The Impact of Suburban Design on Water Use and Microclimate

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Keywords: *evapotranspiration, water balance, urban microclimates.*

EXTENDED ABSTRACT

With over 84% of Australians living in urban areas (populations over 30,000), the outcome of the current debate on water use in cities and how to match water demand to supply under both current and future climates, has the potential to affect many Australians. Lacking in this debate is a sound quantitative basis for assessing the environmental and economic benefits of water use in urban areas.

As an example, while water sensitive urban design (WSUD) is widely accepted as a tool to manage the impacts of urbanisation by careful design at the house and street scale, its focus has largely been on managing and re-using the runoff (stormwater and wastewater) component of the water balance. Much less attention has been paid to the role of urban evapotranspiration (ET) by urban hydrologists, even though this it is often the biggest output in the water balance. Evapotranspiration is the process that links the movement of water through a landscape with the local climate, with the process using energy that would otherwise contribute to elevated air temperatures. This passive control of the local climate *via* urban vegetation and ET has a direct influence on quantities of energy used in space heating and cooling through the role of urban ET and also because trees provide shade and shelter.

This link between the urban water and energy balances, and microclimate, is demonstrated by considering the following simplified expressions for i) the urban water balance:

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

where the inputs are: P = precipitation; I = piped water supply (for external and internal uses); and the outputs are: ET = urban evapotranspiration; D = stormwater and wastewater; ΔS = change in stored water on and within the surface materials; and ii) the urban energy balance:

$$Q^{*} + Q_F = Q_H + Q_E + \Delta Q_S \qquad (2)$$

where the energy inputs and outputs are: Q^* = net all-wave radiation; Q_F = anthropogenic energy sources (space heating, cooling etc.); Q_E = energy used to evaporate the water flux E; Q_H and ΔQ_S = energy used to heat the air, soil and built surfaces.

Urban ET also contributes to reducing net greenhouse gas emissions, directly because water loss via transpiration is the consequence of the uptake of CO_2 during photosynthesis, and indirectly because reduced energy consumption reduces greenhouse gases consumed in burning fossil fuels to generate electricity. Maintaining urban greenspace *via* irrigation is therefore a quantifiable benefit of water use in terms of reduced energy consumption and net greenhouse gas emissions. Quantifying these benefits is critical if they are to be included in current discussions about urban water use.

To address the gap in current WSUD practice, and investigate the potential to realise multiple benefits from urban vegetation, we use a calibrated urban water cycle model to quantify the impact of urbanisation and different suburban designs (layout, population, style and size of housing etc.) on the seasonal and annual urban water balance, especially ET, in an Australian city. We show that urban ET is the largest output term in the average urban water balance (almost twice the size of urban runoff) and is sustained during periods of low rainfall by the use of imported water to irrigate household gardens and larger urban parks. We show that this urban ET lowers air temperatures to reduce energy demand for cooling during peak air temperatures. The simulations demonstrate that the magnitude of urban ET can be manipulated through different suburban designs, e.g. urban consolidation reduces urban ET by about 50%, doubles the urban runoff, and increases afternoon air temperatures by about 1°C. Such an increase could increase energy consumption by 3%.

1. INTRODUCTION

Water sensitive urban design (WSUD) has emerged as an approach to urban planning that promotes sustainable management of the urban water cycle by manipulating the design of new buildings and the layout of whole suburbs. While WSUD embraces the principle of the whole urban water cycle, much of the WSUD literature and applications have focussed on runoff (stormwater and wastewater; quantity and quality) and options for water re-use, neglecting the possibilities of manipulating the evapotranspiration component of the water cycle. Yet urban evapotranspiration (ET) is often the biggest output in the urban water balance, especially on non-rain days when it is the only output in the external water balance (i.e. not including the wastewater stream from internal water use). Evapotranspiration is also the process that links the cycling of water through a landscape with the local climate.

