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Assessment of hydrologic and environmental performances of green roof system for improving urban water circulation

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ABSTRACT

This study was conducted to assess the applicability of green roofs as a low impact development (LID) technology to reduce storm water runoff volume and nonpoint source pollutants. Specifically, the water cycle effects and pollutant removal efficiency through six monitoring results were analyzed. Based on the results, the green roof system achieved an average runoff discharge rate of 72% for storage, exhibiting a rainfall outflow reduction rate of about six times greater than that of the ordinary concrete rooftop. The average reduction efficiency of pollutants was 77%, 43%, 74%, 57%, and 43% for TSS, BOD, TOC, TN, and TP, respectively. In addition, the reduction efficiencies for heavy metals, including Cu and Zn, and isomers such as n-H were all greater than 72%. However, this removal efficiency was highly dependent on rainfall, which was observed specifically for nutrients, including TN and TP, which showed a negative removal for a 40 mm rainfall. Therefore, it seems to be better when the green roof system was installed with LID technologies such as infiltration trenches, rain gardens, infiltration planters, and other infiltration facilities.

Keywords: Green roof system; Low impact development; Nonpoint pollution source; Runoff reduction

1. Introduction

Recently, the global patterns of rainfall have changed due to climate change, resulting in weather anomalies, including flood, heavy snowfall, and drought [1]. Korea is not an exception in this regard, and local floods and droughts have occurred repeatedly with increasing damage [2]. In addition to climate change, various development projects and urbanization have turned permeable areas, where rainwater may be absorbed into the ground, into impermeable areas such as roads, buildings, and bridges, making the floods and droughts worse by increasing the surface runoff of storm water. Recently, the Ministry of Environment reported that the ratio of impermeable areas, which was just 3% of the entire territory in the 1970s, increased to 22.4% until 2012, except for the water system and forests. Also, over 20% of the areas in Seoul and other metropolitan cities are paved as impermeable areas [3]. The increase in impermeable areas in urban regions not only causes floods and droughts but also various other environmental problems such as exhaustion of groundwater and urban heat islands.

Rainwater management was performed in the past to prevent floods by using large disaster prevention facilities such as dams, storm sewer networks, retention facilities,

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and rainwater pumping stations. Recently, some of the large-scale disaster prevention facilities failed to tolerate the storm water runoff, as the volume of the runoff exceeded the design capacity due to the climate change and urbanization [4]. Hence, the expenditure for establishing new facilities and up-scaling the facilities also increased. In this situation, the application of low impact development (LID) has drawn much attention in being able to manage rainwater at a small scale through infiltration, retention, evapotranspiration, and reusing of rainwater at the location where runoff is generated. LID facilities help to maintain the hydrologic features of land before urban development, even after urbanization, by reducing the storm water runoff volume through increasing the permeable area in a city with large impermeable areas. LID facilities may be installed in urban green areas such as parks, green areas, flower gardens, and roadside tress by using environmentally friendly materials, including wood, soil, gravel, and microorganisms. In addition, LID facilities may prevent floods and deterioration of river water quality by reducing storm water runoff and nonpoint source pollutants through infiltration and retention in soil and filter medium. They can also provide other various effects, including the recharge of groundwater, relief of urban heat islands, provision of biotops through planting vegetation, and improving the landscape. In combination with the citizens' desire to enjoy an elevated living environment, LID may be an optimal method for solving the cities' water environment problems.

Among LID facilities, green roof systems can reduce storm water runoff by filling the roofs of buildings with soil and filter mediums and planting vegetation, as building roofs account for the largest portion of the impermeable areas in urban regions. Since 2006, studies on LID have been steadily conducted and various relevant guidelines and instructions have been developed. However, studies on green roofs are still limited. In the present study, the performance of a green roof system installed on the roof of a post office in the Seogok region in Jeonju, Korea, for reducing pollutants and storm water runoff was assessed, and an appropriate design of green roof facilities was suggested on the basis of the assessment results. The results of the present study may provide meaningful fundamental data for the future design and expansion of LID facilities.

