공학석사학위논문

Study on Hydrologic Performance Evaluation of Green Roof System with Storm Green Roof Response (SGRR) Model

옥상녹화 시스템의 수문학적 성능평가 및 SGRR(Storm Green Roof Response) Model의 적용

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서울대학교 대학원
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지도교수 한 무 영

이 논문을 공학석사학위논문으로 제출함

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김 현 우

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위 원 장 김 재 영 (인)

부 위 원 장 한 무 영 (인)

위 원 남 경 필 (인)

Abstract

Study on Hydrologic Performance Evaluation of Green Roof System with Storm Green Roof Response (SGRR)

Kim, Hyunwoo
Department of civil and environmental engineering
College of engineering
Seoul National University

Until now, hydrological aspect of the green roof system has not been well known due to the focused attention to its aesthetic and thermal effects. However, since the limitation of the infrastructure expansion to the flood that occurred in the center of the big cities, green roof arose as an alternative solution. But, the absences of the evaluation method for the green roof system's hydrological performance as well as a clear standard from green building certification program give the difficulties to the quantifying the effect and proper application of the system.

Thus, the evaluation technique of the hydrologic performance of green roof system was developed in this research, and this technique laid the foundation of objective comparison and proposal of optimum green roof system by evaluating performance quantitatively.

First, the performance evaluation factors were developed by analyzing hydrologic mass balance of green roof system. In this situation, the standards of performance evaluation are the flood mitigation effect and water resource management effect. The flood mitigation is evaluated by peak flow reduction ratio and peak flow time delay factors, and the water resource management is evaluated by total retention factor. This makes the reasonable evaluation of hydrologic performance of green roof system and the evaluation factors has reliability by the possibility of equivalent application at different climate and rainfall condition.

On the basis of Lab & Field scale experiment applied performance evaluation factor developed in this study, Analysis of experimental group performance about evaluation item and performance difference depending on natural and material conditions was investigated. From that test, Investigation about possibility of Green roof system performance evaluation depending on different type of green roof on basis of same performance evaluation factor. and then, Performance analysis about material conditions (soil, vegetation, drain board), natural conditions (rainfall, evapotranspiration) was analysed.

Finally, Storm Green Roof Response (SGRR) Model simulated the runoff of green roof system was used for evaluating the performance by applying developed factors. Then it was estimated the possibility for the performance evaluating model. This model simulates runoff

quantity by using Modified Pul's Method from inflow and out flow relationship equation. The material conditions like soil and plants are possible to modify easily but the evapotranspiration amount is the natual conditon and difficult to get the data normally, so the model is calibrated based on the measuring evapotranspiration data from Seoul National University No. 35. This model shows that high similarity between modeling result and experimental result at performance evaluation. So It is considered that being adaptable to hydrologic performance evaluation of green roof system.

Keywords : Rainwater, Green roof, Flood mitigation, Water storage, Hydrologic performance evaluation

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CHAPTER1. Introduction

1.1. Background

Reduction of the city's green area due to escalation of pavement areas through rapid urbanization causes various environmental issues such as disturbed water circulation and heat island of the city(Schoz-Barth, 2001, Barnes et al., 2001, Stone, 2004, Scholz, 2004). Also the serial flood damages from the strong rainfall circumstances as a result of recent climate change frequently goes beyond the city's flood mitigation infrastructure's limit are promoting the request of new water management strategy to confront the climate change(Villarreal et al., 2004, Sansalone et al., 2008, Han et al., 2012, Kim et al., 2012).

In the past, stormwater management focused on conveyances to route stormwater runoff from urban centers into nearby rivers, streams, and lakes. Dramatic engineering solutions – often for flood control – include armoring streambanks with concrete or riprap, straightening channels, and stream piping. Yet increased stormwater flows can be amplified by kinematic processes as they travel through a municipality′s storm sewer system. These centralized flood prevention infrastructure exhaust high expense and energy to alternate or expand in the cities with many skyscraper and no unused land and creates inconvenience to the local citizens. But most of all, it is not sustainable in current climate change tendency thus builds the vicious circle that requires constant expansion and substitution. Hence it is necessary to supplement the current centralized flood prevention infrastructure and enlarge the distributed detention storage for the sustainable water management of the future(VanWoert et al., 2005, Mentens et al., 2006, Fioretti et al., 2010, Han et al., 2013).

Typical dispersal detention storage facilities include green roof, rainwater store system, and pervious pavement. Among these facilities, green roof is favored as the alternative method to the flood prevention because it utilizes the existing infrastructure of the city, recovers the pervious surface for the preservation of the rainwater, and also provides the green land.

A green roof consists of four district layers: an impermeable roof covering that serves as a root barrier, a drainage net or layer, lightweight growth media, and adapted vegetation(Figure 1). The drainage layer is an open, highly drainable material that quickly channels gravitational water to the roof discharge points. The growth medium performs several functions. In addition to providing a suitable rooting zone for the selected vegetation, the medium should be of low density and have high water-holding capability. The thickness of the medium and its capillary and gravitational water holding capacity play and important role in stormwater retention and attenuation of extreme rainfall events. The plants intercept rainfall, slow its movement into the rooting medium, and are a measurable portion of the green roof's water storage capacity (Miller, 1998).

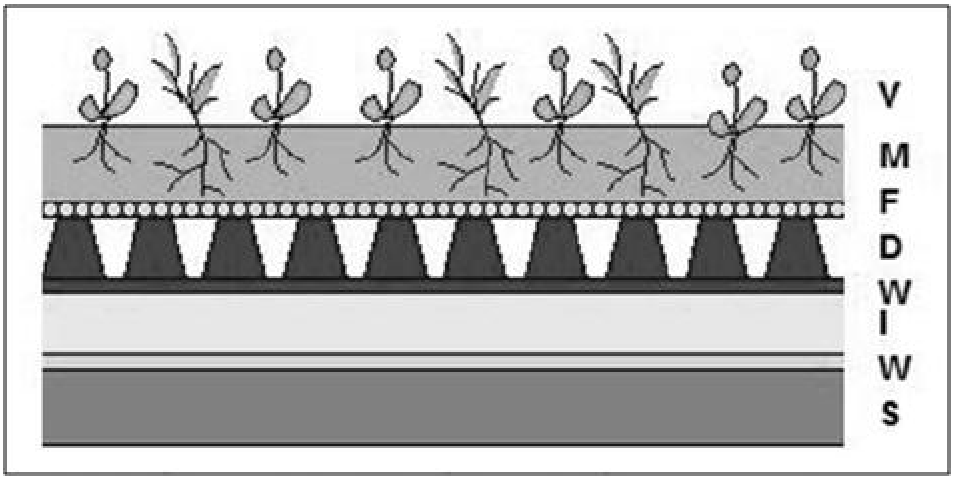


Figure 1. Layers of a green roof unit (V: Vegetation, M: Growing medium, F: Filter membrane, D: Drainage layer, W: Waterproofing/roof barrier, I: Insulation and S: structural support) (Oberndorfer, Lundholm et al. 2007)

The green roof are generally categorized as "intensive" or "extensive" systems depending on the plant material and the planned usage for the roof area. Intensive green roofs normally imitate landscape found at natural ground level by using a wide variety of plant species, even trees and shrubs needing deeper media thickness (usually > 15 cm). Intensive green roofs are often installed as outdoor recreational space with an ability to bear extra weight coming from intense vegetation and human occupancy. With their usually deeper soil medium, intensive green roofs can accommodate a wide range of plants, edibles, shrubs, and even trees requiring regular maintenance and irrigation.

In contrast, extensive green roofs generally require nominal maintenance. They are normally not accessible to the pulic. Because of their shallower media depth (<15 cm), plant species are limited to herbs, grasses, mosses, and drought-tolerant succulents such as sedum. In addition, extensive green roofs can be built upon a sloped surface for proper drainage. They usually require less structural support than intensive green roofs, and are considered to be more environmentally effective(Paudel 2009).

Actually, the building green movement is not new, nor is the practice of using natural resources responsibly to sustain life and encourage the regeneration of natural resources. In the last ten years, the term green roof has taken on ecological and social significance beyond its seemingly simplistic description. As commonly understood, the term has become an epithet for the reduction of pollution and urban heat islands, for large scale mitigation of stormwater runoff, and for maximum utilzation of urban land(Weiler, 2008).

Since 2003, Seoul required the green roof system on public buildings and also on large buildings and proceeding continuous green roof supporting business on private buildings. So far, green roof is installed in about 400 buildings, total area of 160,000m2, however, it only counts for 0.1% of the total roof area of the Seoul. The percentage is unbelievably low respect to increased attention of the public, proving that green roof is not earning enough social support towards the effectiveness of the green roof system.

In case of foreign countries, there have been active researches on quantification of the flood reduction effect of green roof, but in case of Korea, related researches are still insufficient. There has been few attempts to quantify the green roof's flood control effects on Korean climate, where the high humidity and intensive rainfall occur, but mostly ceased in lab scale and had difficulties due to various factors involved with the run off. Even Seoul does not have the confidence over sure effectiveness although they are supporting green roof system politically. Also, even though the green building certification program gives extra points on green roof in Environment-friendly category, unclear numerical value towards the effectiveness degrades the usefulness of the program by giving large points to the application of poor quality green roof system.

1.2. Objectives

Hence this research develops the credible evaluation factor and method to test hydrological aspect of green roof system and improves the existing green roof run off model as an evaluation model.

Specific objectives are as follows.

(1) Developed hydrological performance evaluation by analyzing factors that involves with green roof system's runoff and applying it to Seoul National University(SNU)'s green roof case in building No.35.

(2) Established hydrological performance evaluation model by using existing green roof runoff model

(3) Raised the credibility of green roof's hydrological performance evaluation model through developing accuracy of the model by Korean climate conditions modification and accomplishing concise verification.

1.3. Research scheme

This research is consisted of three sub researches in order to achieve each sub objectives. First of all, this research analyzed the hydrological model of the green roof system and obtained factors to evaluate the performance of the model.

Furthermore, analyzed green roof system's run off characteristics and developed evaluation method with evaluation factors through pilot test on green roof system of SNU in building No.35.

Last but not least, discussed runoff value of the pilot tested green roof system using Storm Green Roof Response(SGRR) and modified it by comparing experiment data.

CHAPTER2. Literature review

2.1. Background

Depending on history most green roofs were functional. They were installed on buildings either for amenity or as a sign of elegance and wealth in a community (Kohler, 2004). Since green roof systems are a beneficial way to bring vegetation back into the city and help restore the natural environment, technological improvement is made on the construction aspects of green roofs in the mid-sixties, particularly in Germany and other European nations (Buesching, 2004). They have been a part of European architecture for a long time and are now beginning to take place in North America (Forrester, 2006). As the green roofs are not so publicized in North America, only little data is available on green roof's performance for quality and quantity improvement of stormwater. In this region, it is seen that the benefits of green roof technologies are poorly understood and the market is still immature. In Europe however, these technologies have become very well established (Mentens et al, 2006).

Urban development alters the hydrology of watersheds and streams by disrupting the natural water cycle (Levallius, 2005). Notable effects include increased runoff volumes, changes to stream geo-morphology, impacts to aquatic habitat and water quality impacts. In recent years, green roof as BMPs have been developed to aid in the improvement of stormwater management. However, the use of a green roof as a BMP for stormwater in an area depends on a number of hydrological and climatic factors in that particular location.

2.1.1. Selection of plants

In addition to media, Eumorfopoulou (1998) says plant uptake and transpiration increases the ability of a green roof to hold water from repeated rain events. Maximizing transpiration from the roof may thus enhance the total amount of water prevented from going into the sewer system (Kohler, 2003). The shallow substrates commonly available in extensive green roof result a periodic drought and rapid fluctuation in soil moisture. Thus drought tolerance or avoidance must be the key criterion for the selection of plant species for green roofs (Onmura, 2001).

The most successful green roof plants are low-growing, shallow rooted perennial plants that are heat, cold, sun, wind, drought, salt, insect and disease tolerant (Snodgrass, 2006). Normally, plants that are highly flammable, that develop large root systems or that are excessively "thirsty" should be avoided (Jenrick, 2005). Since most green roof medium is fractured and lack a continuous column of water that facilitates capillary action, green roof plants must be able to withstand periods of dryness and heat, a factor that eliminates most traditional annuals and perennials (Snodgrass, 2006).

Hardy succulents which display CAM (crassulacean acid metabolism) photosynthesis whereby transpiration is reduced during the day to maintain the minimum water loss are therefore the primary plants for low depth roof systems. Different varieties of succulent sedum are then the obvious and in some cases, the only choices for thin substrate, non-irrigated extensive roof gardens in temperate climates (Snodgrass, 2006).

It is therefore suggested that a basic low maintenance extensive green roof should always be planted with perennials and re-rooting plants such as sedums. Sedums are noninvasive, drought resistant, and come in a wide range of colors from blood reds to evergreens (Durhman et al., 2005). They are categorized in terms of foliage and flower color, typical bloom times and the most suitable hardiness zones, the maximum height of plant and the plant''s annual spread for coverage in particular location. Once established, they can survive on rainwater alone without any additional irrigation and can withstand high temperatures. Snodgrass et al. (2006) list more than 200 different sedum plants that can be applied in extensive green roofs.

Though different sedum plants are available, selection of a variety in a specific project normally follows a practice of using the previously tried and tested plants (Emilson et al., 2006). It is not appropriate to use the same vegetation mixes everywhere. In some places, the ability to withstand summer drought should be the main factor on plant choice, whereas in regions with severe winters, cold hardiness should play a critical role. With this reason, trialing of different species for their suitability in a particular location should be done (Dunnett et al., 2004) before installing a green roof.

2.1.2. Substrates

Except the English version of FLL guidelines developed in Germany and a couple of ASTM documents dealing with the load requirements in a green roof, there are no current specific regulations in the design of substrates for vegetated roofs in North America. These media are therefore designed as a constant trade-off between system weight requirements, substrate water-holding capacity and oxygen diffusion to plant roots. Extensive green roof systems are designed to optimize the parameters affecting runoff. Designers normally optimize different factors such as water holding capacity, weight, and hydraulic conductivity and maintain the required nutrients and moisture to favor the hardy, drought tolerant plants before recommending the media depths.

Emilsson et al., (2005) while investigating the role of establishment method on the installation of green roofs found that pre-fabricated vegetation mats have higher succulent plant cover than on-site constructed roofs. They also suggested that long-term stability of substrates against decomposition and erosion through water, wind or frost is also an important consideration. The final selection is therefore a compromise between the physical and chemical characteristics with material availability on one side and price on the other. When they analyzed substrates such as commercial soil and two other generic products made from crushed roof tiles with low and high organics, in a certain period they observed higher biomass in commercial substrate due to higher nutrient contents.

It is understood that the substrate or medium in most of the green roof cases is supplied as per the specific demand or need. Most common substrate used is custom-engineered growing medium manufactured from expanded shale, mushroom compost and mineral components. These roof media have 90 percent minerals and 10 percent organics. Whatever the media is, thought should be given on the weight of components used and their composite drainage characteristics. Lightweight aggregate with proper drainage and weed-free properties is often preferred.

Ideally, the growing medium or substrate is recommended to have the characteristic of being highly efficient in absorbing and retaining water while at the same time having free-draining properties. This is generally accomplished by granular mineral materials that absorb water and fine particles to which water will cling. Normally artificial soils can be superior to many natural soils, provided they are tailored for the specific type of vegetation they are to support and the location they are to be placed. Light expanded clay granules are widely used on their own or in combination with other materials, and fulfill the requirements of an ideal base for a green roof substrate being lightweight and having some moisture and nutrient storage capability. The most ecologically sound materials are those that are derived from waste or recycled products (Mentens et. al, 2006).