The purpose of this paper is to use a calibrated urban water cycle model, and the climate and land use for Canberra Australia, to quantify:

(1) The impact of urban land-use on all water balance components, especially ET

(2) The impact of different suburban design (layout, population, style and size of housing etc.) on the urban water balance - especially urban ET and thence microclimate and energy consumption.

and thence provide a more quantitative basis for analyses of the environmental and economic benefits of water use in urban areas.

2. MODEL DESCRIPTION

Simulations use Aquacycle, an urban water balance model whose description, calibration and performance for Woden Valley in Canberra, ACT, Australia are documented in Mitchell et al. (2001). The parameterisation of urban ET in Aquacycle is relatively simple: urban greenspace comprises grass only (not trees) and urban ET is modelled using a supply-demand concept - i.e. ET proceeds at the rate determined by the atmospheric demand (potential evaporation, E_P which is equivalent to the measured pan evaporation in Aquacycle) if there is sufficient soil moisture. If potential evaporation exceeds toe soil water supply, then the actual evaporation is equivalent to this supply.

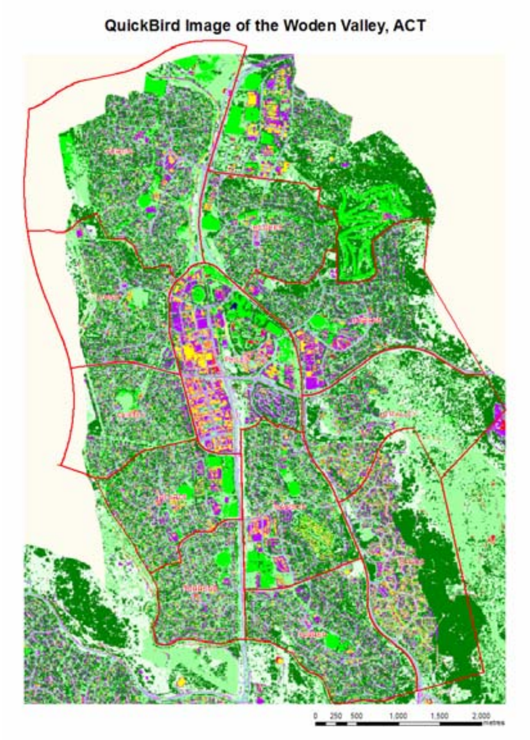


Figure 1. Suburb and catchment boundaries for the Woden Catchment in Canberra, ACT, Australia overlaid on a Quickbird remote sensing image showing the vegetation (bright green and green) and impervious surfaces (roofs and pavement; yellow through purple)

The model has a daily timestep which excludes the fine time scale dynamics of the external urban water balance such as the rapid drainage and evaporation of intercepted water held on roofs and pavement (Grimmond and Oke, 1991). Nonetheless, Aquacycle has been successfully calibrated and tested for the Woden Valley, an urbanised catchment in Canberra, Australia, and is sufficiently robust to simulate the impact of suburban design on the water balance components at monthly to annual time scales.

2.1 Input

Daily climate data (rainfall, air temperature, humidity and pan evaporation) were sourced from the Bureau of Meteorology climate station at Canberra Airport from 1978 – 1995.

2.2 Suburban scenarios

Aquacycle was calibrated for the Woden Valley, located in Canberra's south. Mitchell et al. (2001) provides a complete description of the catchment for the simulations done up to 1995. In 2003 there were 37,500 people residing in 15,000 dwellings.

Woden Valley has a mix of residential 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 1).

