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Linking urban water balance and energy balance models to analyse urban design options

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Abstract:

Using a water balance modelling framework, this paper analyses the effects of urban design on the water balance, with a focus on evapotranspiration and storm water. First, two quite different urban water balance models are compared: Aquacycle which has been calibrated for a suburban catchment in Canberra, Australia, and the single-source urban evapotranspiration-interception scheme (SUES), an energy-based approach with a biophysically advanced representation of interception and evapotranspiration. A fair agreement between the two modelled estimates of evapotranspiration was significantly improved by allowing the vegetation cover (leaf area index, LAI) to vary seasonally, demonstrating the potential of SUES to quantify the links between water sensitive urban design and microclimates and the advantage of comparing the two modelling approaches. The comparison also revealed where improvements to SUES are needed, chiefly through improved estimates of vegetation cover dynamics as input to SUES, and more rigorous parameterization of the surface resistance equations using local-scale suburban flux measurements. Second, Aquacycle is used to identify the impact of an array of water sensitive urban design features on the water balance terms. This analysis confirms the potential to passively control urban microclimate by suburban design features that maximize evapotranspiration, such as vegetated roofs. The subsequent effects on daily maximum air temperatures are estimated using an atmospheric boundary layer budget. Potential energy savings of about 2% in summer cooling are estimated from this analysis. This is a clear 'return on investment' of using water to maintain urban greenspace, whether as parks distributed throughout an urban area or individual gardens or vegetated roofs. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS evapotranspiration; interception; urban water balance

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INTRODUCTION

A combination of climate and population pressures now threatens the sustainability and security of urban water supplies in many of the cities across the globe. The current situation in urban Australia, where prolonged drought, warmer temperatures, and the increasing risk of bushfire damage to water supply catchments have severely curtailed urban water storages, is but one example of the impact of these pressures. A re-evaluation of alternative approaches to securing a reliable and quality water supply for growing cities is now becoming critical. One of the alternative approaches being explored is 'Water Sensitive Urban Design' (WSUD) or 'Low Impact Design' (LID), the purpose of which is to conserve water use by managing design options for reducing and re-using urban waste and storm water (Mitchell, 2005). Similarly there are needs to conserve energy under peak demands conditions. For example during heat waves energy demand is also at a peak because of additional air conditioning loads. Even small reductions in air temperature reduce energy demand significantly (Akbari *et al.*, 2001).

Key for this study is that water appears in both the water and energy balances, either as a mass flux or the energy required for a change in state from liquid water to water vapour, E and Q_E, respectively. This imposes a mass and energy conservation constraint on urban E simulations; it explains why water can modulate the microclimate through the size and variability of urban evaporation; and it demonstrates the potential for using urban design to not just manage the urban water balance, but also to control urban microclimate through the use of urban greenspace. Moreover, given that transpiration is the necessary result of photosynthesis, where plants capture atmospheric carbon dioxide (CO_2), then the opportunity for passively controlling microclimates via urban greenspace can be extended to increasing the sequestration of CO_2 as well.

The objectives of this paper are to: (i) to compare two evapotranspiration (E) models which have different fundamental premises (mass and energy conservation), (ii) demonstrate the impact of a range of water sensitive urban design strategies on water exchanges, and (iii) to infer from the energy balance how these designs would affect air temperature. These objectives sit within the

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broader goal of providing a framework to better quantify the role of urban water use in managing the microclimate, energy consumption and CO_2 emissions in suburban land use; and to improve the ability of urban climate models to represent surface-atmosphere exchanges of water, heat and CO_2.

URBAN WATER BALANCE FRAMEWORK

A complete and integrated understanding of the dynamics of the potable water supply, waste water discharge, and storm water runoff is best achieved by considering the complete urban hydrological cycle (Mitchell *et al.*, 2001). From a modelling perspective this can be achieved using the urban water balance as the conceptual framework:

$$P + I = E + D + \Delta S \qquad (1)$$

where the inputs are rainfall (P), piped water supply (I); the outputs are evapotranspiration (E), drainage (D); and the change in storage (ΔS) in the natural (soil and ground water aquifers) and built components of the urban system. The units for each term in Equation (1) are length (typically in millimetres because of the size) per unit time. In locations with separate drain systems the drainage term has two major components: storm water (D_s) and waste water (D_w). Writing the water balance in this way implicitly assumes a control volume that extends from the soil volume upwards into the urban canopy airspace. This control volume does not have an implicit spatial scale—i.e. it applies equally to a unit block (following Mitchell *et al.*, 2001) such as a single household, industrial site, institution or commercial operation, and is the smallest scale at which water supply and disposal operation can be managed; a neighbourhood (equivalent to Mitchell's 'cluster' scale or the local scale used by micrometeorologists); or a catchment which may be defined using both topography and the pipe supply network (Figure 1).