Though a wide media variety is available, the selection however normally depends on the requirement of that particular location based on a number of tradeoff factors. With the deeper medium and more organic contents, more planting options are available, but a predominantly organic medium is not recommended for extensive green roofs (Hoffman, 2005). Though it increases fertility, it also introduces a set of potential problems, including decreased pore space, higher water retention, increased nutrient loading and reduced medium depth over time caused by decomposition. One of the most important aspects of medium is that the depth should be relatively constant over a long period of time, and a highly organic medium makes this impossible.

2.1.3 Drainage layer

The main function of a drainage layer in any green roof is to protect the waterproof membrane (Connelly et al., 2005). It removes excess water or underflow as quickly as possible to prevent over saturation. This drainage layer expels the surplus water on the roof. In some cases, the drainage layer also provides extra storage as the means of irrigating the green roof and providing additional nutrients for the plants grown (Evaluation of green roof, 2007). Snodgrass et al. (2006) also recommend that an efficient drainage is needed to avoid water ponding that could diminish sufficient oxygen for root systems, ultimately leading to root diseases.

The drainage layer must be provided with evaporation holes and they can be made from drainage free materials such as gravel or plastic layers. The commonly available types are granular materials and porous mats. Coarse granular materials include gravel, stone chips, broken clay tiles, clinker, pumice, expanded shale, or expanded clay granules with large amounts of air or pores between them.

Other most common drainage components include Ethylene Propylene Diene Monomer (EPDM) membrane, granular drainage and a low profile perforated conduit, Soprema, Poly Vinyl Chloride (PVC) membrane, light weight gravel drainage medium, rubberized asphalt membrane, geo-textile filter fabric drain, modified bitumen membrane, perforated recycled plastic container drainage and nylon mesh drainage layer (Hoffman, 2005).

2.2. Stormwater quantity performance

There have been a lot of studies conducted in Europe especially in Germany on green roofs for their performance in a number of areas, while this concept in North America is at a very young stage and research is not extensively published (Corrie, 2008; Kohler, 2004). Because of this a very little data exists on the environmental benefits from the implementation of this technology in the region. Vanwoert (2004) calculates stormwater retention and water use by extensive green roofs. In his work, variables such as roof surfaces, slopes and media depths are used to compare the stormwater retention capacities.

Comparison is also made among extensive vegetated roof, extensive non vegetated roof and a gravel media roof. For a period of more than a year, the vegetated roof results retention of 60 percent of cumulative rainfall whereas the media only roof and the gravel roof retain 50 and 27 percent, respectively. He concludes that the two factors that play major role in retention are rainfall intensity and duration of any rainfall. In slope-media thickness variable the most efficient combination for retention comes out to be 4 cm thick green roof with 6.5 percent slope. This study therefore does not support an initial hypothesis of offsetting media slope by depth for more retention. Figure 2.1 shows the corresponding rainfall retention percentage for light, medium and heavy rainfalls.

In green roofs with two media depths of 102 and 51 mm, Moran (2002) evaluates runoff quantity and plant growth to compare them with a control roof. In dry months, the retention efficiency reached more than 90 percent relative to 60 percent in other seasons. The maximum achieved peak flow reduction is slightly less than 80 percent. Even in this study the depths of green roof media did not play any significant role in stormwater retention and on the values of rational coefficients.

Getter (2006) tries to select the most suitable plant species and makes an observation for the effect of slopes on green roof. Runoff is analyzed from twelve different green roof platforms with varying slopes of 2, 7, 15 and 25 percent. The green roofs retain on average about 80 percent of precipitation. Mean retention is 75 percent for 25 percent slope and 85 percent for 2 percent slope. Getter thus confirms that there is an inverse relationship between retention capacities of green roof with its slope.

Cunningham (2001) evaluates the potential benefits of green roofs on stormwater runoff in the cold climate of Manitoba. Though the plant survival rate in an extremely cold region is very difficult (Wolf, 2008), his research however demonstrates the applicability of green roofs in such harsh climate. Cunningham uses Rational Formula for stormwater runoff estimation taking probability curves (5, 20 and 50 year) for north central United States (TR-55, 1986). The study shows that green roofs achieve a 35 percent reduction in stormwater against existing conditions whereas with the pre-development conditions this value is about 15 percen.

In an establishment believed to be the first of its kind in Canada, Bass (2001) assesses the application of green roof benefits in a local context. A rainfall-runoff modeling with Horton model for infiltration is applied to evaluate the retaining capacity of green roof by simulating two cases for light and hurricane type extreme condition with different soil depth, field capacity and initial moisture condition on the green roof. Both cases confirm that green roof with an appropriate depth of soil plays a role in peak flow attenuation.

In a Southern Illinois University research on evaluation of storm water runoff from a Midwest green roof system, Forrester et al. (2006) determine the depth of substrate for maximum water management. They use different depths such as 5, 10, 15, and 20 cm of growth media with plants. For each independent precipitation it is observed that green roof models with and without plants retain more storm water than the control roofs. The models with and without plants retain almost the same quantity of storm water.

The works discussed so far deal mostly the comprehensive performance of green roof rather than the role of an individual component. Berghage et al. (2007) appraise the relative contribution of media and vegetation on stormwater retention. Researchers in this study have observed the evaporation and evapo-transpiration patterns of water from green roof through three different types of plant species. It is observed that the effect of plants is greatest for initial 5 days after a rainfall event. In these initial days the plants double the media''s rate of moisture holding capacity.

The designers (Project Report, 2006) for a green roof project in the University of Iowa building have done water budget calculation using principles of mass balance to estimate the retention capacity of media in different rainfall events. They use two media depths as 2.5 and 5 cm. Figure 2.2 shows that for the same rainfall event the retention level of thicker green roof is higher than that of thinner green roof indicating direct relationship between retention performance and thickness.

Vanwoert et al., (2005) evaluated the performance of green roofs with different combination of slope, roof surface and media depth to determine the optimal combination for retention performance. They try to find an optimal combination for the best retaining performance. In a number of combinations used, the best performance is achieved by 2 percent green roof slope with 4 cm media depth. For a total of 83 rainfall events collected in 14 month period this combination shows 60 percent retention. This study also indicated that though media thickness and slope are major parameters for retention performance, the best result depends on the intensity and duration of rainfall and initial moisture conditions.

Carter and Rasmussen (2006) tried to determine a relation between rainfall size and retention capacity. With the monitoring data, they found an inverse relationship between the rainfall depth and retention percentage. Their study however does not consider any antecedent moisture presence for retention performance estimation.

Hutchinson et al. (2003) found that to achieve the maximum retention, the vegetative coverage should be at least 70 percent of total roof area for any storm event. Banting et al. (2005), while doing cost benefit analysis of green roof′′s application at municipal level for Toronto, report that there will be a significant level of stormwater flow reduction by extending green roof facility in the existing traditional roofs. This flow reduction will range from 16 to 100 percent depending on the size of rainfall and climatic condition. MacMillan (2004) in Toronto compares the performance of green roof with a traditional control roof on stormwater reduction. He finds that a green roof works better in the spring/summer months than in the fall because of amount of rainfall.

With the results observed it can be concluded that green roof performs better than any traditional roof of the same size on stormwater retaining performance. However, only some of the reviewed works have reported the retention performance values. It is seen that for the varying media depths from 3 to 10 centimeters, the retention ranges from 0.5 to 4 centimeters. It shows that an extensive green roof with 8 to 10 centimeters of media depth will store 2.5 centimeters of rain in average.

2.2.1. Green roof modeling

Green roof stormwater research includes both model simulations and experimental measurement with full- and pilot scale installations. When the runoff is measured experimentally, it is expected that the combined effect of most of the in situ variables is included in the results. Different from these experimental works, some other researchers use either the existing hydraulic-hydrologic models to calculate the runoff or develop models from the experimental data recorded. These developed models after calibration are then used to simulate the runoffs from the storms.

With increasing demand of green roofs'' application for stormwater management, it is always essential to have reliable and valid methods for predicting green roof's performance to accommodate a wide range of design approaches and geographical location. It is not feasible every time in every location to go for an experimental measurement to decide on the possible factors. Runoff simulation for any storm event by a logical model is thus one of the convenient approaches for the purpose of determining the performance. Some of the complex models used take into accounts most of the possible variables during simulation but the others are rather simple which may or may not consider these parameters.

It is well understood that the condition in artificially created green roof is different from the actual physical processes involved in any natural watershed; the commonly used SCS unit hydrograph technique in most of the models is thus not well suited for predicting runoff from green roofs (Miller, 2000). There are however a number of modified hydrologic models to predict runoff using historical precipitation and evapo-transpiration data. These models which are so far successful in predicting the hydraulic properties of green roofs are basically in four forms- empirical models, physical models, analytical models and water balance models.

Empirical models though able to make reliable runoff estimation, need analogies between the green roof system and climatic conditions with intended design. Physical models, on the other hand are capable to predict pattern of two-dimensional seepage flow through the green roof. The main problem with this model is its complexity. One-dimensional approach treats runoff from a multi-layered green roof as a cascade from a combination of linear storage elements (Zimmer et al, 1997). This model considering each soil layer as a separate storage element assumes that the flow from each soil layer is proportional to the amount of water stored in that layer.

A reservoir model is the simplest model and treats a green roof system like a simple reservoir and uses a time stepping analysis to account for additions and losses from the system (Miller, 2000). It is based on the principle that no runoff will take place until the water storage capacity of the green roof is exceeded. When the storage capacity is reached, green roof runoff will take place and will imitate the rainfall flow. Hardin (2006) indicates most of the mass balance models are represented by complex equations and they need a large number of variables for a solution. As they are data intensive, these models may not be equally and efficiently applicable in most of the simple green roof situations for different locations.

Robertson (2007) uses the TR-55 model to estimate the existing runoff for different rainfall events. For a given set-up he considers an inventory of the possible and practical areas for green roof. Applying this model in an area with appropriate green roof coverage and an average CN=82, he finds 29 percent reduction in runoff depth compared to existing conditions. The model estimates that even by replacing only eligible traditional rooftops with green roofs, there is a one-third stormwater runoff reduction for a 2-year storm.

Mike Urban hydrological model (Green build-out model, 2007) can be applied for modeling the stormwater management of green roof in any area after adding green roof component to the original model. Application of this model in District of Columbia shows that media storage fluctuates greatly depending on the initial moisture condition and slopes of green roof.

Prowell (2006) tries to estimate the retention performance of modular green roof by using a simple reservoir equation. In this study the maximum field capacity of modular green roof is experimentally measured and the value is used for model calibration. The assumption here is also same as mentioned earlier, for any runoff to occur, the volume of incoming water should always be more than the maximum storage capacity of the media. Only those events with sizes more than storage capacity and capable to produce runoff have been considered for simulation.

Prowell uses a simple reservoir model with input parameters such as potential and actual evapo-transpiration, water holding capacity and soil moistures of the media. The model is found to perform adequately during simulations. This model is capable enough to reasonably predict runoff quantity and timing and takes care of just monthly runoff rates and on the whole monthly runoff volume without giving any consideration for peak reduction. Peak flow simulations using this simplified method cannot be construed as an accurate representation.

Hardin (2008) deals with an extensive green roof in a completely different way. He uses a case of an irrigated extensive green roof stormwater treatment system. From a water budget experiment and a complex mass balance equation, he develops a continuous stormwater treatment outflow reduction (CSTORM) model and applies this model in design of green roofs in different locations of Florida. With the major inputs as precipitation, irrigation, makeup water and outflow rate the model shows that the efficiency of the system would depend on total precipitation and total outflow. This model can predict the quantity of yearly retention and yearly makeup water requirement for irrigation. It however does not consider the effects of green roof on peak sizes, the most essential factor for any stormwater management project.

Hilten et al. (2006) use Hydrus-1D model to simulate the performance of a modular green roof with the simulation results being verified by the site measured data. The roof''s performance is based on inputs like evapo-transpiration, antecedent moisture conditions and a number of other soil hydraulic properties. The model is actually utilized to simulate runoffs for a number of design storms up to 24- hour, 1-year size equal to 7.9 cm. The model does not include other higher values like 2 or 5- year design storms normally considered for a stormwater management program in its simulation exercise. The model is tested for only smaller events and it does not say anything on the performance for its application to larger and extreme sized events. It also requires cumbersome laboratory experiments to determine the model associated with the particular soil type, thereby limiting its applicability for other locations different from the one where tested.

2.2.2. Simulation of rainwater supply according to storage volume

The amount of rainwater supply is increased as the storage volume increase. Considering construction cost and water saving efficiency (Eq. 2), however, storage volume should be limited and selected by the simulation of rainwater supply according to storage volume.

$$\textit{Water saving efficiency} = \textit{Total supplied rainwater} \,/\, \textit{Total demand of water} \quad \text{(Eq. 2)}$$

A. Fewkes (Fewkes 1999) conducted a field test of a rainwater utilization system and analyzed water saving efficiency based on the model below (Eq 3, 4 and Fig. 14).

$$Y_t = Min(L_t, Q_{t-1}) \text{ (Eq. 3)}$$

$$Q_t = Min(Q_{t-1} + V_t, S) - Y_t \text{ (Eq. 4)}$$

- R_t= Rainfall (mm)
- V_t = Rainwater runoff (l)
- Q_t = Volume in storage (l)
- L_t = WC demand (l)
- S = Store capacity (l)
- t = Time (min)

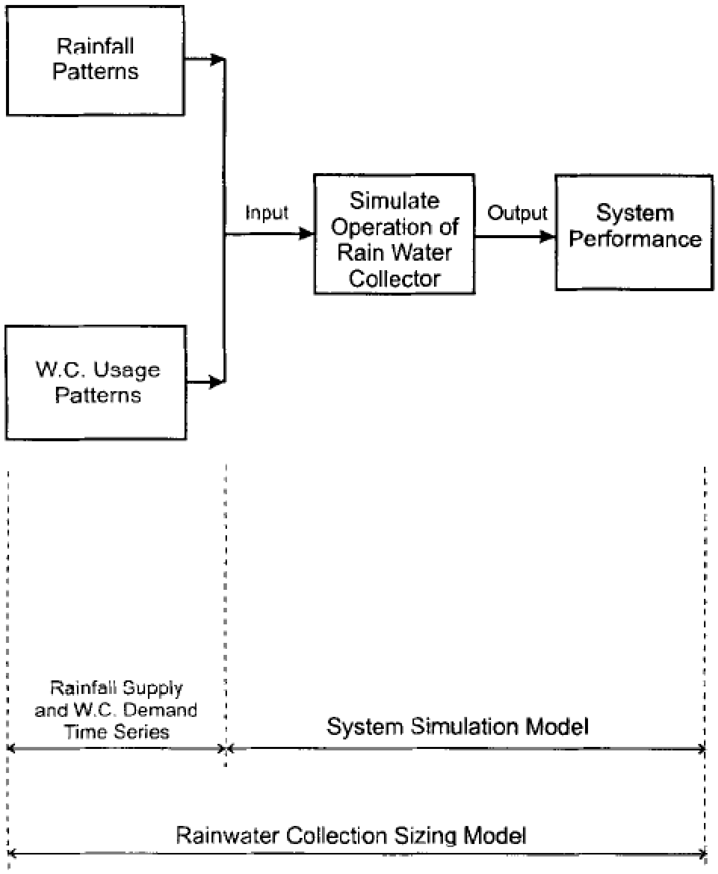


Figure. 2. Components of the rainwater collection sizing model (Fewkes 1999)

A. Fewkes suggested the dimensionless curves which show correlations between storage fraction and WC demand fraction to achieve specific water saving efficiency. If the roof area and demand patterns are known, the storage capacity in order to achieve the goal of water saving efficiency can be simply selected (Fig. 15, Fewkes 1999).