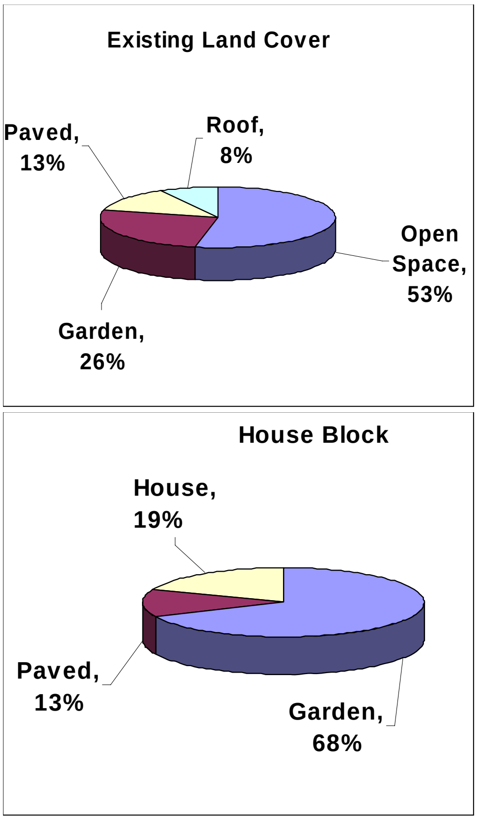


Figure 2. Current land cover for the Woden Valley catchment (upper panel) and an average house block, or lot (lower panel).

Figure 2 illustrates the nature of the land cover in the catchment: 79% is pervious with 53% open space (parks, nature strips etc.) and 26% gardens.

The remaining 21% is impervious, split between rooves (8%) and paved areas (13% - roads, footpaths, parking lots). Almost one third of the average residential block is impervious.

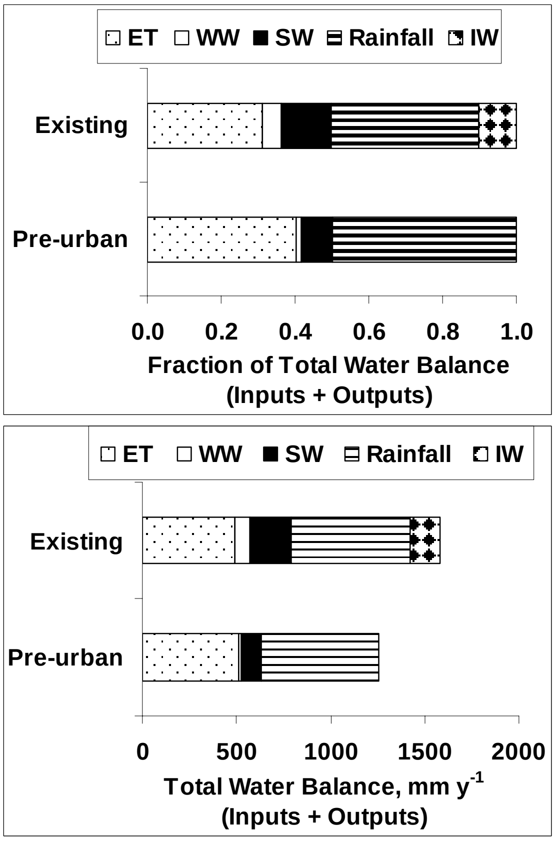
The water balance simulations for the Woden Valley, with its current urban form, land use and population, is used as the reference for the remaining simulations in this study. All calibration parameters for the suburban design scenarios described below are held at the values determined by Mitchell et al. (2001) and the irrigated fraction of the open space and garden areas of the catchment are set to 0.10 and 0.70.

3 RESULTS

3.1 Effect of urbanisation on the seasonal and annual water balance

Figure 3 illustrates the average annual water balance for the Woden Valley as simulated by Aquacycle for i) a pre-urban scenario and ii) the current land-use as described above. The average annual rainfall for Canberra from 1978 – 1995 (inclusive) was 633 mm and Figure 3 shows that most of this (510 mm per year = 81% of rainfall) is lost as evapotranspiration, with just 120 mm (19% of rainfall) contributing to runoff when the catchment was not urbanised.

Figure 3. Impact of urbanisation in the Woden valley expressed as a fraction of the total water balance (upper panel) and in absolute units (lower panel). The current land-use scenario is labelled as “existing”.



The major impact of urbanisation on this annual water balance is that there is now an additional water input, imported water (IW) which adds 164 mm to the annual rainfall of 633 mm. The fate of this imported water and rainfall is to maintain ET via irrigation and contribute to runoff via the wastewater (WW) and stormwater (SW) streams. Runoff (stormwater plus wastewater) is increased as a result of urbanisation – in fact the increase in runoff (178 mm) is of the same magnitude as the quantity of imported water (164 mm).