The urban energy balance, analogous to Equation (1), can be written:

$$Q^* + Q_F = Q_E + Q_H + \Delta Q_S \quad [\mathrm{Wm}^{-2}] \qquad (2)$$

where Q^* is the net all-wave radiation; Q_F is the anthropogenic heat flux (e.g. space heating, transport, etc.); ΔQ_S is the net heat storage change in the urban 'canopy' (buildings, streets, etc.), Q_E is the latent heat flux, the energy used to evaporate the mass flux of water lost via transpiration and evaporation (the conversion between the two needs latent heat of vaporisation (L_V) and density of water (ρ); $E = Q_E/(L_V\ \rho)$; abbreviated to E and referred to as urban evaporation hereafter); and Q_H is the turbulent sensible heat flux. For completeness, the available energy, A, is defined as:

$$A = Q^* + Q_F - \Delta Q_S \qquad (3)$$

Using the same concept of a control volume, the turbulent fluxes of heat and water vapour (i.e. Q_H and Q_E) are areally averaged from a source area with spatial dimensions of about 1 km^2—i.e. the neighbourhood or cluster scale. Eddy covariance methods have been demonstrated to provide reliable direct and continuous measurements of E in suburban land use at this spatial scale (e.g. Cleugh and Oke, 1986; Oke *et al.*, 1988, 1989; Grimmond and Oke, 1995, 1999, 2002).

Models of urban E can therefore be derived from the surface energy balance. These approaches bring two clear benefits to the task of modelling the urban water balance: firstly, the constraint of energy availability is imposed explicitly and secondly, the connection between the water balance and climate is quantified because the partitioning of A into sensible and latent heat fluxes modulates the air and surface temperatures in the urban canopy layer.

There appears to be a 'disconnect' between engineers and atmospheric scientists seeking to quantify both the role and magnitude of urban evaporation, here described as the urban climate/energy balance approach and the urban hydrology/water balance approach. For example, urban hydrology models that are used to underpin WSUD at the house and street scale do not account for the microclimate and energy use impacts of WSUD. These models are also poor tools for exploring how urban E can be manipulated to better manage urban runoff because of their poor biophysical representation of urban E. The corollary to this longstanding weakness in urban climate models (i.e. models that predict or diagnose surface energy exchanges and are either coupled to an atmospheric model or forced by measured meteorology) is the inability of their land surface schemes to quantify the urban surface moisture availability (Ross and Oke,

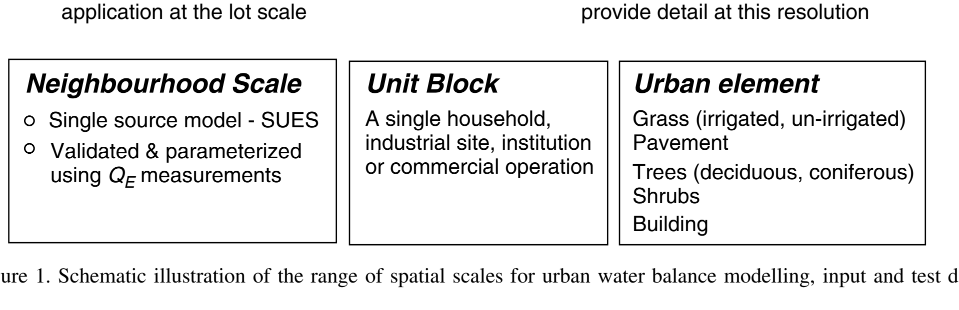

Figure 1. Schematic illustration of the range of spatial scales for urban water balance modelling, input and test data

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1988). The aim of this study is to illustrate the benefits that can result from linking these two domains of research, by quantifying the benefits of urban greenspace and water use, and in improving urban climate models.

METHODOLOGY

Two models of the urban water balance are compared, Aquacycle and the single-source urban evapotranspiration-interception scheme (SUES), through runs for the urbanized Woden catchment in southern Canberra (Mitchell *et al*., 2001, 2003). Following the intercomparison, Aquacycle is then used to explore the water balance, microclimate and energy usage consequences of a series of urban design scenarios. The key difference between the two models is their intended purpose, and therefore the parameterizations for each component. The focus of SUES is the external water balance and the transformation of water inputs (rainfall and irrigation) into E and drainage. Its E model is based on the surface energy balance Equation (2). Aquacycle is more comprehensive, simulating both the internal and external components of the urban water cycle, but it uses a more simplified (than SUES) treatment of transpiration and the fine-scale dynamics of drainage. There is also no direct energy constraint in Aquacycle. The following summary and Table I describe the key attributes of the two modelling approaches in greater detail.

Aquacycle represents the water supply (including options for water re-use and rainwater tanks), and the storm water and the waste water streams. It simulates all water fluxes into, within, and out of the urban environment at three spatial scales (single unit block, cluster, and whole catchment), at a daily time step, with three types of land use (building allotment, road and public open space). Road areas are assumed to be impervious, public open space is pervious (i.e. grassed), and residential areas can be separated into paved, roof and pervious surfaces. The strength of Aquacycle is its ability to represent a wide range of water system configurations to provide a computational tool for exploring alternative urban water resource management options. A complete description of Aquacycle, its calibration and performance for the Woden catchment in Canberra, ACT, Australia are documented in Mitchell *et al*. (2001, 2003).

