CRC for
Water Sensitive Cities

Impacts of harvesting solutions and water sensitive urban design on evapotranspiration

Green cities and microclimate

An Australian Government Initiative

CRC
AUSTRALIA

The impacts of harvesting solutions and WSUD on evaporation and the water balance and feedbacks to urban hydrology and stream ecology
Green Cities and Micro-climate - B3.1 -3-2014

Contributing Authors

Andrew Coutts[1,2]
Matthias Demuzere[3]
Nigel Tapper[1,2]
Edoardo Daly[4]
Jason Beringer[5]
Sultana Nury[1,2]
Ashley Broadbent[1,2]
Richard Harris[1]
Luke Gebert[1]
Kerry Nice[1,2]

[1] School of Earth, Atmosphere and Environment
Monash University, Melbourne, Australia 3800

[2] CRC for Water Sensitive Cities
Monash University, Melbourne, Australia 3800

[3] Catholic University, Leuven, Belgium

[4] Department of Civil Engineering
Monash University, Melbourne, Australia 3800

[5] School of Earth and Environment
The University of Western Australia, Crawley, Australia 6009

Publisher

Cooperative Research Centre for Water Sensitive Cities

Level 1, Building 74, Clayton Campus
Monash University
Clayton, VIC 3800

p. +61 3 9902 4985
e. info@crcwsc.org.au
w. www.watersensitivecities.org.au

Date of publication: December 2014

Executive Summary

Urban development drastically alters the natural hydrology of the landscape as impervious surfaces replace natural vegetation and soils. This reduces the infiltration of water into soils, and increases surface runoff. This leads to a deficit of water in the urban landscape and reduces evapotranspiration. This is widely documented as a contributor to increased urban warming and the formation of the urban heat island (UHI). Water sensitive urban design (WSUD) and urban greening can help to restore a more natural hydrology in urban areas and increase levels of evapotranspiration and help cool the local scale urban environment. This report focusses on how urban development modifies the urban water balance and its links to the urban surface energy balance – which is fundamental to the development of urban climates. This report also explores the impacts of urban water management that may lead to an increase in evapotranspiration, and thereby alter the surface energy balance to improve urban climates.

Research in Melbourne has demonstrated the modification of the surface energy balance from urban development at the local scale. Urban development leads to large reduction in evapotranspiration which can lead to an increase in atmospheric heating, and increases heat storage in the urban fabric (which when released at night supports the development of the UHI). However, this can be combated by WSUD elements and various approaches were explored in this report. Research has also identified key design features that should be considered when implementing WSUD.

Research presented in this report has identified that:

- Green roofs can support high evapotranspiration rates if they are irrigated, and need to be moist on days when atmospheric cooling via evapotranspiration is most needed: on warm and sunny days. Currently, extensive green roofs are designed with thin substrates and planted with drought tolerant *Sedum* species. While this may support stormwater management objectives of reducing roof runoff, it does little for improving urban climates. By irrigated green roofs from a sustainable water source, a wider variety of plant species can be used and increase the cooling efficiency of green roofs.

- Irrigation is an excellent way to disperse water throughout the landscape and can increase local scale evapotranspiration rates. Using an urban land surface climate model, with a detailed water balance included, we explored the role of changing the land surface on evapotranspiration and explored the impacts of changing runoff patterns. Widespread irrigation was most effective, as it could be applied at any time. Redirecting runoff from impervious surfaces to pervious surfaces also increased evapotranspiration, but only following rain. Further model development is planned to integrate water storage (rainwater tanks) into the model to hold back runoff and extend is application to the landscape through irrigation. In response to an increase in evapotranspiration, there was a subsequent reduction in atmospheric heating.

- Biofiltration systems can support evapotranspiration in urban areas based on climate modelling results, and increases as the cover of systems increases up to a surface cover of around 35%, after which additional increases in evapotranspiration begin to diminish. To maximise the evapotranspiration from biofiltration systems, they should include vegetation (especially trees) and loam soils. Research also highlighted that additional benefits could be achieved by supported a biofiltration system with a supplementary irrigation system (rainwater tanks) and can support vegetation health.

Some of these design suggestions may conflict somewhat with stormwater runoff reduction objectives. WSUD is often designed for high infiltration rates of soils, which also means that soils dry out quickly and so are not moist when needed for heat mitigation periods. Therefore, it is important when designing and implementing WSUD, that the key objectives are clearly identified, such as heat mitigation, as this will inform design and placement decisions. Ultimately, a balance is needed in order to achieve both urban hydrology and micro-climate objectives. Harvesting stormwater for distribution and irrigation of vegetation and WSUD features (green roofs, biofilters) can enhance their evapotranspiration capacity and thereby influence local climate development.

Introduction

Stormwater harvesting and water sensitive urban design (WSUD) aim to restore a more natural water balance in urban areas. Retaining water in the urban landscape rather than rapidly exporting rainwater through the stormwater network means that more water may be available for soil moisture. Higher soil moisture levels can improve the health of vegetation, and promote higher rates of evapotranspiration. A potential benefit of this is improved urban climates at a range of scales (Coutts et al., 2012).

This report focuses on the connection between the urban water balance and the urban surface energy balance. Through changes in evapotranspiration, modification of the water balance will lead to changes in the surface energy balance which fundamentally governs the climate of a site (Oke, 1988; Spronken-Smith, 2002). As such, the development of urban climate can be manipulated by intentionally modifying the urban land surface through stormwater harvesting and WSUD.

This report presents both observational and modelling research at the micro- and local- (neighbourhood) scale on the urban water and surface energy balance to date within **Program B3.1 of the Cooperative Research Centre for Water Sensitive Cities (CRCWSC)**. The focus of this report is on evapotranspiration. An extensive review on the impact of urban landscape modification on the development of distinct urban climates, and the potential benefits of stormwater harvesting and WSUD can be found in the *Cities as Water Supply Catchments (CaWSC) – Project 3: Green Cities and Microclimate Literature Review* and the publication of *“Watering our cities: The capacity for Water Sensitive Urban Design to support urban cooling and improve human thermal comfort in the Australian context”* (Coutts et al., 2012).

The Urban Water and Surface Energy Balance

To begin, an overview of the urban water balance and the surface energy balance is provided (figure 1). We focus on the external (outdoor – not including indoor water use) urban water balance as this is directly related to development of the outdoor thermal environment. The external urban water balance is given by (Järvi et al., 2011):

$$\mathbf{P + I_e + F = E + R + \Delta S}$$

where P is precipitation, I_e is external irrigation, F is anthropogenic water vapour emissions, E is evapotranspiration, R is runoff and ΔS is the change in water storage. Many water balance models use ‘potential evapotranspiration’ to describe water loss from the surface through evaporation and plant transpiration. However, potential E describes the maximum possible E rather than actual E that is dependent upon the energy available at the surface, as well as upon surface resistances. Modelling the surface energy balance in combination with the water balance in urban areas provides a more accurate representation of available energy, by consider radiative and energy exchanges with urban surfaces. **Urban energy and water balances are linked through evapotranspiration** (Figure 1), where the energy balance is given by (Grimmond and Oke, 1999):

$$\mathbf{Q^* + Q_F = Q_E + Q_H + \Delta Q_S}$$

where Q* is net radiation which is the total amount of radiation available to the system from solar and terrestrial sources. Q_F is the anthropogenic heat flux which is energy from sources such as cars, buildings and people, Q_E is the latent heat flux (which is equivalent to evapotranspiration where $Q_E = L_V E$; and L_V is the latent heat of vaporisation), Q_H is the sensible heat flux (atmospheric heating) and ΔQ_S is the storage heat flux, or the energy stored within a building-air volume (namely the urban canopy layer [UCL]) (Figure 1).

In urban areas, the replacement of natural surfaces with dry, hard impervious surfaces results in excessive runoff and less vegetation cover that leads to reduced evapotranspiration. When external irrigation is restricted and soil moisture levels are low, Q_E can be further limited. As part of a study on the influence of housing density on the development of local-scale urban climates, Coutts et al. (2007) observed and compared the surface energy balance at a suburban site in Melbourne (Preston) and a rural site on the city outskirts (Lyndhurst) in 2003-04. The average daily cycle of the surface energy balance is presented for January 2004 in Figure 2. Clear differences in energy partitioning are evident (Coutts et al., 2010).

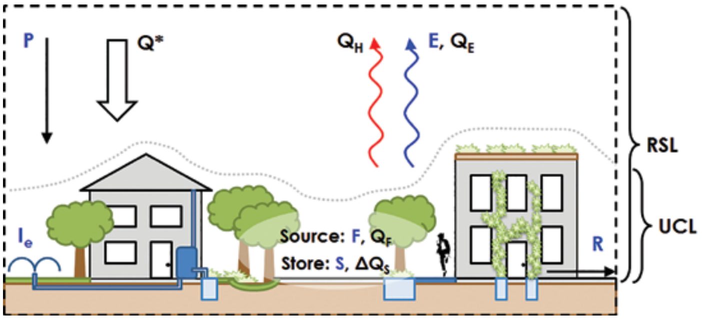
- Storage (ΔQ_S) at the suburban site was much larger due to the high absorption by urban materials with high heat capacities, and the trapping of radiation in the complex 3D structure of cities. This absorbed heat is lost at night and supports the development of the nocturnal Urban Heat Island (UHI). At the rural site, the ground heat flux (Q_G) is much lower as soils have a lower heat capacity and thermal conductivity than many urban materials, and the 3D structure is not present.

- Anthropogenic heat sources are not present in the rural environment. While Q_F was small at the suburban site, in dense urban areas, Q_F can become large. This additional source of heat supports urban heating throughout the entire diurnal cycle.