2. Materials and methods

2.1. Design of green roof system

The green roof system of the present study was installed on the roof of a post office in the Seogok region in Jeonju, Korea (Figs. 1 and 2). The roof's area was 120 m^2, and sand was spread up to the height of 50 cm for the retention of storm water runoff. The design's rainfall retention capacity was about 70 mm of rainfall. On top of the sand, grass (*Zoysia japonica* Steud.) was planted. The green roof system had three effluent outlets at which the flow rate and the pollutant concentration were monitored. The efficiency of the green roof system in reducing storm water runoff was analyzed by applying the study of Hong et al. [5] where the monitoring was performed with a concrete roof of a university's student hall located in Cheonan, Chungnam, Korea and analyzed the characteristics of the pollutant effluent. The area of the student hall's roof was 161 m^2, and the monitoring was performed eight times as exhibited in Table 1. Total rainfall was in the range of 1.5–22.5 mm, with an average of 5.7 mm and total runoff was in the range of 0.03~2.76 m^3/min. The antecedent dry days (ADD) ranged from 1.4 to 21.3 d and average rainfall intensity ranged from 1.1 to 22.5 mm/h.

2.2. Methods of monitoring and analysis

The monitoring of the flow rate was performed at an interval of 5 min from the beginning of the storm water runoff to the end of the runoff. The sampling of the storm water for analyzing pollutants was performed at the time points of 0, 5, 10, 15, 20, and 30 min from the beginning of the storm water runoff and then at an interval of 60 min after the first hour. The inflow volume (vol) was estimated by multiplying the total rainfall and the green roof (GR) area, and the outflow volume (vol_{out}) was calculated as the sum of the flow rates measured at the three effluent outlets. The difference between the inflow volume and the outflow volume is the reduced volume (vol_{red}) consisting of the evapotranspiration volume (vol_{evap}), retention volume (vol_{ret}), and loss volume (vol_{loss}). For the controls, these variables were estimated by the same method as the green roof system but were converted to the values per unit area of the green roof.

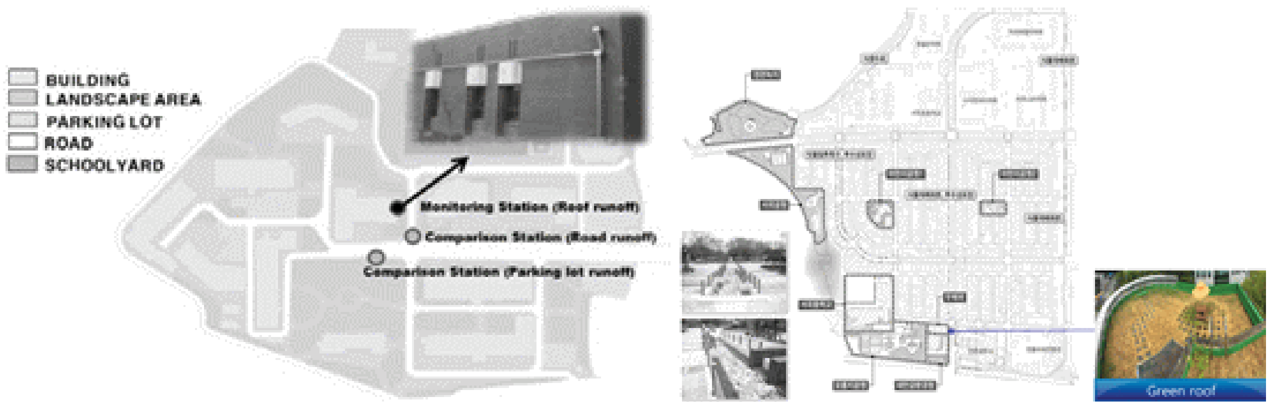

Fig. 1. Location of (a) control area and (b) green roof system.

$$\text{vol}_{\text{red}} = \left(\text{vol} - \text{vol}_{\text{out}}\right) = \text{vol}_{\text{evap}} + \text{vol}_{\text{ret}} + \text{vol}_{\text{loss}} \quad (1)$$

