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Developing a conceptual model for water accounting in peri-urban catchments

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Abstract: Water accounting, i.e. identifying, quantifying and reporting information of water flow in a system, is the first step towards formulating productive and sustainable water management strategies in a region. This requires a significant effort of monitoring, collecting and modelling hydro-meteorological information over both spatial and temporal scales. A number of catchment water balance models developed in Australia and overseas are capable of estimating runoff, evapotranspiration, and streamflow generated from rainfall received in a catchment. However, most existing catchment water balance models do not account for potable water supply, wastewater discharges and surface and groundwater extractions, and yet these components of surface water cycle significantly modify streamflow in peri-urban catchments such as the South Creek catchment in Western Sydney. The South Creek catchment, the main focus of this study, covers an area of around 625 km^2 in gently undulating plains and low hills of Western Sydney. It is a typical example of a peri-urban catchment with urban development over nearly 20% of the land area, and agriculture activities over nearly 17% of the land area. The urban areas in the catchment are serviced with potable water supply from dams outside the catchment, and there are five sewage treatment plants which discharge treated effluent into the South Creek and its tributaries. There are also annual access entitlements to extract water from surface water and groundwater sources mainly for irrigation purposes.

In this paper, we describe the development of a simple conceptual water balance model to account for rainfall, runoff, evapotranspiration, potable water supply, wastewater discharges and surface water and groundwater extractions in a peri-urban catchment. The rainfall-runoff (from infiltration excess, saturation excess and baseflow) and evapotranspiration are simulated using a daily time step rainfall-runoff model, i.e. SIMHYD, for both pervious and impervious surfaces in the catchment. The developed model further combines the modelling of daily rainfall-runoff with monthly potable water supply, wastewater flows, and surface and groundwater extractions to simulate complete surface water cycle of a peri-urban catchment. The input data for the model include daily rainfall, daily potential evapotranspiration, monthly potable water supply, and annual surface water and groundwater access entitlements. Using the annual surface water and groundwater access entitlements as input, the model estimates monthly surface and groundwater extraction amounts depending on water requirement and water availability in the catchment.

The model outputs, on a monthly time-step, includes runoff from infiltration excess, saturation excess and baseflow over pervious areas; stormwater from impervious areas, evapotranspiration from both pervious and impervious areas; residential, non-residential and primary production water use, and monthly surface water and groundwater extractions. The estimated monthly residential and non-residential water uses are further separated into the indoor and outdoor components, and finally estimated are the monthly wastewater discharges and streamflow in a catchment. The developed conceptual water balance model has been tested to estimate monthly water balance components of surface water cycle in the South Creek and its subcatchments over 15 years period (1992 to 2006). The calculated statistical measures such as the coefficient of efficiency (E), the coefficient of determination (R^2), the ratio of mean simulated and observed (Y) and the coefficient of mass residual (CRM) between monthly observed and simulated wastewater discharges, and between monthly observed and simulated streamflow suggest that the model *satisfactorily* reproduced monthly wastewater discharges and streamflow in the South Creek and its tributaries. The developed conceptual water balance model could be very useful for water accounting or hydrological characterisation, and for simulating the impact of increased impervious surface and potable water supply due to urbanization, and projected climate change on surface water cycle of a peri-urban catchment.

Keywords: *Hydrology, Rainfall-Runoff, Stormwater, Wastewater, Water Supply, Water Balance Modelling, South Creek catchment, Western Sydney*

1. INTRODUCTION

The growing population and drying climate is putting enormous pressure on limited fresh water resources, and is forcing to revisit and assess how we manage our water resources in a region. Water accounting, i.e. identifying, quantifying and reporting information of water flow in a system, is the first step towards formulating productive and sustainable water management strategies in a region. Generally there is limited recorded hydro-meteorological data available in catchments and there are often gaps in records to construct complete water budget for a catchment. Furthermore, it is difficult to measure, especially on a spatial scale, water fluxes such as actual evapotranspiration and groundwater recharge. The complied hydro-meteorological datasets are therefore generally augmented with catchment water balance modelling to estimate monthly and yearly water fluxes constructing water budget for a catchment.

