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Modelling the urban water cycle

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Abstract

Current urban water management practices aim to remove stormwater and wastewater efficiently from urban areas. An alternative approach is to consider stormwater and wastewater as a potential resource substitute for a portion of the water imported via the reticulated supply system. A holistic view of urban water resources provides the framework for the evaluation of the demand for water supply, the availability of stormwater and wastewater, and the interactions between them. The water balance model (Aquacycle) developed in this study represents water flows through the urban water supply, stormwater, and wastewater systems. Its daily time step provides temporal distribution of the flows, and enables comparison of the different components of the urban water demand. Aquacycle was tested using data from the Woden Valley urban catchment in Canberra, Australia and found able to satisfactorily replicate its water supply, stormwater and wastewater flows.

Keywords: Stormwater; Wastewater; Water supply; Reuse; Urban water balance model

Software availability

Name of software: Aquacycle
Developer: Grace Mitchell
Contact address: The Director, CRC for Catchment Hydrology, Department of Civil Engineering, PO Box 60, Monash University, VIC 3800, Australia
Tel: +61 3 9905 2704
Fax: +61 3 9905 5033
Internet: http://www.catchment.crc.org.au/
Year first available: 2000
Hardware required: PC 486, 32 MB of RAM, CD-ROM
Software required: Windows 95 or greater
Program language: Visual Basic 6.0
Program size: 1.4 MB
Availability and cost: Contact CRC for Catchment Hydrology (nominal charge)

1. Introduction

The Australian community, like many societies, is becoming increasingly concerned about the protection of the environment. Its water industry is responding to this challenge by looking for new and improved methods for managing water resources. Although 70% of the 22,000 GL of water supplied in Australia during the 1996/97 financial year was used by the agricultural sector (ABS, 2000), urban areas are an important component of water usage (the urban domestic sector used 8% of total water supplied, with the balance of 22% used by the industrial and commercial sectors). Urban areas exert a concentrated demand for water which is met, by and large, through diverting water from surrounding catchments.

The traditional approach in Australia to urban water supply and disposal is to consider the infrastructure that delivers potable water, and disposes of sewage, separately to the provision of stormwater drainage. There is now a need to re-evaluate this approach and to seek ways to minimise the environmental impact of urban areas on supply sources and receiving waters. In the last few years, there has been a movement towards alternative

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methods of water supply, wastewater disposal and stormwater management, as part of the solution to this issue. An important component of these alternative methods is the utilisation of urban stormwater and wastewater for beneficial purposes.

At present, there are few tools to evaluate the feasibility of such projects at anything less than a broad brush scale. There is a need to take a more holistic view, allowing water supply, wastewater disposal, and stormwater drainage to be considered as components within a single system. (Note: separate, rather than combined, stormwater and wastewater drainage infrastructure is predominant in Australia). In order to address this need, a simulation model, Aquacycle, has been developed. By looking at urban water demands and stormwater and wastewater outputs at a variety of spatial scales and at a daily time step, a clearer picture of the performance of stormwater and wastewater utilisation schemes is afforded.

This paper presents the methodology, conceptual framework, and algorithms used to develop the integrated water supply, stormwater, and wastewater model. The process of calibration and verification required to determine the performance of the model is detailed. There follows a discussion of the way in which Aquacycle can be used, and its limitations and potential enhancements.

2. Modelling methodology

Traditionally, the hydrologic cycle has been used to represent the continuous transport of water in the environment (Asano, 1998). The urban hydrologic cycle comprises water supply, wastewater disposal, and stormwater runoff systems, making up the total urban water system. However, the history and fragmentation of the water industry has meant that current research is dominated by detailed modelling of only sub-components of the total water system (Newall et al., 1998). Particularly, the interaction between the potable water supply–wastewater discharge network, and the rainfall–stormwater runoff network, is rarely considered within the same modelling framework.

In order to provide a complete picture of the spatial and temporal pattern of water demand and stormwater and wastewater supply, the water balance approach was selected, i.e. the application of the principle of mass conservation to water (Grimmond et al., 1986). This will account for the movement of water in the land phase of the hydrological cycle for a given area of land and a selected time interval (McPherson, 1973). A water balance can be assessed using a range of methods, from the simple evaluation of the inputs and the outputs, through to complex modelling of all the processes that transform these inputs into outputs.

McPherson (1973, 1981) was a strong advocate of applying the water balance concept to urban water resource issues. He called for an inventory of water "…from its appearance as precipitation, through to its departure from the metropolis as runoff and evaporation". Despite this, the total water balance is a frequently overlooked approach (Uunk and van de Ven, 1984), undoubtedly due to the complexity of the urban water cycle which deters people from conducting a balance (Graham, 1976). However, it is precisely this complexity which makes the framework of a water balance ideal for assessing urban water resources, as it allows a systematic approach to be taken.

There are many ways to integrate stormwater and wastewater reuse within an urban area. The appropriate spatial resolution for modelling such schemes is determined by the scale at which they operate. In order to be able to model a wide variety of schemes, several nested spatial scales were selected for this study, namely, unit block, cluster, and catchment scale.

The **unit block** represents a single household, industrial site, institution, or commercial operation, and represents the smallest scale at which water supply and disposal operations can be managed. Modelling the unit block scale allows the cumulative effect of individuals' actions (i.e. stormwater and wastewater use at unit block scale) on the whole catchment to be determined. Therefore, it is the appropriate fundamental spatial scale for the modelling purpose.

A **cluster** represents a group of uniform unit blocks that form a local neighborhood or suburb and the associated roads and public open space. The cluster can be used within the model to represent the spatial scale at which community supply and disposal operations may be managed.

A **catchment** represents a group of clusters; these clusters may relate to the suburbs in the catchment or areas of single land use. Using catchments as a water resource planning unit has been promoted in the last few years, although, in urban areas, the provision of constructed water supply, stormwater drainage, and wastewater disposal infrastructure has led to the blurring of natural catchment boundaries. Even so, catchments are an appropriate planning unit for urban water resources.

Determining the total yield of stormwater and wastewater available in an urban area requires a continuous, rather than an event-based, model. The hydrograph of each stormwater event is not required; rather, it is the relative timing of the demand for water, and supply and reliability of stormwater and wastewater that is important for reuse evaluation.

To quantify the volume of water consumed, the amount of wastewater discharged, and the flow of stormwater, a daily time step was assessed to be an appropriate interval to provide sufficient information to investigate the possibilities for reuse. The additional accuracy of shorter time steps is out-weighed by the associated increased data requirements.

3. Conceptual representation of the urban water cycle

The conceptual model developed to represent the urban water balance, known as Aquacycle, is shown in Fig. 1; arrows show the way in which water flows between the various surfaces and storages. The urban water cycle receives input both from precipitation and imported water, which together pass through the system and output in the form of evapotranspiration, stormwater, or wastewater. The state of the water stores is used to calculate the change in storage within the system.

