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Effects of land use change and water reuse options on urban water cycle

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Abstract

The aim of this article was to study the effects of land use change and water reuse options on an urban water cycle. A water cycle analysis was performed on the Goonja drainage basin, located in metropolitan Seoul, using the Aquacycle model. The chronological effects of urbanization were first assessed for the land uses of the Goonja drainage basin from 1975 to 2005, where the ratio of impervious areas ranged from 43% to 84%. Progressive urbanization was identified as leading to a decrease in evapotranspiration (29%), an increase in surface runoff (41%) and a decrease in groundwater recharge (74%), indicating a serious distortion of the water cycle. From a subsequent analysis of the water reuse options, such as rainwater use and wastewater reuse, it is concluded that wastewater reuse seemed to have an advantage over rainwater use for providing a consistent water supply throughout the year for a country like Korea, where the rainy season is concentrated during the summer monsoon.

Key words: Aquacycle model; land use change; water reuse

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Introduction

Urbanization is an important factor that distorts the natural water cycle, which affects both the availability and quality of water resources (Pouraghniaei, 2002). Urbanization increases impervious surface areas, which leads to a decrease in infiltration and an increase in the runoff and peak discharge (Michael and Keith, 2006). The development of drainage systems for stormwater and sewage also causes an increase in rapid surface runoff and reduces the amount of natural storage. Reduced infiltration may lead to reductions in groundwater recharge and the stream base flow.

A water cycle analysis involves the quantification of various elements of the hydrological cycle, including evapotranspiration, infiltration and runoff, etc. Such an analysis is important in identifying the aforementioned problems associated with urbanization. Since the impact of urbanization on the hydrological cycle is complex, affecting almost all hydrological processes (Brilly et al., 2006), the water cycle is analyzed using hydrological models. The use of a hydrological model and a quantitative assessment are essential for understanding changes in the water cycle as a result of urbanization and for the recovery of a comprehensive water cycle system in urban areas.

There have been many studies analyzing the effects of the changes in land use on the water cycle and/or quality of water (Filoso et al., 2004; Chen et al., 2005; Olivera and DeFee, 2007; Cuo et al., 2008; Liang et al., 2008; Franczyk and Chang, 2009). There have also been numerous studies evaluating improvements in water cycle utilizing water reuse schemes (Alegre et al., 2004; Sharma et al., 2008; Lekkas et al., 2008; Han et al., 2008; Zhang et al., 2009). However, no attempt has been made to consider alternative water resources to improve the urban water cycle in the context of urbanization.

The objective of this study was to analyze the changes in the urban water cycle due to changes in land use, as well as perform a feasibility analysis of sustainable water use options, such as rainwater use and wastewater reuse, to examine their influences on water cycle. To this end, the Aquacycle model was applied for a water cycle analysis (Mitchell et al., 2001; Mitchell, 2005).

1 Materials and methods

1.1 Description of Aquacycle model

The Aquacycle is a daily urban water balance model in investigating the use of locally generated stormwater and wastewater as substitutes for imported water. The model produces daily, monthly and annual estimates of water demand, stormwater yield, wastewater yield, evaporation, imported water use, stormwater use and wastewater reuse. The model is suitable for assessing the effects of stormwater and wastewater uses, and has been used to analyze the urban water cycle in Australia to determine the optimum

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capacity for rainwater and wastewater storage (Mitchell et al., 1999; Hatt et al., 2004).

1.2 Application of Aquacycle model

This study considered the changes in the water cycle due to urbanization of the Goonja drainage basin (Fig. 1), a small urban basin located in metropolitan Seoul, Korea. The area of the Goonja drainage basin is 0.964 km^2; the Children's Grand Park is situated in the southeast of the basin. The basin drains to the Jungrang River, northwest of the basin.

The climatic data used in this study was the daily rainfall data provided by Gwangjin District Office (2005). The potential evapotranspiration was estimated using the Penman equation (Penman, 1948). There are 8040 households in this district, with a resident population of about 21,230. Therefore, the average occupancy per household has been calculated as 2.64. Input data for the indoor water usage profile was estimated using the data from the survey conducted by the Seoul Development Institute (Kim, 2004b).

The average area of a unit block was estimated from a 1:3500 map of Seoul and the areas of the basin, roads and public open spaces from a digital map of Seoul. The effective impervious area was estimated using the Sutherland equation (Sutherland, 2000). The impervious area maximum initial loss was taken to be 6.55 mm from the survey by Kim (2004a). The maximum recharge rate was estimated using the permeability constant of the soils in the study area. The base flow recession constant and aquifer storage capacity were taken from the study by Lee (1995). Table 1 presents the Aquacycle model parameters used in this study.