The total suspended solids (TSS), biochemical oxygen demand (BOD), total organic carbon (TOC), total nitrogen (TN), total phosphorous (TP), n-hexane (n-H), copper (Cu), zinc (Zn), and chloride (Cl^-) of the collected samples were analyzed by the standard method of examination of water and wastewater [6]. The treatment efficiency was estimated by calculating the event mean concentration (EMC) of the effluent from the green roof system and the control [2,7]. The EMC of the concrete roof (control), from which nonpoint source pollutants were discharged, was assumed as the EMC of the inflow to the green roof system for the estimation.

3. Results

3.1. Rainfall and runoff characteristics

Table 2 shows the characteristics of the rainfall events monitored in the present study. The rainfall was in the range of 10.2–47.5 mm, and the average rainfall was 24.4 mm. Although the amount of rainfall in most of the rainfall events occurring in Korea is 10 mm or less [8], the monitoring was performed only for the rainfall events that had an amount of rainfall of 10 mm or more because the preliminary experiment showed that no runoff was generated from the roof's green system in the rainfall less than 10 mm. The ADD were in the range of 2–7 d. The rainfall intensity was in the range from 1.1 to 5.2 mm/h, and the average was 2.8 mm/h. The average rainfall intensity found here was almost similar to the average rainfall intensity in Korea implying that it represented the characteristics of rainfall in Korea.

3.2. Water balance analysis

To analyze the storm water runoff retention by the green roof system, the water balance between the rainwater inflow and outflow was analyzed for the green roof system and the control system (Fig. 3 and Table 3). In the concrete roof, the retention was from a minimum of 0.01 m^3 to a maximum of 0.7 m^3 in the range of rainfall from 10.2 to 47.5 mm, and the average retention was 0.32 m^3. The runoff reduction

Fig. 2. Figure of green roof.

Table 1
Event table conducted by Hong et al. [5]

Event No.	ADD (d)	Total rainfall (mm)	Total runoff (m^3/min)	Total rainfall duration (h)	Total runoff duration (h)	Average rainfall intensity (mm/h)
1	3.5	3.0	0.80	2.1	2.0	1.4
2	2.7	2.0	0.18	1.1	1.0	1.9
3	20.7	1.5	0.16	1.4	1.0	1.1
4	1.4	2.0	0.03	1.1	1.0	1.9
5	2.0	22.5	2.76	1.1	1.0	20.1
6	6.8	7.0	0.77	4.0	3.8	1.8
7	10.4	2.5	0.29	3.8	3.0	0.7
8	21.3	5.5	0.86	2.1	2.0	22.5
Average	8.6	5.7	0.7	2.1	1.8	6.4

Table 2
Statistical summary of monitored storm events ($n = 6$)

Parameter	Minimum	Maximum	Median	Mean	S.D.[a]
ADD, d	2	7.0	3.5	4.3	2.2
Total rainfall, mm	10.2	47.5	24.3	24.4	13.3
Total rainfall duration, h	1.87	11.5	8.3	7.7	3.3
Rainfall intensity, mm/h	1.1	5.2	2.8	2.8	1.6

[a]Standard deviation

rate was in the range from 0.4% to 50% with an average of 11%, which was very low. In the green roof system, the runoff reduction rate was in the range from 48.3% to 92.8% with an average of 72%, indicating that most of the rainwater could be retained. In particular, the runoff reduction rate was high (48.3%), even in Event 3 with much rainfall (rainfall intensity: 5.1 mm/h; rainfall: 47.5 mm), suggesting that the installation of many green roof systems on many buildings in urban areas may significantly prevent flood damage. The amount of runoff reduction per unit area was 3 L/m^2 for concrete roofs, but that of the green roof system was in the range of 8–23 L/m^2 with an average of 17 L/m^2. Therefore, the amount of runoff reduction per unit area was about six times higher in the green roof system than in the concrete roof.