Three groups of input data are required by Aquacycle: indoor water usage, climate, and physical characteristic data. Indoor water usage data are used to predict the quantity of water used for kitchen, bathroom, laundry, and toilet applications within each unit block in the modelling area (see Section 4.4).

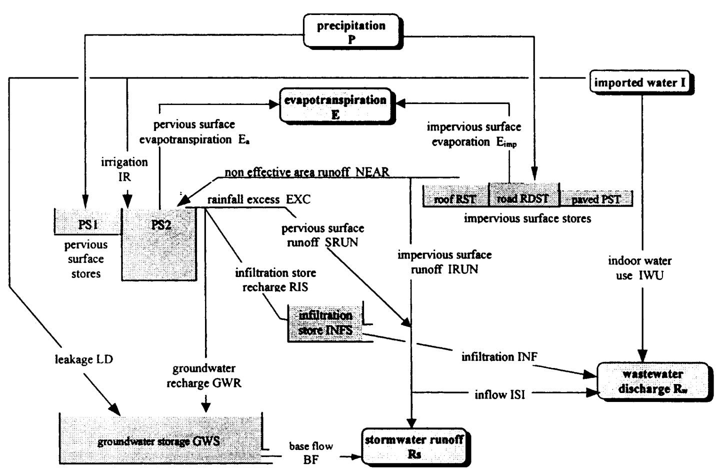
Continuous daily precipitation and potential evapotranspiration for the site are required; the length of available record defines the maximum modelling period. The physical characteristics of the modelled area are described by calibrated and measured parameters.

Each measured parameter relates directly to a physical catchment characteristic; an appropriate value can be determined through measurement, observation, or local experience. A list of measured parameters is given in Table 1, grouped according to their associated spatial area within the modelling area: unit block, cluster, or public open space. The value of each of the measured parameters is fixed during model calibration unless the associated characteristic of the catchment alters during this time period. For example, the construction of a new road would increase the road area and decrease the amount of public open space.

The 16 calibration parameters, along with the associated units, symbols and ranges listed in Table 2 are grouped according to their associated output: stormwater, wastewater, and water use. These values are adjusted during the calibration process to optimise the selected objective function.

4. Model algorithms

This section discusses the main model algorithms shown in Fig. 1; further information can be found in the Aquacycle user manual (Mitchell, 2000).



Water Balance Equation: $P + I = E + R_s + R_w + \Delta S$

P = precipitation
I = imported water
E = evapotranspiration
R_s = stormwater runoff
R_w = wastewater discharge
ΔS = change in storage

Storage Levels:

RST = roof surface storage level
PST = paved surface storage level
RDST = road surface storage level
GWS = groundwater storage level
INFS = infiltration storage level
PS1 = pervious store 1 level
PS2 = pervious store 2 storage level

E_p = potential evapotranspiration
E_{pc} = plant evaporative capacity = 7 mm

Note: See Tables 1 and 2 for further symbol definitions

Main Model Algorithms (relate to flow paths in diagram):

$BF = BRC.GWS$

$E_a = A1.\min\{(PS1/PS1_C).E_{pc}, E_P\} + (100\text{-}A1).\min\{(PS2/PS2_C).E_{pc}, E_p\}$

$E_{imp} = \max(E_P, RST).(roof_{area}/cluster_{area}.$
$\quad + \max(E_P, PST).(paved_{area}/cluster_{area}.$
$\quad + \max(E_P, RDST).(road_{area}/cluster_{area})$

$EXC = \{\max(PS1\text{-}PS1_C, 0)\}.A1 + \{\max(PS2\text{-}PS2_C, 0)\}.(100\text{-}A1)$

$INF = IRC.\sqrt{}INFS$

$IR = \max(TG.PS1_c - PS1, 0).A1.\%GI$
$\quad + \max(TG.PS2_c - PS2, 0).(100\text{-}A1).\%GI$

$IRUN = ERA.(P\text{-}(RIL+RST)).(roof_{area}/cluster_{area}.$
$\quad + EPA.(P\text{-}(PIL+PST)).(paved_{area}/cluster_{area}.$
$\quad + ERDA.(P\text{-}(RDIL+RDST)).(road_{area}/cluster_{area})$

$ISI = \%I.(SRUN+IRUN)$

$IWU = I - IR - LD$

$LD = \%L.(IR+IWU)/(100\text{-}\%L)$

$NEAR = (100\text{-}ERA).(P\text{-}(RIL+RST)).(roof_{area}/cluster_{area}.)$
$\quad + (100\text{-}EPA).(P\text{-}(PIL+PST)).(paved_{area}/cluster_{area}.)$
$\quad + (100\text{-}ERDA).(P\text{-}(RDIL+RDST)).(road_{area}/cluster_{area})$

$GWR = BI.EXC$

$RIS = II.EXC$

$Rs = IRUN + SRUN - ISI + BF$

$Rw = IWU + INF + ISI$

$SRUN = EXC - RIS – GW$

Fig. 1. Structure of the urban water cycle represented by Aquacycle.

Table 1
Aquacycle measured parameters

Spatial scale	Measured parameter	Units	Symbol
Unit block	Number of unit blocks	no.	$block_{num}$
	Average unit block occupancy	persons	occ
	Average block size	m^2	$block_{area}$
	Average garden area	m^2	$garden_{area}$
	Average roof area	m^2	$roof_{area}$
	Average paved area	m^2	$paved_{area}$
	Average % of garden irrigated	%	%GI
Cluster	Cluster area	ha	$clust_{area}$
	Leakage	%	%L
	Road area within the cluster	ha	$road_{area}$
	Cluster stormwater output flows into cluster number?	number	–
	Cluster wastewater output flows into cluster number?	number	–
Public open space	Public open space area within the cluster	ha	POS_{area}
	% public open space irrigated	%	%POSI

Table 2
Aquacycle calibration parameters

Output	Parameter	Symbol	Units	Range
Stormwater	Percentage area of store 1	A1	%	0–100
	Pervious storage 1 capacity	$PS1_c$	mm	≥0
	Pervious storage 2 capacity	$PS2_c$	mm	≥0
	Roof area initial loss	RIL	mm	≥0
	Effective roof area	ERA	%	0–100
	Paved area initial loss	PIL	mm	≥0
	Effective paved area	EPA	%	0–100
	Road area initial loss	RDIL	mm	≥0
	Effective road area	ERDA	%	0–100
	Base flow index	BI	ratio	0–1
	Base flow recession constant	BRC	ratio	0–1
Wastewater	% of surface runoff as inflow	%I	%	0–1
	Infiltration index	II	ratio	0–1
	Infiltration store recession constant	IRC	ratio	0–100
Water use	Garden trigger-to-irrigate	TG	ratio	0–1
	Public open space trigger-to-irrigate	POSTG	ratio	0–1

4.1. Impervious surfaces

Impervious surfaces (roofs, roads, and paved areas) are each represented as single stores that overflow when full. The concept of effective impervious area is used to represent the proportion of impervious surface runoff that directly drains to the stormwater drainage system; the remainder of the impervious surface runoff drains onto adjacent pervious areas. The water retained in these stores represents the initial loss of rainfall due to interception and depression storage. These impervious surface stores are depleted by evaporation each day. The maximum initial loss from an impervious surface (equivalent to the capacity of the store), and the effective impervious area, are assumed to be a fixed constant throughout the rain event, and for all seasons during the year.