SUES (Grimmond and Oke, 1991) is a complete urban evapotranspiration-interception model that focuses on the transformation of precipitation and irrigation into E and storm water runoff (drainage) using both an energy and mass balance framework, where the former constrains the latent heat flux and the latter determines the available water at each time step. The innovation of Grimmond and Oke (1991) was its representation of urban E at a fine timescale. This enabled them to estimate urban E under all conditions, in particular during and immediately following rain when impervious

Table I. Summary of Aquacycle and SUES models

	Aquacycle	SUES
Urban water balance	Complete (i.e. internal and external) urban water cycle	External only
Spatial domain (see Figure 1)	Smallest spatial scale is an urban block (or lot), which can be integrated to clusters, neighbourhoods and catchment	Smallest spatial scale is the neighbourhood
Time step	Daily Does not capture short-term temporal dynamics such as multiple rainfall events within a day, the diurnal variation in E, or the rapid drainage and evaporation of intercepted water held on roofs and pavements	Sub-daily (5 min to 60 mins) Dynamic time-step depending on drainage
Calibration	All parameters calibrated for the Woden valley catchment as described in Mitchell (2001, 2003)	Uses parameters optimized for suburban catchment in Vancouver, Canada.
E Model	Soil moisture supply—atmospheric demand approach for pervious surfaces, with no differentiation between vegetation types Surface wetness—atmospheric demand approach for impervious surfaces	Uses a Penman Monteith type model, see text
Outdoor water use	Calculated by model on a daily basis based on soil moisture levels	Specified model input
Required inputs	Daily precipitation and potential evaporation time series data Land cover characteristics, water system characteristics, unit block occupancy, and indoor water usage data	Hourly meteorology; net radiation, heat storage, humidity, temperature, wind speed and rainfall Surface morphology and vegetation characteristics to parameterize resistances
Surface cover types	Unit block: roof, paved and vegetation/garden (irrigated, un-irrigated) Clusters: unit blocks plus roads and public open space (vegetation) (irrigated, un-irrigated)	Paved, built, coniferous trees, deciduous trees, irrigated grass and un-irrigated grass

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surfaces are wet and water is lost through evaporation and runoff. They took the view that the most rigorous, robust and physically-based approach to estimating E was the Penman–Monteith–Rutter–Shuttleworth evapotranspiration-interception model (Monteith, 1965; Rutter *et al.*, 1971; Shuttleworth, 1978), which has at its core the Penman–Monteith model (see full details in Grimmond and Oke, 1991):

$$Q_E = \frac{sA + (\frac{C_a \delta q}{R_A})}{s + \gamma(1 + R_S/R_A)} \tag{4}$$

where R_A and R_S are the aerodynamic and surface resistances that control the transfer of water from the surface (R_S) up into the urban boundary layer to the height of measurements, z_M (R_A); δq is the humidity deficit at z_M; s and γ are thermodynamic parameters that vary with temperature; C_a is the heat capacity; and A, the available energy. As written, Equation (4) assumes an effective single evaporation source (hence the acronym for SUES). Adopting Shuttleworth's (1978) modifications to the Penman–Monteith equations allows the evaporation process to be simulated for the mix of pervious and impervious surfaces, and also represent the transition of urban E between each of the three phases: (i) evaporation of intercepted water from a fully wet surface, which depends on the atmospheric demand, rainfall amount and the morphology of the urban canopy; (ii) E from partially wet, pervious and impervious surfaces; (iii) transpiration from plants (grass, gardens and trees).

SUES is applicable at the cluster through to catchment spatial scales and is typically implemented using a 5 min time step aggregated to an hour to capture the fine-scale dynamics of rainfall, drainage and evaporation. Land surface cover is disaggregated into six surface types: paved, built, coniferous trees, deciduous trees, irrigated grass and un-irrigated grass. That SUES explicitly includes the urban energy balance to constrain the water balance simulations means that urban water use is coupled to urban microclimates and energy consumption. A complete description of SUES, its calibration and performance for a suburb in Vancouver, Canada is documented in Grimmond and Oke (1991).

Boundary layer model

The effect of changing E on the microclimate, especially air temperature in the urban boundary layer, can be quantified to first order using the very simple modelling approach of Oke (1989) and Cleugh *et al.* (2005). The daytime average warming rate for the urban atmospheric boundary layer, assumed to grow to a maximum depth of 1 km at 15:00 (mid afternoon), can be determined from:

$$\frac{dT_a}{dt} = \frac{H}{z_{UBL}} \tag{5}$$

where dT_a/dt is the diurnal heating rate (in $^\circ$C s^{-1}) of the boundary layer; H is the kinematic heat flux (in m s^{-1} $^\circ$C); and z_{UBL} is the boundary layer depth. Equation (5) is the one-dimensional form of the conservation equation for heat in the urban boundary layer, and does not include the effects of entrainment at the top of the urban boundary layer, or mesoscale and microscale advection. Furthermore, the temperatures predicted are for the lower part of the urban boundary layer, not the air temperature in the airspace within the urban canopy. A three-dimensional, mesoscale urban climate model would be needed to include these additional processes and resolve temperature variations closer to the urban canopy. This means that the estimated effects of WSUD on air temperatures are only a guide and, importantly, they will be smaller than the actual air temperature differences experienced, for example by people, in the urban canopy airspace.

