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Applicability of Aquacycle model to urban water cycle analysis

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ABSTRACT

The Aquacycle model was used in this study to test its applicability for an analysis of an urban water cycle. A sensitivity analysis was initially performed for the Goonja drainage basin in the metropolitan Seoul region to identify sensitive parameters. Based on the sensitivity analysis, using a condition number, which is the degree of variations in the output corresponding to variations in the parameter, the base flow index (BI) was found to be the most sensitive parameter during the wet season, followed by the effective road area, effective roof area, effective paved area and pervious storage 2 capacity. During the dry season, the base flow recession constant was the most sensitive parameter, followed by the BI. The calibration parameters were then estimated using the 2006 rainfall and discharge data. The model was verified for 2007 rainfall and discharge data using the calibrated parameters ($r = 0.97$). The calibrated parameters were found to give satisfactory performance statistics for verification of a run ($r = 0.84$). Finally, the results were compared with previous work on the same drainage basin based only on physical data and values available in the literature. The performance statistics of the calibration run, such as the SIM/REC, correlation coefficient (r), sum of the squared error and the Nash-Suttcliffe efficiency coefficient (E) were found to be better than those used in previous work, emphasizing the necessity of observed data for enhancing the performance of a conceptual model, such as the Aquacycle model.

Keywords: Aquacycle model; Sensitivity analysis; Urban water cycle

1. Introduction

The water cycle constitutes various paths where water flows on surfaces, infiltrates soil, percolates to deeper ground water, flows into rivers and lakes and finally re-circulates to the atmosphere via evapor-transpiration. However, increases in impervious areas, due to urbanization, have caused distortion of the natural water cycle [1]; therefore, the assessment of the effects of urbanization on the water cycle has become an important issue. Such an appraisalwould be useful in identifying problems and evaluating alternative measures for improving the water cycle.

Increasing interest has focused of models that are able to assess the urban water cycle, and many studies have actively used water balance model. In Ref. [2] quantitatively considered hydrological changes following population growth and urbanization using the STORM model. In Ref. [3] analyzed the water cycle of the Chiba-Prefecture basin from 1993 to 2035 using the WEP model, and also predicted change in water cycle assuming changes in future land use and population for

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the Ebi-River basin in Japan [4]. Pikounis *et al*. [5] studied the effects of changes in land use using the SWAT model.

Efforts have also been made to assess the effects of alternative measures to improve the distortion of the water cycle due to urbanization. In Ref. [6] analyzed the water cycle at Woden Valley, Canberra, Australia, using the Aquacycle model, and evaluated the effect of wastewater and rainwater reuse. In Ref. [7] analyzed the effect of wastewater reuse, using the Aquacycle model, assuming the installation of a 10 m^3 rain tank at a residential area in Sydney, Australia. In Ref. [8] analyzed the water cycle and assessed the effects of rainwater and wastewater reuse in South East Queensland. More recently, Ref. [9] evaluated the performance and effectiveness of water sensitive urban design.

The aforementioned Aquacycle model is a unique model, which takes an integrated approach [10, 11] to account for the entire urban water cycle, including both stormwater and wastewater systems. Such a model can be used to evaluate rainwater and wastewater reuse scenarios. Although a few applications have utilized the model, no systematic sensitivity analysis of the model has been performed, which may help users focus on the influential model parameters for calibration of the model.

In this study, a sensitivity analysis of the Aquacycle model was performed using the condition number, which is the degree of variations in the output corresponding to variations in the parameter, to identify sensitive model parameters for both dry and wet seasons. Based on the results of the sensitivity analysis, calibration and validation of the model was performed to test its applicability for an urban water cycle analysis. Finally, the calibration results were compared with those of previous work on uncalibrated runs for the same drainage basin to gain some insight into the role of observations on the accuracy of model predictions.