The catchment water balance modelling is an attempt to conceptualize and aggregate relatively complex hydrological processes and their heterogeneity into simple mathematical equations. These equations are then used to simulate different water fluxes over time and space of a system. This offers a time efficient and cost-effective approach for reasonable estimation of surface water balance components of a catchment. In a review, Boughton (2005) reported that there are about 14 different catchment water balance models used in Australia. It was also noted that there has been primarily development of water balance modelling for rural catchments (Boughton, 2005). Most existing catchment water balance models do not account for potable water supply, wastewater discharges and surface and groundwater extractions, and yet these components of surface water cycle significantly modify streamflow in peri-urban catchments such as the South Creek catchment in Western Sydney.

The objective of this study was therefore to develop a catchment water balance model combining the rainfall-runoff modelling with the modelling of potable water supply, wastewater flows and surface water and groundwater extractions to simulate complete surface water cycle of a peri-urban catchment. The secondary objective was to estimate surface water balance components for water accounting or hydrological characterisation of the South Creek catchment in Western Sydney. The model should sufficiently represent the dominant/key processes of the system, require less input data, and fulfill the purpose of system being simulated. The reasonable estimation of surface water balance components for water accounting or hydrological characterisation could be assisted by simple conceptual modelling of surface water cycle in a peri-urban catchment. These pragmatic considerations lead to the selection of a lumped rainfall-runoff model, SIMHYD (Chiew et al., 2002) for further development to include potable water supply, wastewater discharges and surface and groundwater extractions for simulation of complete surface water cycle in the South Creek catchment (Figure 1).

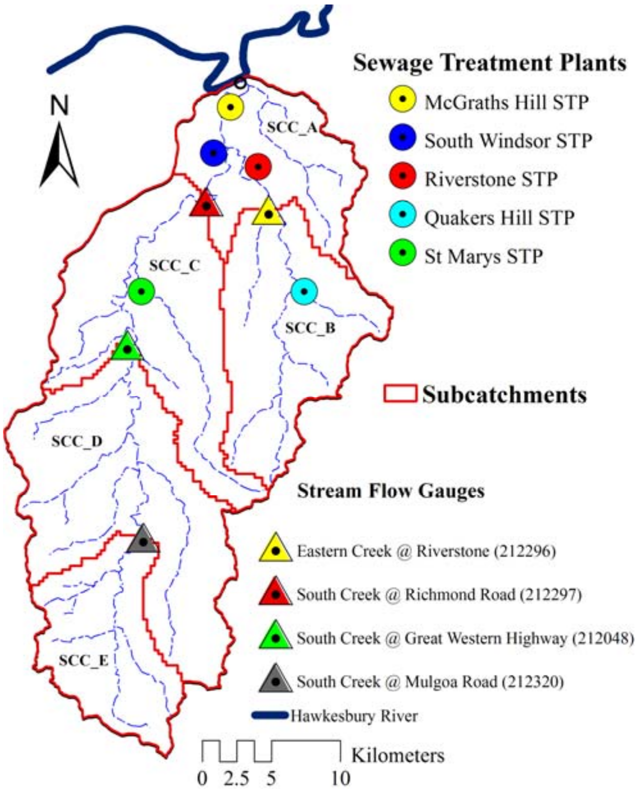


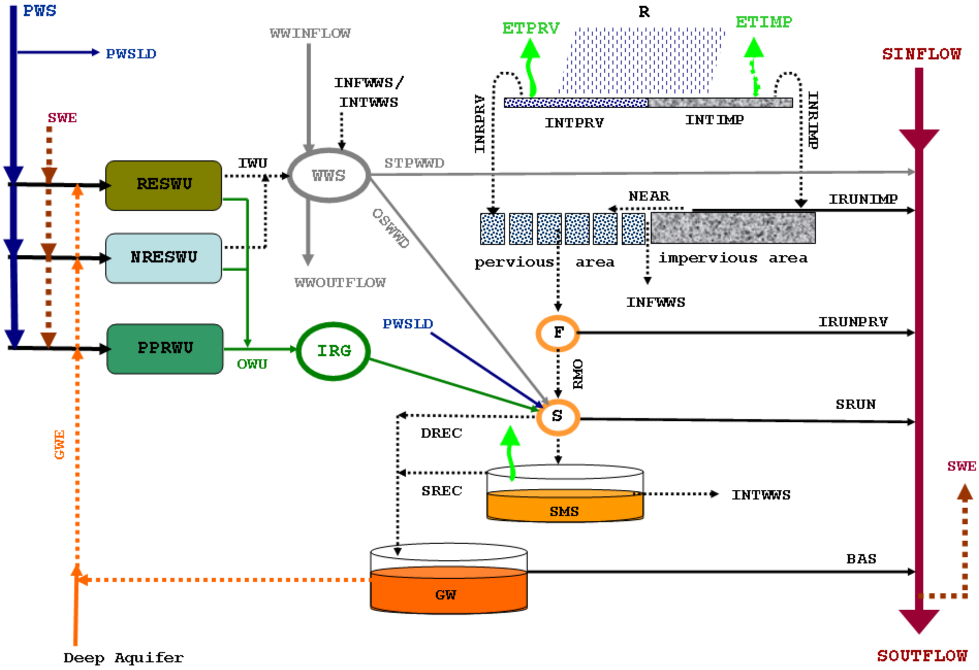
Figure 1. South Creek catchment and its subcatchments.