4.2. Pervious surfaces and groundwater store

The configuration of the two pervious area surface stores, and a groundwater store, is based on the AWBM model (Boughton, 1993), a partial area saturation overland flow model. The use of partial areas divides the catchment into regions which produce runoff (contributing areas), and those that do not, during a rainfall-runoff event (van de Griend and Engman, 1985). These contributing areas vary within a catchment according to the antecedent catchment conditions, allowing the spatial variability of surface storage in a catchment to be modelled. The use of the partial area saturation overland flow approach is simple, and provides a good representation of the physical processes occurring in most Australian catchments. This is because daily infiltration capacity is rarely exceeded, and the major source of runoff is from saturated areas (Chiew et al., 1995).

The two pervious surface stores receive input from precipitation, irrigation, and surface runoff from adjacent impervious areas (as appropriate). The amount of excess water (overflow) from these stores is calculated separately, then combined according to their respective proportional areas of the catchment. The total excess water is then divided into three portions: groundwater recharge, stormwater infiltration of the wastewater system (discussed below) and pervious surface runoff.

The groundwater store is assumed to be an unconfined aquifer, draining according to a simple recession function to simulate stormwater base flow. There is no deep seepage from the groundwater store.

4.3. Evapotranspiration

Over the long term, evapotranspiration from an urban catchment is generally the largest single output (see Bell, 1972; Stephenson, 1991; Grimmond and Oke, 1986; Mitchell et al., 1997a) and therefore is an important component of a water balance. For an urban area, the evapotranspiration process is more complex than in a rural setting, due to a highly variable microclimate. There are oasis-type advections occurring across the many surface discontinuities, altered sub-surface heat flux, complex wind profiles, and a significant increase in water due to human activity (Oke et al., 1988; van de Ven, 1988). The transpiration rate of vegetation present in an urban setting is poorly understood. Research on developing algorithms for urban evapotranspiration has been conducted (Grimmond and Oke, 1991), but not readily applied; values of the relevant variables are often not obtainable. Modellers are still reliant on approximating the evapotranspiration of an urban area by methods designed for rural areas.

In Aquacycle, the amount of evapotranspiration from pervious areas, and of evaporation from impervious surfaces, is calculated separately. Impervious surface evaporation is taken to be the lesser of either potential evaporation, or the depth of water in the impervious store. The maximum rate of evaporation from the impervious surface is assumed to be the potential evaporation as supplied in the climate input file. No allowance is made for the effect that the heating of impervious surfaces may have on the actual evaporation rate. Evaporation is removed from the impervious surface store at the end of the day (effectively after any rain event). The approach taken to calculate evapotranspiration from the pervious store is somewhat more complex, as discussed below.

The evapotranspiration rate from the pervious stores can be estimated by a range of methods. They include complex deterministic models (eg. Federer, 1979), semi-empirical equations including Penman–Monteith, (eg. Denmead and Shaw, 1962; Dyck, 1983; Smith et al., 1992), and those based on the complementary relationship between actual evapotranspiration and potential evapotranspiration (eg. Morton, 1983). These direct approaches for calculating actual evapotranspiration were not adopted for several reasons: i) the difficulty in accounting for antecedent soil moisture conditions and plant characteristics, ii) the empirical constants in the equations which need to be calibrated for local conditions, and iii) uncertainty about their applicability to an urban environment.

An approach, based on work of Denmead and Shaw (1962), used in hydrological models to calculate actual evapotranspiration was presented by Boughton (1966). It assumes that the supply of water to a plant is a linear function of available water in the root zone (Federer, 1979). The maximum daily evapotranspiration is represented by the potential rate. Above field capacity the soil moisture level no longer affects evapotranspiration, although it is limited by the capacity of the vegetative cover to transpire (E_{pc} in Fig. 1).

The capacity of the pervious surface moisture stores in Aquacycle is equivalent to field capacity in the Boughton approach. The zero soil moisture storage level in the model structure is the point at which there is no soil moisture available for evapotranspiration.

4.4. Residential indoor water use

Despite the variation in residential indoor water use from household to household, a typical pattern (referred to as the water use profile) can be developed to provide a reasonable representation of indoor water use, based on the different indoor water use components (kitchen, bathroom, laundry, and toilet) and household occupancy. Table 3 presents a water use profile developed for the city of Canberra.

Aquacycle uses the water use profile input data file along with the user specified household occupancy to determine indoor water use [IWU] (see Fig. 1). It is assumed that all in-house water use becomes wastewater with no consumptive losses as such losses are in the order of 2% of indoor water use.

Table 3
Indoor water use profile for Canberra for 1992–1995, *L/d*[a]

Household occupancy	Kitchen	Bathroom	Laundry	Toilet
1	25	76	32	67
2	40	123	59	110
3	51	167	102	144
4	59	197	128	176
5	63	217	147	196
6	76	246	168	221
7	89	275	189	246

[a] Source: Mitchell (1998)

4.5. Urban irrigation

It can be seen in Fig. 1 that pervious stores receive irrigation input as well as rainfall. Water used for irrigation of private gardens represents between 16% and 34% of the total water supplied to an urban area (Mitchell et al., 1997b). In addition to this, water is used for irrigation of public open space areas such as parks, sporting grounds, and public gardens. The application of irrigation water can greatly affect the antecedent soil moisture conditions.

The quantity of irrigation water is a function of the water requirements of plants in the garden and the personal behaviour of the gardener. The water requirements of plants in a garden are determined from prevailing climatic conditions, type of vegetation contained in the garden, soil type, and the area irrigated (Heeps, 1977; Power et al., 1981). The personal behaviour of the gardener is affected by perceived plant water need, desired garden condition, and response to cost of water. As a result, individual watering practices are extremely variable.

For the purpose of estimating irrigation, the water demand was defined as the amount of irrigation required to supplement precipitation in order to maintain the desired garden condition or growth rate. The gardener's decision to water a garden was formulated as the desire to maintain a specific minimum soil moisture content (or wetness) in the pervious stores termed "trigger-to-irrigate". The trigger-to-irrigate value lies between the bounds of 0, representing an empty pervious store, and 1, representing a full pervious store. If the soil moisture level in either of the two pervious stores drops below the trigger-to-irrigate level, irrigation is applied to make up the deficit.