2. Materials and methods

2.1. Study site

The Goonja drainage basin, in the metropolitan Seoul region, was selected as the test site. This basin has an area of 963,930 m^2, and is located on the left bank downstream of the Joong-rang River. The Goonja drainage basin is composed of 49% residential and commercial areas, 26% road and public areas and 25% green areas. Urbanization has already progressed to the extent that 75% of the area is impervious. The soil type is classed as hydrologic soil group B, as it has a lower runoff potential. The upstream, midstream reach and downstream reach of the river have slopes of 1/29, 1/250 and 1/111, respectively. Fig. 1 shows the land use of the watershed.

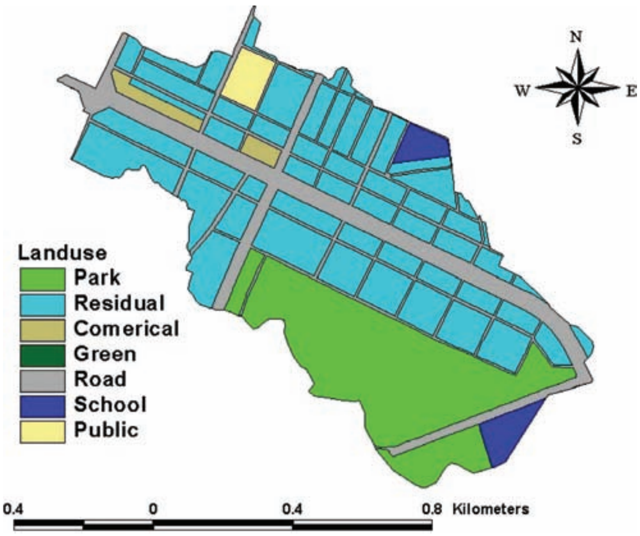

Fig. 1. Land use within the Goonja Drainage Basin.

2.2. Model description

The Aquacycle model is a daily water balance model for the entire urban water cycle, and was developed by CRCCH (Cooperative Research Centre for Catchment Hydrology) in Australia. The model has the objective of simulating the urban water cycle as an integrated system, and can be a powerful tool for investigating the use of locally generated stormwater and wastewater, as a substitute for imported water, to improve the efficiency of water use [12]. The model can be run on a unit block, as a cluster or on a wider catchment scale. The model generates daily, monthly and annual estimates of water demands, yields and uses.

The input data of the Aquacycle model are composed of climate data, including rainfall and potential evapotranspiration, and the profile of indoor water use, including the characteristics of household water use, and measured parameters, such as the characteristics of the physical catchment, the values of which are determined via measurements, observations, local experience and calibrated parameters. There are 14 measured parameters, which can be grouped according to their associated spatial area. There are also 16 calibrated parameters, which can be adjusted during the calibration process [12].

2.3. Sensitivity analysis

To understand the sensitivity of model parameters, the condition numbers (CN) [13] were calculated. These related to the degree of variation in the output, which correspond to variations in the parameter (Δρ) for a given range around the average parameter value (R_{avg}); defined as:

$$\mathrm{CN} = \frac{\dfrac{\mathrm{SSE}_{+20\%} - \mathrm{SSE}_{-20\%}}{2}}{\mathrm{SSE}_{avg}\dfrac{\Delta p}{R_{avg}}} \tag{1}$$

where $\mathrm{SSE}_{+20\%}$, $\mathrm{SSE}_{-20\%}$ and SSE_{avg} are sum of squared error (SSE) for a reference value 20% greater than the average, 20% less than average and the average parameter, respectively. The SSE can be defined as:

$$\mathrm{SSE} = \sum_{i=1}^{n}(\mathrm{SIM}_i - \mathrm{REC}_i)^2 \tag{2}$$

where SIM_i and REC_i are the simulated and observed values on the i-th day, respectively.

Reference values for the parameter of the Curtin & Woden area were taken from the Aquacycle User's Guide [12] and used as base condition. A sensitivity analysis was then performed by calculating the CN for each parameter for the range of ±20% of the base conditions.

