with Lendlease as a graduate in 2018.

Prof. Angus Simpson has been a Professor since 1987 in the School of Civil, Environmental and Mining Engineering at The University of Adelaide. Angus teaches water courses to undergraduates and postgraduates, carries out research and performs consulting. He specializes in research in water distribution systems simulation modelling, optimization, water hammer and developing non-invasive pipe condition assessment techniques.

Dr. Joshua Cantone is currently Product Manager at Optimatics Chicago, the world-leading provider of infrastructure planning software that enables water and wastewater utilities around the globe to avoid billions of dollars in costs while ensuring optimal performance. Josh graduated with First Class honours from the University of Adelaide before working at KBR in Adelaide. With a BHP Fullbright Award, Josh received a Masters of Science in Civil Engineering specializing in Environmental Hydraulics and Hydrology at the University of Illinois at Urbana-Champaign followed by a PhD investigating methods for modelling hydrology and hydraulics in large urban stormwater/wastewater systems.