Fig. 4 shows the water balance in each rainfall class, wherein the rainfall was divided into the classes of 10 < rainfall < 20 mm, 20 < rainfall < 30 mm, and

Table 3
Water balance analysis of control (CA) and green roof system (GR)

Monitoring no.	Amount of storage (m^3)		Outflow rate (m^3)		Total reduced rate (%)		Amount of reduced volume per unit area (L/m^2)	
	CA	GR	CA	GR	CA	GR	CA	GR
1	0.7	2.9	2.6	0.4	21.2	87.8	5.8	23
2	0.5	1.3	1.0	0.1	33.3	92.8	4.2	11
3	0.06	2.9	5.6	3.1	1.1	48.3	0.8	23
4	0.01	2.0	2.8	0.8	0.4	71.4	0.08	16
5	0.5	2.6	2.5	0.4	16.7	86.6	3.3	21
6	0.6	1.0	0.6	0.1	50.0	90.9	4.2	8
Average	0.32	2.1	2.6	0.81	11.0	72.0	3	17

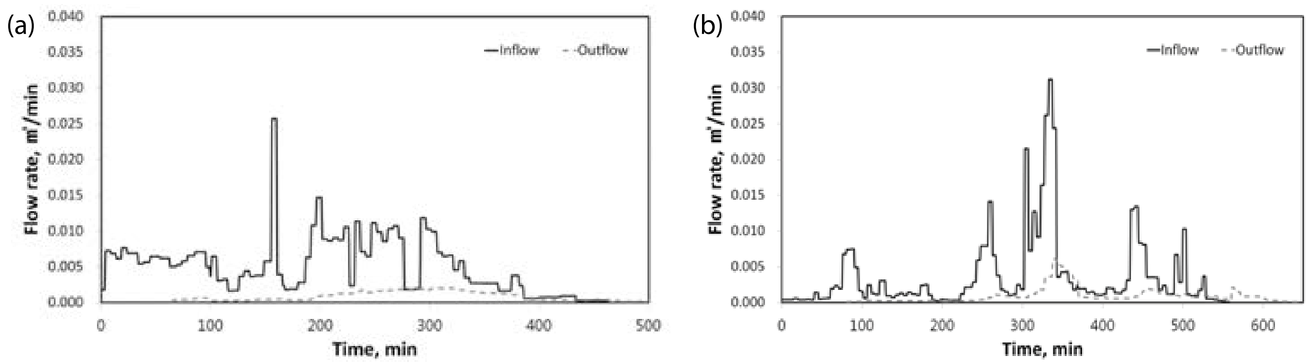

Fig. 3. Inflow and outflow hydrographs for (a) Event 1 and (b) Event 5.