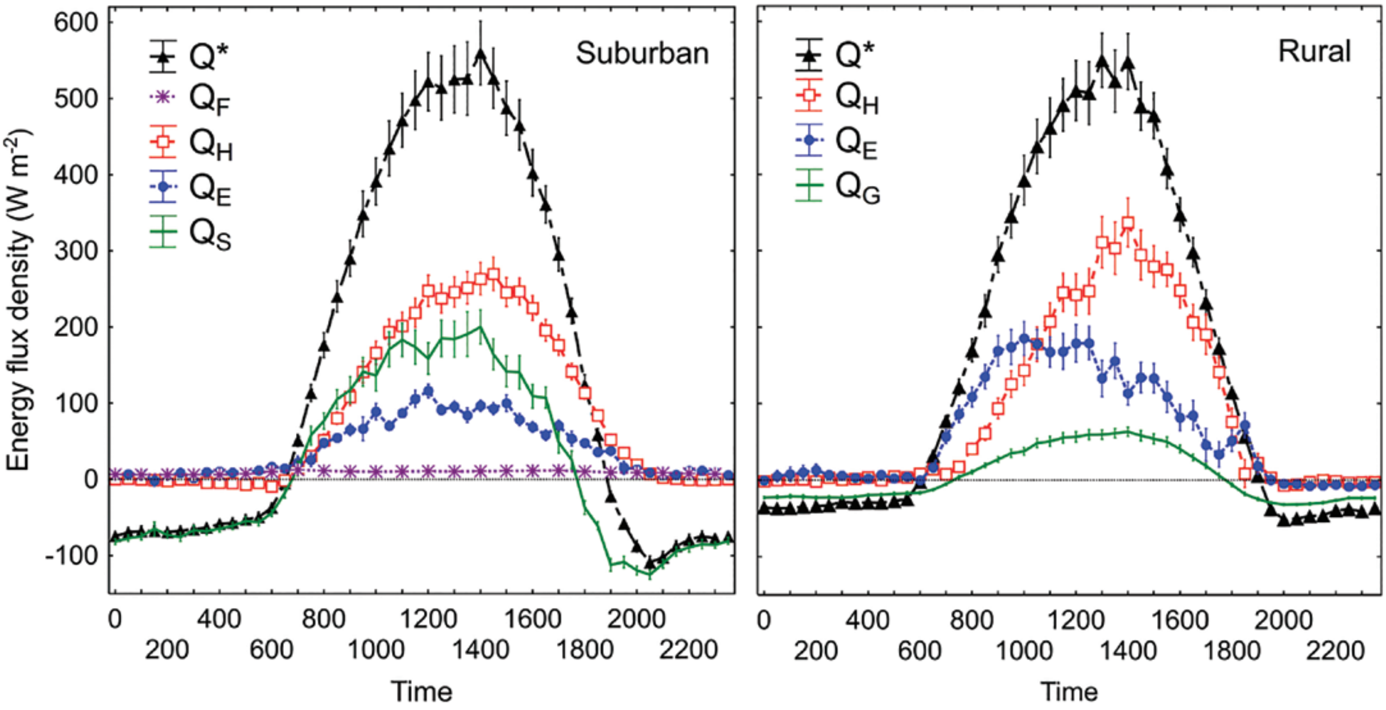
- Q_E is lower at the urban site compared to the rural site due to the waterproofing of the surface and the removal of vegetation. Q_E peaks in the morning at the rural site likely due to the evaporation of dewfall in the morning, and the reduction in transpiration in the latter part of the day.

- Q_H is similar at both sites, though some important differences exist. Q_H remains positive into the evening at the suburban site, supported by the storage heat loss. The peak in Q_H in the late afternoon at the suburban site is typical in urban energy balance studies. However, Q_H at the rural site was also the dominant flux, due to the drop in Q_E in the afternoon and a lower amount of ground heat storage. The rural site was relatively dry during the January period and it should be noted that urban-rural comparisons depend as much on the conditions at the rural site as they do at urban sites.

In summary, modification of the water balance can alter the partitioning of energy at the surface, and thereby influence the development of the local climate. Given the link between the water and energy balances through evapotranspiration, we focus on both aspects throughout this report.



→ *Figure 1: Schematic of the fluxes involved of an urban building-air volume, for the urban external water balance (blue symbols) where $P + I_e + F = E + R + \Delta S$, and the surface energy balance (black symbols) where $Q^* + Q_F = Q_E + Q_H + \Delta Q_S$. UCL is the urban canopy layer, RSL is the roughness sub-layer (Oke, 1987; Järvi et al., 2011; Coutts et al., 2012)*



↘ *Figure 2: Surface energy balance for a suburban (Preston) and rural (Lyndhurst) location in Melbourne for January 2004 (modified from Coutts et al., 2010)*

Evapotranspiration and Energy Balance of a Green Roof

Green roofs are designed to retain water on the rooftop to reduce runoff. Rather than being exported away as stormwater, water is lost through water uptake by vegetation (plant water storage and transpiration) and water storage in, and evaporation from, the soil. As such, green roofs are often cited as a tool for mitigating urban heat as a result of enhanced evapotranspiration. As outlined in the CaWSC Project 3 Interim Report 2012 (*Determine the micro-climatic influence of harvesting solutions and WSUD on household scale systems*), we undertook a monitoring campaign in 2011-12 of an experimental green roof system in Melbourne (Coutts et al., 2013).

We compared four experimental rooftops: conventional rooftop steel sheet roofing (STEEL); a conventional rooftop with a white, elastomeric ceramic coating (WHITE); a rooftop with an extensive vegetated roof (15 cm soil substrate and planted with a succulent vegetation *Sedum Rubrotinctum*) and (VEG); a rooftop with just the soil substrate layer (SOIL). Using a chamber, we undertook hourly measurements of evapotranspiration on four individual days that were warm and sunny (19 Oct 2011, 24 Nov 2011, 22 Dec 2011, 17 Jan 2012). These days tended to be at the end of dry periods when soil moisture levels were low, but were indicative of conditions when enhanced cooling from green roofs is needed. We also used various instruments that allowed us to observe/calculate Q^*, Q_H and ΔQS for each rooftop.

Chamber measurements were undertaken at three points on VEG and two points on SOIL. Evapotranspiration is presented in Figure 4 for each point and for each individual day. Generally, rates of evapotranspiration were low, with most plots <4 mm day-1. Some variability across plots was seen due to the slope of the roof, where the upper part of the slope dried out more quickly. On 24 November 2011, E was higher as a result of greater soil moisture on this day. Despite the low rates observed on these warm and sunny days, E was at least occurring compared with the STEEL roof which was absolutely dry due to rapid runoff after rainfall.

In relation to the surface energy balance, these rates of E are very low which means that very little energy is used in evapotranspiration (QE), and more energy is available for atmospheric heating (QH). This is evident in Figure 5 which compares the surface energy balance for STEEL and VEG. Naturally, E is not present on STEEL due to runoff. On STEEL, the Q^* is lower because the roof actually had a higher reflectivity (albedo = 0.71) than VEG (albedo = 0.15) and so less energy was available at the surface. Despite the presence of moisture in the soil, atmospheric heating was higher on VEG. Heat storage was also higher on STEEL, which further reduced available energy for atmospheric heating. This highlights that simply increasing evapotranspiration rates may not necessarily lead to cooling, as local climates are a result of each component of the energy balance.

We also explored the effects of irrigating VEG and SOIL to observe changes in E. Prior to a period of warm and sunny conditions, we irrigated the green roofs until the soil was fully saturated, and then monitored the green roof for three consecutive days (1-3 Feb 2012). Immediately following irrigation, E more than doubled compared to the dry days observed prior, before subsequently reducing as the soil dried out (Figure 6). Interestingly, E was higher for SOIL than VEG. This result was to be expected because of water uptake by the vegetation and lower soil temperatures due to shading of the soil by the vegetation. On dry days when soil moisture was low, E was slightly higher on VEG, as moisture was retained in the soil and vegetation for a longer period, thereby extending the duration over which E occurred, compared to the more rapid loss of moisture from SOIL. Following irrigation, QH from VEG was lower than the QH observed for STEEL.

For green roofs to be an effective approach to urban cooling they need to be irrigated and the plants need to be good users of water (not succulent). Harvested stormwater from nearby rooftops could be used to irrigate green roofs, though any irrigation regime would need to be designed carefully so as to not compromise the water capture capacity of the roof during rainfall events. This highlights the need to clearly define the objectives for WSUD interventions and suggests that designs may need to be altered if improved external micro-climate is a key objective.

Further results and findings from the experimental roof research and comparisons with cool (white) roofs can be found in Coutts et al. (2013) in a paper titled “Assessing practical measures to reduce urban heat: green and cool roofs” published in Building and Environment.

Figure 3: Photo of the VEG, SOIL and STEEL experimental roofs

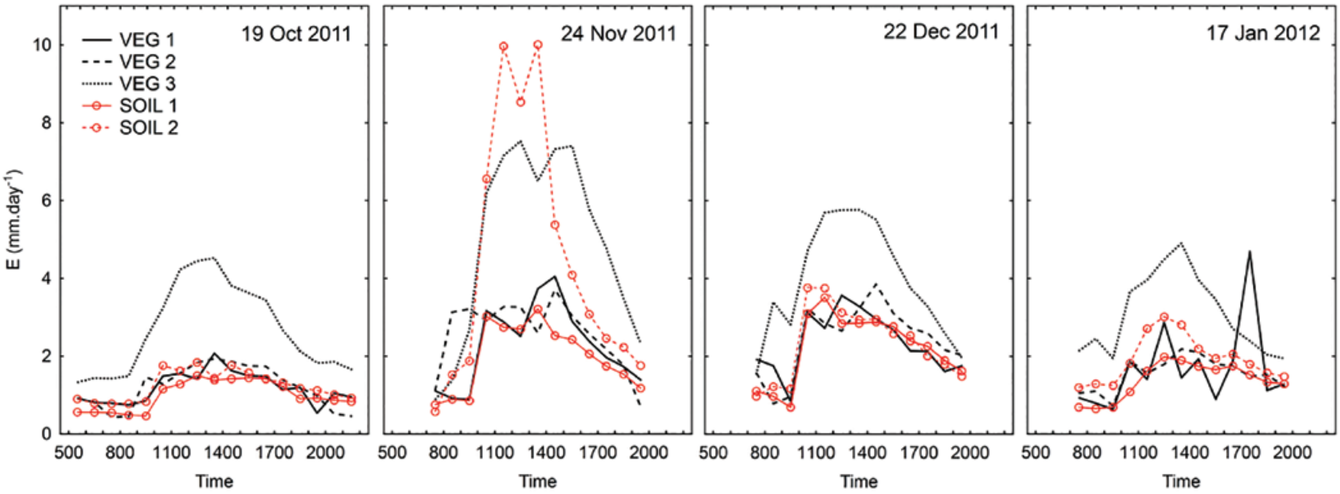


Figure 4: Evapotranspiration on the VEG and SOIL roofs for each individual plot (Coutts et al., 2013)