2.4. Application of Aquacycle model

The model parameters were calibrated on the basis of the sensitivity of parameters, as represented by condition number, using observed rainfall and discharge data for 2006. The final set of parameters was determined as those that gave the smallest SSE between the simulated and observed flows. Using these calibrated parameters, the Aquacycle model was further verified using observed rainfall and discharge data for 2007. The results were finally compared with those of previous work on uncalibrated runs for the same drainage basin to evaluate the performance.

Performance statistics of the calibration run, such as the SIM/REC, correlation coefficient (r), sum of the squared error (SSE) and the Nash-Suttcliffe efficiency coefficient (E), were defined as follows:

$$\mathrm{SIM/REC} = \sum \mathrm{SIM} \Big/ \sum \mathrm{REC} \tag{3}$$

where SIM and REC are the simulated and observed values, respectively.

$$r = \frac{n\sum_{i=1}^{n}\mathrm{SIM}_i\mathrm{REC}_i - \sum_{i=1}^{n}\mathrm{SIM}_i\sum_{i=1}^{n}\mathrm{REC}_i}{\sqrt{n\left(\sum_{i=1}^{n}\mathrm{SIM}_i^2\right) - \left(\sum_{i=1}^{n}\mathrm{SIM}_i\right)^2}\sqrt{n\left(\sum_{i=1}^{n}\mathrm{REC}_i^2\right) - \left(\sum_{i=1}^{n}\mathrm{REC}_i\right)^2}} \tag{4}$$

where n, SIM_i and REC_i are the number of data pairs, and the simulated and observed values, respectively.

$$E = \frac{\left[\sum_{i=1}^{n}(\mathrm{REC}_i - \overline{\mathrm{REC}})^2 - \sum_{i=1}^{n}(\mathrm{REC}_i - \mathrm{SIM}_i)^2\right]}{\sum_{i=1}^{n}(\mathrm{REC}_i - \overline{\mathrm{REC}})^2} \tag{5}$$

where $\overline{\mathrm{REC}}$ is the average of the observed values.

3. Results and discussion

3.1. Model calibration

The calculations of the CN for the ± 20% range of each parameter around the base conditions are given in Table 1.

Fig. 2 summarizes the sensitivity ranking based on the sensitivity analysis using the condition number; it was found that the base flow index (BI) for the wet season was the most sensitive parameter, followed by the effective road area (ERDA), the effective roof area (ERA), the effective paved area (EPA) and the pervious storage 2 capacity ($\mathrm{PS2}_c$). During the dry season, the base flow recession constant (BRC) was the most sensitive parameter, followed by the BI.

Based on the results of the sensitivity analysis, the calibration parameters were then estimated using the 2006 rainfall and discharge data. During the wet season, the BI, was found to be the most sensitive parameter, followed by the ERDA, ERA, EPA and $\mathrm{PS2}_c$. During the dry season, the BRC was initially calibrated, with the final set of parameters determined as those that gave the smallest SSE between the simulated and observed flows. Figure 3 shows the comparison of the simulated and observed discharges, based on the calibrated parameters, using the data observed for 2006.

3.2. Model verification

The final calibrated parameters were further verified using the observed data for 2007. Figure 4 shows the

Table 1
Results of the sensitivity analysis of the model parameters.