In practice, part of the water applied to a garden will be lost; depending on the timing of irrigation and the method used, part will evaporate before soaking into the soil and not be available to the plant roots. However, the model assumes irrigation to be fully effective in recharging the soil moisture stores to the prescribed level with no such loss.

4.6. Inflow and infiltration

Inflow and infiltration of stormwater into wastewater sewers has been modelled by Gustafsson et al. (1991, 1993), Deen et al. (1989), Mein and Apostolidis (1992) and West et al. (1992) among others; most consider the processes of inflow and infiltration separately. All of the inflow and infiltration models reviewed used a time step considerably smaller than the daily value adopted in Aquacycle. The modelling of the inflow and infiltration at a daily time step represents a significant simplification of the processes, providing an estimate of the total quantity but no information on the shape of the resultant wastewater hydrograph.

Groundwater infiltration into wastewater pipes occurs in locations where groundwater levels are higher than pipe invert levels. Due to the persistent nature of this form of infiltration, it is difficult to detect and separate from wastewater flows generated by indoor water use, particularly at a daily time step. As a result, groundwater infiltration to pipes is not represented by Aquacycle.

Deen et al. (1989) investigated various methods of modelling inflow and infiltration (unit hydrograph, single non-linear model, dual non-linear model, and ILSAX (O'Loughlin, 1988)) and came to the conclusion that a dual non-linear model was best. This approach separates the inflow and infiltration components of the process allowing them to be described by different parameters (also see Deen et al., 1992). Mein and Apostolidis (1992) built upon Deen et al's (1989) work and found that a slow response store of form $S=kQ^2$ (where S is the water in temporary storage, k is a constant, and Q is discharge) is theoretically and practically suitable to model the process of infiltration. Aquacycle assumes that stormwater infiltration occurs following periods of excess pervious area storage. A proportion of this excess water enters a temporary infiltration store, which then drains into the wastewater system according to the slow response storage equation of Mein and Apostolidis (1992).

Aquacycle calculates the inflow of stormwater into the wastewater system as a proportion of the total surface runoff generated. This is more suitable than the alternative of using a set percentage of the rainfall depth, as the former allows for varying catchment characteristics and antecedent conditions.

4.7. Leakage

The amount of leakage from a reticulation system varies from location to location, due to differences in construction methods, age, and condition. The condition of the reticulation system is affected by soil movement, corrosive conditions, pipe material, workmanship, age, supply pressure, number of joints and connections, and the occurrence of bursts/cracks result from overburden loading or water hammer (Heeps, 1977). The leaked water either recharges the groundwater, drains away via the wastewater and stormwater systems, or is intercepted and used by vegetation (Foster et al., 1994).

Aquacycle assumes that leakage from the reticulation system is proportional to the daily bulk water use (the sum of indoor water use and irrigation) of an area. The water leaking from the reticulation system is directed into the groundwater store.

5. Representation of stormwater and wastewater reuse

A range of small to medium scale technologies have the potential to provide individual or community scale water service systems (Clark, 1990); eg. rain tanks, package wastewater treatment plants, domestic greywater systems, and aquifer storage and recovery. A common element of these technologies is the collection, storage, and subsequent distribution of the water. The sources from which the water is collected, and the locations to which it is then distributed, vary. Treatment may or may not be required depending on the water source and the proposed use. Rather than attempt to simulate in detail the operation of a large number of different stormwater and wastewater utilisation schemes, a smaller number of generic approaches were modelled to represent the common elements of the different schemes, and capture the essence of a range of these reuse technologies.

A number of stormwater and wastewater reuse methods have been chosen to represent a range of approaches to stormwater and wastewater utilisation (Table 4). They relate to the different spatial scales at which water can be managed; all result in the beneficial use of the stormwater or wastewater. Combining several of these schemes can result in both stormwater and wastewater being re-used within a particular catchment, allowing for optimum use of urban water resources.

5.1. Stormwater storage

All stormwater stores, from unit block rain tanks to catchment stores, can be represented as simple vertical walled tanks or reservoirs. Water held within the storage is assumed to be available for use, i.e. the active storage equals the storage capacity.

Evaporation from an open water surface is assumed to occur at the potential rate. The amount of precipitation falling directly onto the surface of the stormwater store also depends on the area of open water surface.

The first flush of runoff generated from an impervious surface such as a roof may contain higher concentrations of pollutants than the rest of the flow; this first flush may or may not be of sufficient quality to be used for the purpose selected (Duncan and Wigth, 1991). Stormwater runoff from larger areas, such as an urban catchment, can also display a pattern of initially higher concentrations of contaminants (Cordery, 1977). In order to increase the overall quality of runoff entering the stormwater store, the model allows an initial quantity of runoff to be diverted from the inflow.

Table 4
Methods for stormwater and wastewater reuse available in Aquacycle

Spatial scale	Method	Source(s) of water[a]	Uses[a]	Comments
Unit block	Rain tank	Roof runoff.	Kitchen, bathroom, toilet, laundry, unit block irrigation.	May have a first flush device. Can only supply the unit block that the rain tank is located within.
	Sub-surface irrigation of greywater	Greywater flows: kitchen, bathroom, and laundry.	Unit block irrigation only.	Distributes greywater directly to the garden through a sub-surface drainage field according to the daily irrigation requirement.
	On-site wastewater treatment unit	Wastewater flows: kitchen, bathroom, laundry, and toilet.	Unit block toilet flushing, irrigation.	Can store treated effluent. Can only supply the unit block that it is located within. Option of disposing of effluent to stormwater or wastewater system.
Cluster	Stormwater store	Unit block runoff, road runoff, public open space runoff, stormwater from other cluster(s).	Unit block toilet flushing, irrigation.	May divert a first flush to wastewater system. Any unit block or cluster can be supplied by any cluster stormwater store in catchment.
	Wastewater treatment and storage	Unit block wastewater and wastewater from other cluster(s).	Unit block toilet flushing, irrigation.	Any unit block or cluster can be supplied by any cluster wastewater store in catchment. Option of disposing of effluent to stormwater or wastewater system.
	Aquifer storage and recovery	Cluster scale stormwater store.	Unit block toilet flushing, irrigation.	Recharge and recovery is limited by rate at which water can injected into and pumped.
Catchment	Stormwater store	Catchment stormwater runoff.	Unit block toilet flushing, irrigation.	May divert a first flush. Any unit block or cluster can be supplied by catchment stormwater store.
	Wastewater treatment and storage	Catchment wastewater discharge.	Unit block toilet flushing, irrigation.	Any unit block or cluster can be supplied by catchment wastewater store. Option of disposing of effluent to stormwater or wastewater system.

[a] Where more than one source or use is listed, any or all of the different sources/uses can be selected by the user.