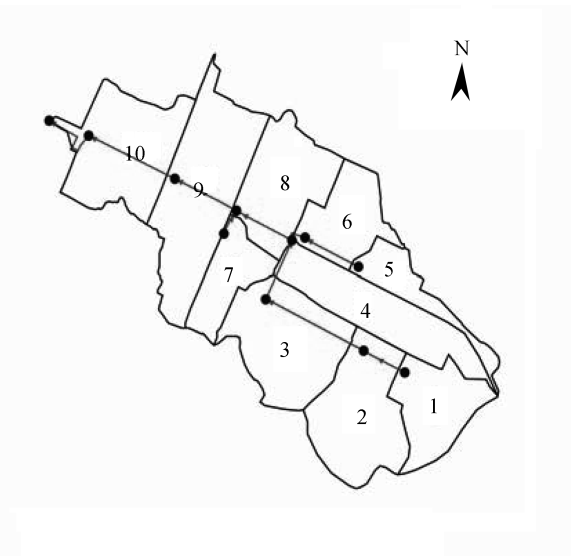

Fig. 1 Schematic of the Goonja drainage basin. 1–10: subcatchments.

2 Results and discussion

2.1 Water cycle analysis of the Goonja drainage basin

A water cycle analysis was performed for the Goonja drainage basin, which consists of 83% impervious areas in 2005, using the Aquacycle model. Figure 2 illustrates the annual water cycle of the Goonja drainage basin. From the simulation of the urban water cycle, it was identified that, of an annual total of 1388 mm rainfall, 306 mm were lost through evapotranspiration. The annual total surface runoff was 1044 mm, of which 937 and 107 mm were from impervious and permeable areas, respectively. Finally, an annual total of 99 mm of rainfall was recharged into the groundwater. In summary, of the total rainfall, 75% formed surface runoff; whereas, groundwater recharge accounted for only 7%. This suggests a serious distortion in the water cycle, which can be attributed to urbanization.

It was also identified that annual leakages from the reticulation system accounted for 357 mm, which is greater than the amount of groundwater recharge. This implies that leakages may be able to replenish the decrease in groundwater recharge caused by urbanization. Another source for recharge can be from water imported for landscape irrigation, which may also increase the stream base flow (Hirsch et al., 1990; Paul and Meyer, 2001; Greer and Stow, 2003; Michael and Keith, 2006). However, there are instances where part of these leakages flow into the sewage collection system; therefore, not all of the leakages can be considered as contributing to groundwater recharge.

Another problem caused by urbanization is the drying of stream, which also relates to a decline in the groundwater

Table 1 Model parameters for the application of the Aquacycle model.

Unit block scale		Cluster scale	
Measured parameters			
Average of unit block (m^2)	74.83	Total area (ha)	96.39
Area of garden (m^2)	4.54	Road area (ha)	23.87
Area of roof (m^2)	45.41	Area of public open space (ha)	12.39
Area of pavement (m^2)	24.88	Leakage rate (%)	11
Calibrated parameters			
Percentage area of storage 1 (%)	28	Road area maximum initial loss (mm)	6.55
Pervious storage 1 capacity (mm)	36.80	Effective road area (%)	96.90
Pervious storage 2 capacity (mm)	86.50	Base flow index (ratio)	0.45
Roof area maximum initial loss (mm)	6.55	Base flow recession constant (ratio)	0.012
Effective roof area (%)	96.90	Infiltration index (ratio)	0.10
Paved area maximum initial loss (mm)	6.55	Infiltration store recession constant (ratio)	0.12
Effective paved area (%)	96.90	Surface runoff as inflow (%)	15
Aquifer storage and recovery parameters			
Storage capacity (m^3)	653,389	Maximum aquifer recharge rate (m^3/day)	13.83

