Evapotranspiration in Urban Water Balance Models: A Methodological Framework

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EXTENDED ABSTRACT

A complete and integrated picture of the spatial and temporal dynamics of the potable water supply, wastewater discharge, and stormwater runoff is best achieved by considering the complete urban hydrological cycle (Mitchell et al., 2001) with the water balance as the underpinning conceptual framework. Following Grimmond and Oke (1991), we can write a simplified water balance for an urban area as:

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

where the inputs are rainfall (*P*), piped water supply (*I*); the outputs are evapotranspiration (*ET*), drainage (*D*) – wastewater and stormwater; and the change in storage (ΔS) in the natural (soil and groundwater aquifers) and built components of the urban system. Adopting the urban water balance as the underpinning conceptual framework has several advantages:

a) It enables a continuous rather than an event-based simulation of the urban water system.

b) It makes explicit the need to quantify urban evapotranspiration, which is the largest output term in dry periods and can be manipulated through design of the greenspace and built components.

c) Urban ET links the urban water and energy cycles and therefore the impact of changes in the former on urban climate. This formal link between energy and water also provides a powerful constraint for urban water cycle models.

These advantages highlight the importance of representing the process of evapotranspiration in urban hydrological models – a task that is complicated by the ET process in urban landscapes which comprises, often simultaneously, transpiration from urban vegetation (grass, shrubs, trees) and evaporation from wet pervious and impervious surfaces.

This paper addresses the current imperative to develop and test urban ET algorithms, incorporate these into urban water balance models, and develop these into tools to underpin and guide Water Sensitive Urban Design (WSUD) and integrated urban water management. Two approaches to modelling the urban water balance focusing specifically on urban evapotranspiration are presented: i) SUES (Single-source Urban Evapotranspiration-interception Scheme, Grimmond and Oke, 1991); and ii) Aquacycle (Mitchell et al., 2001). Aquacycle is a continuous water balance model that represents both the internal and external components of the urban water cycle: the water supply (including options for water re-use and rainwater tanks); the stormwater and the wastewater streams.

SUES focuses on simulating the external water balance with the imported water component specified. Its great strength is that it represents urban ET as continuous transition from wet surface evaporation through to evapotranspiration from partially dry surfaces to transpiration from urban vegetation. This means that SUES not only represents urban ET in a biophysically reasonable way, but the fine-scale dynamics of interception and evaporation are captured. SUES explicitly includes the urban energy balance to both constrain the water balance simulations and provide a link to the effects of the water system to urban microclimates and energy consumption.

The implementation of Aquacycle and SUES for an urbanized catchment in Canberra, Australia is described. Preliminary simulations of urban ET demonstrate adequate agreement between the two models. We conclude with a brief description of an integrated software system, *Greenscape Planner*, that facilitates the use of urban water balance models to underpin urban design.

1. INTRODUCTION

A complete and integrated understanding of the spatial and temporal dynamics of the potable water supply, wastewater discharge, and stormwater runoff is best achieved by considering the complete urban hydrological cycle (Mitchell, 2001). From a modelling perspective this necessitates using the urban water balance as the conceptual framework, where the water balance for an urban area has been defined above (1).

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) where “a unit block represents 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 their cluster scale or the local scale used by micrometeorologists); and a catchment which may be defined using both topography and the pipe supply network.

A simplified urban energy balance, analogous to (1) can be written:

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

where Q^* is the net all-wave radiation; Q_F is the anthropogenic heat flux, ΔQ_S is the heat storage in the urban “canopy” (buildings, streets etc.), Q_E is the latent heat flux (energy used in evaporation) and Q_H is the sensible heat flux.

Thus water, as a mass flux or the energy required to change its state from liquid to vapour, appears in both the water and energy balances which imposes an energy and mass conservation constraint on urban ET simulations. The urban energy balance also provides the mechanism to explore the impact of urban evaporation, and hence land use and vegetation type and layout, on urban microclimate.

The following sections describe two urban water balance models, Aquacycle and SUES; compares their strengths and simulations of the urban water balance for an urbanised catchment in Canberra, ACT, Australia with a focus on urban ET. The paper concludes with a description of a software tool, Greenscape Planner, that is being designed to work with both or either of these two water balance models.