The sensible heat flux used in Equation (5) is at the scale of the whole suburb and is computed as a residual in the urban energy balance (Equation (2)) expressed as H, where the available energy is specified at a fixed maximum value at solar noon (600 W m^{-2}, which is the average of the midday summertime values for A simulated using SUES) and the latent heat flux is calculated from the daily E simulated by Aquacycle for each of the scenarios earlier. The hourly available energy and evaporation rate is determined by imposing a sinusoidal variation about the midday peak (for A) that matches the daily total E simulated by Aquacycle. The heating rate is for the daytime average between 07:00 and 15:00.

Study area

The study area, Woden Valley in southern Canberra, is described in detail by Mitchell *et al.* (2001, 2003). Canberra is an inland city located in the south-east of Australia at an elevation of about 600 m above sea level. It experiences a mild, dry climate with annual average rainfall (630 mm) distributed fairly evenly across the year. In 2003 the population of Woden Valley was 37,500 with a mix of residential (15,000 dwellings) and commercial land-use with some light industry. Much of the commercial and industrial activity is located in and around the Woden town centre and neighbouring suburb of Philip (Figure 2).

The suburb of Mawson, used in the second part of the study to investigate urban design scenarios, is positioned at the head of the Woden Valley. As a predominantly residential suburb, Mawson has a substantial area of adjacent open space (Table II). Reticulated potable water is supplied to Mawson, as it is to all of Canberra and, as is usual practice in Australia, the storm water drainage network is separate from the waste water system.

Data input

Water balance simulations conducted to compare Aquacycle and SUES for Woden neighbourhood of Canberra for the period 1978–1995 were conducted using the following:

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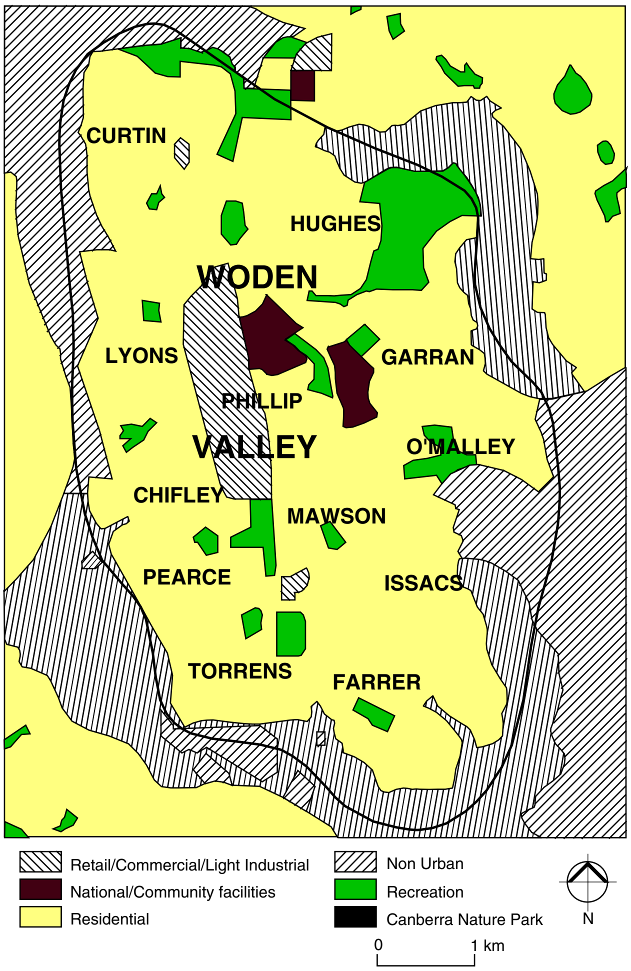

Figure 2. Land use and suburb locations (in capitals) within the Woden Valley catchment in Canberra, ACT, Australia. Suburb names are in capitals. Non Urban and Canberra Nature Park land use areas are predominantly scattered trees and grass while Recreation is predominantly grass sports fields.

Table II. Average land cover land use and residential water usage components for the residential suburb of Mawson for the period 1991 to 1995 (Mitchell *et al.*, 2003)

Land use and land cover	
Dwellings	1298
Occupancy (persons)	2·23
Household block size (m^2)	977
Household roof area (m^2)	237
Household paved area (m^2)	65
Residential blocks (ha)	126·8
Public open space (ha)	43·5
Road area (ha)	18·6
Residential water usage components	
Kitchen (%)	7
Bathroom (%)	21
Laundry (%)	10
Toilet (%)	18
Outdoor (%)	44

- Daily climate data (rainfall, air temperature, humidity, solar radiation, daily sunshine hours, and wind run) from the Bureau of Meteorology climate station at Canberra Airport, 10 km away. However, when Aquacycle is used to explore the water balance, microclimate and energy usage consequences of the urban design scenarios, daily records from three rainfall gauges were used to calculate the mean daily depth of precipitation with the Theissen method for the period 1978 to 1995.
- Morton's (1983) wet environment areal E was used to estimate potential evaporation (E_{p}) for Aquacycle, calculated using data from the Bureau of Meteorology's Canberra Airport station.
- The external water use required by SUES is from Aquacycle, which predicts the quantity of irrigation required to maintain the pervious soil water store(s) at a specified level.
- Calibrated parameters from Mitchell *et al.* (2001) are used for Aquacycle. The exception is that the size of pervious store 1 is set to 30% with a capacity of 30 mm, compared to that used by Mitchell *et al.* (2001) of 22% and 32 mm.
- Grimmond and Oke (1991) values are used for the SUES simulations (surface conductance, drainage modules and the storage capacities for all surface elements) parameter.
- The land cover for the Woden catchment as described in Mitchell *et al.* (2001) and Cleugh *et al.* (2005) is used for both SUES and Aquacycle.
- Net all-wave radiation and storage heat fluxes use parameterizations in Offerle *et al.* (2003) and Grimmond and Oke (2002), respectively; with albedo = 0·14 and the anthropogenic heat flux (Q_{F}) neglected.