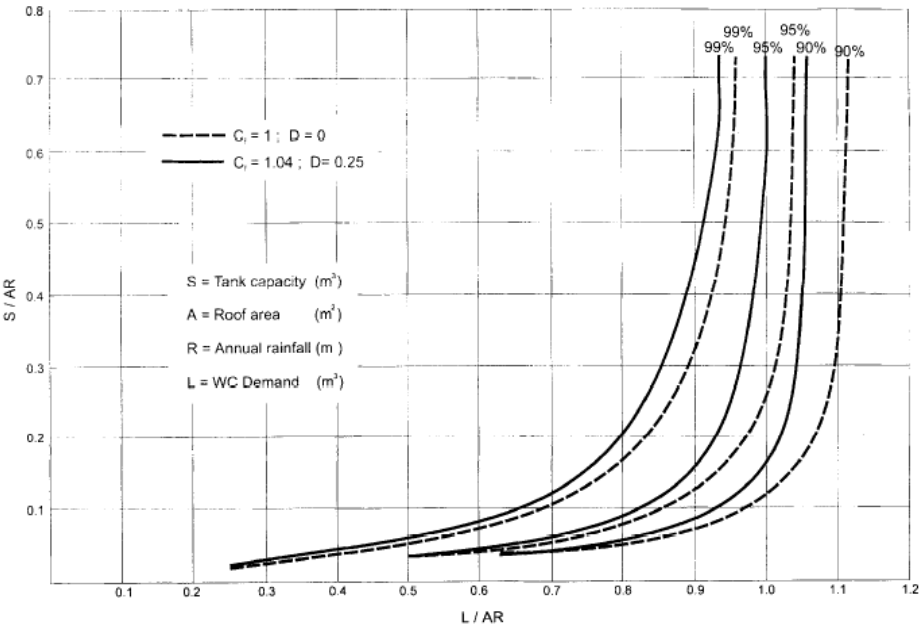


Figure. 3. Rainwater collector performance curves (Fewkes 1999)

김영진 (김영진 2008) suggested an improved algorithm for rainwater supply simulation based on water balance equation (Fig. 16, 17, Eq. 5 and Table 2). This model simulate the amount of rainwater supply more precisely than A.Fewkes's one (Fewkes 1999).

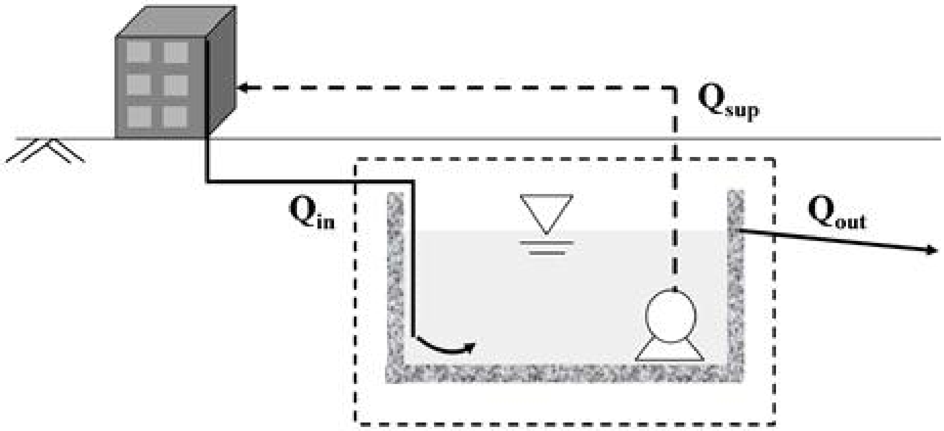


Figure. 4. Schematic diagram of water flow in a rainwater harvesting tank (김영진 2008)

$$V_{t_i} = \int_{t_0}^{t_i} (Q_{in} - Q_{out} - Q_{sup})dt \quad \text{(Eq. 5)}$$

- t = A day time in a simulation period
- V_t = Stored water volume at a day of t (m^3)
- Q_{in} = Inflow into a rainwater tank (m^3/day)
- Q_{out} = Overflows (m^3/day)
- Q_{sup} = Average water demand quantity (m^3/day)
- Initial condition; V_0 = 0, V_{max} = A given tank capacity

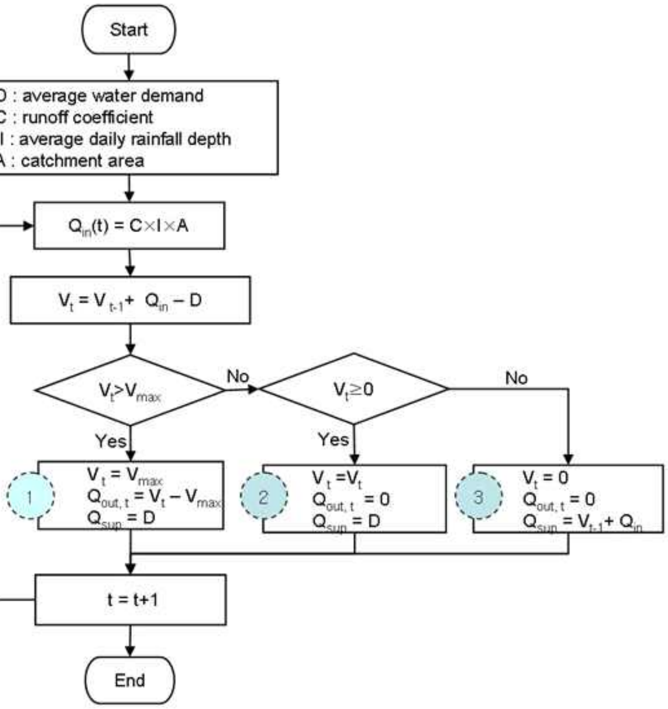


Figure. 5. Flow chart for the water supply simulation of a rainwater tank (김영진 2008)

Table 1. Parameters for rainwater harvesting simulation (김영진 2008)

Condition parameters	Daily average water demand (D) Catchment area (A) Daily rainfall depth Rainwater tank volume (V_{max})
Simulated parameters	Stored water volume in rainwater tank (V_t) Daily outflow quantity (Q_{out}) Daily supplied water quantity (Q_{sup})

2.3.2 Design of storage volume for G.R.S.

To design a storage volume for G.R.S, green roof characteristics such as catchment efficiency (Eq. 6) and water retaining capacity (Eq. 7) which affect on runoff amount into storage should be considered as input data in the simulation model but it's not easy since the green roof characteristics are fluctuated according to substrate type and depth, vegetation type and moisture content which were mentioned in previous section 2.2.2.a.

No researches have been conducted yet in order to provide a guideline or a direction for storage volume design of G.R.S through quantitative analysis of green roof runoff characteristics.

$$\textit{Catchment efficiency} = [\textit{Runoff/area}]\ (\textit{mm}) \,/\, \textit{Rainfall depth}\ (\textit{mm}) \qquad \text{(Eq. 6)}$$

$$\textit{Water retaining capacity}\ (\textit{mm}) = \textit{Rainfall depth}\ (\textit{mm}) - \textit{Runoff/area}\ (\textit{mm}) \qquad \text{(Eq. 7)}$$

CHAPTER3. Analysis of the runoff characteristic for hydrologic performance evaluation of green roof system

In this study, model has been established with factors that influence outflow characteristics after the experiment is developed to investigate the green roof system's outflow characteristics. And then through the analysis of established hydrological model of green roof system, developed evaluation factors by distinguishing the factors that influence the outflow directly. The experiment has been done by lab scale and field scale, and outflow characteristics of both cases were analyzed to develop the evaluation method.

3.1. Analysis of hydrologic model of green roof system

3.1.1. Hydrologic mass balance of green roof system

The areas with the hydrological effects of green roof can be largely divided to drain area, soil deposits, and planting layer. And at this time, the factors that involve directly are the volume of precipitation, irrigation water, soil moisture, evapotranspiration, fabric absorption, drain board. the evapotranspiration that occurs in 식생 and soil is heavily influenced by dry days, and it largely affects the moisture content of the soil layer. The relationship between factors that involve with hydrological circulation of green roof can be written as this equation.

$$P + I + Si = ETp + ETs + Sf + Rg + Rr + D \quad \cdots\cdots\cdots\cdots\cdots\cdots \text{(Eq. 1)}$$

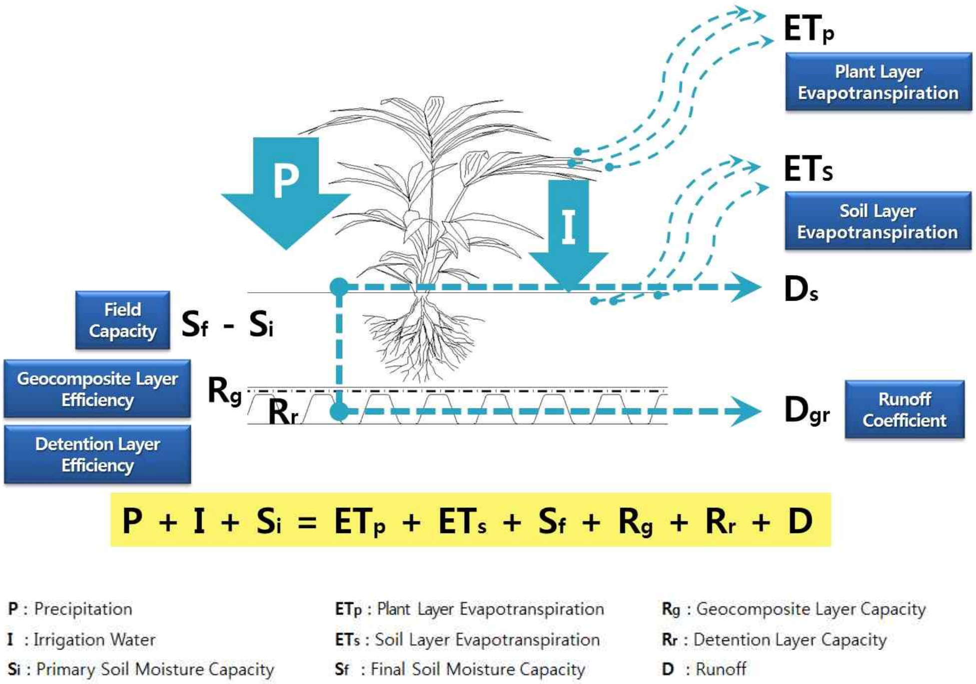


Figure 6. Hydrologic model of green roof system

If the irrigation water factor is left out to analyze the relationship between amount of precipitation and green roof system only, the equation can be written like this.

$$P + Si = ETp + ETs + Sf + Rg + Rr + D \quad \text{(Eq. 2)}$$

The main consideration is the characteristics of outflow when there is a rainfall. When there is a rainfall, evapotranspiration is close to zero so it can be omitted, and on dry days, there is a need to consider the evapotranspiration. Thus it can be written as this equation.

$$P + Si = Sf + Rg + Rr + D \quad \text{(Eq. 3)}$$

In this equation, it is considered that concave type green roof system is applied and there is no overflow. This shows the difference with the existing green roof system's hydrological circulation system and it is anticipated to have the better peak outflow reduction effect than the existing one. Based on these hydrological circulation system, hydrological performance evaluation factor considering green roof system's outflow characteristics were developed.

3.1.2. Development of hydrologic performance evaluation facters

For the hydrological performance evaluation of green roof system, city flood reduction performance and water resources securement performance has been categorized. Hydrological models have been simplified in order to quantify each performance. Evapotranspiration is omitted even though it is expected to have an influence on the changes of green roof system's outflow because of the fact that there is no evapotranspiration during a rainfall and it can be considered when dry days are applied as the main factor. Also, the moisture content of the fabric and drain board has been calculated altogether. The outflow is the subtraction of the total moisture content of soil from the addition of the rainwater inflow and initial moisture content of soil, and the amount of outflow can be schematized as the diagram below.

$$D = P + Si - (Sf + R) \quad \text{(Fig. 4)}$$

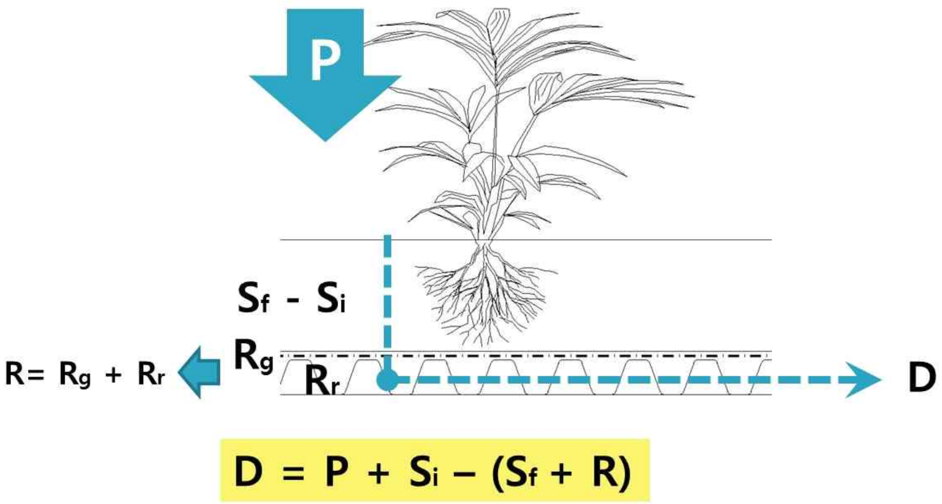


Figure 7. Modified hydrologic model of green roof system

The outflow take place after the addition of rainwater inflow before the outflow and initial moisture content of the soil is same as the addition of the outflow and the total moisture content of the soil. After this, outflow of the soil increases, and it affects the amount of the peak outflow according to the intensity of the rainfall. Thus when analyzing the flood reduction performance, the comparisons between the peak outflow of the normal roof system and the peak outflow of the green roof system act as the main factor. And this can be written as equation below.

Peak Reduction (Pr)
= Peak flow reduction at green roof (Pg)
/ Peak flow reduction at normal roof (Pn) (Eq. 5)

Peak Time Delay (Td)
= Peak flow time at green roof (Tg)
- Peak flow time at normal roof (Tn) (Eq. 6)

Water Storage (Ws)
= Total rainfall amount (Dr)
- Total runoff amount of green roof (Dg) (Eq. 7)

3.2. Experimental methods

3.2.1. Lab scale experiment

The quantity and quality of runoff were evaluated by 4 type pilot facilities that acryl, concrete and 2 different green roof models on rooftop of Seoul National University 35 building, Gwanak-Gu, Seoul, Korea (Table 2). There were 7 rainfall events for test period from May 7, 2011 to Sept 29, 2011. Total rainfall data and rainfall intensities were obtained from Seoul from Seoul Meteorological Office. 7 rainfall events were simulated by Norton Rainfall Simulator with 2 head model (DIK-600) which developed by USDA-ARS.NSERL at Purdue University-West Lafayette, Indiana.