2. MODELLING THE URBAN WATER BALANCE

2.1 AQUACYCLE

A complete description of Aquacycle, its calibration and performance for the urbanised Woden catchment in Canberra, ACT, Australia are documented in Mitchell et al. (2001, 2003). As described in those publications, Aquacycle can simulate the urban water balance at three spatial scales: a single unit block, a cluster and a whole catchment. It uses a daily time step and recognizes three types of land use: residential, 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.

Evaporation from impervious and pervious surfaces is simulated separately and summed across each spatial unit (block, cluster and catchment). The evaporation loss is removed daily from each store and so the dynamic process of evaporation and runoff of intercepted water, which operates on a much finer time scale, is not represented in Aquacycle.

Impervious surfaces: Evaporation from impervious surfaces (E_{imp}) is determined as:

$$E_{imp} = \sum_{i=1}^{n} \left[\max(E_P, S_i).A_i \right] \qquad (3)$$

where E_P is the potential evaporation rate; S_i is the depth of water stored on impervious element i; A_i is the fractional area of surface element i in each cluster; and n is the number of impervious elements in Aquacycle, currently these are paved, road and roof (i.e. $n = 3$).

Pervious surfaces: Urban greenspace is either a residential garden or public open space (i.e. a park or sports field) and comprises grass only – not trees. Evapotranspiration is modelled using a supply-demand concept – the evaporation rate varies as a linear function of available soil water (θ) and atmospheric demand. This means that if there is sufficient soil moisture, ET proceeds at the rate determined by the atmospheric demand but otherwise it proceeds at the rate of soil water availability. The atmospheric demand is the energy limited evaporation rate and in Aquacycle this is determined using Morton’s wet environment areal evaporation model, as described in Mitchell et al. (2001, 2003).

Mathematically, this is expressed as:

$$E_{pervious} = A_1 \min\left[\left(\tfrac{\theta_1}{\theta_{1c}}.E_{Pc}\right), E_P \right] + \left[100 - A_1 \min\left(\left(\tfrac{\theta_2}{\theta_{2c}}.E_{Pc}\right), E_P \right) \right] \quad (4)$$

where $E_{pervious}$ is the evapotranspiration from the pervious component, which has two stores with fractional areas A_n; θ_m/θ_{mc} is the available soil water in store m (where m = 1 or 2) and E_{pc} represents the maximum transpiration rate for a plant canopy (currently set to 7 mm d^{-1}).

2.2 SUES

Following the approach and logic of Grimmond and Oke (1991, hereafter GO91), for each surface i in the urban system, the storage of water, S is computed by rearranging (1):

$$\frac{dS_i}{dt} = (P_i + I_i) - D_i - ET_i \qquad (5)$$

GO91 identified six surface types: paved, built, coniferous trees, deciduous trees, irrigated grass and unirrigated grass. Apart from defining D_i, I_i and storage capacity (S_{ci}), GO91 also developed and tested a biophysically and hydrologically sound approach of estimating urban ET.

A continuous urban water balance model requires ET to be determined during and immediately following rain when the impervious surfaces are wet and water will be lost either through evaporation and runoff. GO91 took the view that the most rigorous, robust and physically-based approach was the Penman-Monteith-Rutter-Shuttleworth evapotranspiration-interception model. The following section describes this ET model in more detail. Parameterisations of the remaining water fluxes are described in full in GO91.

2.2.1 Evapotranspiration Model

Evaporation from urban surfaces is complicated by the wide array of surface materials, aspect and morphology (height, spacing, width) present in the urban canopy. Considerable progress has been made in the last 20 y by defining an appropriate spatial scale at which some integration can be achieved. Using the same concept of a control volume, we can define Q_E as the areally-averaged evaporation flux from a source area whose spatial dimensions are roughly 1 km^2 – this equates to a neighbourhood or cluster. At this scale, direct measurements of Q_E can be obtained using atmospheric approaches such as the eddy covariance method and, providing some key assumptions are met, we can also adopt a single source ET model such as the Penman-Monteith equation:

$$Q_E = \frac{sA + \left(\frac{C_a \delta q}{R_A}\right)}{s + \gamma(R_S / R_A)} \qquad (6)$$

where R_A and R_S are the aerodynamic and surface resistances, that control the transfer of water from within the sub-stomatal cavities into the canopy airspace (R_S) and from there 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; and A, the available energy, for an urban area is:

$$A = Q^* + Q_F - \Delta Q_S \qquad (7)$$

The process of evapotranspiration in an urban area, with its mix of pervious and impervious surfaces, has three phases:

1) **Evaporation from a fully wet surface:** Evaporation of intercepted water is determined by the atmospheric demand, which sets the maximum evaporation that can be sustained by the atmosphere and is ultimately driven by the energy supply, and the supply of moisture, which depends on both the precipitation amount and the morphology of the urban canopy as the latter determines surface storage and drainage.