2. SOUTH CREEK CATCHMENT

The South Creek catchment covers an area of around 625 km^2 in gently undulating plains and low hills of Western Sydney. It is a typical example of a peri-urban catchment with urban development over nearly 20% of the land area, and peri-urban agriculture activities such as market gardens, cut flowers, greenhouse, nursery, orchard, turf farming, and improved pasture over nearly 17% of the land area (EPA, 2001). The South Creek catchment currently supports a population of around 390,000 with the majority being resident in urban areas established in the central belt across the subcatchments SCC_B and SCC_C (Figure 1). The urban areas in the catchment are serviced by the Sydney Water Corporation supplying potable water from dams outside the catchment, and there are five sewage treatment plants which discharge treated effluent into the South Creek and its tributaries. The Sydney Water Corporation also supplies potable water to non-residential properties, and also for irrigation of recreation spaces (parks and golf courses) and some intensive agriculture activities such as market gardens, hydroponics, greenhouses and nurseries. There are also annual access entitlements to extract water from surface water and groundwater sources mainly for irrigation purposes. The South Creek drains in and has a major influence on water quantity and quality of the Hawkesbury River downstream of Windsor (Figure 1).

3. CONCEPTUAL WATER BALANCE MODEL

The conceptual water balance model (Figure 2) is developed to estimate monthly surface water balance components accounting rainfall, runoff, evapotranspiration, potable water supply, wastewater discharges and surface water and groundwater extractions in the South Creek catchment. The rainfall-runoff (from infiltration excess, saturation excess and baseflow) and evapotranspiration components are simulated by a daily time-step conceptual rainfall-runoff model, SIMHYD over both previous and impervious surfaces in the catchment (Chiew and McMahon, 1999; Chiew et al., 2002). The concept of *effective* impervious area, i.e. the impervious area directly connected to the drainage system, is used to separate stormwater from impervious surface runoff, and the remainder amount flows onto adjacent previous surfaces (Mitchell et al., 2001).



Model Variables:

R = Rainfall

ETIMP = Evapotranspiration over impervious surface
ETPRV = Evapotranspiration over pervious surface

INTIMP = Interception storage of impervious surface
INTPRV = Interception storage of pervious surface

INRIMP = Rainfall excess over impervious surface
IRUNIMP = Impervious surface runoff
NEAR = Near flow from impervious to the adjacent previous surfaces

INRPRV = Rainfall excess over pervious surface
RMO = Rainfall infiltrated
IRUNPRV = Pervious surface runoff
SRUN = Interflow/ saturation excess runoff

SMS = Soil moisture storage

DREC = Direct groundwater recharge
SREC = Saturation excess groundwater recharge
GW = Groundwater storage
BAS = Baseflow runoff

PWS = Potable Water Supply
PWSLD = Potable Water Supply Leakage
SWE = Surface Water Extraction
GWE = Groundwater Extraction

RESWU = Residential Water Use
NRESWU = Non-Residential Water Use
PPRWU = Primary Production Water Use
IWU = Indoor Water Use
OWU = Outdoor Water Use

