Modeling role of rice paddy field and its implication in water management
Hyunju Park, Tschungil Kim, Hyunwoo Kim and Mooyoung Han

ABSTRACT
The objective of this study is to develop a conceptual model to analyze the role of rice paddy fields in water management and to use the model to suggest an appropriate countermeasure for land development. Rice paddy fields are traditionally seen in East and South-East Asia, particularly in areas that have a considerable seasonal variation in rainfall resulting in flooding and drought. One of the advantages of these fields in East Asia is that the period of rainfall is similar to the period of the water demand of the rice paddy. In this study, the water management functions of rice paddy are evaluated using rainfall–storage–discharge (RSD) modeling. The RSD system is a type of onsite structure used for rainwater management. In this study, the area of the rice paddy is assumed to be 10,000 m², and the rice paddy is considered to perform the storage and catchment functions of a rainwater harvesting system. The RSD system can be used for analyzing the outflow rate according to the rice paddy area and the peak outflow curves for a 100-year period; further, the effectiveness of the RSD system in reducing the final water discharge rate through a rice paddy is evaluated.

Key words | infiltration, rainwater, rice paddy, RSD, runoff

INTRODUCTION
Rice farms function as reservoirs that do not send water resources to a river directly, because rice paddy needs to store water in the farms. This prevents the flooding of rivers in the summer flooding season. Further, in Korea, groundwater levels and ground subsidence have decreased because of the overuse of underground water. In such a case, rice paddy replenishes the groundwater with the infiltration water (Kwak et al. 2008; Kim et al. 2006).

Eco-friendly public benefits of rice farming, such as flood control, recharging of water resources, air purification, acclimation, soil loss prevention, water purification, and organic wastewater digestion, are reported in this paper.

Korea needs better water resource management and prevention of disasters because of its rainfall pattern, which indicates that two-thirds of the annual rainfall occurs in summer and one-fifth of the annual rainfall occurs from October to March. At the moment, Koreans reduce the damage caused by floods and droughts by managing water through rice farming, which has a crop growth cycle that is in sync with the local rainfall pattern (Kim & Han 2007).

Figure 1 shows the change in the farmland area in Korea. The area ratio of rice paddy in 1990 was 22.1%; however, it decreased to 18.8% in 2001 because of modern industrialization and urbanization. Rice farming has lost its function of environmental conservation and water management because several rice paddy fields have been converted into impermeable areas such as paved roads and sites. In other words, the potential flood damage has increased because of the decreased water retention ability and groundwater recharge ability owing to the decreasing area of rice paddy. Thus, an appropriate alternative for the recovery of the water management function of the rice paddy is required.

Rainwater retention and permeation facilities deal with the created runoff by increasing the permeable layers. Small-scale rainwater facilities perform the functions of flood control, recharging of water resources, and
acclimation in summer. These functions are similar to the environmental preservation functions of rice farming.

Therefore, in this research, we investigate the environmental preservation brought about by rice farming and suggest a rehabilitating function of the water management of rice farming by a comparative analysis with a rainwater harvesting facility.

**MATERIALS AND METHODS**

**Composition of preliminary data**

Korean climate data are used for calculating the average annual temperature and the mean annual precipitation, provided by the National Weather Service (Figure 2). The functions of flood control and recharging of groundwater resources of the Korean rice paddy are one of the primary topics of study of the National Institute of Agricultural Science and Technology of Rural Development Administration (National Institute of Agricultural Science & Technology 2008) (Seo 2001; Seo et al. 2009). Further, the data related to the changing territory and the changes in the rice paddy field area are obtained from the Agriculture and Forestry Statistical Yearbook (Korea National Statistical Office 2009).

**Public function of rice paddy and rainwater harvesting facility**

Controlling floods, recharging groundwater, and decreasing the environmental temperature are some of the functions of a rice paddy field; these functions are closely related to the precipitation measurement and some of the other objectives of a rainwater harvesting facility. The factors related to the quantification estimation model of each detailed function are investigated on the basis of a field study, existing reference books and reports, and official statistics.

**Rainfall–storage–discharge (RSD) model**

In this study, the water management functions of a rice paddy are evaluated using an RSD model. The RSD system is a type of onsite structure used for rainwater management. Figure 3 shows the design parameters of the RSD system used in this study. During rainfall, building roofs collect rainwater, which is transferred to a rainwater tank by the roof drainage system. The system controls the process of storing rainwater as well as the outflow into the receiving water channels such as drainage systems. Pumps can be used for supplying the stored water for domestic use, generally as non-drinking water.