Urban design case study scenarios

A series of urban design scenarios are used to explore the impact of vegetated WSUD features on the urban water balance, microclimate and hence energy consumption in the suburb of Mawson. These scenarios are as follows:

(1) A conventional urban layout as represented by the characteristics of Mawson during the early to mid-1990s (Table II).
(2) The inclusion of a 1·45 ha wetland, representing 1% of the residential block and road area of the catchment.
(3) The inclusion of a 2 ha of lined grassed swales, representing 1·4% of the residential block and road area of the catchment.
(4) The replacement of all (impervious) roofs with un-irrigated extensive (thin) vegetated roofs which comprise of a drainage layer, soil/growth media layer and plant layer.
(5) The inclusion of vegetated roofs, grass swales and the wetland used in series (in accordance with the WSUD treatment train approach) within Mawson.
(6) A halving of garden watering levels and the inclusion of the treatment train of vegetated roofs, grass swales and the wetland within Mawson.
(7) No garden watering and the inclusion of the treatment train of vegetated roofs, grass swales and the wetland within Mawson.

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The first scenario acts as a baseline against which the impact of WSUD can be compared. Scenarios (2) and (3) approximate best practice recommendations for the use of WSUD to manage storm water quality, whereas scenarios (4) and (5) utilize an alternative WSUD practice (vegetated roofs) which has the potential to provide storm water, microclimate and energy benefits. Scenarios (6) and (7) build on scenario (5) by also implementing a water demand management strategy in the form of restricting garden watering.

The wetland is modelled as an open water body, with a surface area of 1·45 ha, depth of 1 m, and evaporation from the water surface occurring at the potential rate. The latter is because Aquacycle does not represent wetland vegetation. The grass swale was represented as a shallow soil store (100 mm capacity), with wetting losses only, i.e. no exfiltration. Exfiltration occurs when either the swale is unlined or is constructed on top of soil which has a lower hydraulic conductivity compared to the swale material. The vegetated roof was modelled as a shallow soil store with 10 mm capacity (Villarreal and Bengtsson, 2005). This storage capacity can be compared to conventional metal or tile roofs whose storage capacity is of the order of 1 mm (Hollis and Ovenden, 1988; Ragab *et al.*, 2003).

Wetlands and grass swales are employed as storm water pollution control techniques in Australian, European and North American urban areas. Vegetated roofs are employed for a wider range of benefits such as mitigation of the urban heat-island effect, improving air quality, extending the service life of the roof, reducing the buildings internal energy usage, fire protection, providing sound installation, creating habitat for fauna, and providing an aesthetic environment (VanWoert *et al.*, 2005; Villarreal and Bengtsson, 2005), but many consider storm water flow mitigation to be the primary benefit of green roofs (VanWoert *et al.*, 2005). They are more commonly used in parts of Europe and North America compared to their infrequent use in Australia. Vegetated roofs can be designed to be un-irrigated requiring suitable selection of plant species to ensure their survival during prolonged periods without rainfall. In the last few years, water supply demand management strategies have often aimed at reducing garden watering levels, although usually by more modest amounts than 50–100%. The high levels of reduction in garden watering used in this scenario analysis were selected primarily for illustrative purposes, to highlight the potential role of garden water irrigation in moderating urban microclimate and energy usage.

RESULTS AND DISCUSSION

Comparison of Aquacycle and SUES

Figures 3(a) and 4(a) compare the monthly E simulated by SUES and Aquacycle, which are integrated from the hourly (SUES) and daily (Aquacycle) model simulations. There is reasonable agreement between SUES and Aquacycle in terms of general trends, especially considering that SUES has been applied to this catchment without calibration. The agreement is good for low rates of E, but at the height of the growing season there is greater variance between the two models (Figure 3) and the difference in average monthly E for 1978–1995 is quite large (11·8 mm, or 23% of the mean monthly E).

The correlation between annual rainfall anomaly (Figure 4) and the SUES–Aquacycle discrepancy (i.e. the difference is greater when rainfall is reduced, e.g. between 1978 and 1983) points to the surface resistance algorithm as the cause of the model differences. Indeed, SUES was originally implemented using measured LAI (a measure of the vegetation cover in the pervious areas of the catchment) as an input—i.e. LAI was dynamic (Grimmond and Oke, 1991). The initial implementation of SUES in this study, however, used a constant LAI to most closely match the modelling philosophy of Aquacycle. Given the results (Figures 3a and 4a), LAI was varied on a monthly basis to investigate the effect of LAI on model performance. The result is a significant improvement in the agreement between SUES and Aquacycle (Figures 3b and 4b). The difference in the average monthly E is very small (<0·5 mm), and the line of best fit between the two estimates has a slope of 0·71 with an offset of 12·41 mm, and explains about 80% of the variance ($R^2 = 0{\cdot}79$).