2) **Evapotranspiration from a partially wet surface:** Evaporation occurs from impervious and pervious wet surfaces, and transpiration from dry pervious surfaces.

3) **Transpiration from vegetated surfaces**: Transpiration from plants such as grasses and trees.

SUES simulates the transition across these three phases by firstly defining a canopy storage capacity for each surface element, i (S_{ci}). This is the amount of water left on the canopy after rainfall and throughfall and is similar to the concept of field capacity. Secondly, GO91 adopt the method of Shuttleworth (1978) to replace the surface resistance in equation 6 (R_S) with a resistance (R_{SS}) that varies continuously across Phases 1 – 3:

$$R_{SS} = \left[\frac{W}{r_b(\frac{s}{\gamma}+1)} \right] + \left[\frac{1-W}{R_S + r_b(\frac{s}{\gamma}+1)} \right]^{-1} - r_b(\tfrac{s}{\gamma}+1) \quad (8)$$

$W = 1$ and $R_S = 0$ when $S(t) \geq S_c(t)$, i.e. when the surface is wet. When the surface is dry and $S(t) < S_c(t)$:

$$W = \frac{R-1}{R - {S_c(t)}/{S(t)}}$$

where

$$R = \frac{{R_S}/{R_A}\,(R_A - r_b)}{R_S + ({s}/{\gamma}+1)\, r_b} \quad (9)$$

Essentially this model treats the urban canopy (where the canopy now comprises built and vegetated surfaces) as a single layer moisture store with all the individual stores (surfaces 1 – 6, above) functioning in parallel. Following the arguments of GO91, the throughfall and stemflow terms are negligible in an urban water balance.

Thus, a running water balance (5) is maintained for each individual surface and *ET(t)* is weighted by the fraction of each surface type.

2.1.2 Parameterising Inputs to SUES

There are two challenges to the routine implementation of the ET component of SUES in water balance simulations: i) providing meteorological forcing such as available energy, wind speed (to compute the aerodynamic resistance) and humidity deficit at an hourly time-step; and ii) parameterising the aerodynamic (r_b, R_A) and surface resistances (R_S).

We address the first of these by making use of the standard climate station observations of maximum and minimum temperature, humidity, daily wind run and solar radiation. We develop a sub-diurnal interpolation scheme to interpolate these daily meteorological data to an hourly timestep.

To determine net all-wave radiation, we use these solar radiation data, a specified surface albedo and emissivity, and the equations developed in Offerle et al. (2003). The equations and coefficients in LUMPS (Local-Scale Urban Meteorological Parameterization Scheme, Grimmond and Oke 2002) are used to calculate the storage heat flux, with land use fractions derived from the land cover analysis described below.

It remains to parameterize the boundary layer, aerodynamic and surface resistances (r_b, R_A and R_S). The aerodynamic resistance under neutral atmospheric stability (R_{An}) can be estimated from near-surface wind speeds, $U(z_M)$, and the aerodynamic roughness length for the "patch" or "neighbourhood" using the following:

$$R_{An} = \frac{\ln\left[\frac{(z_M - d)}{z_{om}}\right] \ln\left[\frac{(z_M - d)}{z_{ov}}\right]}{k^2 U(z_M)} \quad (10)$$

The roughness length for momentum can be determined from the morphology of the urban surface using the formulae of Grimmond and Oke (1999). GO91 assume that $z_{0v} = 0.1\ z_{0m}$, and for this implementation of SUES, we set r_b to be a simple function of wind speed.