5.2. Wastewater treatment and storage

Compared to stormwater runoff (which is intermittent), the generation of wastewater is continuous. It can be assumed, at a daily scale, that there is no lag between inflow and the consequent outflow; hence, a continuous flow of effluent leaves a treatment unit, which can be stored for later reuse. Hence, wastewater storage is modelled in the same manner as stormwater storage, with the exception of the first flush facility.

5.3. Aquifer storage and recovery

Artificial recharge of an aquifer is the deliberate transfer of surface water to the groundwater system (Digney and Gillies, 1995). This is done to: i) increase the yield of a aquifer that is already exploited, or ii) take advantage of its natural storage capacity instead of relying on surface storage. Aquifer storage and recovery (ASR) is the process of storage of water in an aquifer for later withdrawal and use.

The response of an aquifer to artificial recharge or water abstraction is a complex one. Mathematical approaches, such as finite element analysis or finite difference equations, are often used to describe the movement of water within aquifers. Such approaches are not appropriate here; a simple representation of the transfer of water into and out of the aquifer is deemed sufficient. In Aquacycle, the aquifer is assumed to have a fixed storage capacity, with all recharge water retrievable at a later time. An aquifer has a finite maximum rate at which it can accept water through an injection well (Pavelic et al., 1992). This rate is a function of the hydraulic gradient, aquifer permeability, and length and type of screen in the injection well (Oaksford, 1985). The maximum rate of retrieval of the injected water, through pumping, is also finite.

In Aquacycle, the recharge of the aquifer is limited by the maximum rate of recharge and the availability of the aquifer storage, while the recovery of water from the aquifer is limited by the maximum rate of recovery and the availability of water in the aquifer. Since the aquifer is an underground store, there is no loss due to evaporation or storage gain through incident precipitation. It is also assumed that there is no deep seepage from the aquifer. The use of a temporary surface store can provide a buffer to lessen the limitation of maximum recharge or recovery rates during periods of plentiful supply or high demand. Therefore, the ASR facility is linked to the stormwater store in cluster, which acts as this temporary store.

6. Calibration and verification — testing the performance of Aquacycle

To test the performance of the Aquacycle model, an urban catchment with concurrent water use, stormwater runoff, and wastewater discharge data, is required. Few such sites exist. The Woden Valley, ACT, Australia, was chosen as it has an extensive network of gauges which record rainfall, stormwater flow, and wastewater flow data.

6.1. The Woden Valley study area

The Woden Valley is a region in the south west of the city of Canberra (Fig. 2); it is some 30 km^2 in area, containing 12 suburbs. Canberra is located some 110 km inland from the south east coast of Australia (Fig. 3), at an altitude of 600 m above sea level. The climate is mild, with average daily maximum temperatures ranging from 28°C in January to 11°C in July. Rainfall is fairly uniform throughout the year, with an average of 630 mm/y; annual pan evaporation averages 1390 mm/y (Bureau of Meteorology, 2000).

The terrain in the Woden Valley varies from undulating at the floor of the Valley, through to hill peaks which encircle the site. It is serviced by traditional water supply and wastewater disposal infrastructure in which the stormwater and sewage are transported in separate systems. Many of the natural watercourses have been converted into open lined channels to facilitate rapid conveyance of runoff during storm events. By Australian standards, the stormwater drainage network is considered to be well constructed and well maintained.

The data from the Mawson and Curtin stormwater gauges, and Woden Valley wastewater gauge, were selected for model calibration and verification. The location of the stormwater and wastewater catchments are given in Fig. 2, while the characteristics of these catchments are given in Table 5. Water use for the Woden Valley was estimated from daily bulk water use records for Canberra and Queanbeyan (a township located 4 km to the east of the outskirts of Canberra, across the state border, in New South Wales).

6.2. Calibration of Aquacycle

The calibration of a computer model like Aquacycle is not particularly straightforward. Firstly, there are three model outputs (stormwater, wastewater, and water use) which must be fitted to observed values. Secondly, a number of parameters influence more than one output. Thirdly, there is the potential difficulty of different catchments for each of the three outputs, all overlapping but not matching. (Note: the difficulty of overlapping catchments is unavoidable in the development of a model that simultaneously estimates stormwater flows, wastewater flows, and water consumption, because of the way in which urban water infrastructure is constructed). As a result of these three factors, an iterative approach to parameter calibration was adopted.

The model does not have auto-calibration capabilities;

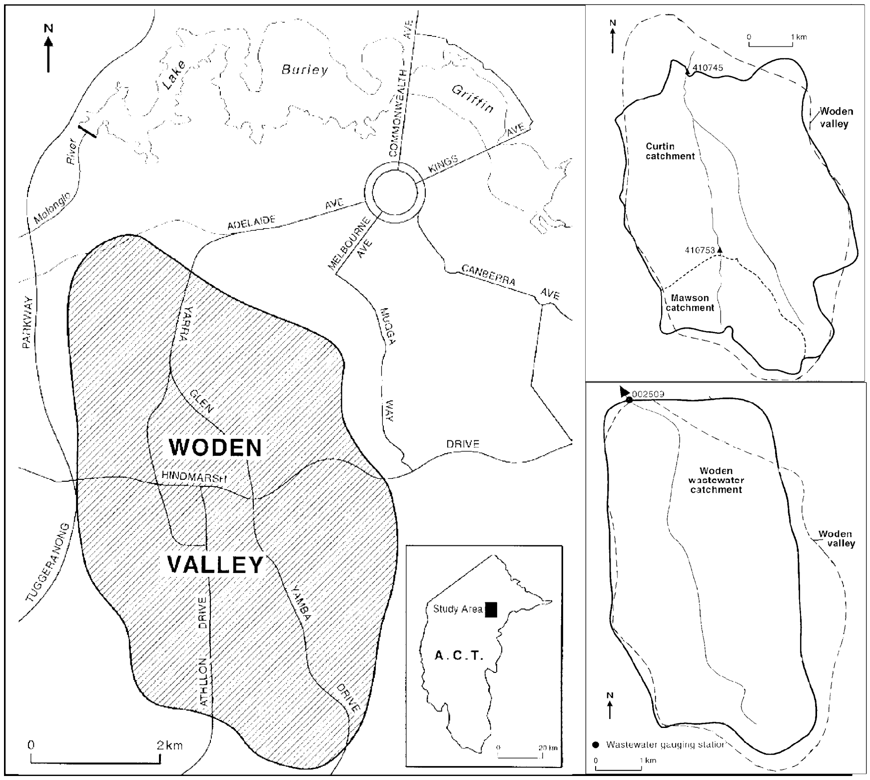


Fig. 2. Location of the Woden Valley and the stormwater and wastewater catchments.

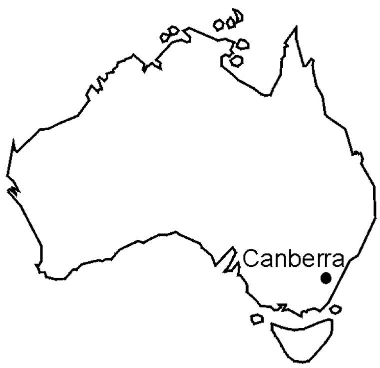


Fig. 3. Location of the city of Canberra within Australia.

