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Effects of Decentralized Rainwater Management on the Energy Balance in the City

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ABSTRACT

In this study, the influence of decentralized rainwater management over the energy balance of urban climate was analyzed. The analysis method was obtained by establishing the decentralized rainwater management plan according to different scenarios, and subsequently examined evapotranspiration in the plan.

Scenario 1 refers to the analysis of the existing situation, in which was 100% of a parking lot is asphalt pavement. In Scenario 2, the pavement of the parking surface in the parking lot is replaced with lawn blocks. In Scenario 3, some asphalt pavement was removed to establish a flower-bed type infiltration system to allow rainwater to permeate. In Scenario 4, infiltration and storage of rain water would be achieved by transforming the parking surface into lawn blocks, keeping the asphalt for the parking road while establishing a vegetation strip. The amount of evapotranspiration of the target site was analyzed with a water budget analysis program (CAT) using the 2001 meteorological data for each scenario.

According to the analysis values of S2 and S3, it was found that evapotranspiration is critically affected by the amount of area replaced with pervious area in the total target site. An energy equivalent to 680kWh is required for 1 ton of water to evaporate. Hence, it can be seen that the active inducement of evapotranspiration in urban area makes a positive contribution not only to heat island mitigation, but also to the small water circulation process in a city.

Keywords: Small Water Circulation, Energy Balance, Decentralized Rainwater Management, Climate Change, Evapotranspiration, Latent Heat of Evapotranspiration

1. Introduction

1.1 Background and Objective of the Study

With the recent rush of large-scale development projects such as Sejong city, Innovation city, Company city, etc. during 2006 and 2010, the annual average area of the previously agricultural land that has changed its original usage has reached 20,000 hectares[1)]. This was mainly due to the use of agricultural land for developing plant establishment and residential facilities, such as the establishment of industrial complexes accompanying urbanization. It was found that as of 2010, the Korean urban region

[1)] 2011 Press release material from the Korean Ministry of Food, Agriculture, Forestry, and Fisheries

accounts for 17,492 ㎢, which is 16.6% of the entire territory. The urbanization rate[2)] of the city area is growing close to 90.0%.

It could be noted that most urban areas are physically composed of paved regions and pavements with scarce vegetation. The local and regional climates of these areas seem to be dramatically changing due to urbanization and other changes in land use. Urban climate is transformed by water balance variation, radiant and energy balances, and changes in wind fields (Gross, 1996)

Sustainability and the countermeasure against climate change are prevalent as overarching concepts for recent urban development. A straightforward example can be found in the active implementation of low impacts development techniques and the drive to realize decentralized rainwater management. It has become especially crucial to manage rainwater and maintain the natural state of water circulation to respond to climate change. This is because re-circulated rain via evaporation generates rainfall, which in turn constitutes the so-called “small water circulation’ in the land surface and occupies a sizable portion of local-level rainfall generation (Schmidt, M.2009)[3)].

So far, decentralized rainwater management has been focused on the use, infiltration, and storage of rainwater to treat the increased overflow caused by development in local areas in an environmentally friendly manner. Despite the fact that it is significantly advantageous to infiltrate rain in a decentralized way in comparison with existing conventional rain drains, this approach fails to fully consider the aspect of energy circulation related to natural water circulation.

According to a recent study conducted by the Berlin Senate for Urban Development Department, the problem of urban areas is not in decreasing infiltration rate but in insufficient evapotranspiration due to the lack of vegetation covered soil.

Therefore, it is the intention of this study to concentrate not just on decentralized rainwater management that has been discussed in terms of water circulation, but also on its effects on the energy balance in the urban area that is connected to the water circulation process.

1.2 Study method and details

The details of the study are as follows.

This study attempts to analyze the effect of evapotranspiration on the energy balance in urban areas by calculating the evapotranspiration of the decentralized rainwater management facilities that have been discussed before. To do so, one target site was selected to set up a decentralized rainwater management planning scenario. The variations of evapotranspiration in the different scenarios were subsequently analyzed.

A part of parking lot site within the Korea Institute of Construction Technology will be selected for analysis, and the evapotranspiration of the target site will be analyzed by using the Catchment hydrologic cycle Assessment Tool (CAT) for each scenario so that they can be compared from the energy perspective.