In Phase 3 (transpiration from plants) the surface resistance, R_S will be equivalent to a bulk canopy resistance (R_C) which is the parallel sum of the leaf stomatal resistances (r_{st}) that comprise the canopy. Kelliher et al. (1995) describe how to scale-up from a stomatal conductance ($g_s = r_{st}^{-1}$) to a canopy conductance ($G_C = R_C^{-1}$) for a plant canopy using leaf area index and incident radiation but because this does not account for the combination of species and their microclimate setting, GO91 used an empirical approach to estimate an *actual* bulk canopy conductance by discounting the maximum conductance (G_{Cx}) for a suite of environmental factors that impose stress on the plant, increase R_S, and thereby limit ET. The general form of the model is:

$$G_C = G_{Cx}\ \Lambda\ f(p_{1..n}) \quad (11)$$

where Λ is the leaf area index and $f(p_{1..n})$ refers to functions that vary from 0 to 1 for the environmental stress discount factors, usually: incident solar radiation ($S\downarrow$), vapour pressure deficit (δq), soil moisture availability (θ) etc. GO91 determine these empirically from measurements of the surface conductance that have been derived by using measured, neighbourhood-scale evaporation and solving the Penman Monteith equation (6) for G_S. GO91 replace the leaf area index (Λ) in the general form of (11) with the following expression, which correctly weights Λ for irrigated and unirrigated portions:

$$p(\Lambda) = \frac{A_U \left(\frac{\Lambda}{\Lambda_M}\right) + A_I}{A_U + A_I} \qquad (12)$$

where A_U and A_I are the unirrigated and irrigated areas, respectively, and Λ_M is the maximum leaf area index for the unirrigated area.

The functions and parameters required to use (11) are then optimised using measurements. The optimal parameter set determined by GO91 is used in the implementation of SUES for Canberra described next.

3. COMPARING SUES AND AQUACYCLE

In terms of representing the *complete* (i.e. internal and external) urban water cycle at a fine spatial (unit block) and daily time scale, Aquacycle is a more comprehensive model than SUES. However, Aquacycle's representation of evapotranspiration across the mix of pervious and impervious surfaces that exist in urban land-use is perhaps weaker than in SUES. The daily timestep will not capture 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.

There are two other key differences between Aquacycle and SUES. Firstly, SUES is only applicable at the neighbourhood spatial scale (LHS of Figure 1), while ET in Aquacycle can be determined at the unit block and cluster scales (RHS of Figure 1). A second key difference is in the way that evaporation from the pervious components respond to limitations in soil water availability. Aquacycle uses a supply – demand approach, where the *supply* is determined by the field capacity of the pervious store and the simulated pervious store in the preceding time step, and the *demand* is determined by a measure of potential evaporation. In the current version of Aquacycle, this is calculated using Morton's (1983) wet environment areal evapotranspiration as described in Mitchell et al. (2001, 2003). Furthermore the pervious store is quite generic, for example there is no differentiation between trees and grass.

SUES provides more of a biophysical basis by using the Penman Monteith model, which constrains ET through available energy and includes all the key drivers, *viz*: available energy, aerodynamic transport, humidity deficit and stomatal control. Parameterising the role of the latter remains a challenge to the implementation of SUES and, as we demonstrate in §3.1, is definitely an area requiring further investigation.

3.1 Comparing ET Simulations

Aquacycle has been calibrated using hydrological measurements for the urbanised Woden catchment in southern Canberra. Mitchell et al. (2001, 2003) provide a complete description of the catchment and its urbanisation history until 1995. 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 (see Figure 2 in Cleugh et al., 2005).

Canberra is an inland city located in the south-east corner 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.