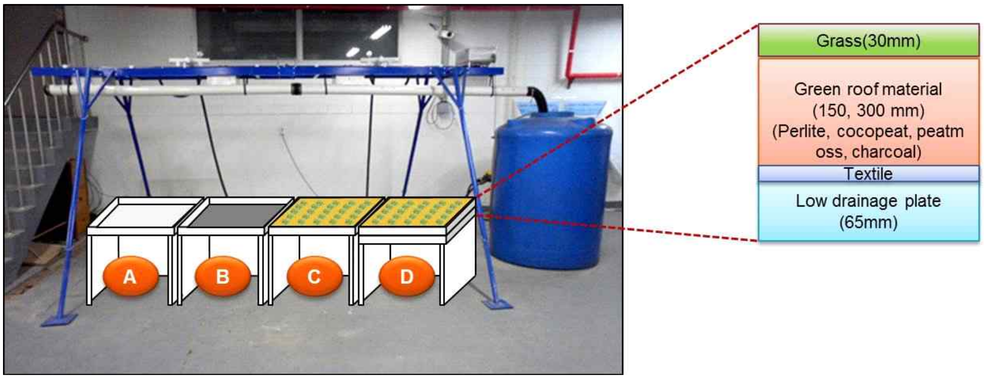


Figure 8. Lab scale experimental setting

For the harvesting rainwater (runoff quantity) unaffected by catchment area, the catchment facility was made with acrylic material

(Figure 3-a). The catchment installed in test batch B is made with concrete for examining effect of catchment area to runoff quality (Figure 3-b). In Figure 2-c, the batch C (150 mm) and D (200 mm) tests were composed at different soil depth for examining relationship between runoff quantity and water retaining with soil depth. Also, Figure 3-c shows a cross-section of batch test C and D. Tests were composed of the layer of sedum, volcanic materials and soil with peat moss (50 mm), perlite (100 mm for test C and 150 mm for test D) and drainage plate (40-50 mm). The soils were provided by the producer (GreenInfra, Co. Ltd, South Korea). These porous media were widely employed in green roof systems. Total average diameter and density was 2.2 mm and 0.1~0.12, including 0.2 mm perlite as growth type. For batch C and D, runoff quantity and quality were measured by 1 L graduated cylinder every hour.

Table 2. Lab scale experimental condition

<table>
<tr><th colspan="2" rowspan="2">Material</th><th colspan="3">Size (mm)</th><th rowspan="2">Soil</th><th rowspan="2">Vegetation</th><th rowspan="2">Purpose</th></tr>
<tr><th>Width</th><th>Length</th><th>Height</th></tr>
<tr><td>A</td><td>Acrylic</td><td>1000</td><td>1000</td><td>-</td><td>-</td><td>-</td><td>Rainfall sampling</td></tr>
<tr><td>B</td><td>Concrete</td><td>1000</td><td>1000</td><td>-</td><td>-</td><td>-</td><td>Rainfall sampling</td></tr>
<tr><td>C</td><td rowspan="2">Green roof</td><td rowspan="2">1000</td><td rowspan="2">1000</td><td>150</td><td rowspan="2">Perlite</td><td rowspan="2">Sedum</td><td rowspan="2">Green roof outflow</td></tr>
<tr><td>D</td><td>300</td></tr>
</table>

Table 3. Lab scale experimental rainfall events

Rainfall events (2011)	Rainfall duration	Sustainment time (hr)	Total rainfall (mm)
	Date. Beginning ~ End		
E1	6.22. 08:00 ~ 6.22. 24:00	14	16
E2	7.07. 04:00 ~ 7.07. 21:00	17	42.5
E3	8.30. 16:00 ~ 8.30. 19:00	3	8.5
E4	9.29. 05:00 ~ 9.29. 13:00	8	22.5

3.2.2. Field scale experiment

Field scale experiment was processed on the roof top of the SNU Gwanak campus building no.35. For the process of the experiment, experimental group was fixed as three green roof with varying systems, and control group was fixed as the normal roof top(Figure9). In each area, a flow meter was installed on the letdown line and a rain gauge was also installed to measure the precipitation. Also, in order to measure the evapotranspiration of the dry days, evapotranspiration meter was installed as well.

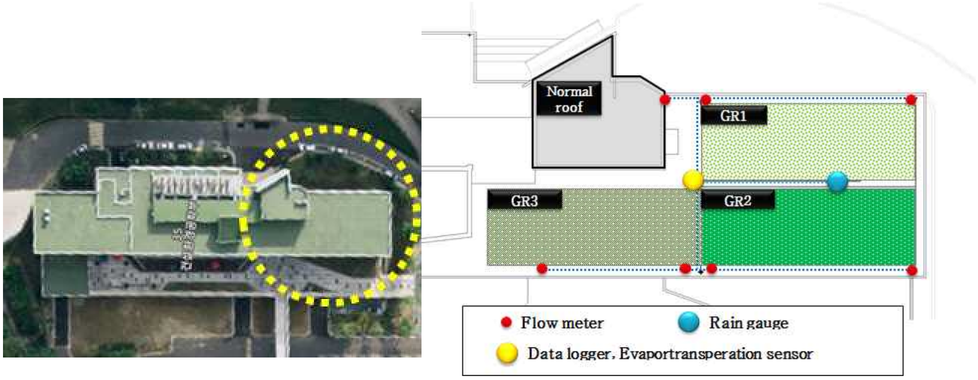


Figure 9. Plan of field scale experiment

Table 4. Field scale experimental rainfall events

	Area(m²)	Type	Soil Depth(mm)	Soil composition
N.R.	100	Normal roof	0	Cocopeat (30%) Bottom ash (20%)
GR1	140	Extensive (low bush, 50/m2)	150	Zeolite (5%) Leaf mold (15%)
GR2	140	Extensive (high bush, 100/m2)	150	Peat (10%) Perlite (10%)
GR3	140	Intensive	300	Peatmoss (10%)

The area of the three green roof experimental group were 140m² respectively, and the area of the control group, the normal roof, was 100m²(Table 4). Each green roof systems were differentiated with the depth of the soil and planting condition.

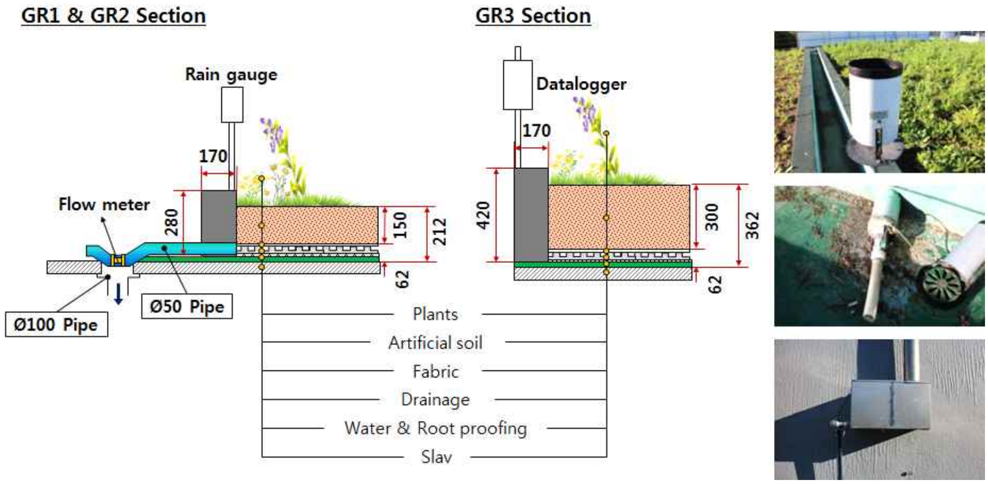


Figure 10. Section of field scale experiment

As described in figure 10, in addition to the water proofing layer and drainage layer at the bottom of the green roof, extensive green roof system has the soil depth of 150mm, and intensive green roof system has the soil depth of 300mm. And in order to make the data more accurate, outer-wall was constructed with the soil height for the prevention of the rainwater overflow.

Table 5. Field scale experimental rainfall event

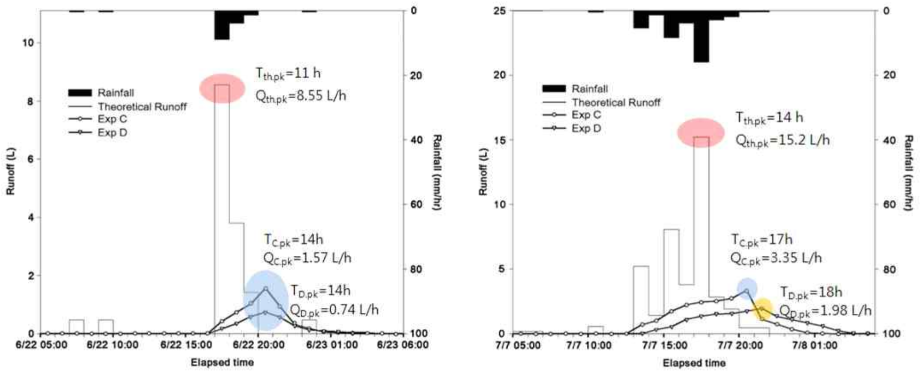
Rainfall events (2013)	Rainfall duration (Date. Beginning ~ End)	Sustainment time (hr)	Antecedent rainfall event (day)	Total rainfall (mm)	Data
E1	7.2. 05:00 ~ 7.2. 22:00	17	13.2	35	O (None outflow)
E2	7.4. 17:00 ~ 7.4. 24:00	7	1.8	24	O (None outflow)
E3	7.8. 02:00 ~ 7.9. 06:00	25	3	68.5	O
E4	7.12. 14:00 ~ 7.13. 11:00	21	3.3	130.5	O (None outflow)
E5	7.15. 08:00 ~ 7.15. 15:00	7	1.7	25.5	X (mechanical problem)
E6	7.17 00:00 ~ 7.18. 08:00.	31	1.6	41	X (mechanical problem)
E7	7.22. 03:00 ~ 7.22. 11:00	6	3.7	109	O
E8	7.23. 04:00 ~ 7.23. 15:00	11	0.7	65.5	X (mechanical problem)
E9	7.28. 08:00 ~ 7.28. 12:00	4	4	20	X (mechanical problem)
E10	7.30. 23:00 ~ 7.31. 04:00	7	1.5	18	X (mechanical problem)
E11	8.5. 09:00 ~ 8.5. 24:00	16	4.5	47.5	O (None outflow)
E12	8.10. 12:00 ~ 8.10. 14:00	2	3.8	8.5	X (mechanical problem)
E13	8.23. 05:00 ~ 8.23. 09:00	4	12.5	46.5	O
E14	8.29. 07:00 ~ 8.29. 15:00	8	5.9	22.5	O (None outflow)
E15	9.11. 01:00 ~ 9.11. 18:00	17	12.1	44	O (None outflow)
E16	9.13. 00:00 ~ 9.13. 12:00	12	1.3	90	O
E17	9.14. 01:00 ~ 9.14. 07:00	6	0.5	11	O
E18	9.28. 20:00 ~ 9.29. 09:00	13	14.3	22	O (None outflow)

Actual precipitation condition was applied on field scale experiment, and 12 rainfall events out of the 18 rainfall event from July to September of 2013 were used to measure the run off (Table 5). And through the measurement, precipitation duration time, antecedent rainfall condition, and the total amount of the precipitation.

3.3. Quantitative characteristic of green roof runoff

3.3.1. Result of lab scale experiment

The experiment result from the lab scale is shown on figure 11. For the total four times of precipitation event, each peak outflow and exact time of the peak outflow occurrence. Each experimental groups' outflow characteristics varied with different depth of the soil were presented different, thus showed the delayed effect of the peak outflow clearly.



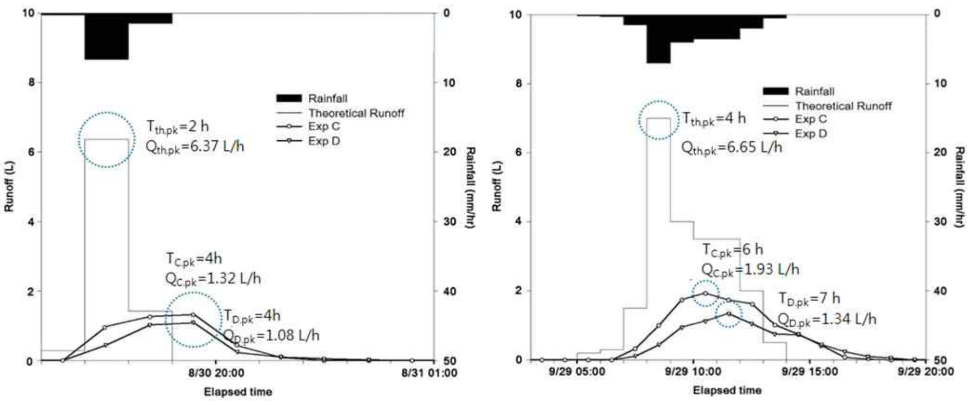


Figure 11. Lab scale runoff results

Table 6. Results of lab scale test about peak reduction ratio and peak delay time performance

Events	Duration(Time)	Theoretical max runoff	Method	Peak delay (L/hr)	Peak reduction ratio
E1 (2011.6.22)	07:00 ~ 24:00	T_{peak} = 11 hr (6.22.17:00)	C (Thk = 150)	$T_{pk.C}$ = 14 hr (3 hr) $Q_{pk.C}$ = 1.57 L/h	$Q_{pk.C}$ / $Q_{th.pk}$ = 0.18 → 0.82
		Q_{peak} = 8.55 L/hr	D (Thk = 300)	$T_{pk.D}$ = 14 Hr (3 hr) $Q_{pk.D}$ = 0.74 L/h	$Q_{pk.D}$ / $Q_{th.pk}$ = 0.09 → 0.91
E2 (2011.7.7)	04:00 ~ 21:00	T_{peak} = 14 hr (7.07.17:00)	C (Thk = 150)	$T_{pk.C}$ = 17 Hr (3 hr) $Q_{pk.C}$ = 3.35 L/h	$Q_{pk.C}$ / $Q_{th.pk}$ = 0.22 → 0.78
		Q_{peak} = 15.2 L/hr	D (Thk =300)	$T_{pk.D}$ = 18 Hr (4 hr) $Q_{pk.D}$ = 1.98 L/h	$Q_{pk.D}$ / $Q_{th.pk}$ = 0.13 → 0.87
E3 (2011.8.30)	16:00 ~ 19:00	Tpeak=2 hr (8.30.17:00)	C (Thk = 150)	T_{peak}=4 hr (2 hr) Q_{peak}=1.32 L/h	$Q_{pk.C}$ / $Q_{th.pk}$ =0.21 → 0.79
		Qpeak=6.37 L/hr	D (Thk = 300)	T_{peak}=4 hr (2 hr) Q_{peak}=1.08 L/h	$Q_{pk.C}$ / $Q_{th.pk}$ =0.17 → 0.83
E4 (2011.9.29)	05:00 ~ 13:00	Tpeak=4 hr (9.29.08:00)	C (Thk = 150)	T_{peak}=6 hr (2 hr) Q_{peak}=1.93 L/h	$Q_{pk.C}$ / $Q_{th.pk}$ =0.29 → 0.71
		Qpeak=6.65 L/hr	D (Thk =300)	T_{peak}=7 hr (3 hr) Q_{peak}=1.34 L/h	$Q_{pk.C}$ / $Q_{th.pk}$ =0.20 → 0.80

Peak flow delay time from the green roof system's lab scale experiment were similar from 3 to 4 hours regardless of the green roof depth, and peak flow reduction ratio represented above 0.7, which is highly effective(Table 6). Peak flow reduction effect of the green roof with the 300mm depth showed 10% higher result than the green roof with the 150mm. Peak flow delay time and peak flow reduction effect demonstrated the evident differences for the different depth, but the disparity was insignificant.