IRG = Irrigation Water
WWS = Wastewater System

WWINFLOW = Wastewater Inflow
WWOUTFLOW = Wastewater Outflow
INFWWS = Rainfall Derived (I/I) Inflow to the Wastewater System
INTWWS = Rainfall Derived (I/I) Infiltration to the Wastewater System
STPWWD = Sewage Treatment Plant Wastewater Discharge
OSWWD = Onsite Wastewater Discharge

SINFLOW = Stream/Waterways Inflow
SOUTFLOW = Stream/Waterways Outflow

Figure 2. Conceptual water balance model and its variables

The potable water supply from outside of the catchment is included as inflow component to the system (Figure 2). There are generally leakage losses from a pressurised potable water reticulation system. If in large amounts the leakage may affect the antecedent soil moisture conditions, and thereby interflow, saturation excess runoff, evapotranspiration and groundwater recharge in a catchment. The leakage/transmission losses from potable water reticulation system are therefore simulated as a portion of total potable water supply in the catchment (Mitchell et al., 2001). The recorded monthly potable water supplies for residential, non-residential and primary production water use are provided as input to the model.

The surface water and groundwater extractions may have a significant impact on the water balance and streamflow in a catchment. Unfortunately, no monitored records of surface water and groundwater extraction amounts in the South Creek catchment are available. However, information on annual access entitlements for surface water and groundwater extractions for different purposes is available from one of the government agencies. In the absence of actual recorded data, the model estimates monthly surface and groundwater extraction amounts based on assumptions that the farmers (or water users), if they have access entitlements, would extract surface water and groundwater depending on water requirement and water availability. Since much of the water used in residential and non-residential properties is associated with indoor water use and have a fairly constant demand over the years, it is assumed that annual access entitlements of surface water and groundwater for residential and non-residential water use are fully used if there is water available to extract from the source. In the model (Figure 2), surface water is extracted from the streamflow, and groundwater is extracted from the groundwater storage or deep aquifer in case groundwater storage reaches zero. The use of annual access entitlements of surface water and groundwater for primary production water use, i.e. irrigation, depends upon weather, rainfall and irrigation requirements in a year. The annual surface water and groundwater extractions for primary production water use are therefore set to the minimum of the annual access entitlements or the estimated annual irrigation water requirement or the water available in the source.

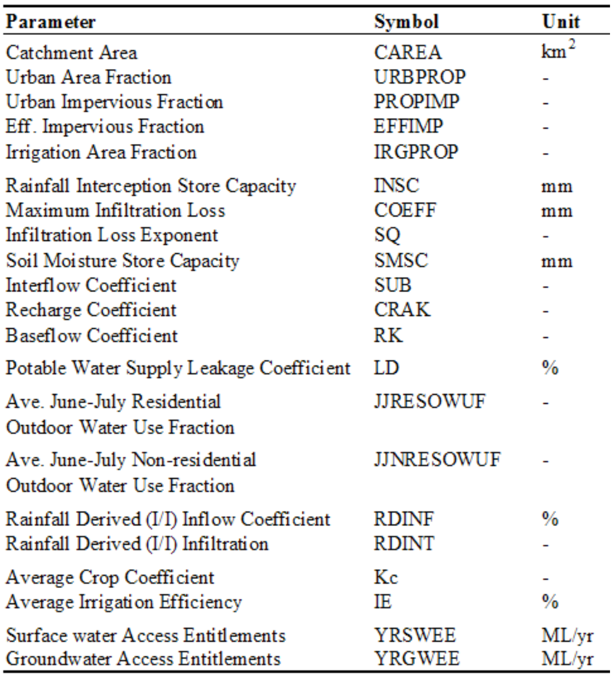
The estimated monthly residential and non-residential water use is further separated into indoor and outdoor water use components. The residential and non-residential indoor water use becomes wastewater in the catchment. The wastewater is either discharged through onsite sewage systems or piped to a sewage treatment plant. In the model, the onsite wastewater discharge is added to the soil moisture storage, and the sewage treatment plant wastewater is discharged to the streams/waterways of the catchment (Figure 2). The model also simulates the process of rainfall derived inflow/ infiltration to the wastewater system. The rainfall derived infiltration component refers to the seepage of rainwater through soil profile to a sewer system, and could be analogous to the interflow/baseflow concept used in rural hydrology (Mein and Apostolidis, 1992). They suggested a slow response store of form $S=KQ^2$ (where S is the water in temporary storage, Q is the discharge and K is a constant) is theoretically and practically suitable to model infiltration component. In the model, the rainfall derived infiltration component is simulated as a slow response of soil moisture storage over the urban area served by the sewer system. The rainfall derived inflow refers to the direct entry of rainwater into a sewer system, and is of very quick response to rainfall in a catchment (Deen et al., 1992). The rainfall derived inflow component is simulated as a portion of surface water, i.e. rainfall excess from impervious surface and pervious surfaces of the urban area served by the sewer system (Mitchell et al., 2001).