Monthly water balance simulations using

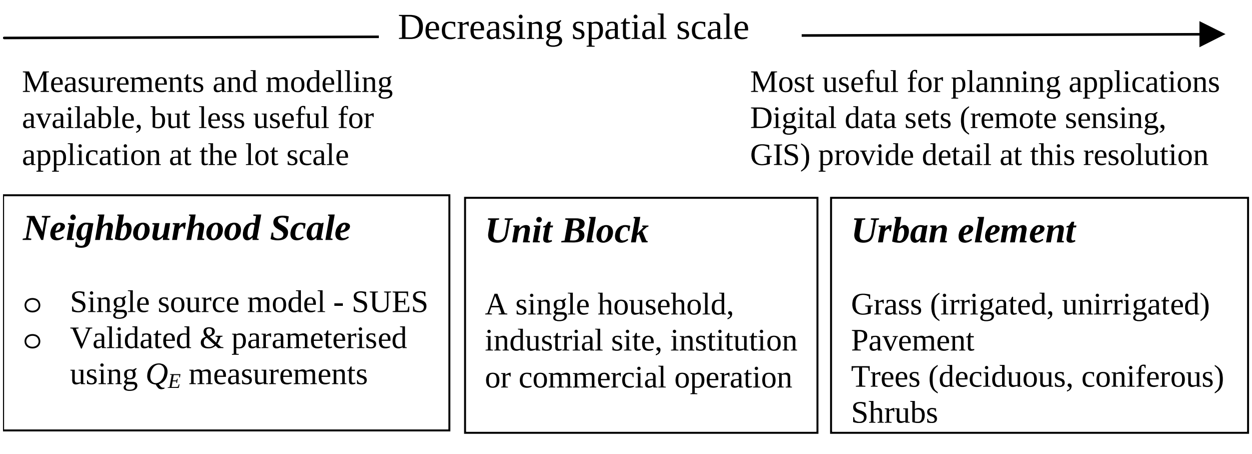

Figure 1. Schematic of the range of spatial scales for urban water balance modelling, input and test data.

Aquacycle and SUES for this catchment from 1978 – 1995 were conducted using the following setup:

- Daily climate data (rainfall, air temperature, humidity, solar radiation and wind run) were sourced from the Bureau of Meteorology climate station at Canberra Airport.
- The external water use required by SUES is sourced from Aquacycle, which predicts the quantity of irrigation required to maintain the pervious soil water store(s) at a specified level.
- Optimised parameters from Mitchell et al. (2001) and GO91 (surface conductance drainage modules and the storage capacities for all surface elements) are used for the Aquacycle and SUES simulations, respectively.

  The exception is that the size of pervious store 1 (A_1 in (4)) is set to 30% with a capacity of 30 mm, compared to that used by Mitchell et al. (2001) of 22% and 32 mm.
- The land cover for the Woden catchment as described in Mitchell et al. (2001) and Cleugh et al. (2005) are used for both SUES and Aquacycle.
- Net all-wave radiation and storage heat fluxes use parameterisations in Offerle et al. (2003) and Grimmond and Oke (2002), respectively; with albedo = 0.14 and the anthropogenic heat flux (Q_F) is neglected.
- The parameterisations used in SUES are uncalibrated, in particular the surface conductances.

3.2 Results

Figures 2 and 3 compare the monthly ET simulated by SUES and Aquacycle. There is surprisingly good agreement between SUES and Aquacycle, especially considering that SUES has been applied to this catchment without calibration. The difference in average monthly ET for 1978 – 1995 is quite large (11.8 mm, or 23% of the mean monthly ET), but reduces to 7.19 mm (14% of monthly ET) if only the 1989 – 1995 period is used (see also Figure 3).

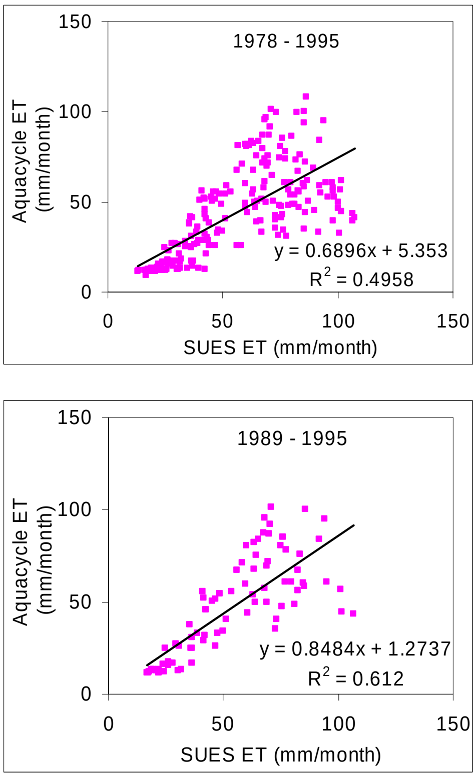

Figure 3. Agreement between Aquacycle and SUES for two time periods discussed in text.