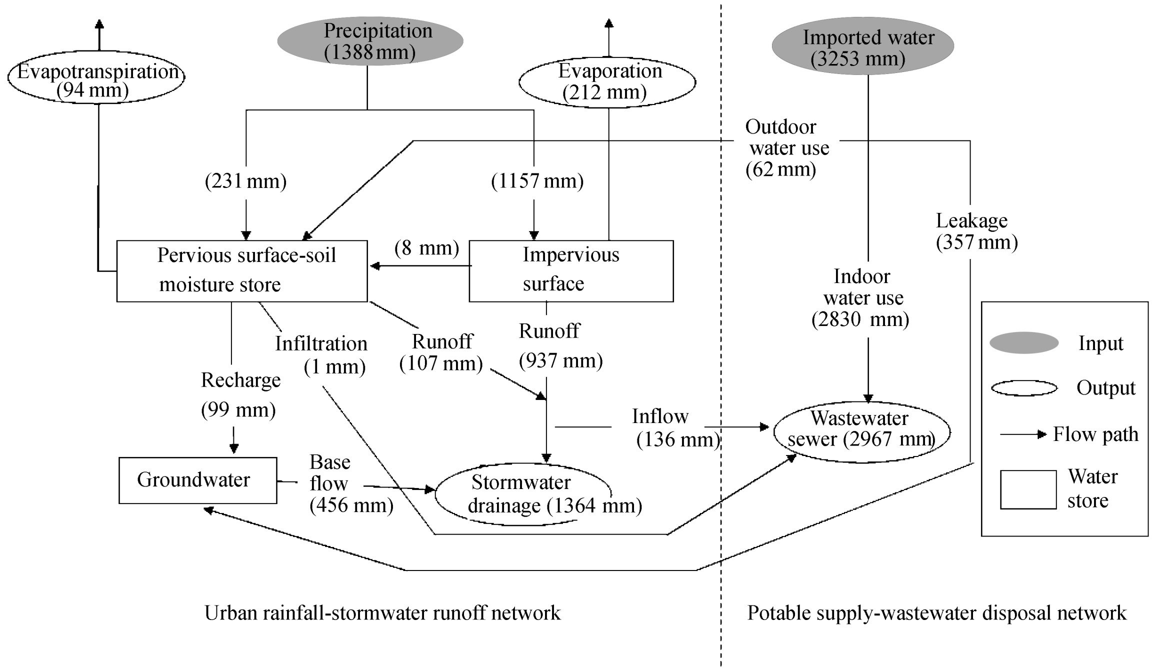

Fig. 2 Annual water cycle of the Goonja drainage basin.

level. A separate calculation, using an accounting model of groundwater storage, was performed using the amount of recharge obtained from the Aquacycle model to assess the effects of groundwater use and forced pumping. For 2005, for which data for the groundwater usage and forced pumping at a subway station were available, the groundwater storage level was estimated to decrease by about 110 mm per year.

From our experience of the Aquacycle model, the estimation of the recharge parameter, BI (base flow index), has been identified as being rather empirical, as it lacks physical meaning. For a more systematic determination of this parameter, the use of the well-established SCS Curve Number method was considered for the computation of the recharge. To incorporate this method with the Aquacycle model, groundwater recharges obtained using the Aquacycle model were fitted to those estimated via the SCS curve number method for different hydrological soil groups (A to D). Table 2 presents the groundwater recharge values for each SCS hydrological soil group and the relevant BI of the Aquacycle model. The proposal of using the SCS curve number method was thought to provide a more systematic way in determining the BI value.

2.2 Effects of urbanization on water cycle

The chronological effects of urbanization on the water cycle were studied for the Goonja drainage basin from

Table 2 Groundwater recharge corresponding to different hydrological soil groups

Soil group	Groundwater recharge (mm/yr)	Base flow index (BI)
A	783	0.60
B	666	0.51
C	532	0.41
D	430	0.33

1975 to 2005, at five-year interval, using land use maps. Figure 3 shows the change in the water cycle due to urbanization over this period.

The water cycle analysis clearly showed that the hydrological components, such as evapotranspiration, surface runoff and groundwater recharge, were highly dependent on changes to impervious areas. Especially, a sharp change in hydrological components occurred between 1975 and 1985 when Seoul experienced the greatest amount urbanization due to the increased industrialization of Korea. From 1975 to 2005, the impervious areas doubled, resulting in a reduction in evapotranspiration of 29%, an increase in surface runoff of 41% and a decrease in groundwater recharge of 74%.

2.3 Effectiveness of rainwater use and wastewater reuse

The effects of rainwater use and wastewater reuse on the water cycle in the study area were also examined using the Aquacycle model to evaluate potential improvements of the water cycle. The use of reusable water was limited to landscape irrigation and toilet water; the analysis showed an annual maximum reusable water demand of 890 mm. This translates to an annual reduction of 1000 mm in the imported water supply when the leakage from the reticulation system is considered.