Table 5
Catchment characteristics

Catchment	Gauge number	Area, ha	% urbanised	% impervious
Mawson	410753	445	70	26
Curtin	410745	2690	60	20, 24[a]
Woden Valley	002509	2870	59	21, 24[a]

[a] Percentage impervious before and after the 1987–1991 phase of urbanisation in Woden Valley.

given the above data complexities, a manual, trial and error process, is considered to be more suitable. Appropriate objective functions and graphical plots (hydrographs and *x*–*y* plots comparing observed and simulated flows) are used to determine the "goodness-of-fit" achieved by a particular parameter set. Appropriate objective functions were found to be i) SIM/REC, the sum of simulated flow (SIM) divided by the sum of recorded flow (REC) and ii) SDOF, the sum of squares of differences of simulated and recorded flows (Diskin and Simon, 1977).

Aquacycle provides the user with the ability to conduct an assessment of the "goodness-of-fit" of the parameter set, showing annual SIM/REC, daily and weekly SDOF, and *x*–*y* plots (as well as daily or weekly coefficient of efficiency (Nash and Sutcliff, 1970) for use in the verification period) on the computer screen for a simulation "run".

A split-sample test, using recorded water supply, stormwater and wastewater data for the Woden Catchment, was adopted to test the operational adequacy of Aquacycle. The first year of model simulation (1978) was used as an initialisation phase, and the available data records were split approximately 50/50 into a calibration period and a verification period as shown in Table 6. The periods of record for the water supply, stormwater and wastewater catchments differ, so the calibration and verification period for the catchments are not exactly the

Table 6
Calibration and verification periods

Output	Catchment	Calibration Period	Verification period
Stormwater	Mawson	Jan 1979–Dec 1986	Jan 1987–Dec 1995
	Curtin	Jan 1979–Dec 1983	Jan 1984–Dec 1988
Wastewater	Woden Valley	Jan 1979–Dec 1986	Jan 1987–Dec 1995
Water use	Woden Valley	Jul 1986–Jun 1989[a], Jul 1993–Jun 1595[b]	Jul 1989–Jun 1993[a], Jul 1995–Jun 1996[b]

[a] Pre-education campaign portion of the water supply data record.
[b] Post-education campaign portion of the water supply data record.

same. In addition, there was a marked change in seasonal water use patterns in the last 4.5 years (Jan 1992 to Jun 1996) due to an extensive water conservation education campaign. As a result, the calibration and verification period for water use is split into two sections, one relating to the pre-education campaign portion of the water supply data record, and the second relating to the post-campaign portion of the data record.

Annual precipitation and potential evaporation for the simulation period is shown in Fig. 4. The average annual rainfall during this period is 630 mm/y, equal to the long-term average for the area. The earlier years in the simulation period tend have lower annual rainfall totals compared to the later years; for instance, 1979 and 1982 have the lowest annual rainfall totals, while 1992 and 1995 have the highest annual rainfall totals. As the calibration periods selected tend to be in the first half of the model simulation period, the average annual rainfall is lower in the calibration period of each catchment in comparison to the verification period.

A parameter set was fitted to the recorded data in the calibration period (Table 7). This parameter set was then used to simulate the water supply, stormwater and wastewater flows in the verification period. The performance of Aquacycle during the verification period is discussed in the following section.

Note that sub-areas of a catchment can have different parameter values in order to represent the varying characteristics of an urban area. As can be seen in Table 7, this feature was used when calibrating Aquacycle to the Woden Valley; the Mawson stormwater sub-catchment consistently produced higher rates of runoff than the remaining catchment, implying the need for a different set of parameters from the rest of the Curtin stormwater catchment. Different water use calibration parameters were also used for the pre- and post-education campaign periods of the water supply data record (Table 7).

6.3. Verification of Aquacycle

Two measures of performance were used to judge the model's ability to simulate flows during the verification period: SIM/REC and the coefficient of efficiency, *E*. Table 8 presents a summary of the simulation performance for the calibration and verification periods. The relationship between daily simulated versus daily recorded stormwater flows and wastewater flows, and the relationship between weekly simulated versus weekly recorded water use for the verification period in the form of *x*–*y* plots are illustrated in Figs. 5–8.

6.4. Representation of stormwater flows in verification period

Aquacycle's performance in simulating stormwater flows in the Mawson catchment during the verification

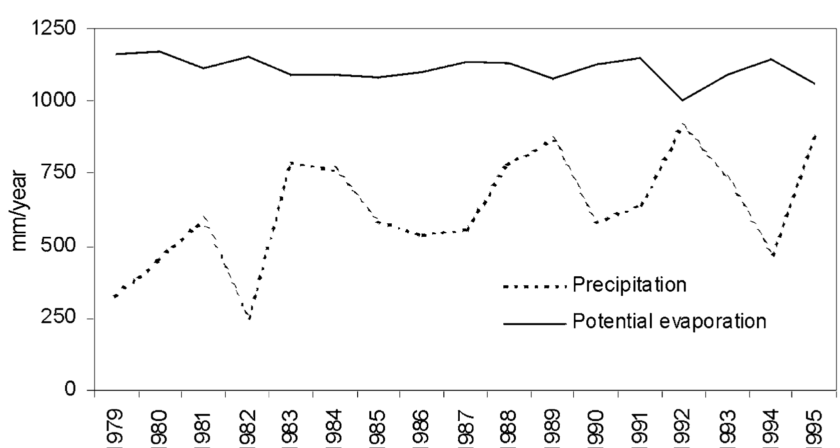


Fig. 4. Annual precipitation and potential evaporation for the Woden Valley.

Table 7
Aquacycle calibration parameter values for the Woden Valley catchments

Output	Parameter	Sub-catchments	
		Mawson	Curtin and Woden
Stormwater	Percentage area of store 1	42	22
	Pervious storage 1 capacity	30	32
	Pervious storage 2 capacity	130	240
	Roof area initial loss	0	0
	Effective roof area	100	100
	Paved area initial loss	0	0
	Effective paved area	100	100
	Road area initial loss	0	0
	Effective road area	100	100
	Base flow index	0.55	0.55
	Base flow recession constant	0.02	0.0025
Wastewater	% of surface runoff as inflow	3	
	Infiltration index	0.095	
	Infiltration store recession constant	0.12	
Water use	Garden trigger-to-irrigate	0.50 (0.31)[a]	
	Public open space trigger-to-irrigate	0.46 (0.35)[a]	

[a] Parameter values used in the post-education campaign period.