The primary production water use is mainly used for irrigation of peri-urban agricultural activities such as market gardens, nurseries, greenhouse crops, turf farming and pasture fields. The residential and non-residential outdoor water use is also mainly for irrigation of backyards, lawns, sporting ground, parks and golf courses. The irrigation water affects the antecedent soil moisture conditions, and thereby interflow, saturation excess runoff, evapotranspiration and groundwater recharge in a catchment. The outdoor water use assumed mainly irrigation in the model (Figure 2) is therefore added to the soil moisture storage of the catchment. The streamflow is finally simulated as a balance of runoff (from infiltration excess, saturation excess and baseflow) plus wastewater discharges minus surface water extractions in the catchment.

3.1. Model calibration and cross-validation

The conceptual water balance model (Figure 2) has been set up for five (SCC_A, SCC_B, SCC_C, SCC_D, and SCC_E) subcatchments (Figure 1), and over 15 years period (1992-2006) to construct spatial and temporal water balance of the South Creek catchment. The subcatchments are determined based on the selected stream gauges, landuse and hydrology network in the catchment. The boundaries of subcatchments are delineated using ArcHydro (Maidment, 2002) within ArcGIS environment processing a 250 m * 250 m digital evaluation model, hydrology network and location of stream gauges as outlets of subcatchments (Figure 1). The main input parameters required for the simulation of each subcatchment are listed in Table 1.

Table 1. List of the model's main input parameters.



Parameter	Symbol	Unit
Catchment Area	CAREA	km^2
Urban Area Fraction	URBPROP	-
Urban Impervious Fraction	PROPIMP	-
Eff. Impervious Fraction	EFFIMP	-
Irrigation Area Fraction	IRGPROP	-
Rainfall Interception Store Capacity	INSC	mm
Maximum Infiltration Loss	COEFF	mm
Infiltration Loss Exponent	SQ	-
Soil Moisture Store Capacity	SMSC	mm
Interflow Coefficient	SUB	-
Recharge Coefficient	CRAK	-
Baseflow Coefficient	RK	-
Potable Water Supply Leakage Coefficient	LD	%
Ave. June-July Residential Outdoor Water Use Fraction	JJRESOWUF	-
Ave. June-July Non-residential Outdoor Water Use Fraction	JJNRESOWUF	-
Rainfall Derived (I/I) Inflow Coefficient	RDINF	%
Rainfall Derived (I/I) Infiltration	RDINT	-
Average Crop Coefficient	Kc	-
Average Irrigation Efficiency	IE	%
Surface water Access Entitlements	YRSWEE	ML/yr
Groundwater Access Entitlements	YRGWEE	ML/yr

These inputs were estimated from the collected hydro-meteo-geographical information for the South Creek catchment. The urban area fraction, urban impervious fraction of each subcatchment were estimated based on the landuse map of the catchment in year 2000 (EPA, 2001) and the imperviousness of various urban landuse categories in Western Sydney region (Zaman and Ball, 1994). The *effective* impervious fraction is related to the impervious fraction (urban area fraction * urban impervious fraction), and is estimated to be about 0.75 of impervious fraction (Boyd et al., 1993). The required continuous time series of daily rainfall and potential evapotranspiration were downloaded from the SILO's Data Drill, and of monthly potable water supply for residential, non-residential and primary production were sourced from the Sydney Water Corporation. The stream outflow from an upstream subcatchment became the stream inflow for a downstream subcatchment. There were also simulated wastewater inflow and outflow among subcatchments. The sewage treatment plants, McGraths Hill and South Windsor (Figure 1), received wastewater inflow from the outside of the South Creek catchment. Therefore, the recorded monthly average wastewater discharges from the McGraths Hill STP and the South Windsor STP were included in the simulation of streamflow in the lower subcatchment, SCC_A (Figure 1).