The time series in Figure 2 clearly show very large differences in predicted ET in the 10-year period from 1978 – 1989, especially in the first half of this period. We have yet to identify the cause of this apparent shift in model performance between 1978 – 1989, and 1989 – 1995, except to note that the Aquacycle ET rates are low in the first period compared to the longer time series. Figure 4 is a plot of the annual rainfall anomaly and illustrates that the 1978 – 1983 period, when the discrepancy is the largest, coincided with lower than average rainfall, which points to SUES

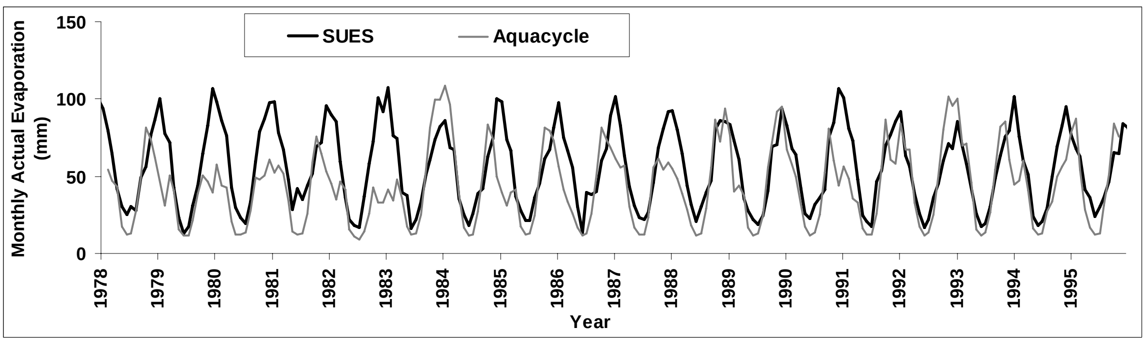

Figure 2. Comparison of monthly ET simulations for the Woden catchment

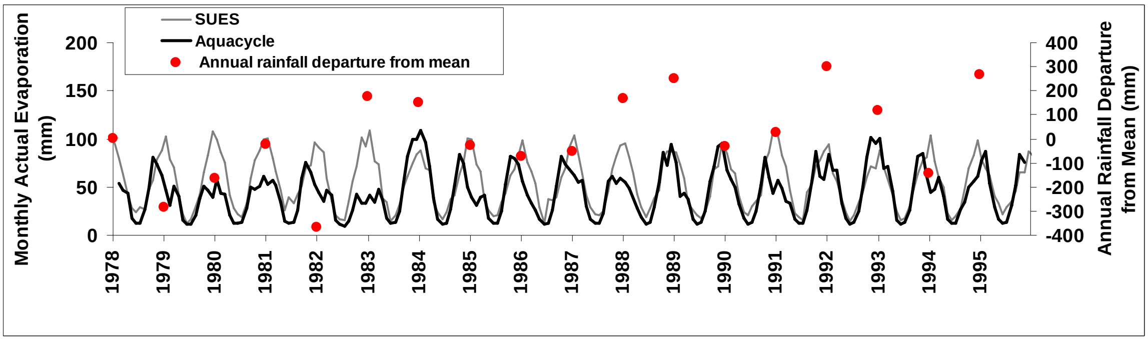

Figure 4. Aquacycle and SUES ET simulations compared to annual rainfall anomaly.

over-estimating ET in this dry period because the surface resistance algorithm has not been correctly calibrated for Australian cities. Obtaining such critical datasets for model validation is a critical next step in this work.

4. CONCLUSIONS

We have described and compared two urban water balance models that differ in their purpose and, especially, their representation of urban ET. An intercomparison between SUES and Aquacycle demonstrates that SUES is able to replicate the urban ET reasonably well with minimal calibration and using daily climate station data as the meteorological forcing.

We recognise that these two approaches are complementary, and that there is also a need for software tools such as Aquacycle and SUES to assist planners in designing suburban developments that meet various environmental goals, such as WSUD, improved energy efficiency and reduced net greenhouse gas emissions. To meet these needs, a prototype software package, *Greenscape Planner*, has been developed that combines urban water balance models such as Aquacycle and SUES through a user-friendly interface accessible *via* the world-wide web. *Greenscape Planner* has pre- and post-processors to interpolate daily meteorological data to an hourly timestep; exchange outputs between the models; and display the results graphically. Users are able to access *Greenscape Planner* to explore the impact of suburban design and urban greenspace on the urban water balance – especially imported water requirements, wastewater, grey water re-use; urban climate and the ability of the urban greenspace to sequester CO_2 and thus reduce greenhouse gas emissions.

While state-of-the-art climate models now incorporate increasingly sophisticated urban surface parameterisation schemes, these are not yet suitable for urban hydrological applications such as WSUD.

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