Table 8
Summary of simulation performance for the Woden Valley catchments[a]

Catchment	SIM/REC		Daily E		Weekly E	
	Calibration	Verification	Calibration	Verification	Calibration	Verification
Mawson stormwater	1.00	1.08	0.92	0.94	0.94	0.94
Curtin stormwater	1.00	0.95	0.96	0.90	0.96	0.92
Woden Valley wastewater	0.99	1.02	0.44	0.33	0.59	0.46
Woden Valley water use	0.99	0.99	0.42	0.21	0.63	0.49

[a] Objective functions defined in text.

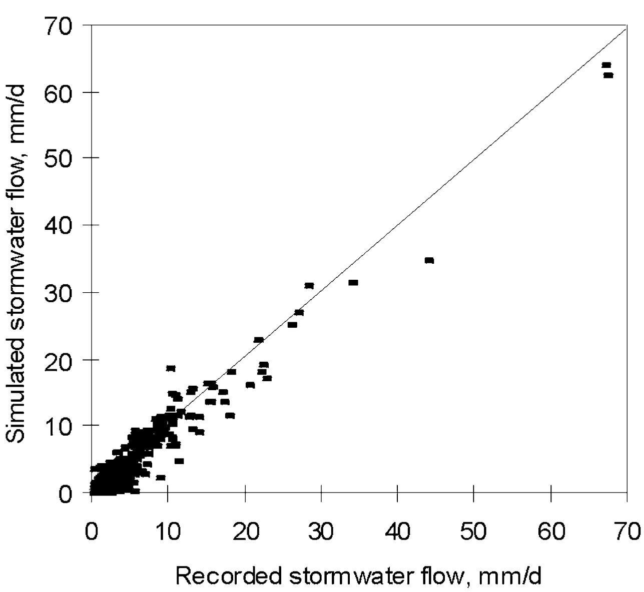


Fig. 5. Daily simulated versus recorded stormwater flows, Mawson (410753), for verification period (1/1/87–31/12/95).

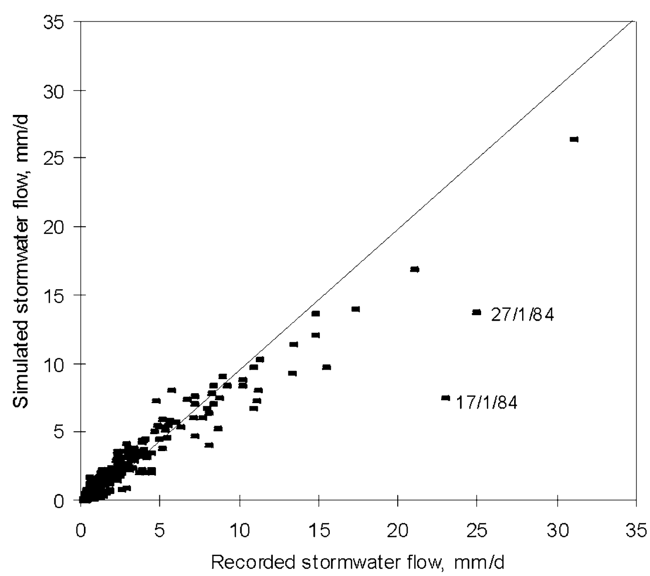


Fig. 6. Daily simulated versus recorded stormwater flows, Curtin (410745), for verification period (1/1/84–31/12/88).

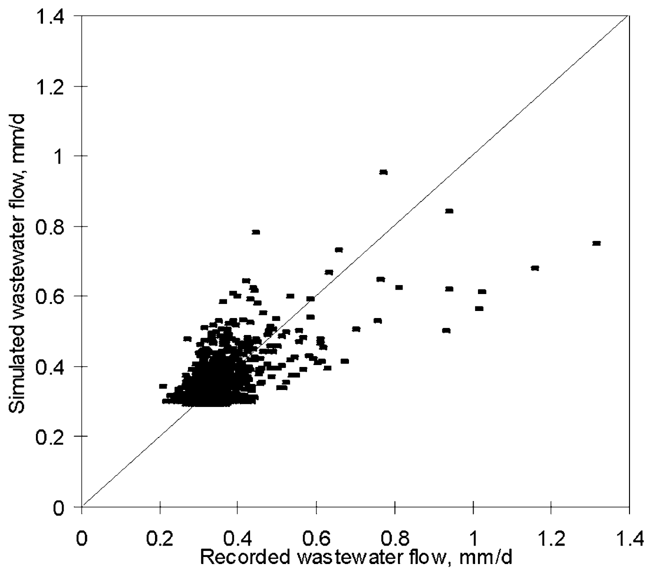


Fig. 7. Daily simulated versus recorded wastewater flow, Woden Valley (002509), for verification period (1/1/87–31/12/95).

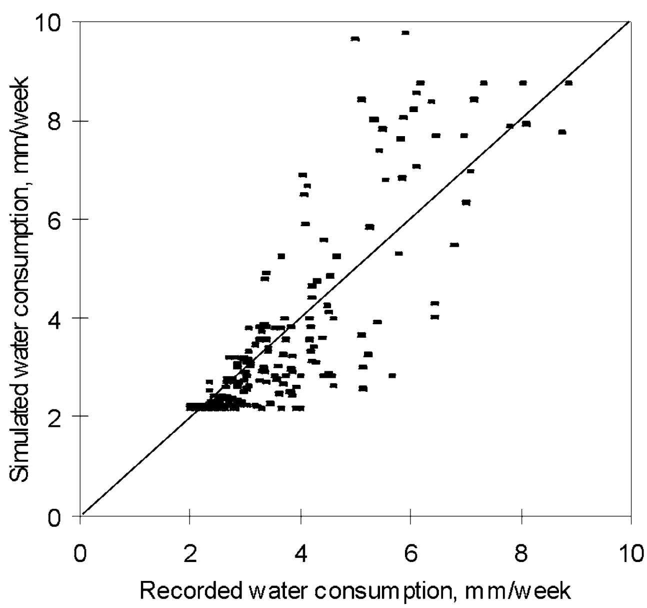


Fig. 8. Weekly simulated versus recorded water use flow, Woden Valley (002509), for verification period (1/7/89–30/6/93, 1/7/95–30/6/96).

period is considered acceptable, although the over-estimation of yield (SIM/REC equal to 1.08) was poor compared to the accuracy of the yield estimation in the calibration period. Simulated base flow levels are over-estimated following medium to large rain events.

The parameters which govern base flow were calibrated during a dry period; however, the verification period was wetter than the calibration period, and the average daily discharge 70% greater. The model was unable to replicate the behaviour of the catchment following the larger rainfall-runoff events. The daily coefficient of efficiency for the Mawson catchment was slightly higher in the verification period, compared with the calibration period, although both are very high, signifying a good replication of stormwater flows overall. This measure of model performance is biased towards the prediction of high flows and is therefore little influenced by the periods of poor base flow estimation. The plot of daily simulated stormwater flow against daily recorded stormwater flow (Fig. 5) shows that, although there is a fair amount of scatter about the 1:1 line, surface runoff events were modelled with reasonable accuracy.