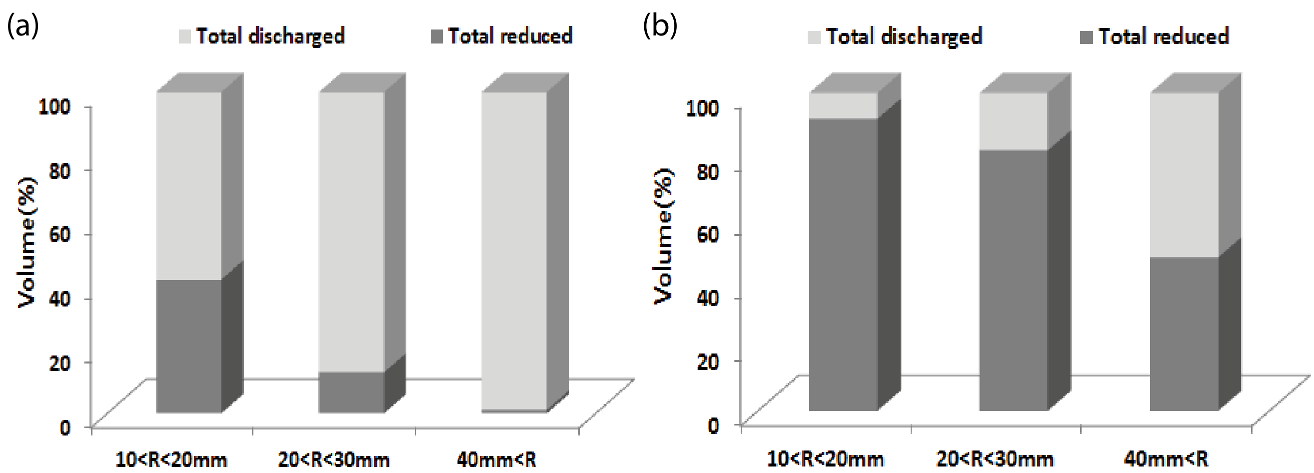

Fig. 4. Comparison of water balance in the (a) control area and (b) green roof system at varying rainfall depth ranges.

40 mm < rainfall based on the monitoring results. In contrast to the concrete roof, the average runoff retention rate was very high (91%) in the rainfall class between 10 and 20 mm, and it was also high (81%) in the rainfall class between 20 and 30 mm. As described above, the average runoff retention rate in the rainfall class over 40 mm was also high as 48.3%, but further studies are needed because of the limited monitoring in the present study.

The runoff retention rate found in the present study was slightly higher than that of other LID facilities (tree box filter: 63%; small constructed wetland: 39%; tree filtration facility: 45%), but lower than that of the rain garden (98%) and bioretention system (89%) [9–12]. The capacity of storm water runoff storage of LID facilities may be increased by deepening the soil or filter medium layer to increase the vacancies between the filter medium particles. About 25 to 50 cm of filter medium is filled in a green roof system, which depends on the specific weight of the filter medium and the load [13]. Therefore, the filter medium layer is relatively shallow in a green roof system in comparison with other LID facilities. However, the storm water retention rate was high in the present study, despite the shallow filter medium layer, because the rainwater underwent absorption and evapotranspiration due to the grass planted at a high density.

Fig. 5 shows the regression analysis of the variation of the retention and runoff volume in a green roof system depending on the rainfall amount. The plot shows that the retention decreased, and the runoff increased as the rainfall increased. The retention rate was over 60% up to the rainfall of about 35 mm, but it drastically decreased as the rainfall increased. The retention rate was below 40% in the rainfall events with more than 50 mm of rainfall.

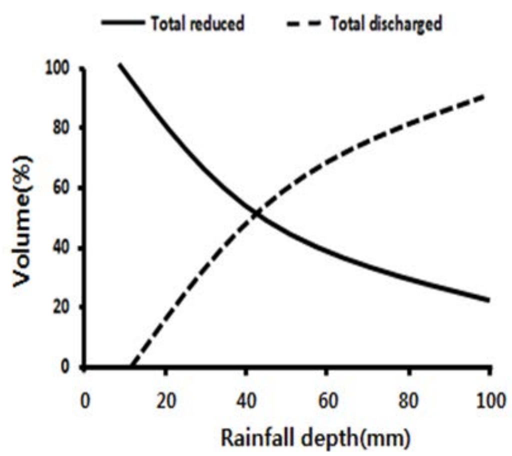

Fig. 5. Regression plot of discharged and reduced volume at varying rainfall depths.

3.3. Analysis of pollutant reduction efficiency

The pollutant reduction efficiency was calculated to evaluate the performance of the green roof system to reduce nonpoint source pollutants (Table 4). The monitoring that was performed six times in the present study showed a satisfactory average removal rate from 43.5% and 98.4% in all the pollutant variables. In particular, the removal rate of n-H, heavy metals such as Cu and Zn and Cl^- was in a high range from 69.5% to 98.4%. The pollutant removal efficiency was relatively low in BOD, TN, and TP. The standard deviation of the removal efficiency for TN and TP was high, suggesting that the pollutant removal efficiency was significantly varied by a factor, which was proved in Fig. 6 to be the amount of rainfall.