The determination of the optimal rainwater and wastewater storage capacities is based on the volumetric reliability, which is defined as the ratio of total volume supplied to that demanded during the simulation period (Mitchell, 2005). Optimization of the storage size is achieved by finding the optimal volumetric reliability at which any further gain in the volumetric reliability is insufficient to justify an additional increase in the storage size.

In the case of rainwater use (Fig. 4a), the Aquacycle model determined that a rainwater storage capacity of 500,000 m^3 was required to meet the maximum reusable

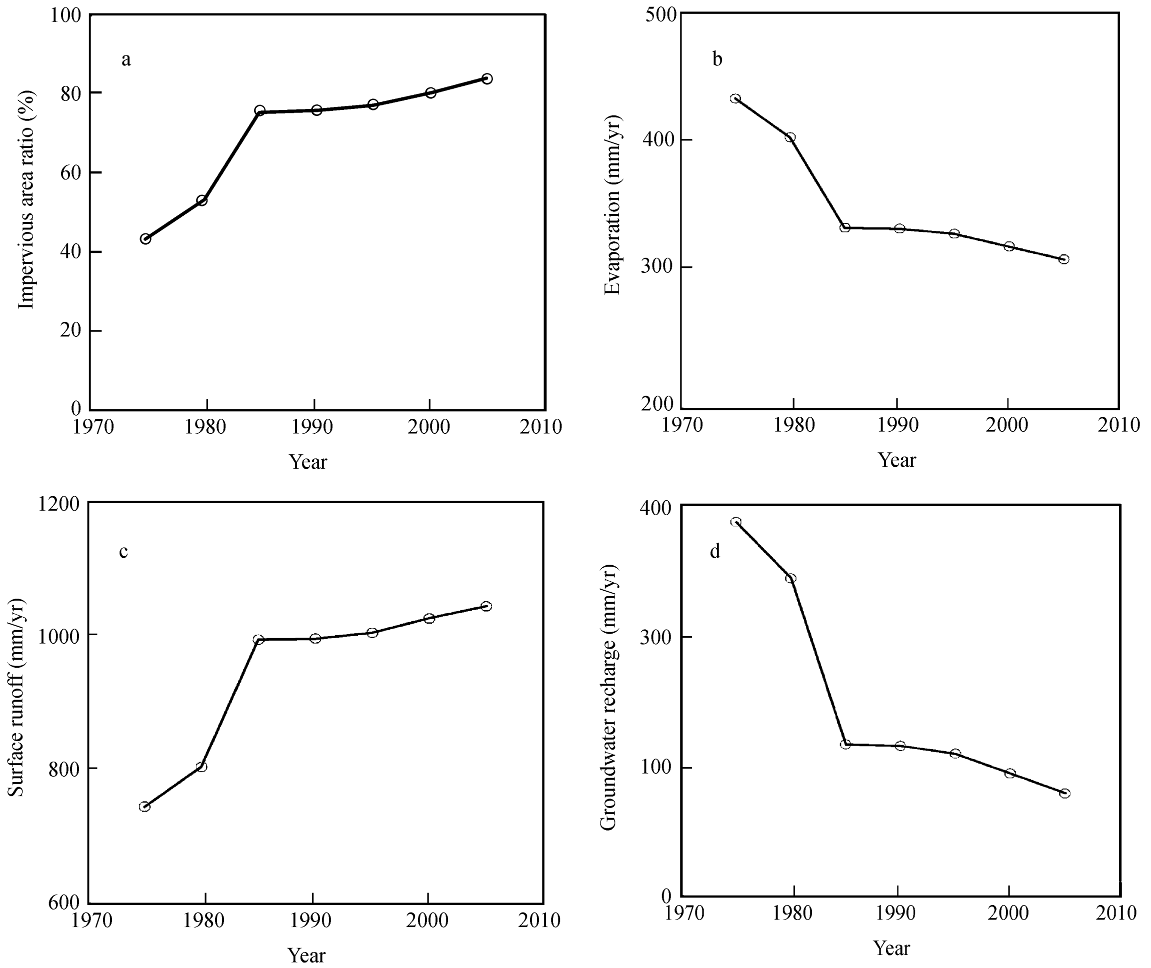

Fig. 3 Changes in the water cycle due to urbanization. (a) impervious area ratio; (b) evapotranspiration; (c) surface runoff; (d) groundwater recharge.

water demand. Such a requirement was identified as being practically impossible (62 m^3/household) considering the reasonable size of a rainwater tank for installation at each household. The optimal capacity estimated using the Aquacycle model was 25,000 m^3, which translates to a more realistic 3.1 m^3/household. It was shown that an annual imported water supply of 427 mm can be saved through rainwater use, which translates to a water supply saving of 13%, with a 36% reduction in surface runoff.