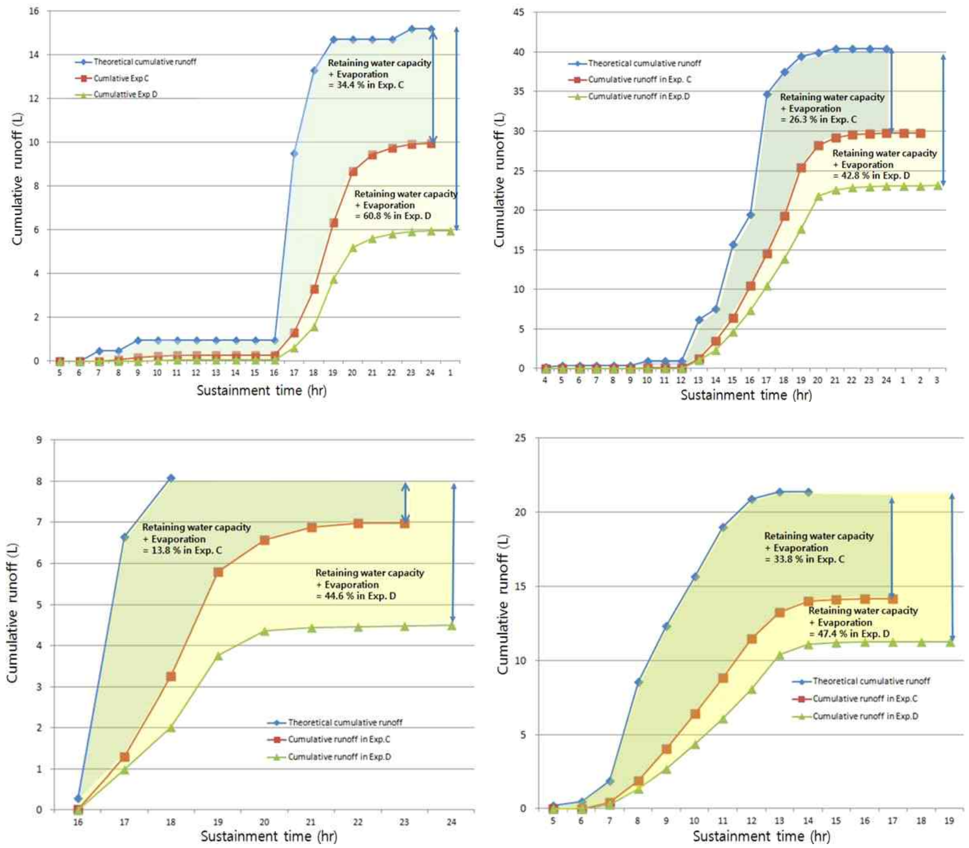


Figure 12. Lab scale accumulated runoff results

Table 7. Results of lab scale test about water storage performance

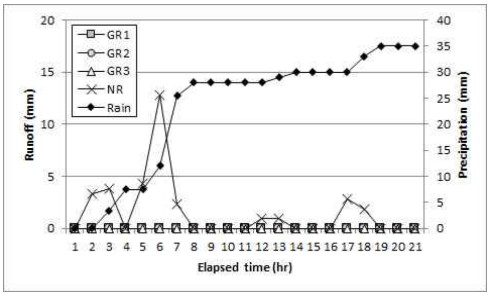
Rainfall event	Rainfall Characteristic	Test	Total runoff (mm)	Water storage (mm)	Reduction ratio
E1 (2011.6.22)	Total rainfall: 16 mm Theoretical runoff: 15.2 L Duration of Rainfall: 14 Hr	C	9.97	5.23	34.4 %
		D	5.96	9.24	60.8 %
E2 (2011.7.7)	Total rainfall: 42.5 mm Theoretical runoff: 40.4 L Duration of Rainfall: 17 Hr	C	29.77	10.63	26.3 %
		D	23.12	17.28	42.8 %
E3 (2011.8.30)	Total rainfall: 8.5 mm Theoretical runoff: 8.1 L Duration of Rainfall: 3 hr	C	6.98	1.12	13.8 %
		D	4.49	3.61	44.6 %
E4 (2011.9.29)	Total rainfall: 22.5 mm Theoretical runoff: 21.4 L Duration of Rainfall: 8 hr	C	14.16	7.24	33.8 %
		D	11.25	10.15	47.4 %

Accumulated runoff curve of the lab scale experiment is shown in figure 12. Storage amount difference of the varying soil depth was evident, and intensive green roof system showed 40% higher effects than the extensive green roof system. Also even from the shallow soil depth of the 150mm, it was verified the rainwater store effect of more than 5mm (Figure 12). And although weak rainfall reduces the peak flow effectively than strong rainfall, strong rainfall holds more amount of the rainwater than the weak rainfall(Table 7).

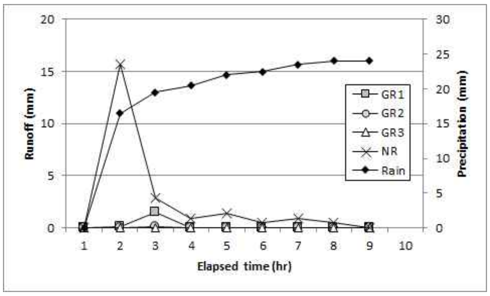
3.3.2. Result of field scale experiment

The run off monitoring result of the 12 measured rainfall event out of 18 rainfall event from July to September 2013 are shown in figure 14. From these, total of five rainfall event showed the run off, and peak flow reduction effect and peak flow delay effect from the green roof were researched.

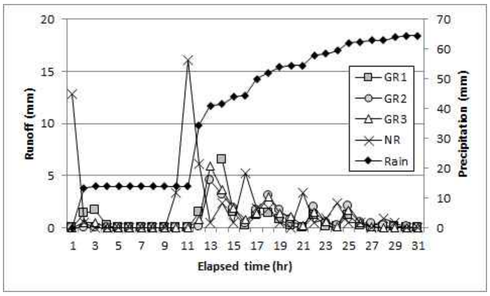
July 2nd



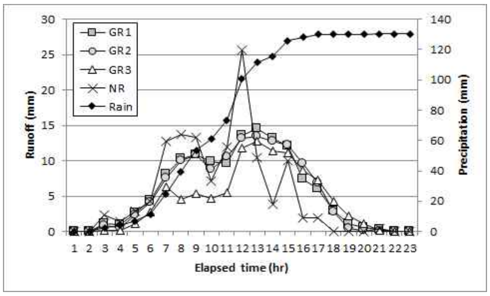
July 4th



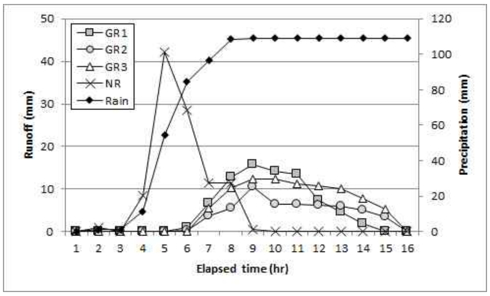
July 8th



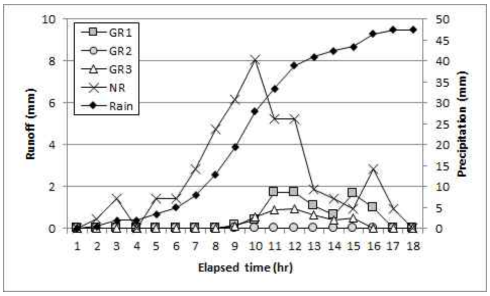
July 12th



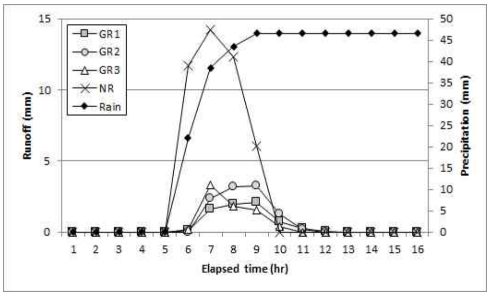
July 22th



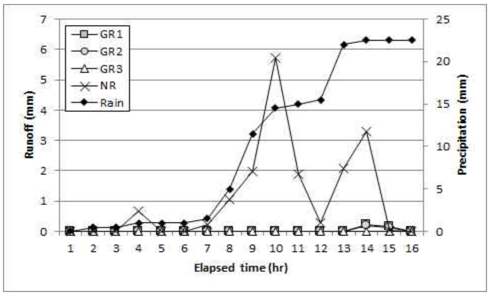
August 5th



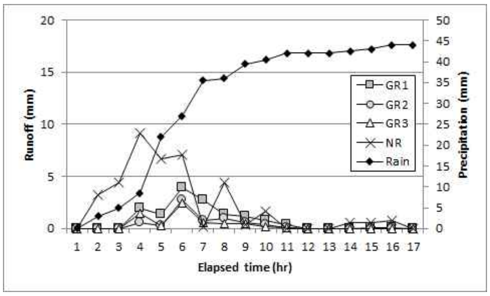
August 23th



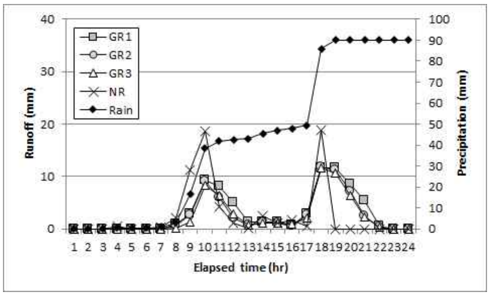
August 29th



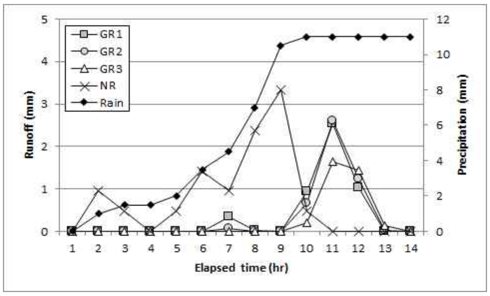
September 11th



September 12th



September 14th



September 28th

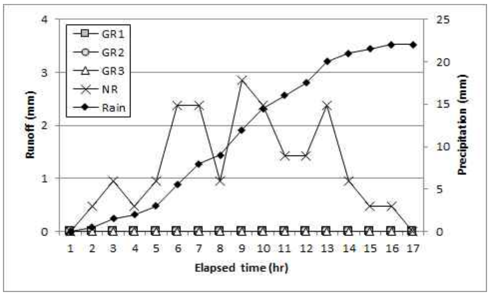
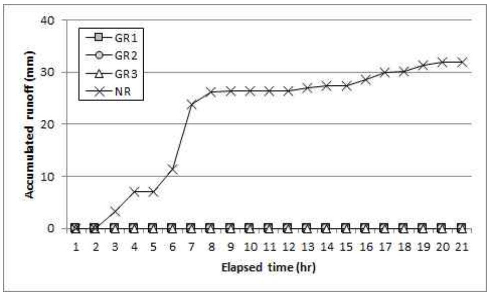
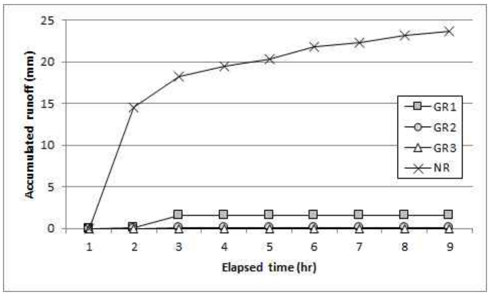