Water used indoors – in baths, showers, laundry etc. – makes up the bulk of the wastewater output. This is seen here by the observation that about half [1] of Canberra’s water is used externally (irrigation, car washing etc) and half internally. So we’d expect about 82 mm of the imported water to be used internally and then enter the wastewater stream – almost identical to the wastewater simulated by Aquacycle.

Stormwater is water that enters the urban drainage system as runoff from paved areas and rooves, and pervious areas with low infiltration capacity. Increases in stormwater are one of the best known impacts of urbanisation. Annual stormwater increases linearly with increasing impervious area in these simulations - the rate of increase is about 50 mm for a 10% increase in impervious area starting from a baseline of 107 mm runoff for a non-urbanised catchment. It is therefore not surprising that 27% (218 mm) of the water input (rainfall plus imported water) to Woden Valley enters the stormwater system.

ET is little changed by the urbanisation of Woden Valley that increases the impervious area to 21% of the total catchment area. While this may be a surprising result, many observational studies (see Grimmond and Oke, 1995 and Cleugh, 1995 for reviews) in North American cities show that urban evapotranspiration rates can exceed those of the surrounding rural environs – in part because of the security and reliability of the urban water supply that enables irrigation of urban greenspace. These simulations show a similar process at work. On an annual basis about 90 mm of water is applied externally (mostly garden irrigation) to supplement the rainfall and this maintains ET at a rate almost equivalent to its rate prior to urban development despite the smaller transpiring fraction of the catchment.

Analysis of the seasonal trends provides even further insight (Figure 4). Summer and autumn ET is slightly higher (~10 mm) compared to the pre-urban scenario while winter and spring ET rates are 26 mm lower. The higher ET rates in summer are supported by summer irrigation - 69% of the water imported in the summer period is used in irrigation. In winter and spring, when water availability is high and evaporative demand low, the imported water sustains some of the spring ET but otherwise contributes to the slightly higher runoff in winter and spring (Figure 5).

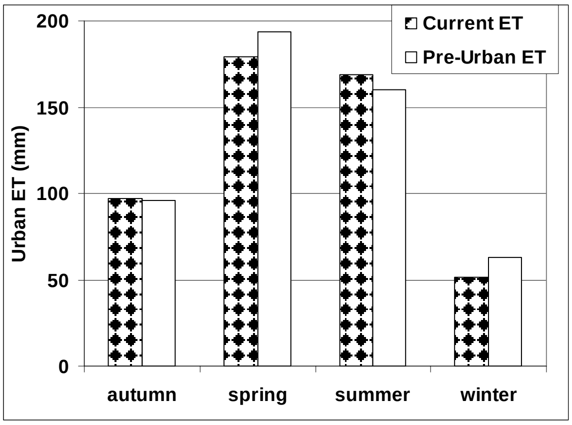


Figure 4. Seasonal variation of ET for current land-use and pre-urban simulation.