In the case of wastewater reuse (Fig. 4b), a wastewater treatment plant with a capacity of 2700 m^3 was determined as the optimal capacity, and this would meet the maximum reusable water demand. It was shown that a water supply saving of 31% could be achieved from the reuse of wastewater, with a 30% reduction in wastewater.

Figure 4c illustrates the effects of the reuse options on the urban water cycle. From the analysis of the reuse options, it was identified that wastewater reuse was more effective than rainwater use in reducing the imported water supply (more than three times) for a heavily populated

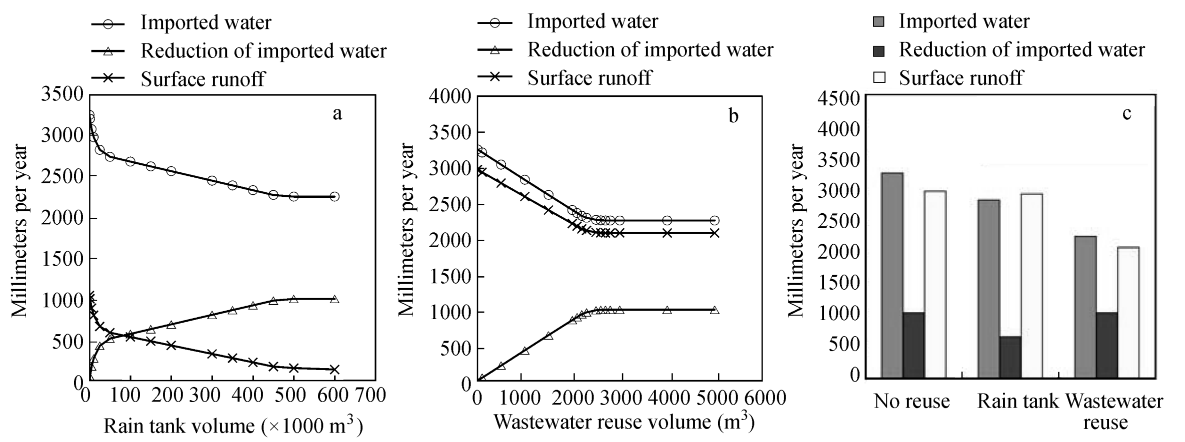

Fig. 4 Determination of the optimal capacities and their effects on the water cycle. (a) rainwater; (b) wastewater; (c) effects of reuse options.

district, such as the Goonja drainage basin. Korea is rich in rainfall, but about two-thirds of the rainfall occurred during summer months. It would require a huge storage volume to contain this rainwater for reuse, which was identified as an impractical option. For a reasonable sized rain tank, as estimated above, the amount of reusable water that can be held is limited due to the excessive surplus of rainfall. In contrast, a large volume of wastewater occurs steadily throughout the year. Therefore, it can be said that wastewater reuse has an advantage over rainwater use in providing a consistent water supply for the climatic conditions experienced by Korea. However, in terms of flood control, rain tanks still have an edge over wastewater reuse, which contribute to reducing surface runoff when there is no difference between the potential wastewater reuse options.

3 Conclusions

In this study, the Aquacycle model was used to estimate the components of the annual water cycle for the Goonja drainage basin in metropolitan Seoul. The results suggest there has been a serious distortion in the water cycle, characterized by increased stormwater runoff (75% of the total rainfall) and decreased infiltration (7% of the total rainfall), which can be attributed to urbanization.

Chronological effects of urbanization were also assessed for land uses of the Goonja drainage basin from 1975 to 2005, where the impervious area ratio increased from 43% to 84%. Progressive urbanization was identified as leading to a decrease in evapotranspiration (29%), an increase in surface runoff (41%) and a decrease in groundwater recharge (74%).

The performance of water reuse scenarios was evaluated to assess their feasibility for improving the water cycle by promoting less stormwater runoff and reducing the need for imported water supply. It was shown that a saving of 13% in imported water supply could be achieved by the use of rainwater, with a surface runoff reduction of 36%. It was also found that a water supply savings of 31%, with a 30% reduction in wastewater, could be achieved by the reuse of wastewater.

Wastewater reuse seems to have an advantage over the use of rainwater for providing a consistent water supply throughout the year for a country like Korea, where the rainy season is concentrated during the summer monsoon.

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