Figure 13. Field scale runoff results

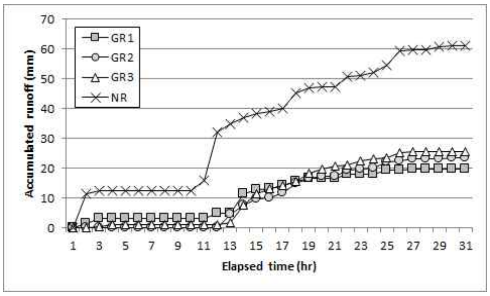
July 2nd



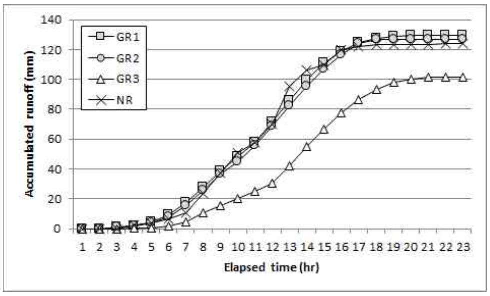
July 4th



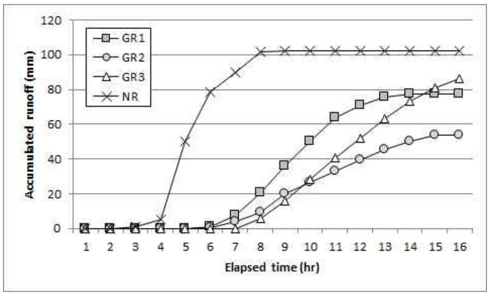
July 8th



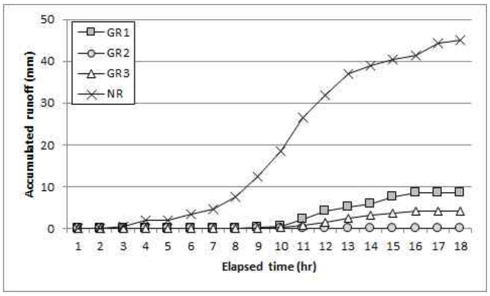
July 12th



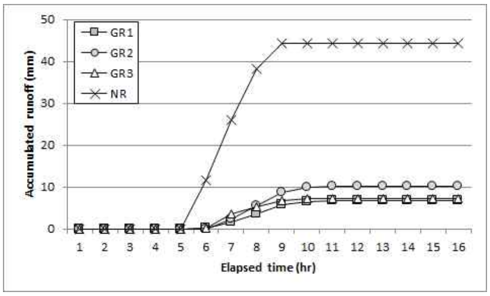
July 22th



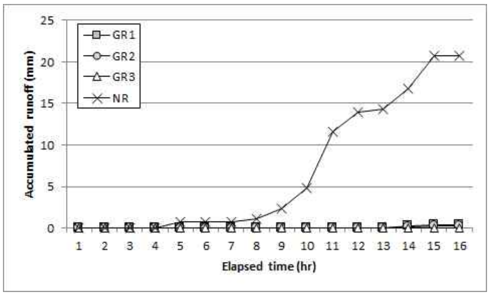
August 5th



August 23th



August 29th



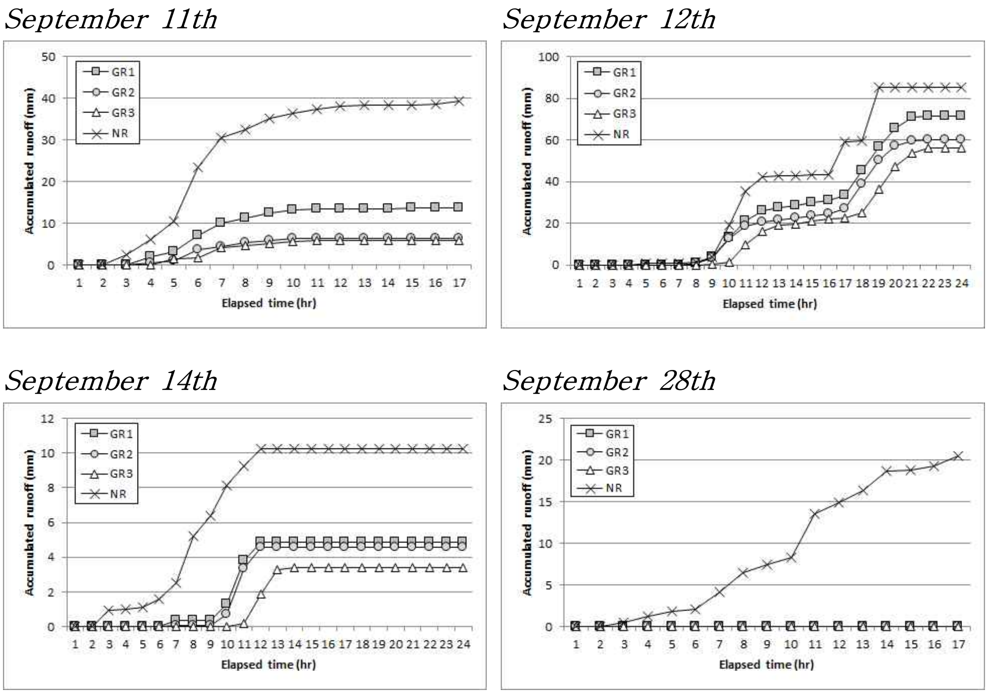


Figure 14. Field scale accumulated runoff results

Table 8. Field scale experimental results

Rainfall events (2013)	Antecedent rainfall event (day)	Total rainfall (mm)	Test	Peak flow reduction ratio	Peak flow time delay (hr)	Water storage (mm)
E1	13.2	35	GR1	1	-	35
			GR2	1	-	35
			GR3	1	-	35
E2	1.8	24	GR1	0.90	1	22.4
			GR2	0.99	1	23.9
			GR3	1	-	24
E3	3	68.5	GR1	0.43	2	39.6
			GR2	0.72	2	45.1
			GR3	0.63	2	42.8
E4	0.3	130.5	GR1	0.43	1	1
			GR2	0.47	1	3.5
			GR3	0.50	1	29.2
E7	3.7	109	GR1	0.68	4	50.2
			GR2	0.75	4	55.1
			GR3	0.71	4	45
E11	4.5	47.5	GR1	0.79	2	39
			GR2	1	-	47.5
			GR3	0.88	2	43.3
E13	12.5	46.5	GR1	0.80	2	37.5
			GR2	0.74	2	34.2
			GR3	0.71	1	37.7
E14	5.9	22.5	GR1	0.96	4	22.2
			GR2	0.96	4	22.2
			GR3	1	-	22.5
E15	12.1	44	GR1	0.57	2	30.3
			GR2	0.69	2	37.5
			GR3	0.74	2	38
E16	1.3	90	GR1	0.39	0	18.7
			GR2	0.37	0	30
			GR3	0.38	0	33.7
E17	0.5	11	GR1	0.24	2	6.1
			GR2	0.21	2	6.4
			GR3	0.52	2	7.5
E18	14.3	22	GR1	1	-	22
			GR2	1	-	22
			GR3	1	-	22

Table 9. Field scale experimental results of occurring outflow

Events	Total rainfall (mm)	Duration of Rainfall (hr)	Antecedent rainfall (day)	Method	Peak flow (mm/hr)	Td (hr)	Pr	Total runoff (mm)	Ws (mm)
E3 (2013.7.8)	68.5	25	3	NR	16.1	**10.7**	**-**	63.3	**5.2**
				GR1	9.1	**11 (0.3)**	**0.43**	28.9	**39.6**
				GR2	4.5	**11.5 (0.8)**	**0.72**	23.4	**45.1**
				GR3	5.9	**11 (0.3)**	**0.63**	15.7	**52.8**
E7 (2013.7.22)	109	6	3.7	NR	42.1	**5.7**	**-**	102.0	**7.0**
				GR1	13.0	**6.7 (1)**	**0.68**	58.8	**50.2**
				GR2	10.6	**7 (1.3)**	**0.75**	53.9	**55.1**
				GR3	12.4	**7.1 (1.3)**	**0.71**	64.0	**45.0**
E13 (2013.8.23)	46.5	4	12.5	NR	6.2	**4.9**	**-**	42.4	**4.1**
				GR1	2.1	**7.2 (2.3)**	**0.80**	9.0	**37.5**
				GR2	3.3	**7.2 (2.3)**	**0.74**	12.3	**34.2**
				GR3	1.8	**7 (2.1)**	**0.71**	8.8	**37.7**
E16 (2013.9.13)	90	12	1.3	NR	18.9	**2.4**	**-**	85.1	**4.9**
				GR1	11.5	**4 (1.6)**	**0.39**	71.3	**18.7**
				GR2	11.9	**4 (1.6)**	**0.37**	60.0	**30.0**
				GR3	11.7	**4.1 (1.7)**	**0.38**	56.3	**33.7**
E17 (2013.9.14)	11	6	0.5	NR	3.3	**9.2**	**-**	10.3	**0.7**
				GR1	2.5	**9.7 (0.5)**	**0.24**	4.9	**6.1**
				GR2	2.6	**9.7 (0.5)**	**0.21**	7.6	**3.4**
				GR3	1.8	**9.9 (0.7)**	**0.45**	3.5	**7.5**

Peak flow delay time was between 3 to 5 hours, which was similar to the lab sale experiment result, represented the similarities of the field experiment's peak flow delay performance. Peak flow delay time in other green roof condition did not show the significant difference from the soil layer or planting condition. On contrary, peak flow reduction rate was influenced by soil characteristics and planting condition more than the depth. From the E3 and E7, which has similar amount of the rainfall, E3 showed higher peak flow reduction rate and shorter peak flow delay time (Table 9).

According to this result, it is known that the performance assessment results vary with the rainfall duration time although the rainfall amounts are similar. Mostly peak flow reduction amount from the field experiment showed better effect than the result of the lab scale experiment and influenced by the planting condition and the soil condition. Also without many plants, the moisture of the soil layer is not sustained long enough due to inactive evapotranspiration, thus declines the rainwater store performance during the rainfall.

Peak flow reduction rate, peak flow delay time, and total stored amount was compared through the dry days and the amount of the rainfall in order to analyze the run off characteristics of the five rainfall events (Figure 15, 16, 17).

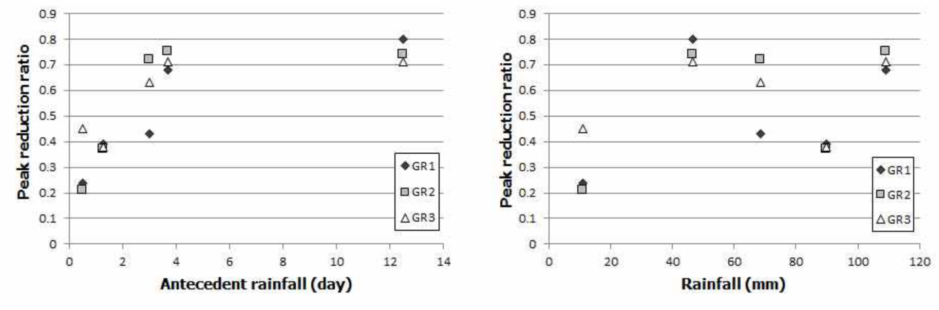


Figure 15. Peak flow reduction ratio(Pr) performance evaluation

From figure 15, the highest peak flow reduction rate is achieved when three days of the dry days condition has been met. Also, it showed less impact due to the depth of the soil layer, and shorter time to reach the highest peak flow reduction rate as more plants exist. Furthermore, similar peak flow reduction rates from the three types of the green roof system shows the effect of the same drain board application.

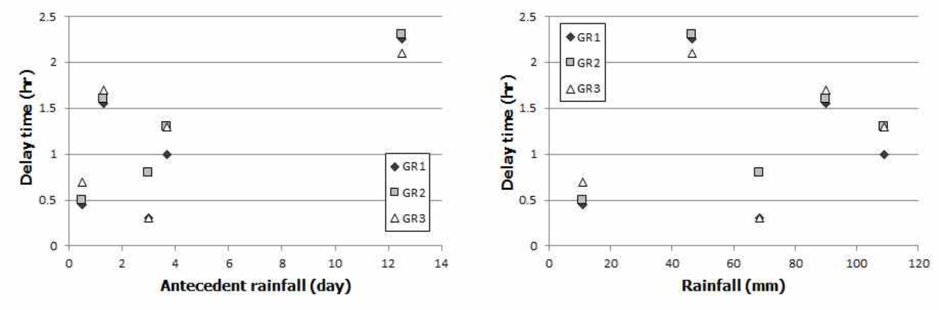


Figure 16. Peak flow time delay(Td) performance evaluation

Figure 16 represents the longer peak flow delay time, the longer the dry days from the green roof system. This research produced the highest peak flow delay time after 6 days of the dry days.

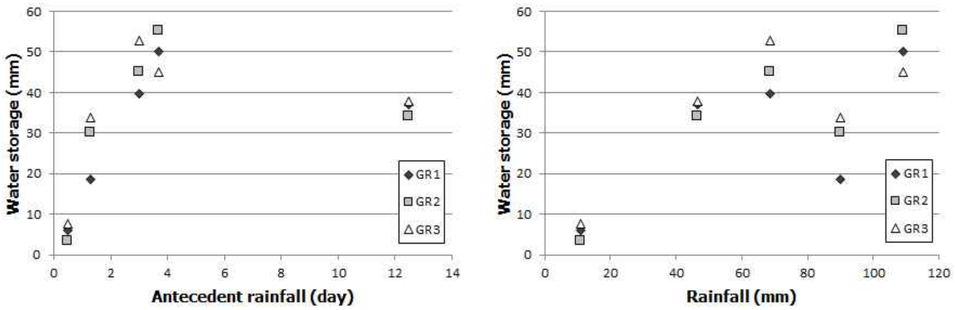


Figure 17. Water storage(Ws) performance evaluation

Figure 17 shows the maximum store amount of the green roof system from the three dry day condition. Soil depth and 식재조건 were influenced before it reaches the maximum amount, but it showed similarity after the maximum amount has been achieved.

Also, effect of the drain board condition are considered high because the store amount did not show the big difference even with the high rainfall amount.

CHPTER4. Suggestion of performance evaluation of green roof system by Storm Green Roof Response (SGRR)

Hydrologic routing methods were developed as the need for simplified routing techniques became apparent. Hydrologic methods are based on the concept that inflow, outflow, and storage have to relate to the conservation of mass principle, described by the following equation:

$$I - O = \frac{\triangle S}{\triangle t} \quad \text{(Eq. 8)}$$

I = inflow to the reach, in cms

O = outflow from the reach, in cms

$\triangle S$ = change in storage within the reach, in cubic meter

$\triangle t$ = time increment, in seconds

Hydrologic methods can effectively reproduce flood flows when a storage-discharge relation is calculated or routing coefficients are fitted to the storage-discharge relation. However, the computed relation is typically single valued whereas the dynamic properties of a flood wave create a looped relation between storage and discharge. This is apparent when considering that the transverse water surface slope and storage are greater during the rising stages of a flood wave than during the falling stages(Bedient and Huber, 1992; Fread, 1985).

4.1. Description of Modified Pul's Routing Method

4.1.1. Introduction

Modified Pul's routing utilizes the simple concept that storage is a function of outflow. Correct computation of the outflow hydrograph rests on the assumption that storage depends primarily on outflow rate. For this reason, Modified Pul's routing is typically used for reservoir routing where a unique storage-outflow relation is likely. Strelkoff (1980) stated that determination of this relationship is a key factor in the application of the Modified Pul's method. To perform the routing, a relationship between storage and outflow is calculated and plotted as a curve. The following form of the continuity equation is then solved for each time step.

$$\left(\frac{S_2}{\Delta t} + \frac{O_2}{2}\right) = \left(\frac{S_1}{\Delta t} + \frac{O_1}{2}\right) - O_1 + \left(\frac{I_1 + I_2}{2}\right) \quad \text{(Eq. 9)}$$

Modified Pul's routing proves valid for reservoirs when the effects of a flood wave (differences in storage due to rising and falling stages) are dampened, if not eliminated, by the reservoir. Modified Pul's can be used for channel routing in a similar manner where each subsection of the reach is considered to behave like a cascading reservoir. Some error is inherent in this concept since storage in a river reach is not a function of outflow alone.

4.1.2. Data requirements

The Modified Pul's method requires either a known stage-storage -discharge relationship, or hydraulic geometry data adequate to calculate this relationship for each reach. An appropriate computation time step also must be selected, which requires an estimate of the travel time through the reach.

4.1.3. Development of Equation

The heart of the Modified Pul's equation is found by considering the finite difference form of the continuity equation (5) which may be written as:

$$\frac{I_1 + I_2}{2} - \frac{O_1 + O_2}{2} = \frac{S_2 - S_1}{\Delta t} \quad \cdots\cdots \text{(Eq. 10)}$$

After an algebraic transformation, The above equation is written:

$$I_1 + I_2 + \left(\frac{2S_1}{\Delta t} - O_1\right) = \frac{2S_2}{\Delta t} + O_2 \quad \cdots\cdots \text{(Eq. 11)}$$

4.1.4. Application of the equation

In the equation above, the left side is known at a given time, while the right side is to be calculated. Basically, the solution to the Modified Puls method is accomplished by developing a graph (or table) of O versus [2S/Ît + O]. In order to do this, the relationship between outflow O and storage S must be known, assumed, or derived.