Output	Parameter		Mean	CN (Condition number)		
				Wet season	Dry season	Whole year
Storm water	A1	Percentage area of store 1 (%)	22	0.0129	−0.0112	0.0114
	$PS1_c$	Pervious storage 1 capacity (mm)	32	−0.0015	0.0060	−0.0010
	$PS2_c$	Pervious storage 2 capacity (mm)	240	−0.1418	0.0204	−0.1316
	RIL	Roof area maximum initial loss (mm)	16	−0.0166	0.0000	−0.0157
	ERA	Effective roof area (%)	100	0.2004	0.0598	0.1916
	PIL	Paved area maximum initial loss (mm)	16	−0.0071	0.0000	−0.0067
	EPA	Effective paved area (%)	100	0.1692	0.0513	0.1618
	RDIL	Road area maximum initial loss (mm)	16	−0.0116	0.0000	−0.0109
	ERDA	Effective road area (%)	100	0.3192	0.0666	0.3034
	BI	Base flow index (ratio)	0.55	−0.5591	−0.1346	−0.5326
	BRC	Base flow recession constant (ratio)	0.0025	0.0081	−0.4939	−0.0233
Waste water	%I	Percentage of surface runoff as inflow (%)	3	−0.0170	−0.0087	−0.0164
	II	Infiltration index (ratio)	0.019	0.0032	0.0054	0.0033
	IRC	Infiltration store recession constant (ratio)	0.12	0.0005	−0.0002	0.0004
Water use	TG	Garden trigger to irrigate (ratio)	0.5	0.0029	0.0011	0.0028
	POSTG	Public open space trigger to irrigate (ratio)	0.46	−0.0273	0.0760	0.0695

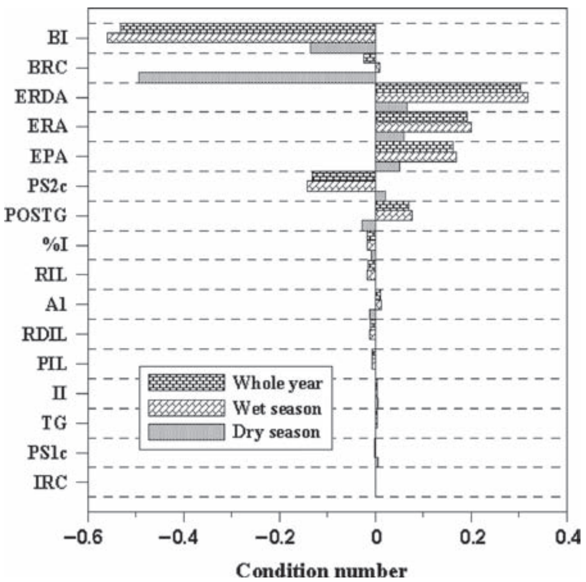

Fig. 2. Parameter sensitivities by condition number for an entire year, and the wet and dry seasons.

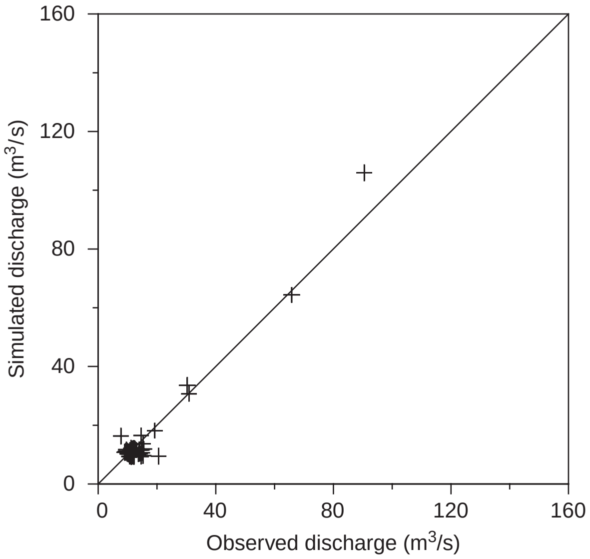

Fig. 3. Comparison of the simulated and observed discharges based on the calibrated parameters using the observed data for 2006 (whole year).

comparison of the simulated and observed discharges, which were used in verification runs for the wet and dry seasons, as well as an entire year. The calibrated parameters were found to give satisfactory performance statistics for verification of the runs.