These results show that the greatest improvement in SUES will arise primarily from determining the seasonal variation and magnitude of LAI much more precisely, at least on a monthly basis, and secondarily by improving the surface resistance algorithm—ideally by acquiring measurements to parameterize the algorithm and also improve the process representation. Importantly for this

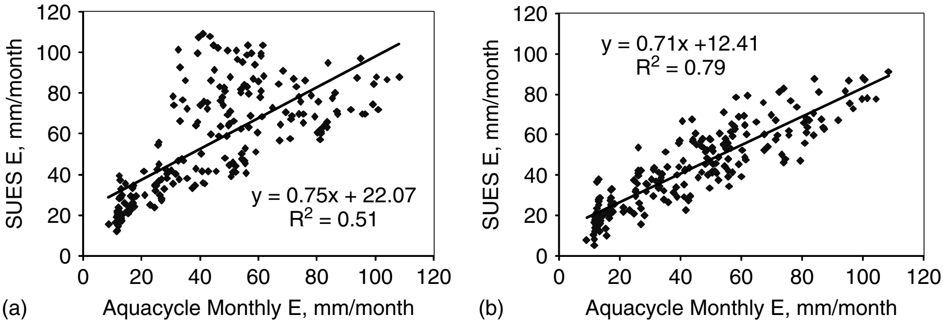

Figure 3. Agreement between Aquacycle and SUES: (a) using a constant LAI and (b) using a varying (by month) LAI (see text for details)

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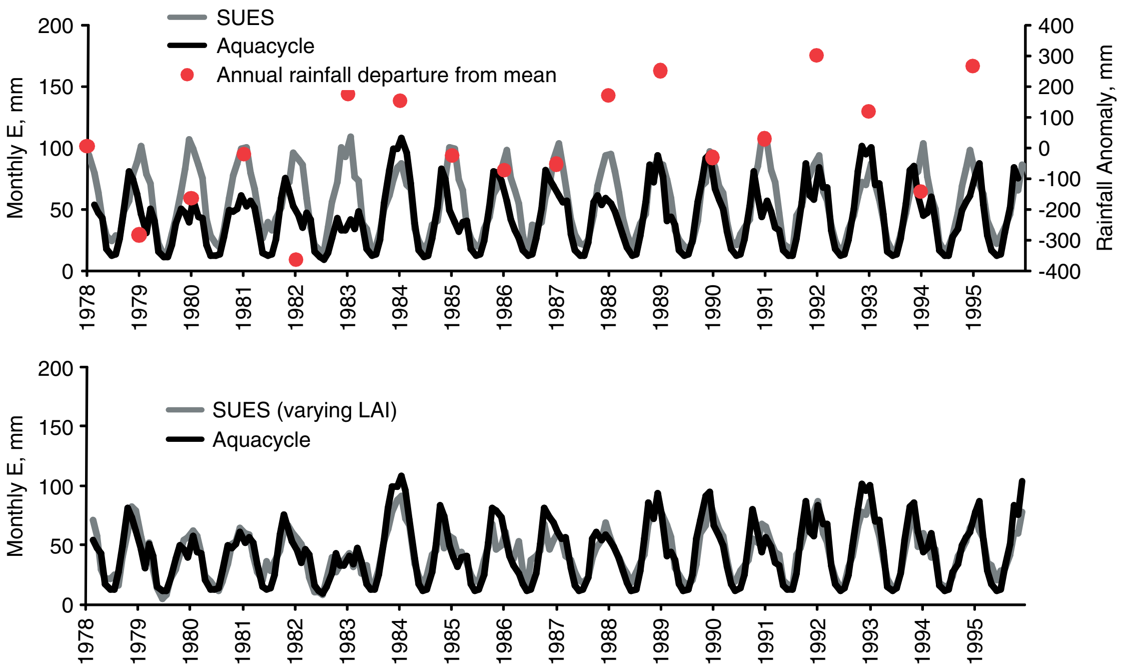

Figure 4. Comparison of monthly E simulations using Aquacycle (bold line) and SUES (light grey line) for the Woden catchment using (a) fixed LAI and showing the annual rainfall anomaly and (b) varying (by month) LAI (see text for details)

paper, it shows that SUES is an appropriate modelling framework for quantifying the effects of urban vegetation on microclimate and carbon sequestration, because it is sensitive to the amount and physiological attributes of the pervious component of the urban system.

This highlights the potential of SUES as a modelling tool for linking the urban water and energy balances. The constraint provided by using an energy balance approach also ensures that the model is robust—i.e. the simulated E rates are constrained despite the fact that SUES has not been calibrated. Further development of SUES is needed to realize its potential to explore the links between water sensitive and climate sensitive urban design. In particular evaluation and optimization of parameterizations need to be conducted using flux measurements obtained in a larger range of suburban land uses—especially Australian cities for which very few such data are available.

Results of the urban design scenario case study

For the following discussion, scenario (1) is used as the reference point, as it represents a typical suburban area in Canberra that does not contain vegetated WSUD features.