[2)] Urbanization rate is an index to show how much urbanization has progressed compared to the past. The urbanization rate in urban areas refers to the percentage of the residential population in the urban area among the total population. It is represented by (urban population of specific use area/total population)*100 .http://www.index.go.kr/)

[3)] Rainfall evaporated from the sea and moved to the land generally occupies a small portion for the local based rainfall generation. Most of the rain fall is generated by the evaporation from the relevant land (Kravč.íik, M.et al 3).

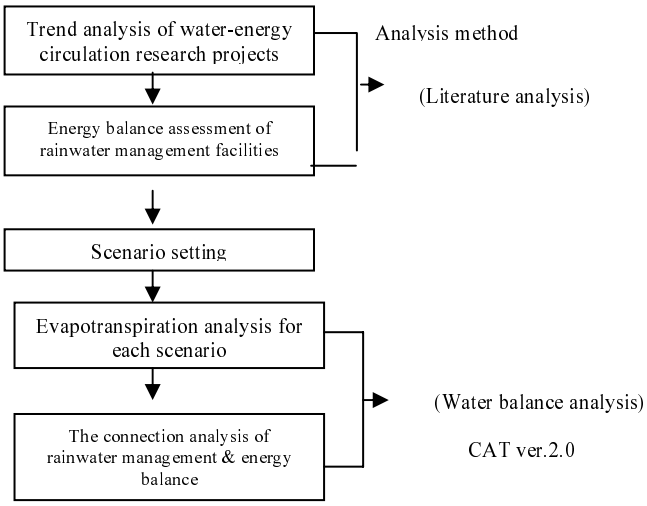

Fig.1. Research Process and Key Contents

2. Related Korea & International Trends

2.1 Korea

In Korea, reserch about the heat island phenomenon in urban areas and urban thermal environment improvement has developed in relation with greenbuffer zone establishment. Research projects and studies include the following: green network and wind corridor (Cha, Jae-gyu et al. 3, 2007; Kim, Soo-bong et al. 3, 2004), the relationship between green buildings and the urban thermal environment (Kim Geum-ji et al. 3, 2011), roof planting and changes in building thermal environment (Park, Chan-phil et al. 1,2004; Jeong, Jae-woong et al. 2,2008; Jang, Dae-hee et al. 3, 2006, etc.), and the type of land surface pavement and characteristics of thermal environment (Han, seung-ho et al. 2008, Ryu, Nam-hyong et al. 1,2006, etc.).

These studies investigated the changes caused by different land covers and mostly start from the basis that the state of urban climate is caused by paved roads, buildings, rooftops because their surfaces are different from natural land covers.

Another commonality among these previous research projects is that planting has been presented as the solution for the urban heat island effects. The approaches to constructing green systems at the urban level or the introduction of planting at the building level are eventually based on the theory that the surrounding temperature will fall by the latent heat during the evapotranspiration process by plantation.

As for the distribution characteristic of surface temperature according to different pavements, it was found from Seo, Ung-cheol (1995)'s pilot study for asphalt pavement and lawns based on the climate data in the Daegu region to delineate the distribution characteristic of surface temperature that asphalt surface has at least 65.4℃ and that the high temperature tendency was very conspicuous during sunny daytime. On the other hand, lawn surfaces did not show a dramatic increase in surface temperature during the daytime and only exceeded the outside air temperature by a small amount, which indicates that low temperatures could be traced to latent heat generation from the evapotranspiration of the lawn and evaporated moisture in soil.

These investigations are still limited to single experiments of rooftop plantations, pavement layers, and their effect analysis. Their spatial application mainly relies on effect analysis by computer programs.

2.2 International

The great deal of discussion on the microclimates of cities has led to studies on the characteristics of land surface temperature according to the component land surface materials (Landsderg, 1981: Robinette, 1977: Suh, 1995, Yoshino, 1981) and studies on microclimate characteristics for larger regions.

There has been a very interesting study focusing on the heat storage capacity of pavement and its impact on urban climate. It showed that surface temperature, heat storage capacity, and emitted temperature to air of concrete or asphalt is significantly higher than that of natural soil. Asphalt pavement emits a maximum of 150 W/㎡ more infrared rays than concrete or natural soil and 200 W/㎡ more visible rays. The temperature gap between the air and land surface reaches its peak at noon, and asphalt has higher infrared ray absorption than natural soil by 60W/㎡ (Takashi Asaeda et al 2. 1996).