3.3. Comparison with prior work on uncalibrated runs

To check the difference in the model performance both with and without calibration, the calibration results were compared with those of previous work [14] on uncalibrated runs for the same drainage basin based only on physical data and values available in the literature. Table 2 shows a comparison of the performance statistics for base conditions, and the calibration and verification runs conducted in this study and those from previous work. The performance statistics of the calibration run were found to be better than those of the previous work, emphasizing the necessity of observed data to

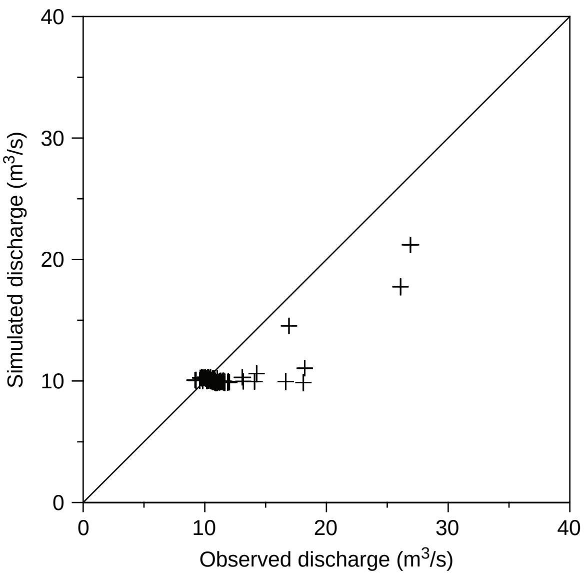

Fig. 4. Comparison of the simulated and observed discharges based on the calibrated parameters using the observed data for 2007 (whole year).

Table 2
Comparison of the performance statistics for different model runs during 2006.

Model run	SIM/REC	r	r^2	SSE	E
Base condition					
Whole year	0.953	0.981	0.962	4,950.4	0.511
Wet season	1.145	0.983	0.967	4,545.6	0.487
Dry season	0.834	−0.261	0.068	404.8	−4.146
Calibration					
Whole year	0.969	0.974	0.948	760.3	0.925
Wet season	0.937	0.980	0.960	664.3	0.925
Dry season	0.989	0.254	0.065	95.9	−0.220
Verification					
Whole year	0.889	0.842	0.709	347.8	0.491
Wet season	0.730	0.893	0.797	277.2	0.475
Dry season	0.930	−0.682	0.465	70.6	−1.619
Prior work [14]					
Whole year	0.927	0.979	0.959	5,730.2	0.434
Wet season	1.075	0.982	0.964	5,349.6	0.397
Dry season	0.835	0.372	0.139	381.2	−3.847

enhance the performance of a conceptual model, such as the Aquacycle model.

4. Conclusions

A sensitivity analysis of the parameters of the Aquacycle model was performed using the condition number to identify important parameters that influence the model results. The condition number is defined as the variation in the output relative to the parameter, which can serve as a measure of a parameter's sensitivity.

Based on the parameter sensitivity analysis, the BI was found to be the most sensitive parameter affecting the combined runoff discharge during the wet season, followed by the effective impervious area (EIA). During the dry season, the BRC was found to be the most effective calibration parameter.

A calibration run was conducted using the parameter sensitivity, with the performance statistics of the calibration run, such as the SIM/REC, r (correlation coefficient), SSE and the Nash-Suttcliffe efficiency coefficient (E), found to be very satisfactory (e.g. $r = 0.97$). Using the calibrated parameters, a verification of the model was carried out by comparing the model results with actual discharge data for 2007. The performance statistics were also found to be satisfactory during verification runs (e.g. $r = 0.84$); thus, the calibrated parameters were found to be reasonably estimated.

The information identified for the sensitive parameters could be useful in guiding other users of the Aquacycle model through the calibration process. From the results of the calibration and verification, the Aquacycle model was considered very applicable and; with proper calibration, could be a useful tool for an integrated watershed management approach for investigating the effects of alternative water reuse scenarios for improving the water cycle.

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