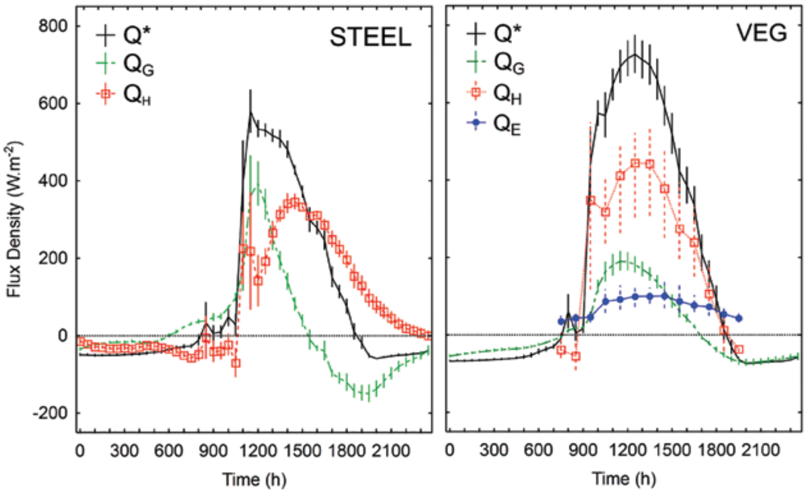


Figure 5: Average surface energy balance of the STEEL and VEG experimental roofs over the four days observed (Coutts et al. 2013)

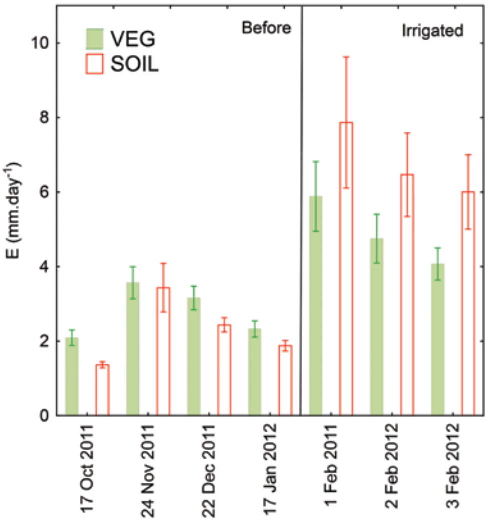


Figure 6: Average evapotranspiration rates (mm.day-1) between 12:30 and 19:30 on the days of chamber measurements before and after the irrigation event

Assessing Neighbourhood Scale Water and Energy Balances

Implementing well-designed stormwater harvesting and WSUD features at the micro-scale (lot or streetscape) throughout the urban environment has the potential to reduce local-scale (neighbourhood) air temperatures. Several studies have identified that increasing vegetation cover or water availability at this scale can reduce local temperatures (e.g. Mitchell et al., 2008; Grossman-Clarke et al., 2010; Gober et al., 2010; Rosenzweig et al., 2009 – see the CaWSC Project 3 Literature Review). Urban climate modelling is a tool that can be used to explore the effects of changes in land use and land cover on urban water and energy balances. A range of local scale, urban land surface parameterisations are available (Grimmond et al., 2011) which vary in complexity in how they represent the urban land surface. Further, these models have varying levels of complexity when it comes to modelling the urban water balance. More information can be found in Grimmond et al. (2011) and the CaWSC P3 Deliverable "Urban climate model selection for modelling WSUD features".

Our assessment of urban climate models identified that the Surface Urban Energy and Water balance Scheme (SUEWS) (Järvi et al., 2011) was a suitable scheme to investigate land use and land cover changes and their effect on urban water and energy balances. SUEWS is a local (neighbourhood) scale model (102-104m) that utilises commonly accessible meteorological input data and details of land surface cover to model the urban water and energy balance of a location. This simplicity makes the model attractive as a potential tool for industry to explore changes land surface conditions. Here, we apply SUEWS to Preston, Melbourne, where the flux tower described earlier was located.

SUEWS takes into account several major surface types: roofs, paved (e.g. concrete, roads), trees and shrubs (deciduous and coniferous), grass (irrigated and un-irrigated), un-managed land (e.g. bare soil) and water. Each surface (except water) has a soil water store below, and when saturated, creates runoff (surface and deep soil). Runoff and soil water can flow between different surface types (Figure 7) and be directed to pipes or directed to infiltration. SUEWS allows for daily irrigation regimes to be specified, as well as day of the week variations, which allow for the investigation of irrigation restrictions on water and energy balances. The energy balance model runs at hourly time-steps, while the water balance component can run using a 5 minute time-step. SUEWS is considered to be a simple urban land surface as it is a slab surface scheme which does not explicitly model urban canyons More information on SUEWS can be found in (Järvi et al., 2011).

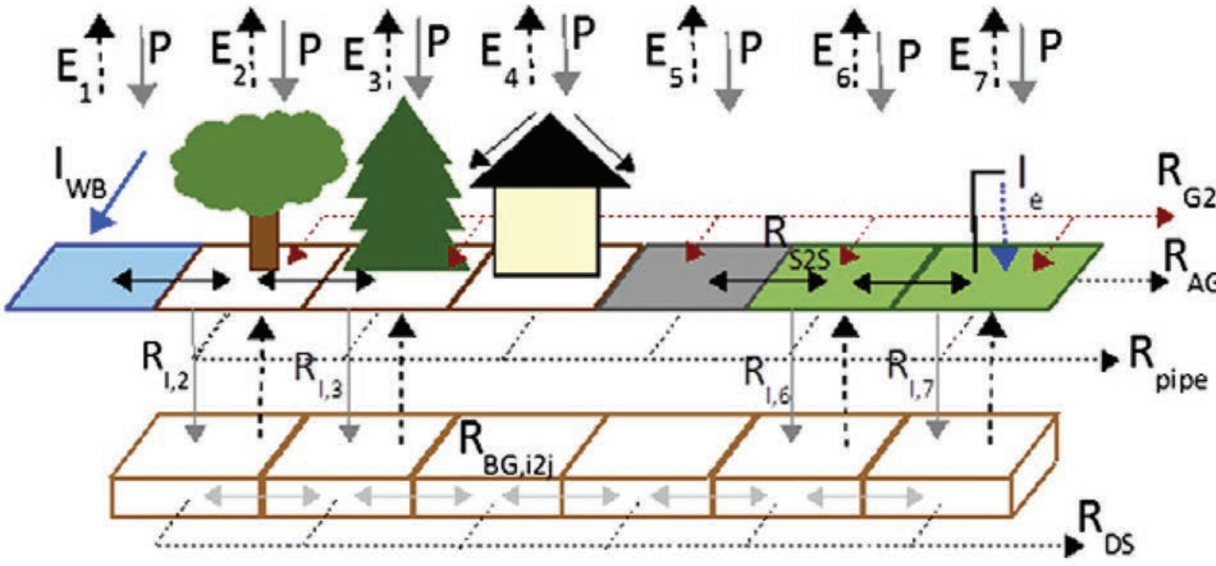


Figure 7: Conceptual diagram of the seven parallel surface types (i) with the horizontal and vertical flows of water within a grid cell and between grid cells. E is the evapotranspiration, P the precipitation, Ie the external irrigation, and R the runoff (Järvi et al., 2011)

Model application to Preston, Melbourne

Given that the surface energy balance is fundamental to development of local climates, it is important that models accurately capture and model urban energy partitioning at the surface. In 2003-04, a study was undertaken to document surface energy balance partitioning at Preston (as part of a network of stations across Melbourne) (Coutts et al., 2007). Preston is a residential area in the northern suburbs of Melbourne, characterised by low density detached housing. From August 2003 to November 2004, observations of net radiation, sensible heat flux, storage heat flux and latent heat flux (evapotranspiration) were undertaken on a tall tower using the eddy covariance technique (Figure 8).

Such observations are a challenge to collect in urban areas, and relatively few 'flux towers' have been established. Preston is one of a few towers globally with >1 year of observations. Figure 9 displays the network of current and past urban flux towers across the globe. The data from Preston (Coutts et al., 2007) were used in the International Urban Energy Balance Model Comparison project (Grimmond et al., 2011). These data present a unique opportunity to evaluate the SUEWS model against observations of the surface energy balance collected in Australia.

SUEWS model set-up

SUEWS was set up to run for the entire period for which observational data were available (Aug 2003 – Nov 2004). Meteorological input data included hourly values for incoming solar radiation, incoming long-wave radiation, air temperature, relative humidity, wind speed, pressure, and rainfall. As can be seen, these are commonly accessible input data that would be available from nearby weather stations (except possibly incoming long-wave radiation, but the can be modelled using either temperature and humidity, or cloud cover which may be more accessible (Loridan et al., 2010). Surface cover inputs for the site were taken from Coutts et al. (2007) and Nury et al. (2012) (Table 1). Values for QF were also taken from (Coutts et al., 2007) as input.However SUEWS can also model QF where data are unavailable.

To account for the dominant tree cover type at Preston, we changed relevant values for coniferous trees to those of evergreen trees; namely the leaf area index (LAI) and water storage capacity of Eucalyptus trees based on (Breuer et al., 2003). Also, the land cover fraction of vegetation cover at Preston was not separated by tree species, so we distributed the total vegetation fraction between evergreen (71%) and deciduous (29%) based on Frank et al. (2006). Some initial conditions were required to initialise the model such as wetness state of the soil and leaf area index.