With regard to the thermal flow relation between the forms and materials of cities and surfaces, there is a study on the relationship between thermal flow and shape of city blocks, materials, and surfaces in Tokyo Tama Newtown. In six sample sites, the urban blocks were categorized by five different types according to different piloti types, and thermal flow was analyzed from the total surface of each block based on the thermal characteristics of each building, the relationship with shapes, and the relationship with land covers (vegetation, vacant land, asphalt, building) (A. Hoyano et al. 3, 1999).

Based on these research results, it can be seen that while it is expected that the use of permeable pavement material to solve the problem of local high temperature in urban areas could be effective in establishing more pleasant external environments and in reducing cooling load for buildings, local pavement change in some regions is more or less limited to controlling microclimate. In the end, it is conjectured that efforts for balanced land pavement improvement for the entire urban area can lead to the control effect of urban microclimate.

3. Evapotranspiration analysis according to land surface change

Simultaneously consider both water circulation and energy circulation by selecting a facility, from among decentralized rainwater management facilities, where it is possible to have land surface change in order to apply to the target site so that the varying evapotranspiration can be analyzed.

3.1 Scenario setting

① S1. Existing situation – impervious surface

Analyze evapotranspiration for the existing parking lot situation. The total area is 553 ㎡, and both the parking surface and parking road are composed of asphalt pavement.

② S2. Partial removal of impervious pavement surface

By replacing the parking surface within the parking lot with lawn blocks, part of the impervious pavement surface is transformed into pervious surface. The parking road where vehicle transportation is frequent was left unchanged and retained the asphalt pavement surface. The replaced area accounted for 332 ㎡, which is 60% of the total area.

③ S3. Establishment of green-type infiltration facility in the parking lot

The green area in the existing parking lot was established as a flowerbed type infiltration system that allowed both the infiltration and storage of rainwater. The area of the system was 115 ㎡, which 20% of the total area.

④ S4. Partial removal of impervious pavement surface & the installation of infiltration system

As an integrated application example of S2 and S3, the parking lot surface was made into lawn blocks with asphalt parking road and adopted a flowerbed type infiltration system for the green zone in the parking lot. Compared to the existing situation, about 80% of the total area was free from pavement in this new form which induces active evapotranspiration and infiltration/storage of rainwater.

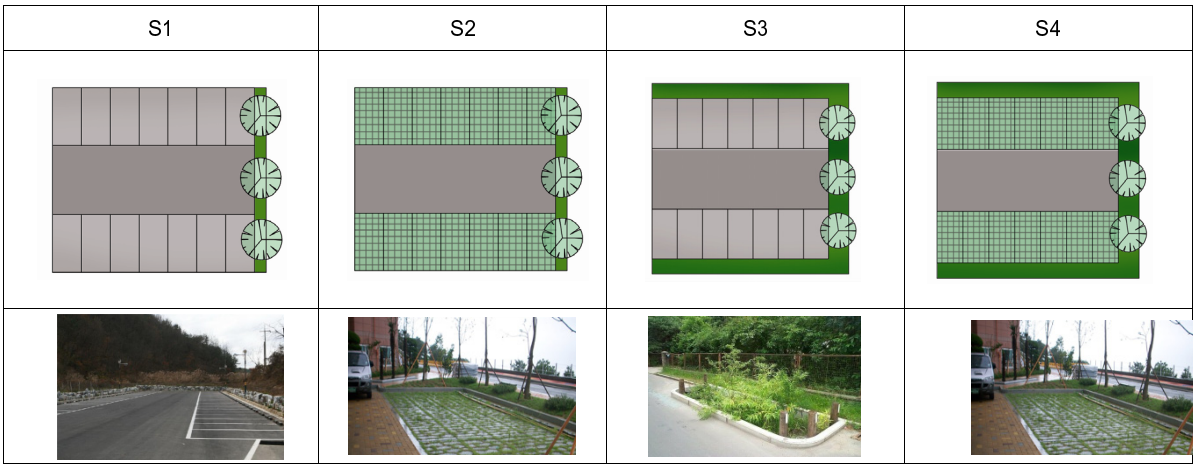

Fig.2 Content and application example of the Scenario

3.2 Analysis method

The evapotranspiration of the target site was obtained by using the Catchment hydrologic cycle Assessment Tool (CAT) for each scenario. In this program, the estimation of latent evapotranspiration that encompasses evapotranspiration from soil and vegetation cover, transpiration, sublimation, the evapotranspiration from the land surface is based on the Penman-Monteith method.