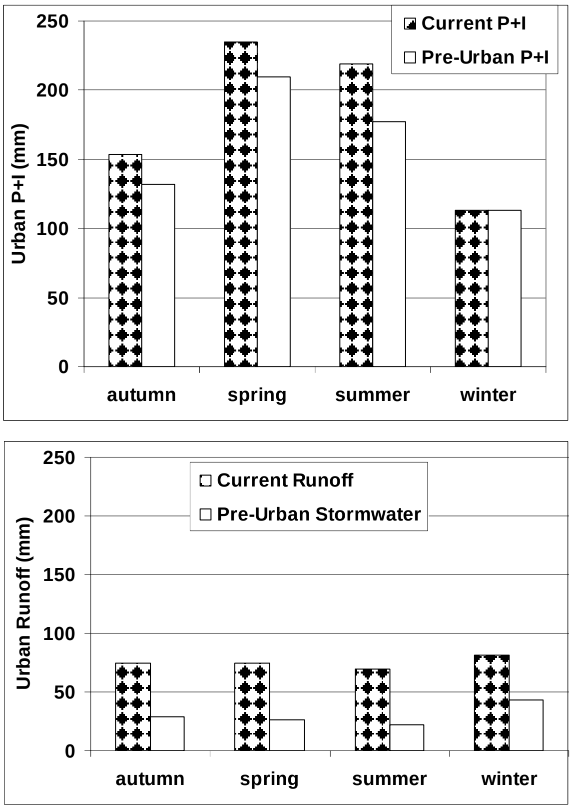


Figure 5. Seasonal variation in other water balance components: (a) rainfall plus imported water (P+I) and (b) runoff (SW+WW).

The implications of these changes, in terms of stormwater and wastewater, have been well documented for urban areas. The combination of impervious surfaces and a reliable supply of water for consumption indoors means that the catchment delivers slightly more water downstream (179 mm) than it diverts into storages to maintain Canberra’s water supply (imported water is 164 mm). The difference (16 mm)

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[1] ACTEW website: (http://www.actewagl.com.au/education/water/)

reflects the slight reduction in ET that results from urban development.

In terms of ET – the significant result is that despite the 'waterproofing" of the catchment, the combination of urban greenspace (parkland and gardens) and a reliable water supply for irrigation in the growing season is able to maintain the urban ET rate at a level commensurate with that prior to urban development. Maintaining a sizeable, irrigated urban greenspace has quantifiable environmental benefits through the microclimate, energy consumption and CO_2 sequestration effects demonstrated below, in addition to the more intangible aesthetic and health benefits.

If increased delivery of runoff to the downstream catchment is seen as an undesirable outcome of urbanisation, we can also explore the possibilities of using urban greenspace to store this runoff – thereby contributing to the benefits described above with less reliance on imported water. Using the annual budgets, the total runoff is 298 mm (218 mm + 80 mm) while the external water use requirement is just 88 mm – i.e. re-directing just 30% of the annual runoff to urban greenspace could offset the annual external water requirement. Alternatively, the entire wastewater stream could be harnessed to meet the external water use demand if it could be stored and treated to maintain the quality and quantity.

Realistically, rainfall does not occur at the time when irrigation demand is high, so considering just the summer and autumn period when the irrigation water requirement is greatest, the external water requirement of 63 mm is less than half the total runoff for that period (144 mm). This illustrates the large potential for re-using stormwater and/or wastewater for maintaining the urban greenspace.

3.2 Impact of Suburban Design

In this section, we present the impact of suburban design on the terms in the annual water balance using three suburban design scenarios (Table 1):

1. The "quarter acre section" – essentially very similar to the present urban layout and characterised by large blocks with sizeable gardens and small houses.

2. Urban consolidation – reduction in open spaces (parks and sportsfields); reduction in size of average residential block and area of garden per block; and an increase in population housed in single-storey dwellings.

3. The "McMansion" style of development - a design where the house occupies a large proportion of the house block, with larger blocks and garden areas, common on the periphery of large cities such as Melbourne and Sydney.

Table 1. (a) Land cover for existing and each of the suburban design scenarios.

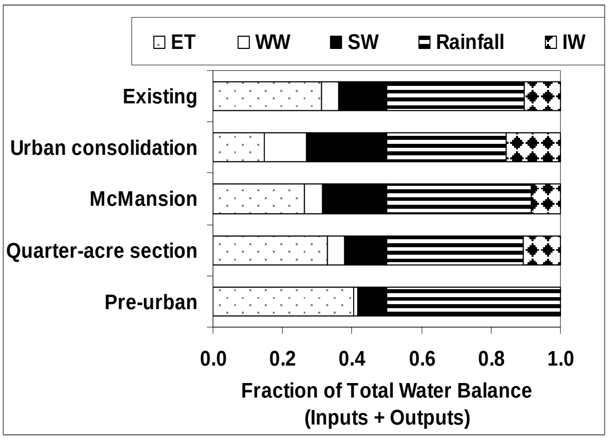
Design	Percentage of House Block		
	Roof	Garden	Paved
Existing	19	68	13
1.Quarter acre section	7	80	13
2. McMansion	50	37	13
3. Urban Consolidation	50	37	13