Input	
Plan area fraction of paved areas	17.50%
Plan area fraction of buildings	44.50%
Plan area fraction of evergreen trees	16.10%
Plan area fraction of deciduous trees	6.90%
Plan area fraction of irrigated grass	0.00%
Plan area fraction of un-irrigated grass	15.00%
Plan area fraction of water	0.00%
Plan area fraction of un-managed soil	0.00%
Mean building height	**4.22m**
Mean vegetation height	**4.15m**

Table 1: Surface cover inputs in SUEWS for Preston

↑ *Figure 8: Eddy covariance flux tower established in Preston in 2003-04 (Coutts et al., 2007)*

June 6, 2012: The latest issue of the Fluxnet Newsletter features the Urban Flux Network.

Sites directory

●	**London** KSS	E C ☐ ☐
○	**Los Angeles** San Gabriel	E ☐ ☐ ☐
○	**Los Angeles** Arcadia	E C ☐ ☐
○	**Los Angeles** Arcadia	E ☐ ☐ ☐
○	**Marseille** CAA	E C ☐ ☐
○	**Melbourne** Preston	E C ☐ ☐
○	**Melbourne** Surrey Hills	E C ☐ ☐
●	**Mexico City** Escandon	E C A T
○	**Mexico City** Iztapalapa	☐ C ☐ T
○	**Miami** West Miami	E ☐ ☐ ☐
○	**Minneapolis** Roseville	E C ☐ T
○	**Montreal** Rue des Ecores	E C ☐ ☐

Interactive Map - Click on markers to display site details

← *Figure 9: The urban flux network (http://www.geog.ubc.ca/urbanflux/)*

At the time of the collection of this dataset, Melbourne was experiencing what were then, Stage 2 water restrictions*. This involved no watering of lawns at all, automatic sprinkler use between 11pm and 6am, and manual sprinkler systems between 5am and 8am, and 8pm to 11pm. Figure 10 presents the hourly external water use profile for the study area as a fraction of the total daily water use drawn from the Yarra Valley Water 2004 Residential End Use Measurement Study (Roberts, 2005). Peak irrigation occurred in the late evening during the prescribed manual irrigation hours. This external water use profile was used as input for the hourly external irrigation model in SUEWS, and irrigation was allowed for all properties on all days. For additional water use inputs based on Roberts (2005), households generally watered 3-4 times per week, so for any given day, 50% of households watered their gardens. Further, it was assumed that only 50% of the vegetation was irrigated (Pappas et al., 2007). SUEWS also allows for prescription of where surface water flows, either to another surface, into the soil, or runoff into the pipe network and hence removed.

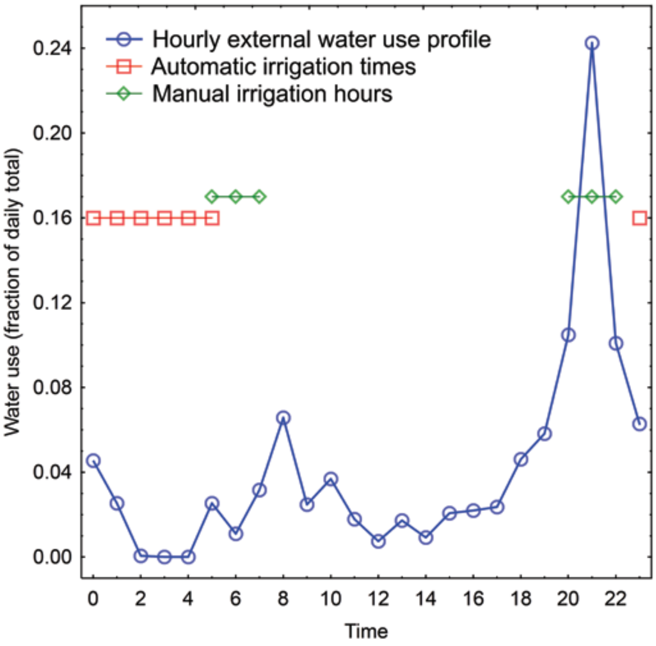


Figure 10: Hourly irrigation profile in the summer of 2004 for suburbs in the Yarra Valley Water service area

Evaluation

Figure 11 presents the mean modelled and measured surface energy balance for Preston in January 2004. SUEWS performs very well, modelling the important features of urban energy partitioning, with similar magnitudes to those observed. QH was the dominant flux, while QE was low during the day. The positive QH into the evening observed at the Preston site was captured, as was the large QS throughout the day. However, the evaluation revealed that throughout the year, the model generally underestimated QE and as a result, QH was overestimated. This observed underestimation in QE in SUEWS was also noted in North American evaluations in Vancouver and Los Angeles leading to overestimated QH (Järvi et al., 2011) and may be due to uncertainty in roughness length of heat or surface resistance.

As a coarse evaluation of the daily model for external water use within SUEWS, the pattern of daily external irrigation (mm) was compared with the daily bulk consumption from Yarra Valley Water (YVW) (Figure 12) which services the Preston area. Given a base daily consumption of around 400 ML over this period for the YVW area, the variability above this amount can be attributed to irrigation. The daily water use model in SUEWS is based on mean daily air temperature and days since rain. Overall, the daily water use from SUEWS follows a very similar pattern to the variability in the bulk YVW consumption. For the evaluation, Figure 12 highlights that daily irrigation for the Preston area during these water restrictions was very small at < 0.5 mm.

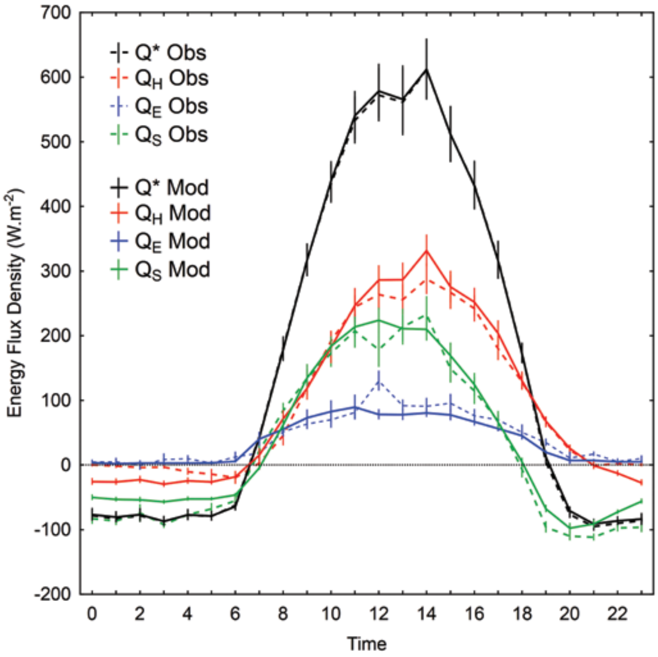
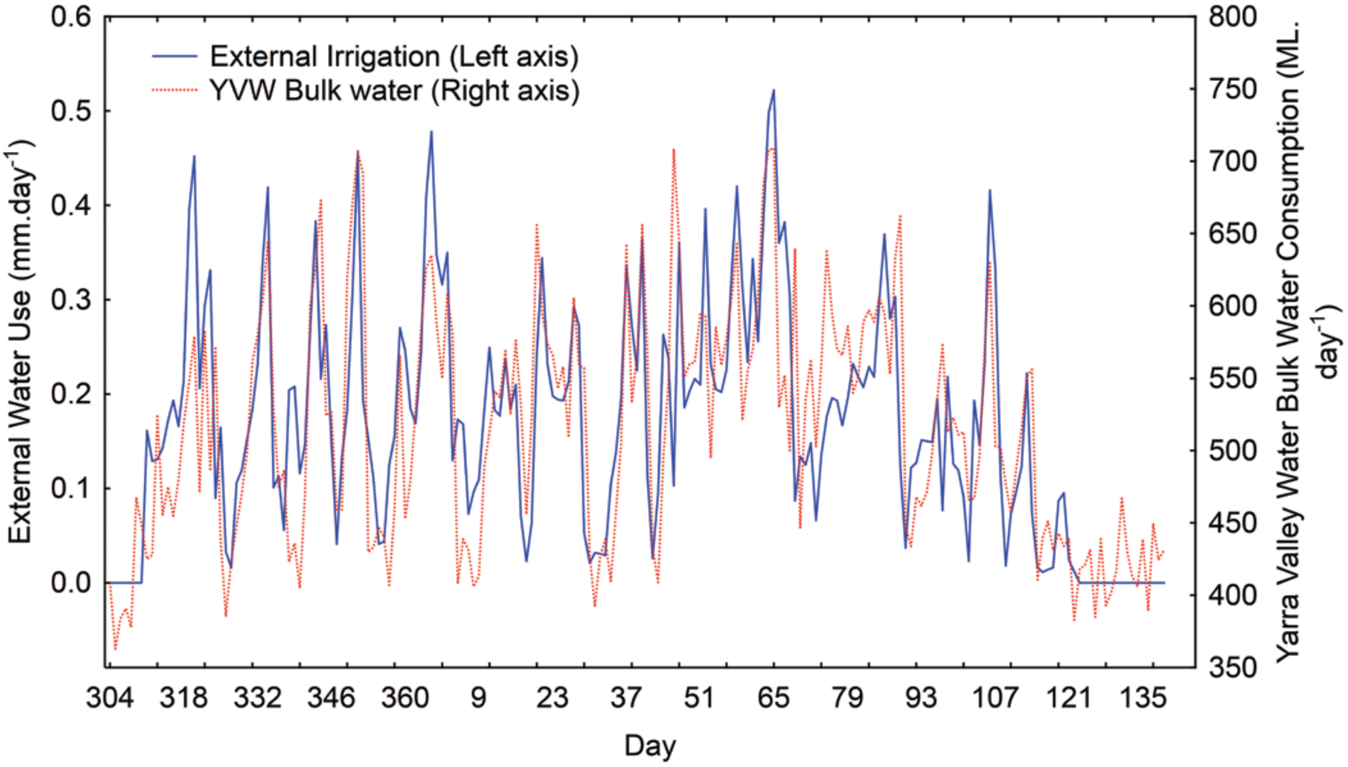
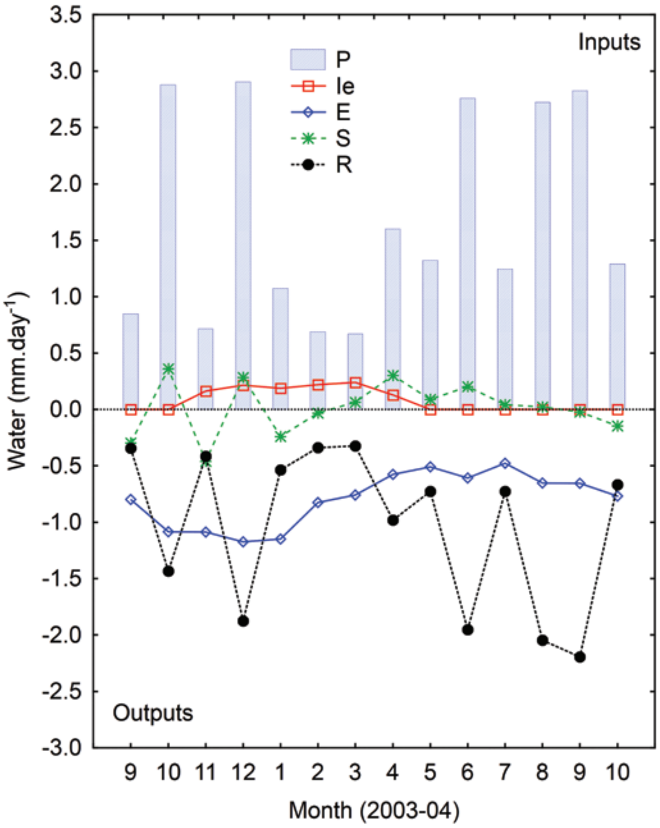