The Penman-Monteith method accounts for elements to explicate energy to maintain evapotranspiration, strength of mechanism to remove vapor, aerodynamic resistance, and surface resistance. The formula for this method is as follows (Korea Institute of Construction Technology, 2011).

$$\lambda E = \frac{\Delta \cdot (H_{net} - G) + \rho_{air} \cdot c_p \cdot [e_z^0 - e_z]/r_a}{\Delta + \gamma \cdot (1 + r_c/r_a)} \qquad \text{Formuala 1}$$

Here,
λ: latent heat strength (MJm-2d-1)
E: Depth of evaporation rate (mm/d)
Δ: Slope of Saturated Vapor Pressure-temperature curve de/dT (kPa/℃)
Hnet: net radiation (MJm-2d-1)
G: heat flux density to the ground (MJm-2d-1)
P air: Air density (kg/㎥)
Cp: Specific heat in a certain pressure (MJkg-2d-1)
e0z: Saturated Vapor Pressure at the height of z (kPa)
ez: Vapor pressure at the height of z (kPa)
v: the psychrometric constant (kPa/℃)
rc: vegetation cover resistance (s/m)
ra: Spreading resistance of atmosphere (aerodynamic resistance) (s/m)

As for the actual evapotranspiration (ET_method), the Penman-Monteith method was used to calculate latent evapotranspiration. The monthly crop coefficient (FAO 56) was then considered to obtain actual evapotranspiration.

Table. 2 monthly crop coefficient

Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
0.3	0.3	0.3	0.3	0.5	0.5	0.5	0.5	0.5	0.3	0.3	0.3

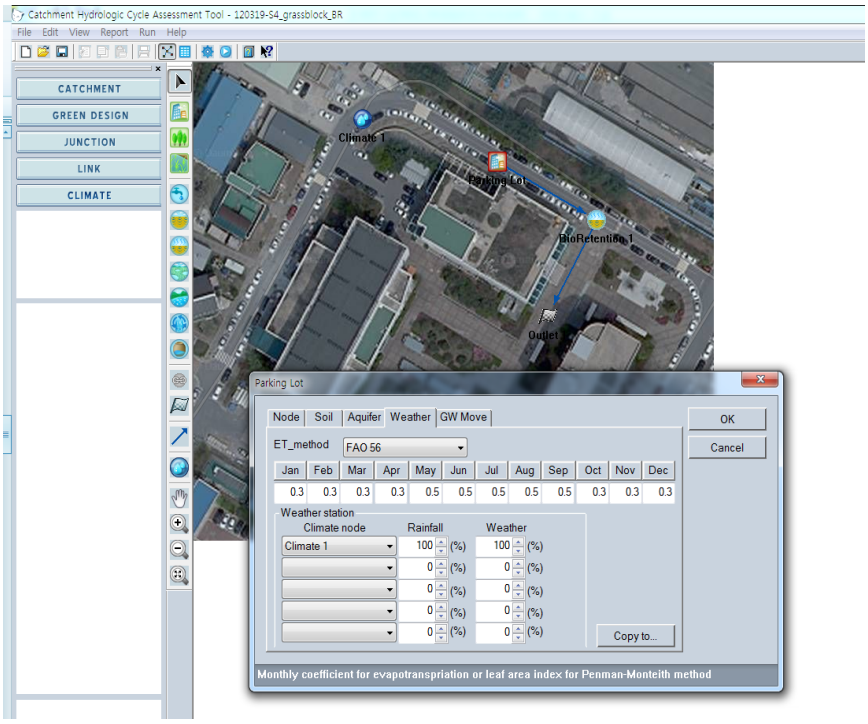

Fig. 3. Pilot Evapotranspiration view of S4

3.3 Analysis result

The analysis of the climate data from January to December 2001 resulted in the evapotranspiration by each pavement type as shown below.

It was found that about 140mm of rainwater was evaporated over a year in asphalt pavement, 380mm was evaporated in lawn blocks, and 393mm in the flowerbed type infiltration system. The value for lawn blocks is about 2.7 times higher in evapotranspiration per unit area than that of asphalt. In the analysis, it was found that the difference between lawn blocks and flowerbed type infiltration system was not very significant.

When the actual annual evapotranspiration of the target site was calculated, it was found that the evapotranspiration of Scenario 2 was about 2 times higher than Scenario 1 and 1.36 times higher than Scenario 3. A comparison of evapotranspiration between these cases, in which part of the impervious pavement surface was replaced with lawn blocks and in which a flowerbed type infiltration system was implemented, demonstrates the critical influence of how much area is changed into pervious surface in the total target site over its evapotranspiration.