The model was calibrated optimizing the sensitive and most uncertain model input parameters, and then cross-validated to evaluate whether the calibrated model could successfully simulate monthly wastewater discharges and streamflow for an independent period that is not included in the model's calibration. In the "*Calibration*" run, the wastewater input parameters: JJRESOWUF, JJNRESOWUF, RDINF and RDINT (Table 1) were first calibrated for the whole South Creek catchment using all available monthly observed wastewater discharges from the St. Marys, the Quakers Hill and the Riverstone STPs (Figure 1), and then the rainfall-runoff input parameters: INSC, COEFF, SQ, SMSC, SUB, CRAK and RK (Table 1) were calibrated for each subcatchment using, available and screened for obvious recording errors, monthly observed streamflow data at the corresponding stream gauges in the South Creek and its tributaries (Figure 1) over the years from 1992 to 2006. The calibrated model was further cross-validated using the *k*-fold cross-validation method (Efron and Tibshirani, 1993, Young et al., 2006). In the *k*-fold cross-validation run, the observed dataset is divided into three (k=3) almost equal subdatasets. The model is then calibrated using two subdatasets leaving out one subdataset as a validation dataset. The cross-validation run is repeated *three* times (the *folds*) leaving each subdataset once as validation dataset, and using the other two subdatasets in the calibration of the model. The validation datasets from each run are then combined into a composite "*Cross-Validation*" dataset for the entire period of available observations. This makes possible the direct comparison of the "*Calibration*" and "*Cross-Validation*" to assess the ability of the model to simulate monthly streamflow for the periods which were not included in the model's calibration. The calibration process was achieved by linking the conceptual water balance model with a Parameter ESTimation (PEST) (Doherthy et al., 1995) program adjusting the calibrating parameters to minimize the differences between monthly observed and simulated wastewater discharges or streamflow in the South Creek and its tributaries.

4. RESULTS AND DISCUSSION

The performance of a modeling effort is generally evaluated by calculating statistical measures such as the coefficient of efficiency (E) (Nash and Sutcliffe, 1970), the coefficient of determination (R^2), the ratio of mean simulated and observed (Y) and the coefficient of mass residual (CRM) comparing the observed and simulated state variables, i.e monthly streamflow and wastewater discharges in this study. In catchment streamflow estimates, the flow simulations are considered *perfect* if the $E \geq 0.93$ or $R^2 \geq 0.97$ or $R^2 \geq 0.93$ and $0.90 < Y < 1.10$, and *acceptable* if the $E \geq 0.80$ or $R^2 \geq 0.90$ or $R^2 \geq 0.77$ and $0.90 < Y < 1.10$ (Chiew and McMahon, 1993). The streamflow simulations are generally considered *satisfactory*, at least for approximation of flow volumes and preliminary investigative studies, if the valve of $E \geq 0.60$ (Chiew and McMahon, 1993). In this study, the developed conceptual water balance model showed a *perfect* calibration with the $E \geq 0.93$ and $R^2 \geq 0.94$ for the stream gauges SCC_E_212320 and SCC_D_212048, and an *acceptable* calibration with the $R^2 \geq 0.80$ with $Y = 0.97$ and 1.06 for the stream gauges SCC_B_212296 and SCC_C_212297, respectively (Table 2). The value of E is also in *acceptable* range being 0.92 for the SCC_B_212296, and 0.77 for the SCC_C_212297. The ratio of simulated and observed mean monthly streamflow (Y) varied from 0.95 to 1.06, and the coefficient of mass residual (*CRM*) varied from -0.05 to 0.06 suggesting that the simulated mean monthly streamflow and cumulative streamflow are *within ten percent* of the observed streamflows (Table 2). The model performance indices in the '*cross-validation*' run are similar as in the '*calibration*' run (Table 2) validating that the calibrated conceptual water balance model could simulate monthly streamflow *satisfactorily* in the South Creek and its tributaries for an independent period not included in the model's calibration.

Table 2. Statistics of monthly observed and simulated streamflow in the South Creek and its tributaries during the years from 1992 to 2006.