Impacts of the vegetated urban design scenarios on the water balance. Precipitation is the largest water balance input while E is the largest output (Table III). Due to the extensive amount of garden watering, in scenarios (1)–(5), less than 60% of the imported water input leaves the suburb as waste water while the remainder is used for garden irrigation which is then converted into E and storm water outputs.

The inclusion of a wetland within the suburb of Mawson (scenario (2)) is predicted to have a modest effect on the average annual water balance, with a 5 mm year^{-1} increase in E and a 5 mm year^{-1} decrease in

Table III. Average annual Mawson water balance for each of the seven scenarios predicted by Aquacycle—ordered according to decreasing actual E output estimates (areal mm year^{-1})

Scenario	Imported water (I)	Actual E	Storm water (D_s)	Waste water (D_w)
(5) Full vegetated WSUD treatment train	170	493	206	98
(4) Vegetated roof conversion	170	485	217	98
(6) Full vegetated WSUD treatment train with 50% reduction in garden watering	132	460	201	98
(3) Grass swales added to conventional urban layout	170	442	260	98
(2) Wetland added to conventional urban layout	170	441	261	98
(1) Conventional urban layout	170	436	266	98
(7) Full vegetated WSUD treatment train with 100% reduction in garden watering	94	427	197	97

Note: Precipitation inputs = 630 mm year^{-1}, and change in storage (ΔS) = zero, for all simulations.

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storm water output. The inclusion of 2 ha of grass swales instead of a wetland (scenario (3)) has a similar effect, while the conversion of the roofs to extensive vegetated roofs has a more significant effect (scenario (4)), with a 49 mm year^{-1} increase in E that is matched by a similar decrease in storm water. Linking all of these vegetated WSUD features into a single scenario (5) increases E and decreases the storm water further while having no effect on the water balance inputs. The vegetated WSUD features have converted storm water runoff into E and therefore have influenced the output terms only—mostly due to the conversion of impervious roofs to vegetated roofs.

In scenarios (6) and (7) the reduction in garden watering level (−50% and −100%) reduces both the imported water and storm water terms in the water balance of the suburbs. For scenario (6), annual E exceeds the reference (scenario (1)) because of E from the vegetated components of the WSUD measures, especially the vegetated roofs.

But, in scenario (7), the complete cessation of garden watering reduces average annual E to below the levels in the conventional urban layout. This indicates that although the moisture store in the suburbs has been enhanced by the addition of a wetland, swales and vegetated roofs, the rainfall alone cannot meet the evaporative demand. That the cessation of garden watering on E in scenario (7) had the greatest effect in the summer months, when garden watering and evaporative demand are at their highest rates, reinforces this point (Figure 5). The cessation of garden watering does not affect winter E rates as garden watering is not occurring in these months. The presence of the vegetated roofs leads to the rise in winter E in this scenario, as discussed earlier.

The value of E increases in the winter months in scenarios (4)–(7), each of which contains vegetated roof surfaces (Figure 5). The enhanced soil retention capacity of the vegetated roof, and hence the increase availability of water in the urban landscape, is significant enough to noticeably increase the winter levels of E.

Scenario (6) offers the combined benefits of reducing the amount of water imported into the suburb and maintaining E at levels greater than in the conventional suburban design. The consequences of this enhanced E are explored in the next section.

It needs to be noted that covering all conventional roofing surfaces (tiles and zincalum) with vegetated roofs is an ambitious scenario, whereas the sizing of the wetland and swales is fairly representative of current storm water management practice.

Effects of vegetated urban design scenarios on microclimate and energy use. Table IV shows the effect of the different WSUD treatments on summertime E, and heating, rates. The effect on peak afternoon temperatures (δT_{amax}) is determined by comparing the afternoon temperatures for each WSUD scenario to those for a 'desert' city with no vegetation and no E (i.e. $Q_H = A$), and assuming that both the desert and the suburb equilibrate to the same minimum temperature of 15 °C at dawn (06 : 00).

While the impact of these bulk air temperature changes on energy consumption cannot be determined, the results of other studies can help to translate them into potential savings in energy use. For example, Akbari *et al.*

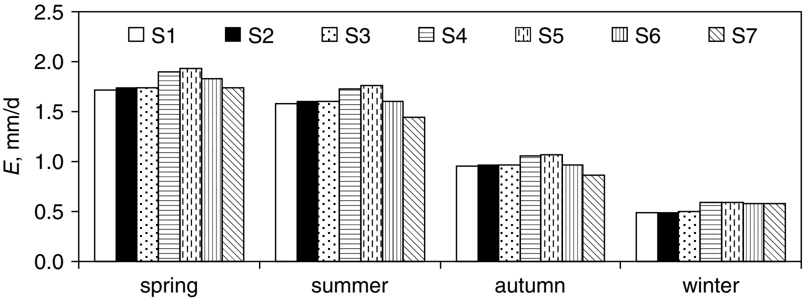

Figure 5. Seasonal E rates for the seven scenarios (S1–S7) (see text)

Table IV. Summertime E (from Aquacycle simulations) converted to diurnal heating rates and the consequent effect on peak afternoon air temperatures for each of the seven scenarios relative to a 'desert' (see text for assumptions)