Fig. 6 shows a log-regression analysis of the removal efficiency of individual pollutants in the green roof system depending on the rainfall. Overall, the pollutant removal efficiency was significantly affected by the rainfall. The plot in Fig. 6 shows that the TSS and TOC removal efficiency remained constant at over 50% as the rainfall increased up to 50 mm. On the contrary, the removal efficiency of other pollutants significantly decreased as the rainfall increased. Particularly, the TN and TP removal efficiencies were greatly decreased by an increase in the rainfall, even recording a negative efficiency at rainfall over 40 mm. This may be because the nitrogen and phosphorous included in the fertilizer for the plant growth in the green roof were discharged together with the storm water runoff. This suggested that a green roof facility may accomplish the dual purposes of storm water runoff volume reduction and nonpoint source pollutant removal up to the rainfall of 20–30 mm. However,

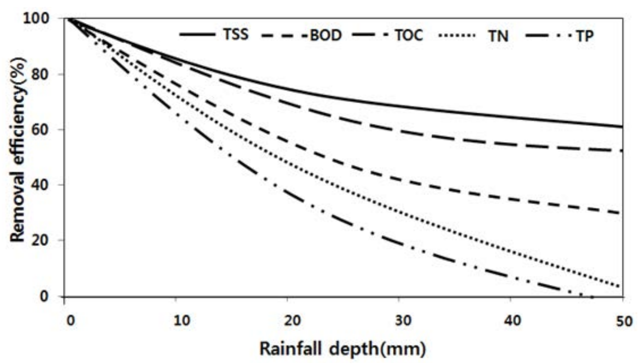

Fig. 6. Regression plot of pollutant removal efficiency with respect to rainfall.

Table 4
Pollutants removal efficiency of green roof system

Parameter	TSS (%)	BOD (%)	TOC (%)	TN (%)	TP (%)	n-H (%)	Cu (%)	Zn (%)	Cl^- (%)
Average	77.0	42.4	74.2	57.8	43.6	98.4	72.7	92.4	69.5
S.D.	13.6	25.6	14.2	35.4	30.2	1.9	23.3	6.7	0.2

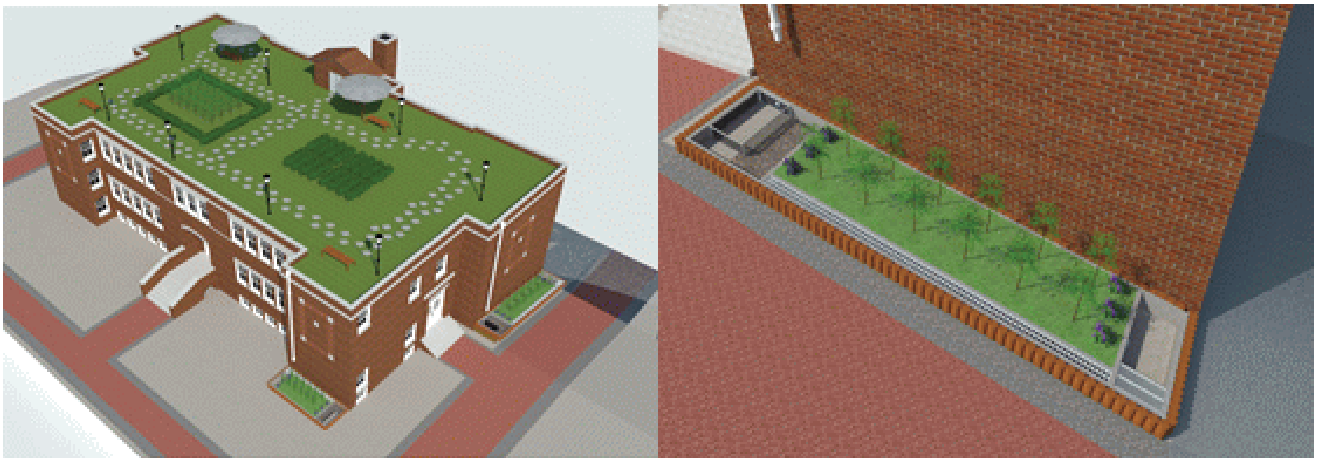

Fig. 7. LID technology conceptual design including green roof system.

for the rainfall events with more rainfall where nitrogen and phosphorous are discharged together with the storm water runoff, a green roof facility should be installed by focusing more on the effect of preventing urban floods rather than the effect of removing nonpoint source pollutants.