Subcatchment/ Stream Gauge	Number of Obs. (N)	Model Run	Model Performance Indicator			
			E	R^2	Y	*CRM*
SCC_B_212296	157	**Calibration**	**0.92**	**0.92**	**0.97**	**-0.03**
		Cross-Validation	0.89	0.89	0.99	-0.01
SCC_C_212297	159	**Calibration**	**0.77**	**0.80**	**1.06**	**0.06**
		Cross-Validation	0.69	0.76	1.06	0.06
SCC_D_212048	142	**Calibration**	**0.93**	**0.94**	**0.95**	**-0.05**
		Cross-Validation	0.92	0.93	0.99	-0.01
SCC_E_212320	168	**Calibration**	**0.95**	**0.96**	**0.98**	**-0.02**
		Cross-Validation	0.92	0.94	0.99	-0.01

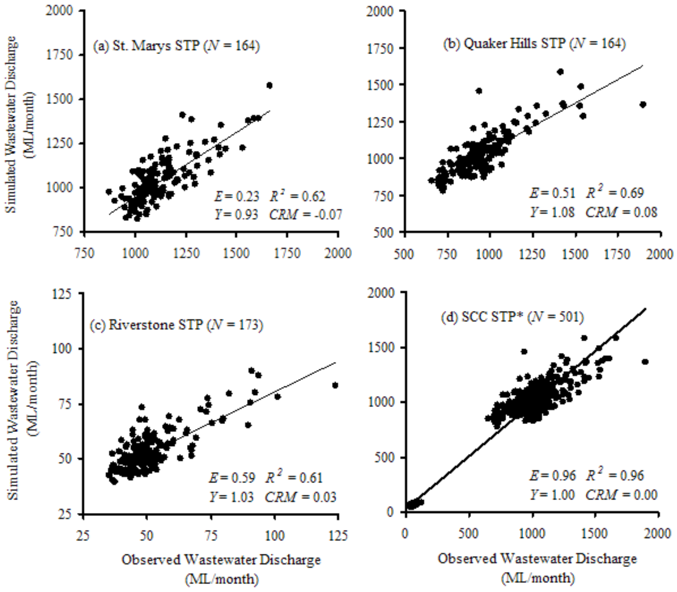


Figure 3. Observed vs. simulated monthly wastewater discharges in the South Creek and its tributaries during the years from 1992 to 2006. *SCC STP = St Marys STP + Quakers Hill STP + Riverstone STP.

The calibrated conceptual water balance model simulated somewhat poor monthly wastewater discharges with the coefficient of efficiency (E) ranging from 0.23 to 0.59 and the coefficient of determination (R^2) ranging from 0.61 to 0.69 for the individual sewage treatment plants, i.e. the St. Marys STP (Figure 3a), the Quakers Hill STP (Figue 3b), and the Riverstone STP (Figure 3c). The model has a tendency of over-estimation of the monthly wastewater discharges for the Quaker Hills STP ($Y = 1.08$, and $CRM = 0.08$) while under-estimating for the St. Marys STP (Y=0.93, and $CRM = -0.07$). However, the *CRM* and Y are calculated 0 and 1.0, respectively for the composite SCC STP* dataset (Figure 3d) combining all the monthly wastewater observations from the St. Marys STP, the Quaker Hills STP and the Riverstone STP during the years from 1992 to 2006. This suggests a good simulation of overall monthly wastewater discharges in the South Creek and its tributaries. Considering the complexity of modelling the rainfall derived inflow and infiltration (RDI/I) to the wastewater system and the fact that a simple lumped model is used, the simulation of monthly wastewater discharges is considered satisfactory.

The results presented in Table 2 and Figure 3 suggests that the developed conceptual water balance model (Figure 2) performed *satisfactorily* in the simulation of monthly wastewater discharges and streamflow in the South Creek and its tributaries. The calibrated model estimated, on a monthly time-step, a wide range of surface water balance components including runoff from infiltration excess, saturation excess and baseflow over pervious areas; stormwater from impervious areas, evapotranspiration from both pervious and impervious areas; residential, non-residential and primary production water use, and surface water and groundwater extractions (*see* the model variables in Figure 2). The estimated monthly residential and non-residential water uses are further separated into the indoor and outdoor components, and finally estimated are the monthly wastewater discharges and streamflow in the South Creek catchment and its subcatchments over 15 years period (1992 to 2006).