Figure 11: SUEWS modelled surface energy balance for Preston, Melbourne in January 2004 compared with observations

** Water restrictions have since been modified in Victoria with permanent water saving rules introduced, along with new restrictions for each stage*





Given these promising results, we can be confident in the ability of SUEWS to accurately model the urban surface energy balance and water balance during the Melbourne summer and can therefore be used to explore a range of scenarios of changing irrigation patterns and landscape arrangements.

The monthly urban water balance for Preston from September 2003 to August 2004 is presented in Figure 13. The yearly cycle of evapotranspiration rates is evident, with evapotranspiration generally higher than runoff during the dry summer period. Over summer, as vegetation begins to uptake water and more energy is available, evapotranspiration becomes an important component of the urban water balance. However, in October and December 2003, precipitation was very high, generating large amounts of runoff to the stormwater pipe network; until a dry summer period from January – March 2004. Irrigation of the landscape also became an important contributor to the urban water balance, contributing the equivalent of up to 36% of the precipitation in March 2004. In the winter months, runoff dominates the water balance in terms of urban water losses.

↑ Figure 12: Comparison of modelled external irrigation (left axis) for Preston over the 2003-04 summer and Bulk water consumption (right axis) for the Yarra Valley Water service area. Water for irrigation is a large driver of variability in daily water use

↖ Figure 13: Monthly water balance at Preston modelled by SUEWS where P is precipitation, I_e is irrigation, E is evapotranspiration, S is change in soil storage, and R is runoff.

Water use and design scenarios

We undertook a number of simple scenarios exploring changes in water use and landscape design. The Preston evaluation model set up is used as a 'base case' scenario (see Table 1 for land surface fraction covers and Table 3). We then explored the following scenarios concerning irrigation regimes:

1. **Base Case** — as for Preston 2003-04.

2. **Complete Irrigation** — In this scenario, households continue to water 3-4 times per week, but 100% of the grass and vegetation is irrigated.

3. **No Irrigation** — For this scenario, there is no irrigation of grass or vegetation.

SUEWS allows for redirection of surface water flows following irrigation. In SUEWS, the default drainage pattern reflects traditional urban drainage patterns and sees 90% of roof runoff being removed via piped drainage, and 96% off paved surface runoff. In the following scenarios, we explore redirecting water to pervious surfaces, rather than allowing water to be exported via piped drainage, in an attempt to replicate water flows from WSUD:

4. **Roof redirect** — here, a percentage of roof runoff was redirected to un-irrigated grass (22%), Deciduous trees (20%) and Evergreen trees (44%) (Table 2). In this scenario, only 10% of roof runoff was lost directly to the drainage network and there is no irrigation. Redirection of roof runoff occurs at each time step, meaning that water is not stored in rainwater tanks for controlled irrigation.

5. **Road and roof redirect** — in this case, roof runoff is redirected as above, while 50% of runoff from paved surfaces (e.g. roads + concrete) is redirected to pervious surfaces (Table 2). No irrigation is provided.

Finally, we explored some scenarios of changing urban development, along with changes in irrigation. We use Preston again as a base case location, along with the water use patterns for the 2003-04 summer (50% of vegetation irrigated and watering 3-4 times per week):

A. **Developed** — To represent an idealised future development scenario, we doubled the mean building height, and replaced a portion of pervious surfaces (grass and trees) with impervious surfaces (paved and buildings) (Table 3). Irrigation was not provided.

B. **Developed + Redirect** — We then apply the above development scenario, along with redirection of runoff from impervious surfaces to pervious surfaces (as in the Road & Roof Redirect scenario [5] above).

C. **Developed + Irrigation** — Finally, we take the development scenario, and apply complete irrigation to all the pervious surfaces with no restrictions.

Runoff from surface to →	Paved	Decid. Trees	Everg. Trees	Irr-Grass	Un-Irr-Grass	Runoff (pipe)	to → Soil
Default: Roof to runoff	2%	2%	2%	2%	2%	90%	→8%
Default: Road to runoff	0%	1%	1%	1%	1%	95%	→4%
Roof-redirect							
Roof to pervious	2%	20%	44%	2%	22%	10%	→90%
Roof & Paved-redirect							
Roof to pervious	2%	20%	44%	2%	22%	10%	→90%
Road to pervious	0%	9%	20%	1%	20%	50%	→50%

Table 2: Horizontal water distribution in the SUEWS model and redirection of water flows from impervious to pervious surfaces in scenarios 4 and 5

	Base Case	Developed
Buildings	44.50%	60%
Paved	17.50%	22%
Decid. Trees	6.90%	6.50%
Everg. Trees	16.10%	6.50%
Irr-Grass	0%	0% (5% for Scenario C)
Un-Irr-Grass	15%	5% (0% for Scenario C)
Water	0%	0%

Table 3: Changes in land use cover for the development scenarios

Results for changes in evapotranspiration and runoff of each scenario are presented in Figure 15 in mm.day^{-1}. Evapotranspiration (positive values) represents water losses to the atmosphere, and runoff (negative values) represent water losses to the stormwater drainage pipe network. Beginning with scenarios 1-5 (Figure 15a), the complete irrigation scenario generates the largest amount of E. The irrigation scenario is particularly beneficial, as water is applied continuously across the landscape according to the hourly irrigation profile (Figure 10), so there is regularly water available to support E. However, this irrigation means that the soil moisture stores are higher, and so runoff is also increased, which has implications for stream hydrology. But in the dry months, E in the complete irrigation scenario was up to 4 times higher (Mar 04) than for the no irrigation scenario. Widespread irrigation on this scale would be difficult to achieve and require private householders to regularly irrigate their gardens.

The roof redirect, and road + roof redirect scenarios showed lower E than the base case, but E was higher than that observed in the no irrigation scenario. There is only so much water that can infiltrate and be stored in the soil. Importantly, runoff is also reduced, benefitting stream hydrology. The influence of the redirect scenarios is most evident in the drier months (Feb-Mar) when more capacity is available in the soil for redirection of runoff from impervious surfaces. There is only so much capacity available in the soil and there are limits to rates of infiltration and drainage. In the current version of SUEWS, the pervious surfaces do not adequately represent WSUD features like biofilters which increase infiltration and drainage rates and soil storage capacity.

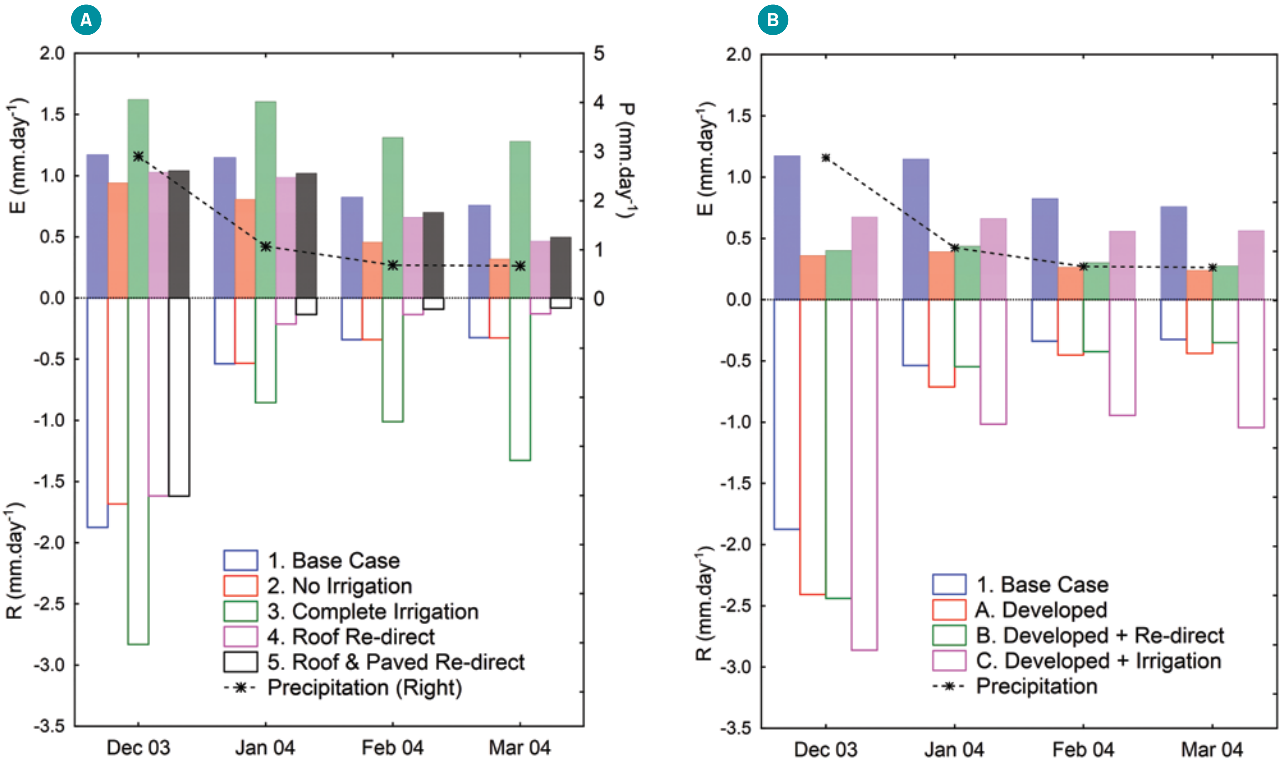
Looking at the development scenarios (A-C), the increase in imperviousness dramatically reduces E and runoff increases. Even with complete irrigation, evapotranspiration is lower than the base case. Further, the influence of redirecting runoff is also reduced. In this denser urban environment, less pervious surface area is available for infiltrating water, and does little for reducing runoff to urban streams. Again, the complete irrigation scenario leaves less capacity for soil storage of water and leading to increases in runoff.