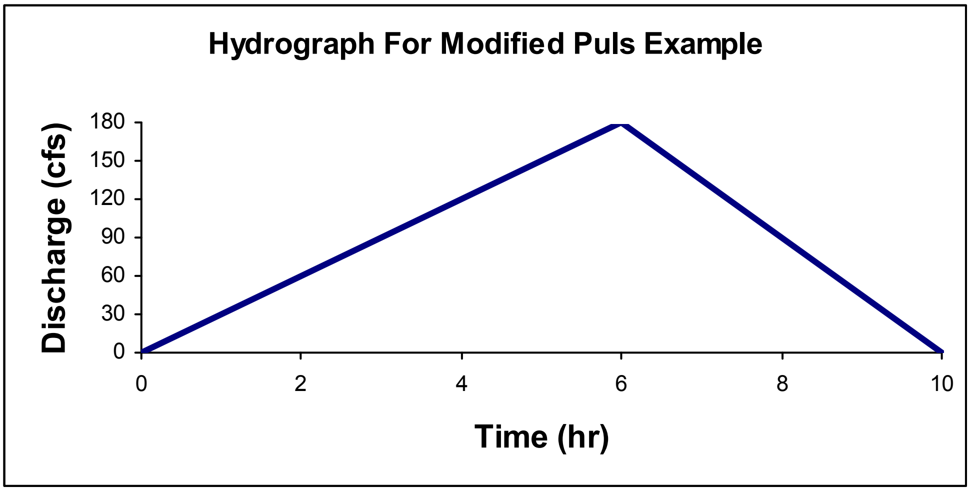


Figure 18. Hydrogragh for Modified pul's method

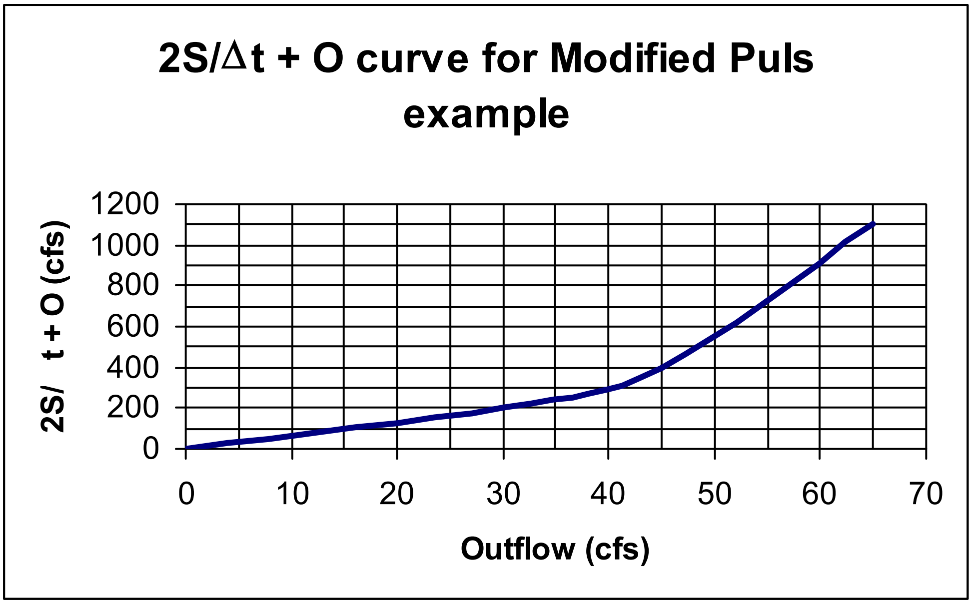


Figure 19. 2S/△t+O curve for Modified Pul's Method

This process can then be repeated for the rest of the columns. A list of the outflow values have been calculated and the problem is complete.

Table 10. Total data of for Modified Pul's Method

Time (hr)	I_n (cfs)	I_n+I_{n+1} (cfs)	$2S_n/t - O_n$ (cfs)	$2S_n/t + O_{n+1}$ (cfs)	O_{n+1} (cfs)
0	0	30	0		0
1	30	90	20	30	5
2	60	150	74	110	18
3	90	210	160	224	32
4	120	270	284	370	43
5	150	330	450	554	52
6	180	315	664	780	58
7	135	225	853	979	63
8	90	135	948	1078	65
9	45	45	953	1085	65
10	0	0	870	998	64
11	0	0	746	870	62
12	0	0	630	746	58

4.2. Description of Storm Green Roof Response (SGRR) Models

The SGRR model is based on three assumptions; 1) that a storm hyetograph is available with uniform times steps between 6 and 60 minutes to be used as input, 2) that a reliable estimate of daily evapotranspiration (ET) can be provided, and (3) that the month of the storm and the number of days since the last rain is known. The SGRR model is a Modified Puls Reservoir Routing Model (Jarrett, 2000) adapted to a green roof.

The stage-storage relationship for the green roof was developed from the green roof drainage layer and roof media characteristics reported by DeNardo et al. (2005). The influence of water stored in the green roof plants was developed from data reported by Rezaei et al. (2005). The 12 mm thick drainage layer had a porosity of 78 % and field capacity of 5.2 %. The 89 mm growth media had a porosity of 55 % and field capacity of 34 %. The plants growing in the media were able to give up and then recover 10 mm of water. The ET was estimated for each month based on the experimental ET results of Rezaei et al. (2005) and the number of days sin the last rain event.

Storm Green Roof Response (SGRR) model developed by Jarrett et al., (2005) uses inputs from storm hyetograph and daily ET to understand how a green roof will respond to a specific rain event. The model considered as a routing model is applied to several synthetic storms with 2, 25 and 100-year return period for a designed area at central Pennsylvania. The study shows that the peak runoff rate for all these storms due to green roof intervention comes to a size comparable to an undeveloped parcel of the same size. In addition to estimating the total runoff volumes this study also calculates decrease in peak flow sizes.

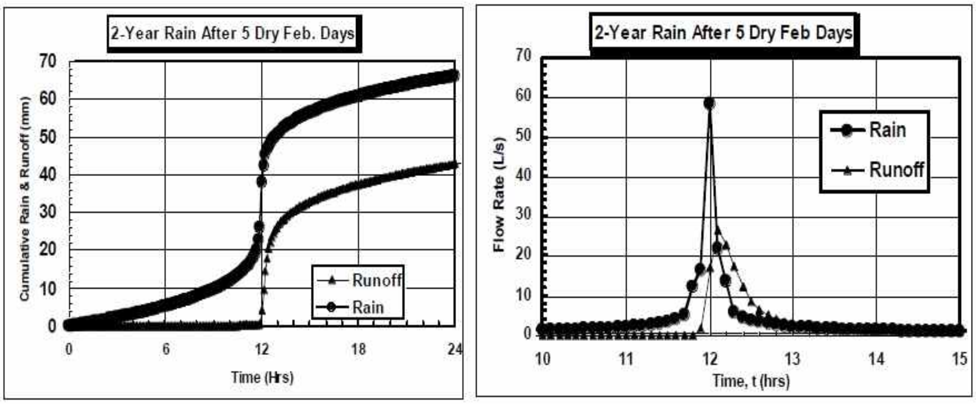


Figure 20. Rainfall and runoff rates and cumulative rainfall depths for a 2-year rain applied to green roof after 5 days without rain in Februry

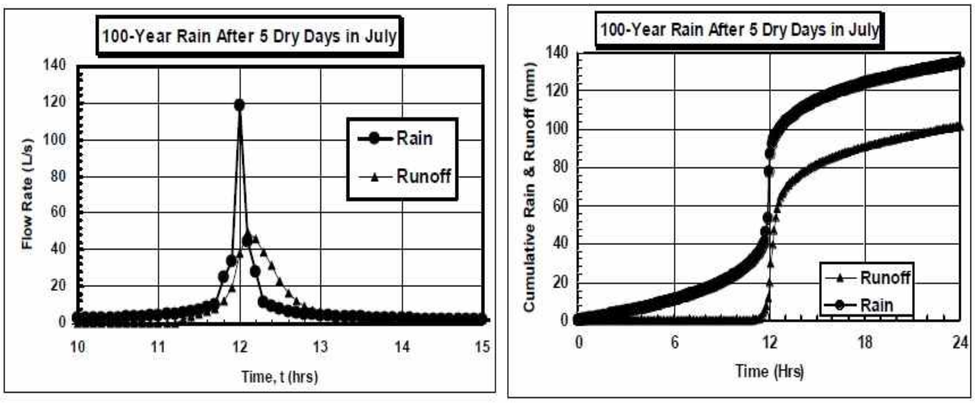


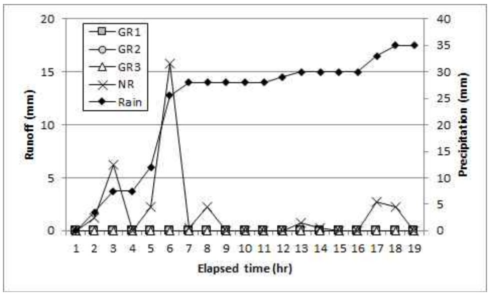
Figure 21. Rainfall and runoff rates and cumulative rainfall and runoff depths for a 100 year rain applied to green roof after 5 day dry period in July

4.3. Results and discussions

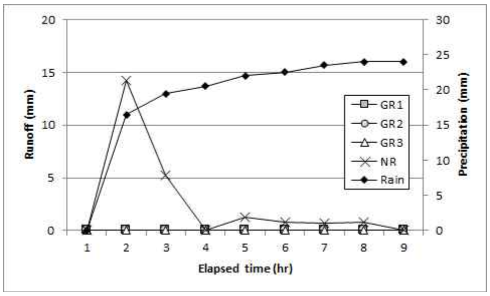
4.3.1. modeling results

The relation between water saving efficiency and rainwater storage volume was analyzed (Fig. 39), in which green roof ratio and rainwater storage volume were set as variables. According to the analysis, a storage volume is decided to be 50m3 regardless of the ratio if water saving efficiency is not taken into account because it takes highest B/C (benefit/economic) ratio. On the other hand, if the target value of water saving efficiency is well considered, the volume can distinctly be increased as green roof ratio increases.

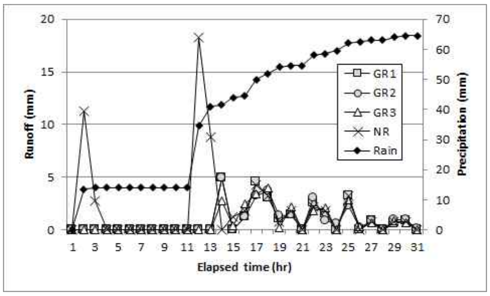
July 2nd



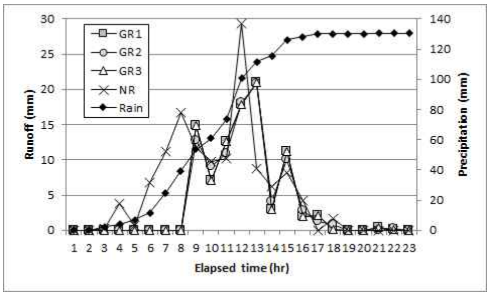
July 4th



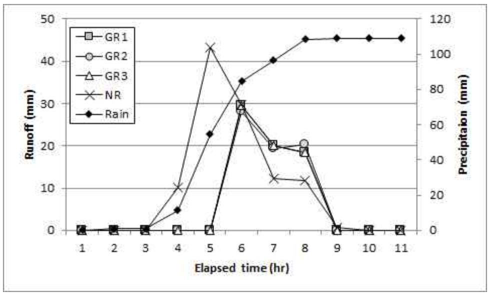
July 8th



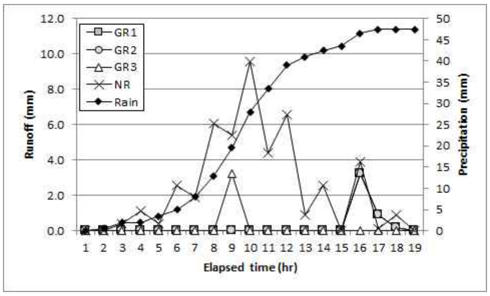
July 12th



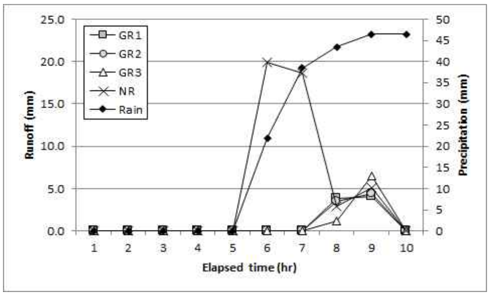
July 22th



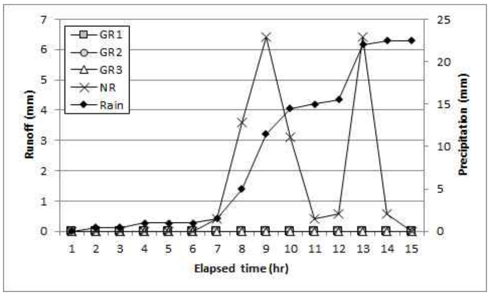
August 5th



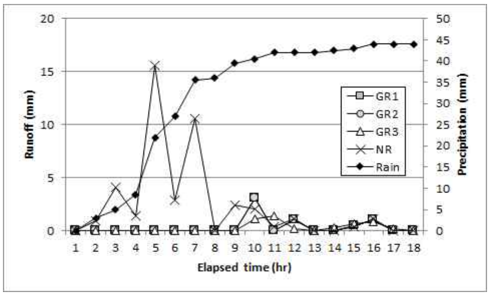
August 23th



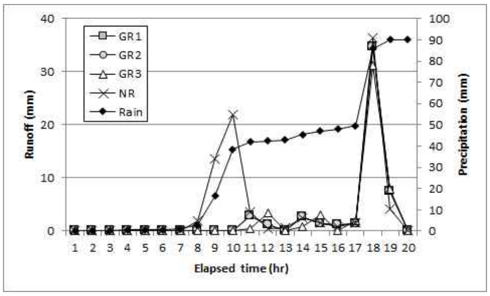
August 29th



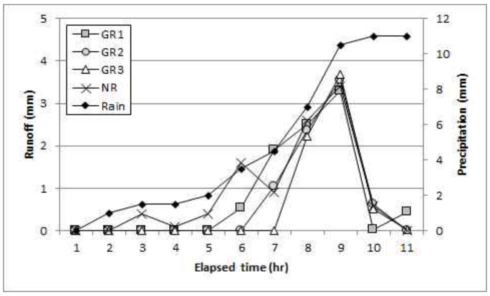
September 11th



September 12th



September 14th



September 28th

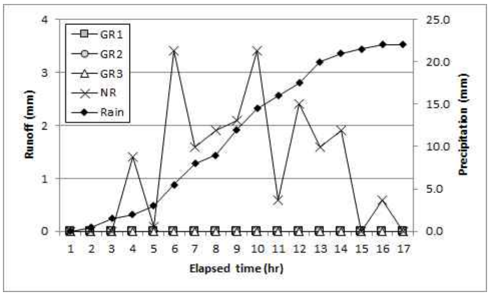
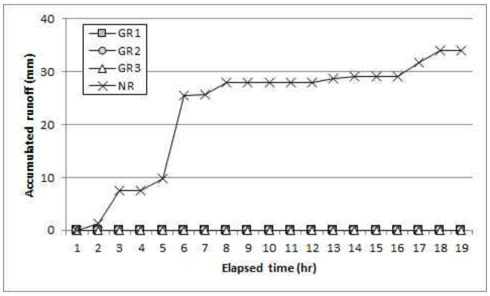
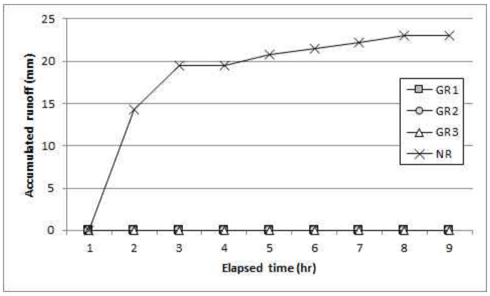