5. CONCLUDING REMARKS

Water accounting facilitates informed water management decision making process and polices for productive and sustainable water management in a region. In addition to the significant amount of recorded hydro-meteorological information, a proper water accounting generally requires water balance modelling to estimate different water fluxes in a catchment. Most existing catchment water balance models do not account for potable water supply, wastewater discharges and surface and groundwater extractions, and yet these components of surface water cycle significantly modify streamflow in peri-urban catchments such as the South Creek catchment in Western Sydney. The conceptual water balance model, described in this paper, combines the modelling of daily rainfall-runoff with monthly potable water supply, wastewater flows, and surface and ground water extractions to simulate complete surface water cycle of a peri-urban catchment. The model reproduced, with an acceptable accuracy, the monthly wastewater discharges and streamflow in the South Creek and its tributaries over a period of 15 years from 1992 to 2006. In addition, the model estimated a wide range of surface water balance components which could be very helpful for water accounting or hydrological characterisation of the South Creek catchment and its subcatchments. The developed conceptual water balance model has a generic structure and could be implemented and tested for other peri-urban catchments simulating the surface water cycle of the region. It does have the capacity of simulating the impact of increased impervious surface and potable water supply due to urbanization, and projected climate change on the surface water cycle of a peri-urban catchment.

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REFERENCES

Boughton, W. (2005), Catchment water balance modelling in Australia. *Agricultural Water Management*, 71, 91-116.

Boyd, M.J., Bufill, M.C., and Knee, R.M. (1993), Pervious and impervious runoff in urban catchments. *Hydrological Sciences*, 38 (6), 463-478.

Deen, A.R., Salbe, I., and Craig, R.W. (1992), Modelling of stormwater ingress into foulwater sewers. In the proceedings of the International Symposium on Urban Stormwater Management, Sydney, 219–223.

Doherty, J., Brebber, L., and Whyte, P. (1995), PEST: Model independent parameter estimation. Australian Centre for Tropical Freshwater Research, James Cooke University, Townsville, Australia, 140 p.

Chiew, F.H.S., and McMahon, T.A. (1993), Assessing the adequacy of catchment streamflow yield estimates. *Australian Journal of Soil Research*, 31, 665-680.

Chiew, F.H.S., and McMahon, T.A. (1999), Modelling runoff and diffuse pollutant loads in urban areas. *Water Science Technology*, 39(2), 241-248.

Chiew, F.H.S, Peel, M.C., and Western, A.W. (2002), Application and testing of the simple rainfall-runoff models SIMHYD. In: Singh, V.P., and Frevert, S.K. (Eds), Mathematical Models of Small Watershed Hydrology and Applications. Water Resources Publications, Littleton, Colo, 335-367.

Efron, B., and Tibshirani, R.J. (1993), An Introduction to the Bootstrap. Chapman and Hall, New York, 436 p.

EPA, (2001), Assessment of diffuse sources of pollution in the South Creek catchment - a GIS approach. NSW EPA Unpublished Report, 49 p.

Maidment, D.R., (2002), Arc Hydro: GIS for Water Resources. ESRI Press. Redlands CA, 220 p.

Mein, R.G., and Apostolidis, N. (1992), A simple hydrologic model for sewer inflow/infiltration. In the proceedings of the International Symposium on Urban Stormwater Management, Sydney, 204–208.

Mitchell, V.G., Mein, R.G., and McMahon, T.A. (2001), Modelling the urban water cycle. *Environmental Modelling and Software*, 16, 615-629.

Nash, J.E., and Sutchliffe, J.V. (1970), River flow forecasting through conceptual models. Part I. A discussion of principles. *Journal of Hydrology*, 10(3), 282-290.

Young, W., Brandis, K., Kingsford, R. (2006), Modelling monthly streamflows in two Australian dryland rivers: Matching model complexity to spatial scale and data availability. *Journal of Hydrology*, 331, 242-256.

Zaman, S., and Ball, J.E. (1994), Simulation of small events in an urban catchment. Water Down Under 94: Surface Hydrology and Water Resources Papers, National conference publication (Institution of Engineers, Australia) no. 94/15, November 21-25, 1994, Adelaide, Australia, 353–358.