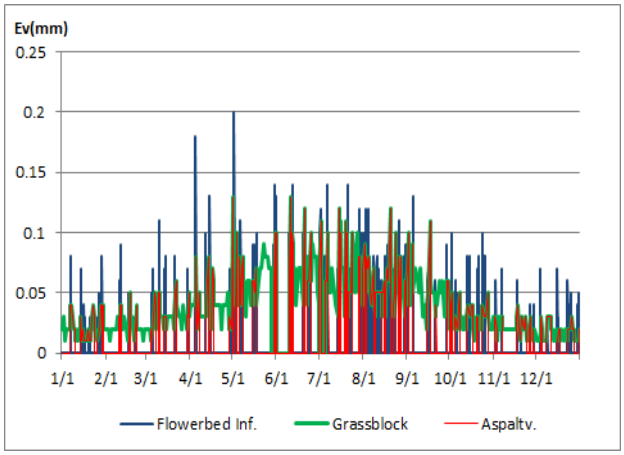

Fig. 4. Daily evapotranspiration for each implemented facility (2001climate data)

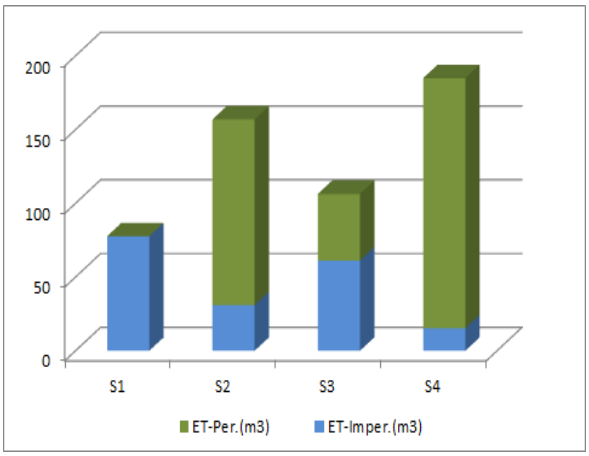

Fig. 5. Evapotranspiration by different scenarios

The latent heat generation by evapotranspiration for each scenario is represented in Table 1. This allows us to expect that when temperature rises due to the energy from solar radiation entering the area and ground reflection, it can decrease temperature just as the relevant values.

Table 3. Evapotranspiration & latent heat of evaporation by different scenarios

	S1		S2		S3		S4		
	Imper.	Per.	Imper.	Per.-GB	Imper.	Per.-BR	Imper.	Per.	
								Per.-GB	Per.-BR
Area(m2	553	0	221	332	438	115	109	328	115
Eta(mm/yr)	140	0	140	379	140	393	140	379	393
total(m3/yr)	77.7		157.0		106.7		185.0		
LHE (Kwh/yr.)	52,836		106,760		72,556		125,800		
LHE (Kwh/㎡ yr.)	95.54		193.0		131.2		227.5		

LHE: Latent heat of Evaporation (kWh)

4. CONCLUSION

To solve the problem of locally occurring high temperature while inducing natural water circulation in urban areas, it is first necessary to remove the pavement from impervious surfaces and turn them into pervious surfaces to induce infiltration and evapotranspiration. Such a measure is expected contribute to the establishment of a pleasant external environment and a decrease in cooling load for buildings, as well as other benefits. Nevertheless, it can be seen that partial pavement changes in some regions is more or less limited to controlling microclimate. In the end, it is conjectured that efforts to achieve balanced land pavement improvement for an entire urban area can lead to a controlling effect of urban microclimate.

As shown in the analysis results in accordance with the several scenarios presented, it was found that the amount of area changed into pervious surface in the total target site has crucial influence over evapotranspiration.

In Germany, studies that focus on decentralized rainwater management are being conducted. It was revealed by many studies that decentralized infiltration is significantly more beneficial than traditional rainwater drains, but this approach fails to fully consider natural water circulation. The problem of urban areas is not in the decrease in infiltration rate but in the insufficient evapotranspiration arising from the lack of vegetation covered soil (Berlin Senate for Urban Development Department VI, Ministerial Building Affairs. 2010).

In consideration of this problem, it is necessary to fully reconsider energy balance and water circulation for urban planning and water control in relation with the current climate change.

POSTSCRIPT

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