Figure 22. Modeling results of runoff

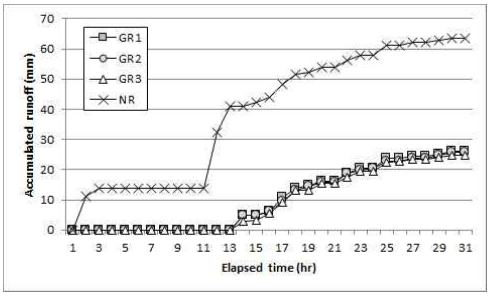
July 2nd



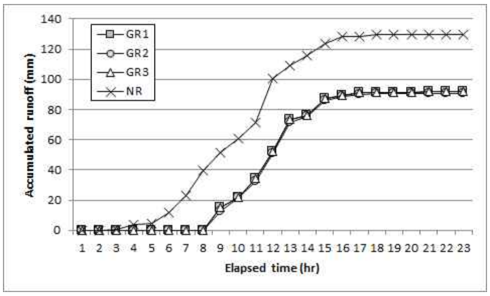
July 4th



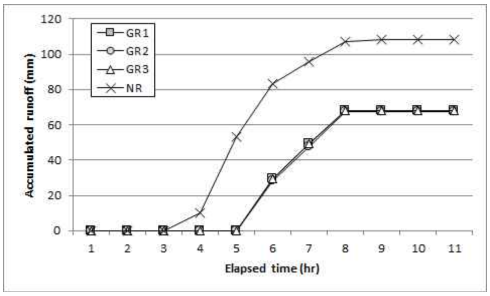
July 8th



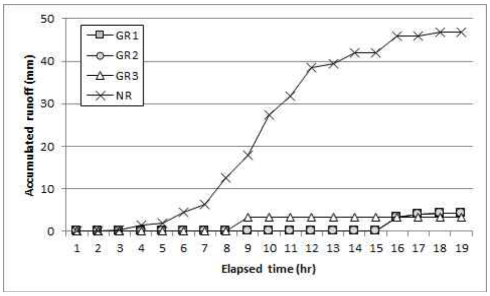
July 12th



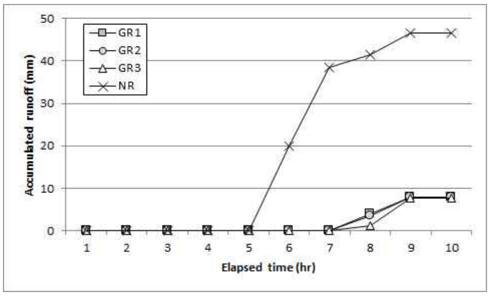
July 22th



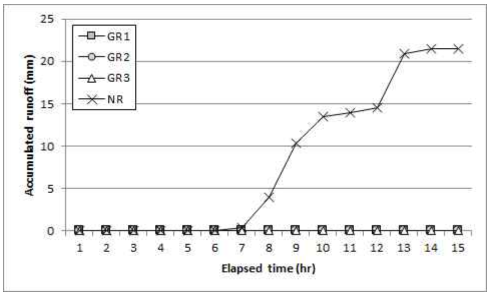
August 5th



August 23th



August 29th



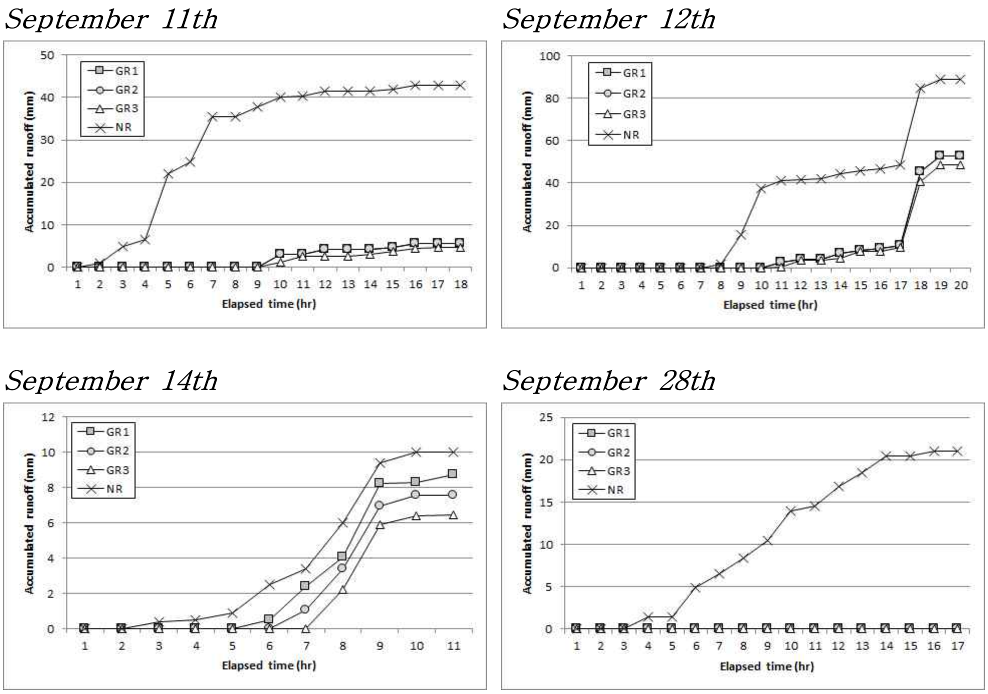


Figure 23. Modeling results of accumulated runoff

Table 11. Modeling results

Rainfall events (2013)	Antecedent rainfall event (day)	Total rainfall (mm)	Test	Peak flow reduction ratio	Peak flow time delay (hr)	Water storage (mm)
E1	13.2	35	GR1	1	-	35
			GR2	1	-	35
			GR3	1	-	35
E2	1.8	24	GR1	0.90	1	22.4
			GR2	0.99	1	23.9
			GR3	1	-	24
E3	3	68.5	GR1	0.43	2	39.6
			GR2	0.72	2	45.1
			GR3	0.63	2	42.8
E4	0.3	130.5	GR1	0.43	1	1
			GR2	0.47	1	3.5
			GR3	0.50	1	29.2
E7	3.7	109	GR1	0.68	4	50.2
			GR2	0.75	4	55.1
			GR3	0.71	4	22.9
E11	4.5	47.5	GR1	0.79	2	39
			GR2	1	-	47.5
			GR3	0.88	2	43.3
E13	12.5	46.5	GR1	0.80	2	37.5
			GR2	0.74	2	34.2
			GR3	0.71	1	37.7
E14	5.9	22.5	GR1	0.96	4	22.2
			GR2	0.96	4	22.2
			GR3	1	-	22.5
E15	12.1	44	GR1	0.57	2	30.3
			GR2	0.69	2	37.5
			GR3	0.74	2	38
E16	1.3	90	GR1	0.39	0	18.7
			GR2	0.37	0	30
			GR3	0.38	0	33.7
E17	0.5	11	GR1	0.24	2	6.1
			GR2	0.21	2	6.4
			GR3	0.52	2	7.5
E18	14.3	22	GR1	1	-	22
			GR2	1	-	22
			GR3	1	-	22

4.3.2. Model calibration

Comparison result of the modeling and the experiment are shown in figure 24. Decreasing similarity between the simulated results and the experiment value has been noticed. Thus storage-outflow relationship was adjusted.

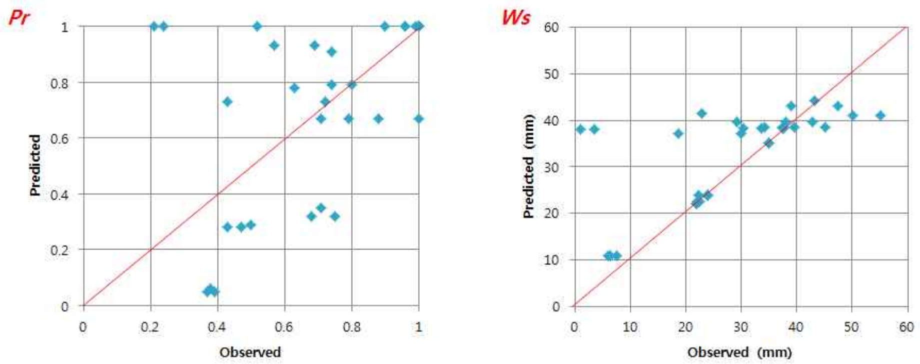


Figure 24. Observed-Predicted relationship before modifying

The evapotranspiration measured from building no. 35 were applied to the model in order to adjust the storage-outflow relationship (Figure 25).

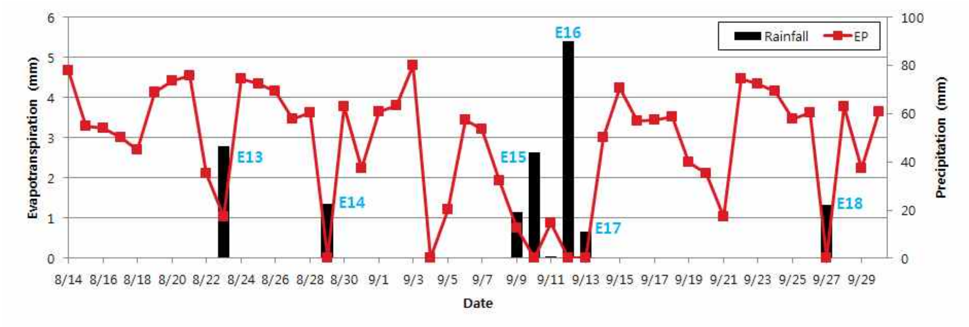
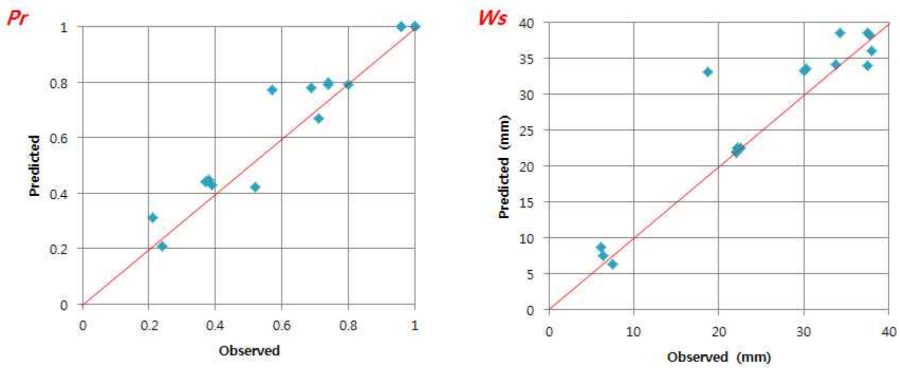


Figure 25. Evapotranspiration condition on SNU #35

Revised result of the model is displayed below (Figure 26). It showed high similarity from the peak flow reduction rate and stored amount. Thus it is considered that SGRR model can be applied in Korea, and it suits for the application of the green roof system.



CHAPTER 5. Conclusions

Hydrological aspect of green roof effectiveness has been neglected over its thermal and aesthetical effects despite the increased attention to the green roof system. Recently there are higher attention on flood reduction, and heat island reduction effects of green roof system but there is yet political support and research due to absence of the evaluation technique to test the green roof system. Thus this research concentrated on green roof system's hydrological performance for the analysis of the performance, development of the performance test method, and investigation of the applicable model.

1. Development of hydrological performance evaluation factor on green roof system

In order to evaluate the green roof system's hydrological performance, this study analyzed the factors that influence the runoff and produced the Mass balance. Influence factors are divided into environmental and physical factors, and with the analysis of these factors, the factor that can achieve the green roofs' performance of the flood reduction and water resources securement. Flood reduction performance can be achieved through Peak flow retention ratio(Pr) and Peak flow time delay(Td), and water resources securement performance can be evaluated through total Water storage(Ws) of the green roof system.

2. Application of the performance evaluation factor

Comparison and quantification of the performance of the flood reduction water resources securement are done by the application of each lab scale and field scale's performance evaluation factors. Performance were evaluated and compared in accordance with soil thickness, material condition of plant, amount of precipitation, and natural conditions of dry days. These enable the performance evaluation in different system and precipitation condition, and precisely evaluate the hydrological performance of the green roof when there is runoff through the precipitation.

3. Application of SGRR(Storm Green Roof Response) Model

Green roof system's evaluation has been attempted through SGRR model using Modified Pul's method. As an model's key point, Storage-outflow relationship is influenced by drain boards, soil characteristics, planting conditions, and evapotranspiration condition. Conditions besides the amount of precipitation and evapotranspiration, can be easily applicable as an material condition, but modification has done on evapotranspiration condition due to its sensitivity to the climate and weather. According to the similarity the modified model showed to the experimented data's evaluation, it is estimated that it is sufficiently applicable.

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국문초록

지금까지 옥상녹화는 미적 효과와 열적 효과에 관심이 집중되어 수문학적 효과는 비교적 잘 알려지지 않았다. 그러나 대도시의 번화가와 같은 곳에서 발생되는 홍수는 기반시설을 확충하기 어려워 다른 대안을 찾아야 했으며, 그 대안으로 옥상녹화의 수문학적 효과가 대두되었다. 그러나 옥상녹화 시스템의 수문학적 성능에 대한 평가 방식이 존재하지 않고 친환경건축물인증제도에서도 뚜렷한 기준을 제시하지 않고 있어 효과의 정량화 및 적절한 시스템 적용에 대해 어려움을 겪고 있다.

따라서 본 연구에서는 옥상녹화 시스템의 수문학적 성능을 평가하는 기법을 개발하고, 이를 통해 옥상녹화 시스템의 효과를 정량적으로 평가하여 객관적인 비교와 적정 옥상녹화 시스템을 제안을 가능하게 하기 위한 초석을 마련하고자 하였다.

먼저 옥상녹화 시스템의 유출 특성을 파악하기 위해 수문학적 물질수지를 분석하였고 이를 바탕으로 성능평가인자를 개발하였다. 이 때 성능평가를 확인하는 기준은 홍수저감효과와 수자원확보효과로 나누었다. 홍수저감효과를 평가할 수 있는 인자로써 첨두유출저감율과 첨두유출지연시간을 개발하였으며, 수자원확보효과를 평가할 수 있는 인자로 총 저류량인자를 제안하였다. 이를 통해 옥상녹화 시스템의 수문학적 성능에 대해 정량적인 기준을 가지고 평가할 수 있으며, 평가인자는 서로 다른 시스템과 기후 및 강우 조건에서도 동일하게 적용이 가능하기에 객관성을 지닌다.

성능평가인자를 개발하고 랩 스케일과 필드 스케일의 실험을 통해 평가항목에 대한 실험군의 성능을 분석하고 자연조건과 물질조건의 차이에 따른 성능의 차이를 살펴보았다. 이를 통해 동일한 성능평가인자를 적용하여 서로 다른 옥상녹화 시스템의 성능을 평가할 수 있음을 확인하였으며, 물질조건(토양, 식생, 배수판)과 자연조건(강우, 증발산량) 에 대한 성능을 분석하였다.

마지막으로 옥상녹화 시스템의 유출예측 모델인 Storm Green Roof Response (SGRR) Model을 사용하여 모델에 성능평가인자의 적용을 통한 옥상녹화 시스템 성능평가 모델로서의 가능성을 평가하였다. 본 모델은 Modified Pul's Method를 이용하여 옥상녹화 시스템의 물의 유출과 유입에 대한 관계를 정의하고 이에 따라 유출량을 모의한다. 토양과 식생과 같은 물질 조건은 쉽게 수정이 가능하지만 증발산의 경우 자연 조건이며 일반적으로 측정이 어려워 서울대학교 35동에서 측정한 자료를 바탕으로 모델을 수정하였다. 수정한 모델을 통해 얻은 모의값과 실험값의 유사성이 매우 높은 것으로 판단되어 차후 옥상녹화 시스템의 수문학적 성능평가에 본 모델의 적용이 가능할 것으로 판단된다.

주요어 : 빗물, 옥상녹화, 홍수저감, 수자원 확보, 수문학적 성능평가

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