3.4. Appropriate design of green roof system

In 2016 when the monitoring was performed, the summer drought was long, and the rainfall was concentrated during fall. Monitoring may need to be performed continuously in the future for various rainfall events to evaluate the appropriateness of the green roof system's design and efficiency. In the present study, an appropriate design for the green roof system was suggested on the basis of the results obtained from the six times of monitoring. The comparison of the EMC measured at the three effluent outlets of the green roof system with the overall EMC showed that the EMC of the pollutants, with the exception of n-H, was similar to the overall EMC. This indicates that the pollutant's concentration at different outlets may be similar if the green roof system was constructed uniformly. This shows that cost-effective water quality monitoring may be performed by using the green roof system. In the six times of monitoring performed in the present study, the storm water runoff reduction rate was 72% at an average rainfall of 24.4 mm, rainfall intensity of 2.8 mm/h, and ADD of 4.3 d. This corresponds to the accumulated rainfall of 18 mm, which is about 26% of the design's rainfall tolerance of 70 mm. Therefore, if the water content in the soil is very low due to a long dry season, the entire design's rainfall tolerance may be retained. However, only a small amount of rainwater may be retained if the rainfall is concentrated on the summer season or if the soil content is high due to a large ADD. Nevertheless, the storm water retention may be higher at an ADD value representing all the rainfall events in a year. This is because the retention volume in the present study was found at an average ADD of just 4.3 d. The results of the present study also showed that the pollutant removal rate was greatly dependent on the rainfall. Particulate materials, organic materials, and nutritive salts may be discharged more at a higher rainfall from the

Fig. 8. Plant mortality in summer season.

soil charged in the green roof system for plant growth and storm water runoff retention. Therefore, the effect of pollutant removal may be enhanced by installing infiltration trenches, rain gardens, and infiltration flowerpots beside the buildings (Fig. 7).

In 2016, many plants in the green roof system withered away due to long-term heat and water shortage and rainfall events not occurring under strong sunlight in summer (Fig. 8). This suggests that the plants planted in the green roof system should be those that can tolerate high water content as well as strong sunlight in summer. In addition, the runoff from a green roof system may be stored in a rainwater tank that is well matched to a building in order to appropriately reuse the water for the gardening of the plants in the green roof system during a dry season.

4. Conclusions

The present study was conducted to assess the applicability of a green roof system as an LID facility for reducing nonpoint source pollutants and storm water runoff. The water circulation effect and the pollutant removal efficiency were analyzed through six times of monitoring in the present study. The results showed that an average of 72%

of the storm water runoff was retained by the green roof system, indicating that the storm water runoff reduction rate was about six times higher than that of the general concrete roof (11%). The storm water runoff retention rate of the green roof system was 91% in the rainfall class between 10 and 20 mm, 81% in between 20 and 30 mm, and 48.3% over 40 mm, showing that the green roof system was more effective than the tree box filter and small-scale constructed wetland facilities. The average pollutant removal efficiency was 77% for TSS, 43% for BOD, 74% for TOC, 57% for TN, and 43% for TP. The removal efficiencies of TSS and TOC were particularly high, but that of TN and TP, the nutritive salts, were low. The removal efficiency of n-H as well as that of Cu and Zn, the heavy metals, was also high over 72%. These results showed that the green roof system has an excellent effect in circulating water to prevent floods in rainfall events and in removing nonpoint source pollutants. However, the pollutant removal efficiency was significantly dependent on the amount of rainfall, even recording a negative value of the nutritive salt removal rate in a rainfall over 40 mm. Therefore, the pollutant removal efficiency may be increased by installing other facilities such as trenches, rain gardens, and infiltration flowerpots beside the buildings with a green roof system.

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