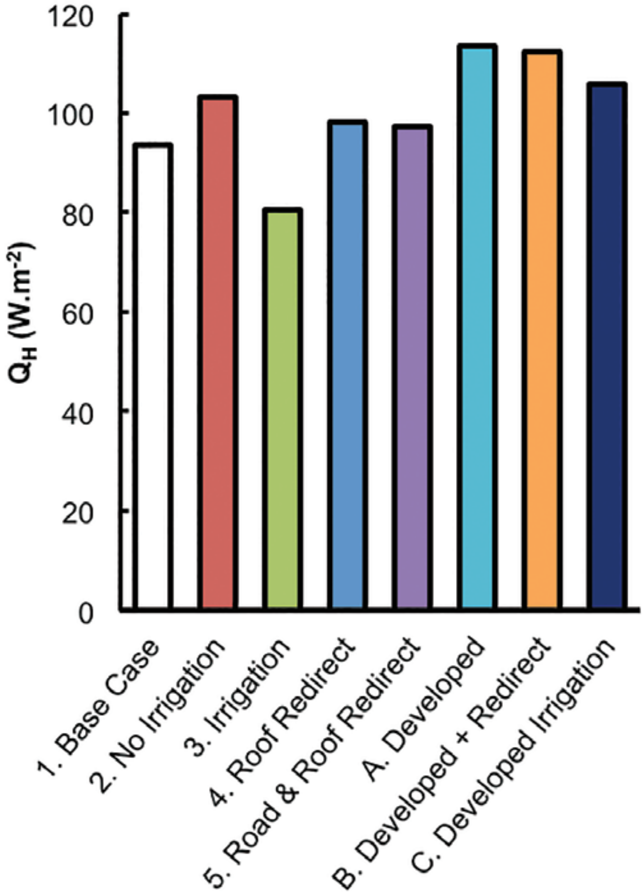
The capacity for WSUD to increase E in these scenarios was dependent on the amount of pervious space available. In a dense urban environment, WSUD approaches need to target grey infrastructure too, such as through permeable pavements. This also applied for irrigation. Having the ability to irrigate widely across the landscape was shown to increase E. Using rainwater tanks and other small, distributed harvesting systems to collect water for this irrigation, while reducing runoff would be extremely beneficial. Even with 90% of impervious surface runoff being redirected to pervious surfaces, runoff still occurred, so additional measures are needed to harvest water.

Future development of SUEWS could further evaluate changes in land cover and horizontal water distribution to better represent WSUD in the model. SUEWS does not currently have rainwater tanks incorporated into the model, and for Melbourne some 22% of households have rainwater tanks. Further, drainage rates in the model could be tailored to better represent WSUD elements such as bio-filtration systems which promote infiltration to help reduce runoff, and such approaches need to be validated. Initial exploration of increasing the soil moisture store for pervious surfaces, and increasing the water capacity of the soil for Scenarios 3, 4 and B did not yield any significant changes to the water balance.

The next question for this work is clearly ‘What do these changes in evapotranspiration mean for air temperatures at the neighbourhood scale?” Work is currently underway to couple a convective boundary layer (CBL) model to SUEWS and validate, in order to model changes in air temperature and boundary layer development for urban landscapes. As an indicator of the effects of land use changes, irrigation and redirection of water, Figure 16 presents the mean monthly sensible heat flux (atmospheric heating) for the month of Jan 04 for each scenario. Widespread irrigation delivers the largest reductions in QH and hence will show the lowest air temperatures. The scenario of no irrigation but with a redirection of runoff to pervious surfaces shows a marginal benefit here compared to a landscape with no irrigation at all, and again is larger for the scenario with greater pervious cover, and also during the drier months.

This neighbourhood scale modelling with SUEWS clearly demonstrates the capacity to intentionally modify the urban surface energy balance and ultimately air temperature through changes in the land surface and various irrigation scenarios.





↑ Figure 15: Mean daily evapotranspiration rates and runoff over the months of Dec 03 – Mar 04. Positive values are evapotranspiration rates and negative values are runoff. Scenarios 1-5 are presented a) and scenarios A-C are presented in b) along with the base case (scenario1). Precipitation is given on the right axis

← Figure 16: Mean monthly sensible hear flux for each scenario for January 2004

Biofiltration Systems (Tree-Pits) in the Street Canyon Environment

While there are many urban land surface parameterisations available for investigating the impacts of a variety of land surface changes on the water balance and in particular, the surface energy balance, very few attempt to explicitly model aspects of stormwater harvesting and WSUD. Using the Community Land Model – Urban (CLM-U), recent research has involved implementing biofiltration systems and an irrigation scheme including a rainwater tank into the land surface parameterisation (Demuzere et al., 2013a). CLM-U is a more complex urban land surface scheme than SUEWS in that it explicitly models urban canyons (the 3D structure of streets). CLM-U has previously been evaluated for Preston and was shown to perform well in simulating the urban surface energy balance (Demuzere et al., 2013b).

Unlike SUEWS, in the model design used here pervious surfaces are altered to represent a lined bio-filtration system. The urban environment in the model is designed to be highly impervious, with 44.5% roof fraction, and 45.5% impervious ground surface, and 10% of the surface covered by bio-filtration systems. Rainwater is harvested from rooftops and stored in tanks (Figure 17). Following the arrangement proposed by (Burns et al., 2012), any overflow from the tank feeds into the biofiltration system. The tank water is also used to irrigate the bio-filtration system and is designed to optimise irrigation based on the moisture content of the soil. The design of the biofiltration system was based on systems installed in Smith Street, Collingwood in Melbourne, Australia (Figure 18) where monitoring of soil moisture has been undertaken previously (Gebert, 2012).

Following the setup of the biofiltration and tank arrangement in the model, the sensitivity of the model to soil parameters was analysed, and the performance of the model to capture the soil moisture dynamics was assessed. The model was run for a two month period 9 February 2012 – 9 April 2012, and the soil moistures was compared with those observed for the tree-pits in Collingwood. The model captured the main dynamics of the soil moisture well (Demuzere et al., 2013a).

Biofiltration system and street design scenarios

A range of scenarios were established using the CLM-U model to evaluate the influences of changes to the design and extent of cover of biofiltration systems in the street canyon environment. A base case scenario was created where there was no biofiltration system in the street, so 100% of the surface was impervious. Following this, the biofiltration system (BFS) was added and assessed for delivering changes in evapotranspiration according to systematic changes in: presence and type of vegetation; soil type; and % cover of systems on the street canyon floor (Table 4).

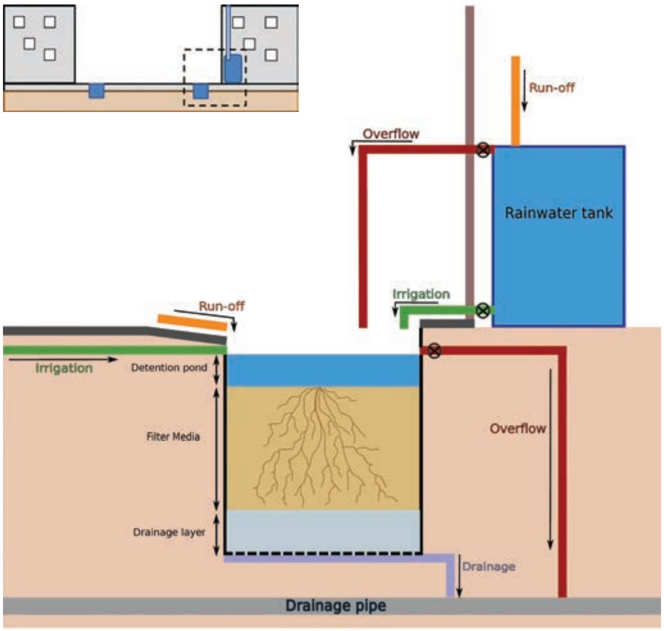


Figure 17 Conceptual overview of the lined biofiltration system as implemented in CLMU (Demuzere et al., 2013a)

Figure 18: Smith St. biofiltration systems

Scenario	Code	% BFS	Description
Base Case	BC	0%	No biofiltration system;100% impervious
No vegetation	V0	10%	Loamy sand soil only; Lined BFS; 94.5% tot. impervious
Vegetation 1	V1	10%	*Melaleuca Argentea*
Vegetation 2	V2	10%	*Carex Appressa*
Vegetation 3	V3	10%	Combined veg (*M. Argentea* & *C. Appressa*)
Sandy Loam	T_sl	10%	Predominantly sandy soil; combined veg
Loam	Tl / F10	10%	Loam soil; combined veg
1% BFS Fraction	F1	1%	Loam soil; combined veg; 99.4% tot. impervious
5% BFS Fraction	F5	5%	Loam soil; combined veg; 97.2% tot. impervious
20% BFS Fraction	F20	20%	Loam soil; combined veg; 88.9% tot. impervious
35% BFS Fraction	F35	35%	Loam soil; combined veg; 80.6% tot. impervious

Table 4: Biofiltration system design scenarios and fraction cover of systems that were assessed

Results are presented for the total water (mm) in evapotranspiration and runoff over the two month period for which the model was run (Figure 19). The Base Case (**BC**) scenario where 100% of the surface was impervious with no biofiltration system shows a very high amount of stormwater runoff (>80 mm). Despite the 100% imperviousness, there is actually a reasonable amount of E occurring over the period, which highlights the importance of ponding on urban surfaces (taken into account in this model) as an important component of the urban water balance.