Scenario	Summer E (mm day^{-1})	Average heating rate (°C h^{-1})	δT_{amax} (°C)
(1) Conventional urban layout	1·58	1·64	−4·6
(2) Wetland added to conventional urban layout	1·61	1·63	−4·7
(3) Grass swales added to conventional urban layout	1·60	1·64	−4·6
(4) Vegetated roof conversion	1·73	1·59	−5·0
(5) Full vegetated WSUD treatment train	1·76	1·58	−5·1
(6) Full vegetated WSUD treatment train with 50% reduction in garden watering	1·60	1·63	−4·6
(7) Full vegetated WSUD treatment train with 100% reduction in garden watering	1·44	1·69	−4·2
Desert	0·00	2·15	0·00

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(2001) found an increase in energy consumption of 2–4% for every 1 °C rise above a baseline of 18 °C in the US. The 0·4–0·9 °C reduction in peak afternoon temperatures in scenarios (4) and (5), compared to scenarios (1) and (7) would therefore translate to a 2% reduction in energy consumption using these results from Akbari *et al.* (2001). These results are similar to those of D. Kingdom (personal communication, 2001) who, using a very small energy consumption dataset for selected suburban substations in Melbourne, Australia, found an increase of 0·71 MWh for every degree rise above a base of 18 °C on a background of about 20 MWh—i.e. an increase of about 3% $^{\circ}C^{-1}$ rise in air temperature.

Within this discussion of energy consumption benefits, it is worth noting that vegetated roofs can also act as a thermal insulation layer, which could reduce household air conditioning usage during hot summer days. Research by Niachou *et al.* (2001) found that the energy savings due to the installation of a vegetated roof in the Athens region in Greece varied, depending on the amount of traditional roof insulation material used in the building construction. The cooling energy savings were estimated to vary from 45% for an otherwise uninsulated roof thorough to 0% for a well-insulated roof.

CONCLUSIONS

The important conclusions of this paper can be summarized as follows:

- Monthly *E*, from 1978–1995, was simulated for a suburban catchment in Canberra, south-eastern Australia (Woden) using two urban water balance models: (i) Aquacycle, a daily time-step model that has been calibrated for the suburb using measured water usage and runoff (storm water and waste water) and (ii) SUES, a model that represents *E* with greater complexity than Aquacycle and has a sub-diurnal time step which has not been parameterized for Woden. The agreement between the two *E* predictions was improved significantly by forcing SUES with a seasonally-varying LAI, which demonstrates, firstly, where improvements in SUES can be made through targeted measurements and analysis and, secondly, that SUES has much potential as a model to explore the links between WSUD, climate, CO_2 sequestration and energy consumption.
- As just stated, further development of SUES is needed, in particular: (i) parameterization of the subroutines that calculate the available energy and the aerodynamic and surface resistances using flux measurements obtained in a larger range of suburban land-uses—especially Australian cities for which very few such data are available; (ii) exploring ways to link and combine the components of strength in each of SUES and Aquacycle. In this work, this was started by using Aquacycle's garden irrigation estimate as an input to SUES, but there are more such links worth developing such as utilizing SUES *E* scheme within Aquacycle.
- Simulations of the water balance for the suburb of Woden confirm that *E* is the largest output term in the water balance, accounting for 55% of the annual rainfall plus irrigation. This contribution is even larger in the summer compared to the winter.
- A range of water sensitive urban design features were simulated using Aquacycle, and their relative impact on the imported water input and storm water, waste water and *E* outputs assessed. Features with relatively limited areal extent, such as swales and a wetland, had only very slight impact on these outputs while the vegetated roof treatment, because of the areal coverage, increased (reduced) the annual *E* (storm water) by 50 mm, which is 11% (19%) of E (storm water). The roof area comprises about 25% of an average block, and residential blocks make up about two-thirds of the land use in this suburb.
- Combining these WSUD features with a 50% reduction in garden watering obviously reduces the water inputs (762 mm compared to 800 mm in a conventional suburban design) and storm water (from 266 mm to 201 mm) while *E* is enhanced (from 436 mm to 460 mm), mostly because of the vegetated roofs.
- A simple atmospheric boundary layer model was used to translate these changes in surface energy partitioning into air temperature changes. The full set of WSUD features, with no reduction in garden watering, yields the highest *E* rate, and the largest effect of maximum daily temperature—about 0·5 °C cooler than a conventional suburban design. A more detailed and thorough analysis is needed to improve these estimates of air temperature changes, e.g. using a three-dimensional atmospheric mesoscale model with adequate space and time resolution to simulate microclimate effects within the urban canopy and their impact on energy consumption.
- These results confirm the potential role of passively controlling urban microclimate, and thence energy consumption, by suburban design features that maximize *E*. Such WSUD features also reduce storm water flows. This analysis therefore quantifies yet another clear benefit of maintaining urban greenspace, whether as parks distributed throughout an urban area or individual gardens or vegetated roofs. The challenge, especially under global warming that has the effect for some regions of both increasing demand and reducing supply, is to maintain the greenness of the urban greenspace. The analysis showed that this was possible, even with a 50% reduction in garden watering. Provision of water in suburban areas to maintain the urban greenspace, *E* and cooling should be seen as an investment with quantifiable returns.

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