The yield of the Curtin catchment was underestimated during the verification period (Table 8). Again, the verification period was wetter than the calibration period, but this did not have the same effect on the Curtin catchment as noted above for the Mawson catchment. Here, the underestimation of yield in the verification period is due to the poor modelling of flows in 1984. If this year is removed from the verification period, SIM/REC rises to 1.01 and the daily coefficient of efficiency to 0.94. In 1984, the peaks of the majority of medium to large rainfall-runoff events were underestimated, a finding inconsistent with the rest of the verification period. The modelling assumption that runoff production is independent of rainfall intensity and due to saturation excess may be the cause of this modelling error. During intense storms, often experienced in Canberra, it is likely that runoff is being generated due to soil infiltration excess, rather than soil saturation excess as assumed in the model.

In Fig. 6, two outliers can be seen in the regression of daily simulated stormwater flow against daily recorded stormwater flow of the Curtin catchment; both occurred in January 1984. The inaccuracy of the estimation of flow on the 17 January 1984 could be due to the timing of a large rain event that occurred on the previous day. The model assumes that runoff generated during a given day flows from the catchment the same day; in practice, if a rain event occurs late in the day, runoff may still be occurring during the next. The objective function is affected by this. The inaccuracy of the estimation of flow on the 27 January 1984 is most likely a result of the rainfall event producing runoff due to soil infiltration excess rather than soil saturation excess. The precipitation recorded on this day was the sixth largest during the modelling period; it followed a week of dry weather, so the surface of the catchment would have been very dry. Overall, surface runoff events for the Curtin catchment were modelled with reasonable accuracy with the exception of flows during 1984.

6.5. Representation of wastewater flows in verification period

Wastewater, as an output, has quite different characteristics to stormwater, having a fairly constant dry weather flow level, and the occasional sharp peak due to inflow and infiltration. Although the SIM/REC of the Woden Valley wastewater catchment was 1.02 for the verification period, the daily coefficient of efficiency indicated a poorer performance than during the calibration period (Table 8). The model was able to predict the occurrence of most of the recorded inflow events, but had only a fair degree of success in predicting the size of the events. There is a tendency to over-estimate the persistence of infiltration into the wastewater system. Given the variability of wastewater flows due to human behaviour, and the difficulty in modelling inflow and infiltration processes, prediction of wastewater flows from the catchment is considered satisfactory.

6.6. Representation of water use in verification period

There is a high degree of short term variation in water use on a daily basis, due to the erratic nature of indoor and outdoor water use. (Another reason for the poor modelling is because gardeners may choose to water in the days before, or the days after, the model determines that irrigation is required). Over a longer time period, such as a week, this erratic variation is removed and trends in water use patterns become apparent. This pattern is due to the seasonal increase in outdoor water use. Because of the high degree of short term variation in water use, a weekly, rather than daily, time step is considered more appropriate for assessing the model's ability to predict this component.

The weekly coefficient of efficiency of 0.49 for the verification period (Table 8) is significantly poorer than for the calibration period. However, all years within the verification period have a weekly coefficient of efficiency greater than zero, while the poorest result during the calibration period was −0.74. Annual water use was predicted with an acceptable level of accuracy, although the temporal pattern due to seasonal demand, even at weekly scale, was not well replicated (see Fig. 8). The household resident may be responding to factors other than soil moisture when deciding to irrigate, such as the number of days since the last rain event, or are irrigating as a form of recreation or habit, with little regard to the actual water requirement. The human factors that determine water use are extremely difficult to model.

The performance of the model in predicting water use is similar to that obtained by other estimates of water demand time series of greater than 10 years (see Coombes et al., 2000; Draper, 1994; Maidment and Parzen, 1984), with the model producing an R^2 of 0.71 for weekly water use and 0.76 for monthly water use. Hence there is room for improvement before a high degree of confidence can be placed in the estimations produced by such models.

7. Discussion

Aquacycle was developed to provide a holistic view of an urban water system, allowing water supply, wastewater disposal, and stormwater drainage to be considered as components within a single modelling framework. To date, there has been limited testing of Aquacycle, restricted to the Woden Valley, Canberra. However, the results from this test indicate that the holistic approach was successful in representing the flow of water through an urban area. It also provides a suitable framework for assessing the potential for integrating stormwater and wastewater reuse options (listed in Table 4) into the urban water system. See Mitchell et al. (1998, 1999) for examples of such assessments.

There is no flow routing within the model. It has been developed to assess the total quantity of water moving through the urban water cycle, rather than estimate peak flows or produce event hydrographs. In most urban catchments, all surface runoff would flow out of the catchment in a matter of hours. Therefore, there is little need for flow routing when using a daily time step.

Several urban hydrological processes are not incorporated into Aquacycle, including imported water application to impervious surfaces, overflow of wastewater from sewers, stormwater pipe infiltration and exfiltration, and wastewater pipe exfiltration. These processes are omitted because either they represent minor pathways of water flow within the total urban water cycle, or cannot be quantified for the purposes of modelling.

Aquacycle currently has no capacity as yet to simulate water quality. Nonetheless, the range of stormwater and wastewater reuse options available in the model has been selected on the basis of water quality requirements eg., a user can select untreated greywater as a source for direct sub-surface irrigation, but not for drinking water. Algorithms could be incorporated which relate water quality to factors such as the source of stormwater or wastewater flow (ie. the different runoff surfaces or water applications), population density, soil type, climate, and level of construction. In this case, the addition of algorithms to simulate the water contaminant flow paths: for example wastewater overflow, infiltration of water into and exfiltration of water out of the stormwater drainage network, and exfiltration of water out of the wastewater network, may be warranted.

8. Conclusion

Many cities are experiencing pressure to satisfy demands for water by urban communities and minimise the environmental impact caused by stormwater and wastewater. One approach to reduce these pressures is to reuse stormwater and wastewater within the urban area for low quality water demands. The advantage of this is to reduce the quantity of high quality water imported into an urban area and reduce stormwater and wastewater discharged to streams and receiving waters. The urban water balance model (Aquacycle) described in this paper has been developed to provide a clearer picture of the resources available, and the possibilities of these alternative sources of supply.

Aquacycle was found able to replicate the importation of water into and the flow of stormwater and wastewater out of the Woden Valley, Canberra. The flow of stormwater was modelled particularly well with a daily coefficient of efficiency of 0.94 for the Mawson stormwater catchment and 0.90 for the Curtin stormwater catchment. Given the variability of water use and wastewater flows due to human behaviour, prediction of these flows was considered satisfactory. The model performed well in this catchment and may be considered to be a suitable model for simulating the urban water cycle. It needs further testing on catchments that have significantly different characteristics such as climate, land use, drainage methods, or topography.

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