For the remaining scenarios, all the stormwater runoff now enters, and drains through, the biofiltration system, so essentially much of the overland runoff ceases (unless the BFS soil is saturated). Of the water that enters, some is filtered through the soil media to the drainage pipe (BFS drainage [Figure 17]), some is stored in the soil, and some is evapotranspired. The amount of water leaving the urban environment is almost halved. The **V0** and **V1** scenarios actually show a small reduction in ET (Figure 19), as water enters and is stored in the soil media. For **V3**, with the combined vegetation types, ET increases as water is drawn from the soil by the root systems of the vegetation and so including vegetation in the biofiltration systems aids in increasing ET (Demuzere et al., 2013a)

The soil type appears to have a strong influence on ET. Changing from a sandy-loam (**T_sl**) to a loam (**Tl**) reduced the amount of drainage out of the bottom of biofiltration system and increased ET due to a greater capacity for water storage in the soil. This is also important for vegetation health, as more water is available for the root systems to draw on. So, from a hydrological and biophysical perspective, the loam soil performs better (Demuzere et al., 2013a), but this is in contrast with a biochemical, stormwater pollution treatment perspective, where sandy loams have a large capacity to remove nutrients and suspended solids (Bratieres et al., 2008).

Finally, as to be expected, increasing the fraction cover of biofiltration systems results in an increase in water retention in the urban environment, and an increase in ET. Results suggest that even when only a small amount of the surface is covered by biofiltration systems, the total amount of ET from this pervious surface is an order of magnitude higher than that from the impervious surface. For instance, for the **F10** scenario where biofiltration systems cover just 10% of the street (which equates to 5.5% of the total urban environment) the total ET from the biofiltration systems was around 5 times larger than the total ET from the remaining impervious area (94.5% including road and roofs) over the 2 month period. When the fraction cover of biofiltration systems reaches above around 35%, the additional benefits in terms of increasing ET begin to diminish (Demuzere et al., 2013a). Irrigating the BFS with harvested rainwater further increased the amount of ET.

It can be seen that both the design and amount of WSUD systems can influence the rate of ET in the urban environment. Including vegetation and more structured soils appears to enhance rates of evapotranspiration. Storage of water in the soil assists with extending periods of ET and is also likely to have benefits for vegetation health. Without irrigation, there were occasions where soil moisture levels dropped below the wilting point for vegetation, which would leave plants stressed. Harvesting stormwater and irrigating the biofiltration systems both with tank overflow and direct irrigation can reduce the occurrence of periods of low soil moisture.

Future work requires the coupling of the CLM-U urban land surface scheme with an atmospheric model to capture the important dynamics and feedbacks between in land-surface/atmosphere interactions. This would then provide the capacity to model changes in air temperature in response to the changes in the surface energy balance resulting from implementation of these biofiltration systems.

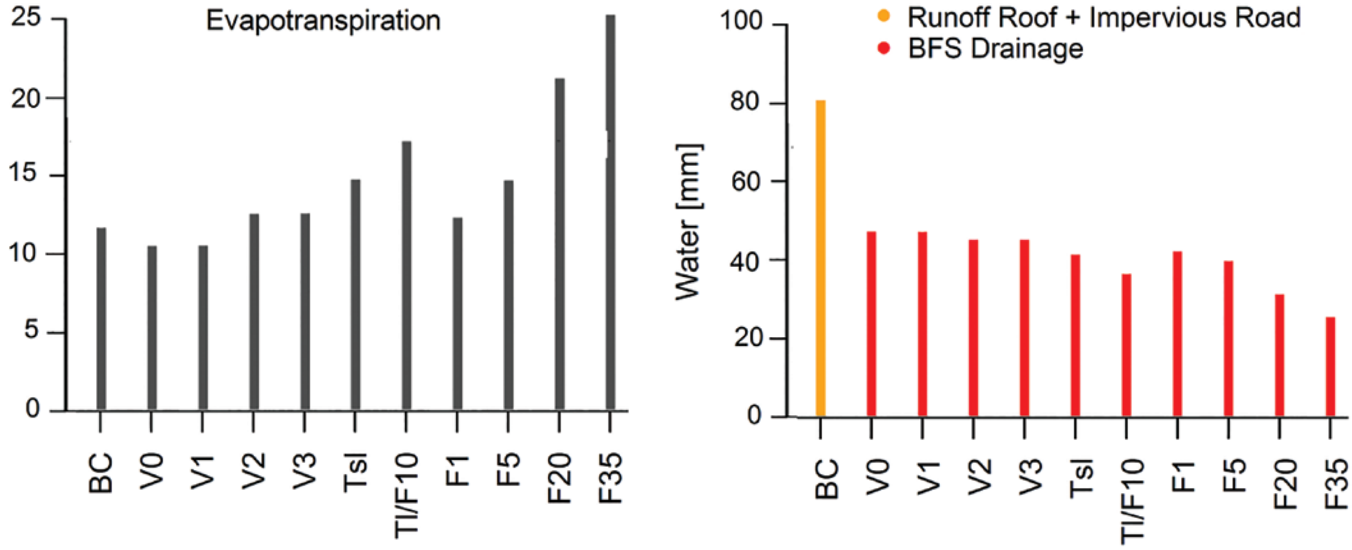


Figure 19: Outcomes of different scenarios of biofiltration system design and areal coverage of biofiltration systems in the urban environment (Demuzere et al., 2013a). Data are accumulated total of water (evapotranspiration or runoff) for a two month period from 9 Feb 2012 – 9 Apr 2012

Feedbacks to Urban Hydrology and Stream Ecology

The focus here has been on the impact of changes to the urban surface through urban development and/or WSUD on the urban water balance and the surface energy balance; in particular, evapotranspiration. As highlighted in the section on the urban water and surface energy balance, increasing evapotranspiration leads to a reduction in energy used in atmospheric heating or heat storage. When designing and implementing WSUD, it is important that the key objectives are clearly identified, such as heat mitigation, as this will inform design and placement decisions.

There appears to be somewhat of a dilemma emerging in some aspects of WSUD in meeting both the objectives of heat mitigation and stormwater runoff and quality management. The features assessed here such as biofiltration systems and green roofs have high infiltration rates, but this also means that they have relatively high drainage rates. While such systems slow down water compared to impervious surfaces, subsurface drainage through highly porous filtration media is often higher than for soils (e.g. loam). The course media used in WSUD features perform well in removing pollutants and suspended solids, and ensures that there is suitable capacity to capture stormwater from consecutive rain events. However, soil moisture levels may not be as high as they could be, particularly during times when it is most needed; at the end of dry spells, on hot, sunny days.

Widespread irrigation is clearly a favourable mechanism for increasing evapotranspiration in the urban landscape. However, the complete irrigation scenario modelled by SUEWS also showed that excessive irrigation limits the capacity for reducing runoff as soils are more frequently moist, limiting infiltration. Ultimately, a balance is needed in order to achieve both urban hydrology and micro-climate objectives. Mitigating excess urban heat through an increase in evapotranspiration requires well maintained soil moisture levels, but urban hydrology objectives rely on the capacity of the soil (or bio-filtration system) to take up water, slow it down for treatment and then remove the water before the next rainfall event. The aim is to increase soil moisture levels without compromising runoff.

The previous section did not include irrigation of the BFS, while this section only address possible irrigation configurations and their effect of E. The modelling with CLM-U highlighted the benefits of rainwater tank harvesting. Figure 20a shows the TI /F10 scenario where 10% of the surface is biofiltration systems and loam soil is used. Here, 22% of households have a rainwater tank (ABS, 2011) of volume 2.5 kL /100m2 (scenario Irrigation Default [ID]). The tank is assumed to be empty at the start of the 2 month period. Water accumulated in the tank can supply water to the biofiltration systems to enhance the amount of evapotranspiration occurring. Water is still needed on some days when soil moisture drops below the wilting point (red bars, Figure 20). The addition of the rainwater tanks increased E over the period by 1.6 mm to 18.8 mm (Figure 20b). Increasing the proportion of households with tanks and/or increasing the tank size further enhances evapotranspiration, and therefore leads to further reductions in sensible heating of the atmosphere. Harvesting stormwater further reduces runoff into urban streams.

As such, the proposed design of WSUD combines tanks and biofiltration systems, as suggested by (Burns et al., 2012) (Figure 20c) and implemented in CLM-U (Demuzere et al., 2013a), will have benefits for urban climate, but will also have positive feedbacks for urban hydrology and stream ecology. Further research is needed to tailor these designs, but for enhancing evapotranspiration, consideration of loam soils and incorporating trees into these systems is likely to provide a greater local climate benefit. Again, it is important to clearly identify the objectives of any WSUD interventions so they can be designed accordingly.