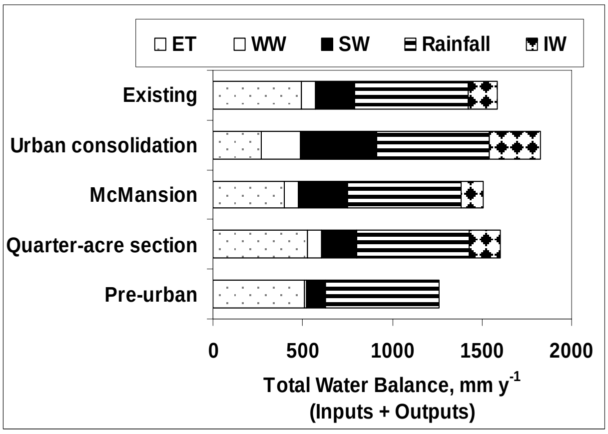
(b) Land cover, population (N_P) and number of houses (N_H) for the pre-urban, existing and suburban design scenarios (1 – 3) defined in Table 1a.

Design	N_P N_H	Percentage of catchment:			
		Roof	Paved	Garden	Open
Pre-urban	32 *13*	0	0	0	100
Existing	37,500 *15,000*	8	13	26	53
1.	37,500 *15,000*	3	13	31	53
2.	37,500 *15,000*	20	13	14	53
3.	116,110 *46,444*	36	25	27	12

Figure 6 summarises the water balance components for each of these design scenarios. As expected, the imported water increases with increasing population, at a rate of ~2.8 mm y^{-1} per 1000 people. This relationship varies with the fraction of the pervious that is garden compared to open space – e.g, the lower imported water use for the "McMansion" compared to the "quarter acre section" scenario. Each have the same population but the garden occupies a much smaller fraction of the block and catchment in the former and this difference is reflected in the water use. In climates where irrigation supplements the rainfall to meet the water demand of household gardens, it is obvious that increasing the area of the block and catchment that is garden increases the quantities of water imported to support irrigation.

Figure 6. Water balance components for the existing land cover and each of the suburban design scenarios described in the text.





The increase in impervious area in both the McMansion and urban consolidation scenarios compared to the pre-urban and quarter-acre section scenarios means that there is an increase in stormwater flows. Whereas runoff is about 19% of the annual water budget prior to urbanisation, it increases to about 25% and then 50% for the quarter acre section and urban consolidation scenarios, respectively. So, the effect of increasing the impervious area is to only weakly affect the volume of imported water, but to increase the output of water via runoff and reduce the output *via* ET.

For every 10% increase in pervious cover, the annual ET increases by 62 mm y^{-1} from a base ET under urban consolidation of about 50% of that prior to urbanisation. Interestingly, the quarter acre section simulation shows an urban ET that is slightly higher than the pre-urban – as mentioned earlier this is not unexpected as the security of water combined with a very large urban greenspace (84% of the catchment) sustains a very high ET.

Simulations for a range of different suburban scenarios and from this larger population of data reveal the following effects of urbanisation:

- While imported water volumes are not highly correlated with urban greenspace, they are quite highly correlated with percentage area of gardens, as these are demand watered.

- Urban ET, on the other hand, is not highly correlated with fraction of the catchment in gardens, or percentage irrigated. It is most strongly correlated with the fraction of open area. This suggests that at a suburb scale, urban parks may be an appropriate strategy for maintaining urban greenspace and ET, and also providing storage areas for capturing urban runoff.

- That the area of garden and fraction of irrigated greenspace is correlated with increases in imported water and reductions in stormwater also reinforces the potential wisdom of maintaining public greenspace in the form of parks to enhance ET at the suburban scale.