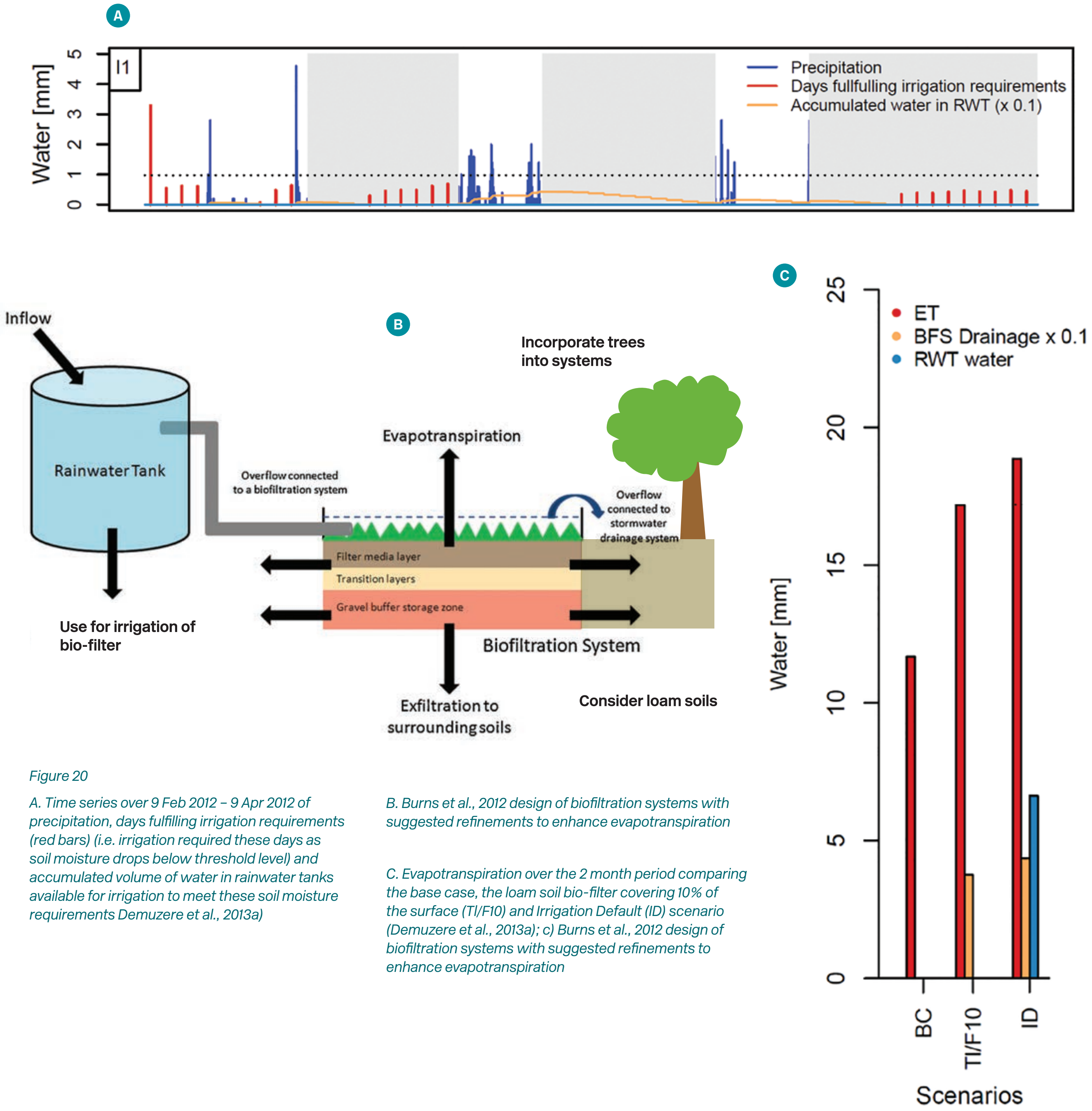


Figure 20

A. Time series over 9 Feb 2012 – 9 Apr 2012 of precipitation, days fulfilling irrigation requirements (red bars) (i.e. irrigation required these days as soil moisture drops below threshold level) and accumulated volume of water in rainwater tanks available for irrigation to meet these soil moisture requirements Demuzere et al., 2013a)

B. Burns et al., 2012 design of biofiltration systems with suggested refinements to enhance evapotranspiration

C. Evapotranspiration over the 2 month period comparing the base case, the loam soil bio-filter covering 10% of the surface (TI/F10) and Irrigation Default (ID) scenario (Demuzere et al., 2013a); c) Burns et al., 2012 design of biofiltration systems with suggested refinements to enhance evapotranspiration

References

Bratieres, K., Fletcher, T. D., Deletic, A. & Zinger, Y. 2008. Nutrient and sediment removal by stormwater biofilters: A large-scale design optimisation study. Water Research, 42, 3930-3940.

Breuer, L., Eckhardt, K. & Frede, H.-G. 2003. Plant parameter values for models in temperate climates. Ecological Modelling, 169, 237-293.

Burns, M. J., Fletcher, T. D., Walsh, C. J., Ladson, A. R. & Hatt, B. E. 2012. Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. Landscape and Urban Planning, 105, 230-240.

Coutts, A., Beringer, J. & Tapper, N. 2010. Changing Urban Climate and CO2 Emissions: Implications for the Development of Policies for Sustainable Cities. Urban Policy and Research, 28, 27 - 47.

Coutts, A. M., Beringer, J. & Tapper, N. J. 2007. Impact of Increasing Urban Density on Local Climate: Spatial and Temporal Variations in the Surface Energy Balance in Melbourne, Australia. Journal of Applied Meteorology and Climatology, 46, 477-493.

Coutts, A. M., Daly, E., Beringer, J. & Tapper, N. J. 2013. Assessing practical measures to reduce urban heat: Green and cool roofs. Building and Environment, 70, 266-276.

Coutts, A. M., Tapper, N. J., Beringer, J., Loughnan, M. & Demuzere, M. 2012. Watering our Cities: The capacity for Water Sensitive Urban Design to support urban cooling and improve human thermal comfort in the Australian context. Progress in Physical Geography, 37, 2-28.

Demuzere, M., Coutts, A. M., Gohler, M., Broadbent, A. M., Wouters, H., Van Lipzig, N. P. M. & Gebert, L. 2013a. The impact of biofiltration systems, rainwater tanks and urban irrigation on urban canopy evapotranspiration. In prep.

Demuzere, M., Oleson, K., Coutts, A. M., Pigeon, G. & Van Lipzig, N. P. M. 2013b. Simulating the surface energy balance over two contrasting urban environments using the Community Land Model Urban. International Journal of Climatology, n/a-n/a.

Frank, S., Waters, G., Beer, R. & May, P. 2006. An Analysis of the Street Tree Population of Greater Melbourne at the Beginning of the 21st Century. Arboriculture & Urban Forestry, 32, 155-163.

Gebert, L. 2012. The response of trees to the urban environment. Honours, Monash University.

Gober, P., Brazel, A., Quay, R., Myint, S., Grossman-Clarke, S., Miller, A. & Rossi, S. 2010. Using Watered Landscapes to Manipulate Urban Heat Island Effects: How Much Water Will It Take to Cool Phoenix? Journal of the American Planning Association, 76, 109 - 121.

Grimmond, C. S. B., Blackett, M., Best, M. J., Baik, J. J., Belcher, S. E., Beringer, J., Bohnenstengel, S. I., Calmet, I., Chen, F., Coutts, A., Dandou, A., Fortuniak, K., Gouvea, M. L., Hamdi, R., Hendry, M., Kanda, M., Kawai, T., Kawamoto, Y., Kondo, H., Krayenhoff, E. S., Lee, S. H., Loridan, T., Martilli, A., Masson, V., Miao, S., Oleson, K., Ooka, R., Pigeon, G., Porson, A., Ryu, Y. H., Salamanca, F., Steeneveld, G. J., Tombrou, M., Voogt, J. A., Young, D. T. & Zhang, N. 2011. Initial results from Phase 2 of the international urban energy balance model comparison. International Journal of Climatology, 31, 244-272.

Grimmond, C. S. B. & Oke, T. R. 1999. Heat storage in urban areas: Local-scale observations and evaluation of a simple model. Journal of Applied Meteorology, 38, 922-940.

Grossman-Clarke, S., Zehnder, J. A., Loridan, T. & Grimmond, C. S. B. 2010. Contribution of Land Use Changes to Near-Surface Air Temperatures during Recent Summer Extreme Heat Events in the Phoenix Metropolitan Area. Journal of Applied Meteorology and Climatology, 49, 1649-1664.

Järvi, L., Grimmond, C. S. B. & Christen, A. 2011. The Surface Urban Energy and Water Balance Scheme (SUEWS): Evaluation in Los Angeles and Vancouver. Journal of Hydrology, 411, 219-237.

Loridan, T., Grimmond, C. S. B., Offerle, B. D., Young, D. T., Smith, T. E. L., Järvi, L. & Lindberg, F. 2010. Local-Scale Urban Meteorological Parameterization Scheme (LUMPS): Longwave Radiation Parameterization and Seasonality-Related Developments. Journal of Applied Meteorology and Climatology, 50, 185-202.

Mitchell, V. G., Cleugh, H. A., Grimmond, C. S. B. & Xu, J. 2008. Linking urban water balance and energy balance models to analyse urban design options. Hydrological Processes, 22, 2891-2900.

Nury, S., Beringer, J., Tapper, N. J. & Coutts, A. M. 2012. Spatial relationship between urban vegetation and land surface temperature in Melbourne, Australia. Poster presentation at the 8th International Conference on Urban Climates, Dublin, Ireland.

Oke, T. R. 1987. Boundary Layer Climates, Great Britain, Cambridge University Press.

Oke, T. R. 1988. The Urban Energy Balance. Progress in Physical Geography, 12, 471-508.

Pappas V., Grimmond C.S.B., Mitchell V.G., Cleugh H.A. 2007. Impact of Climate Variability and Change on Irrigation Demand in Melbourne, Australia ; In proceeding of: Water Management Challenges in Global Change, Leicester, UK. September 2007.

Roberts, P. 2005. Yarra Valley Water 2004 Residential End Use Measurement Study. Yarra Valley Water, June 2005.

Rosenzweig, C., Solecki, W. D., Cox, J., Hodges, S., Parshall, L., Lynn, B., Goldberg, R., Gaffin, S., Slosberg, R. B., Savio, P., Watson, M. & Dunstan, F. 2009. Mitigating New York City's Heat Island: Integrating Stakeholder Perspectives and Scientific Evaluation. Bulletin of the American Meteorological Society, 90, 1297-1312.

Spronken-Smith, R. A. 2002. Comparison of summer- and winter-time suburban energy fluxes in Christchurch, New Zealand. International Journal of Climatology, 22, 979-992.

CRC for
Water Sensitive Cities

Cooperative Research Centre for Water Sensitive Cities

Level 1, Building 74
Monash University, Clayton
Victoria 3800, Australia

info@crcwsc.org.au

www.watersensitivecities.org.au