3.2 Benefits of Urban Greenspace and ET on Microclimate and Energy Use

While a comprehensive analysis would require coupling an urban climate model to a model such as Aquacycle, some quantified estimates of the effect of changing ET on the microclimate, especially air temperature, can be made by using a very simple modelling approach, following that of Oke (1989).

The daily net radiation receipt for each of the surface types described in Table 2 is fixed at reasonable values (~ 150 Wm^{-2}) and the diurnal warming and cooling rates computed from an expression for the heating rate of an urban atmospheric boundary layer, assumed to be 1 km deep (= z_{UBL}) throughout the day with the input of heat from the surface (H) equivalent to the surface sensible heat flux in kinematic units (m s^{-1} ^oC):

$$\frac{dT_a}{dt} = \frac{H}{z_{UBL}} \qquad (3)$$

where dT_a/dt is the diurnal heating rate ($^oC\ s^{-1}$). The surface sensible heat flux is computed from the urban energy balance (2), where the available energy ($Q^* - \Delta Q_S$) is specified and latent heat flux is determined from the average summer daily ET (Table 2). This simple one-dimensional expression does not include the effects of mesoscale advection, but is adequate for this task.

To quantify the cooling realised from urban greenspace, the change in peak afternoon temperature predicted using this equation is compared to that for a "desert" city with no vegetation and no urban evaporation (δT_{amax}).

Table 2. Summertime ET (from Aquacycle simulations) converted to diurnal heating rates and the consequent effect on peak afternoon air temperatures, for a range of landscapes.

Scenario	Summer ET (mm d^{-1})	Heating rate ($^oC\ h^{-1}$)	δT_{amax} (^oC)
Pasture	3.21	0.18	-2.70
Pre-urban	1.78	0.30	-1.49
Current	1.88	0.29	-1.58
1.	2.10	0.28	-1.69
2.	1.48	0.42	-0.34
3.	1.00	0.46	0.06
Desert	0.00	0.45	0.00

To convert these air temperature changes to energy use savings, we can turn to the results of Akbari et al (2001) who found an increase in energy consumption of 2 – 4% for every 1^{o}C rise above a baseline of 18^{o}C in the U.S.. A 2^{o}C reduction in peak afternoon temperatures due to the presence of vegetation therefore translates to a 5 – 10% reduction in energy consumption. These results are similar to those of Kingdom (2001, *pers. comm.*.) who, using a very small energy consumption data set from NEMMCO for selected Melbourne sub-stations and measured air temperature, found an increase of 0.71 MWh for every degree rise above a base of 18^{o}C on a background of about 20 MWh – i.e. an increase of about 3% for every 1^{o}C rise in air temperature.

4. CONCLUSIONS

This study has confirmed that urban evapotranspiration is a sizeable term, for example the average annual urban ET is almost twice the urban runoff in the existing Woden catchment, and can be manipulated through urban design by including urban greenspace in the form of parks, gardens and open areas of vegetation.

Whilst water needs to be imported to sustain the evaporation, these results demonstrate that there are quantifiable benefits associated with this water use in the form of cooler air temperatures and energy savings. Further studies are needed to comprehensively quantify these savings and include the benefits of CO_2 sequestration.

There needs to be an adequate water supply to sustain urban evaporation and prolonged dry periods will severely stress the ability to provide this assured water supply from the existing centralised potable system, as is evidenced by the current situation in many cities in eastern Australia, including Sydney, that are facing severe water shortages. The simulations reinforce the potential for urban greenspace to receive and store some urban runoff and contribute to the microclimate and CO_2 sequestration benefits, providing these open spaces are dispersed through the suburb and that the engineering and water quality control infrastructure requirements are feasible.

This study has also illustrated the usefulness of modelling tools such as Aquacycle for not just traditional WSUD, but also to include the role of urban ET on microclimate and energy use.

Finally, perhaps the most the important point of this work is to demonstrate that water used as irrigation on urban gardens and parks is not a "waste" – it has a quantifiable benefit that must be included in any policy about water use in urban areas.

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