Figure 4 shows the RSD system of a rice paddy. The area of the rice paddy is assumed to be 10,000 m². The rice paddy also performs the storage and catchment functions of the rainwater harvesting system. Further, rainwater infiltrates to the bottom of the rice paddy and is pumped for use later on. The parameters of the rainwater system and the rice paddy, namely catchment, storage tank, pump and discharge parameters, applied to the RSD system, are listed in Table 1.
RESULTS AND DISCUSSION

Function of rice paddy field as flood controller

The effectiveness of the flood control function of a rice paddy field can be estimated on the basis of the height of the rice paddy field and the amount of permeating water, as shown in Equation (1):

\[ W_f = H_f + I_p + D_i \]  

(1)

where \( W_f \) = flood control volume (mm); \( H_f \) = height of the rice paddy field (mm); \( I_p \) = infiltration rate (mm/day); \( D_i \) = flood duration (days).

The range of the levee of the rice paddy is 198–408 mm; therefore, the average height of the rice paddy field was assumed to be 261 mm on the basis of the average height of 570 paddies.

We assumed the average permeability velocity of the rice paddy field to be 7.6 mm day\(^{-1}\), as suggested by Seo et al. (2008).
In order to evaluate the effectiveness of flood control, rainfall data from 1990 to 2010 provided by the meteorological administration was analyzed and used.

Hence, in this research, data related to the rainfall of more than 80 mm day\(^{-1}\) observed across the country were extracted; these data are plotted in Figure 2.

The annual average flood period and the standard deviation were 4.4 and 1.34 days year\(^{-1}\), respectively.

In other words, when the height of the rice paddy field was assumed to be 261 mm, the permeability velocity to be 7.6 mm day\(^{-1}\), and the flood period to be 4.4 days year\(^{-1}\), a value of 294 mm year\(^{-1}\) was obtained by using Equation (1).

In the case of a Korean rice paddy field having an area of 1.084 × 10⁴ km², approximately 3.2 billion tons of water can be controlled for the purpose of flood mitigation. Therefore, a 10,000-m² rice paddy field exhibits a flood control ability equivalent to 3 tons. As a result, if a 10,000-m² rice paddy is converted into an impermeable layer, 3,000 tons of water are discharged.

**Effect of rice paddy on the reduction of peak runoff using RSD model**

The RSD system is a type of onsite structure used for controlling the runoff flow from a building rooftop. Kim & Han (2008) stated that the structure of an RSD system can be considered suitable for the runoff process from building rooftops as catchment surfaces in order to produce a design inflow hydrograph for determining the retention volume for the storage process. As shown in Figure 2, a rice paddy has water storage and infiltration functions similar to those of a rainwater system. In this study, we assessed the effect of a rice paddy on the reduction of the peak runoff by using an RSD model. On the basis of this assessment, we suggest that rainwater tanks can replace the decreasing area of the rice paddy.

**Outflow rate according to rice paddy area**

The outflow of water from the rice paddy field in an RSD system is called the ‘overflow after keeping’. A structural schematic representation, including the flow, for a rice paddy field is shown in Figure 5. Further, the flow rate can be easily represented using a simple water balance equation such as Equation (2). The total quantities of the outflow and the inflow in a rice paddy field are different from each other. The outflow is the loss of water stored in the 10,000-m² rice paddy field. The retention volume of a rice paddy field, as that in the case of a rainwater tank, can hold water to mitigate the peak flow rate:

\[ V_t = \int_{t_0}^{t_1} (Q_{in} - Q_{out} - Q_{inf}) \, dt \]  

(2)

where \( V_t \) = stored water volume at time of \( t; \) \( Q_{in} \) = Inflow rate into the rice paddy field; \( Q_{out} \) = discharged outflow rate from the rice paddy field; \( Q_{inf} \) = infiltrated water from the rice paddy field.

**Initial conditions:**

\( V_0 = 0; \) \( V_{max} = A \times h_0 + A \cdot v_c; \) \( Q_{in} \) = Design inflow hydrographs;

**Boundary conditions:**

\( V_t < V_{max} \rightarrow ax_{out} utVdar \) (inflow stored in the rice paddy field when \( h_0 = 20 \) cm); \( V_t \cdot c_{max} \rightarrow ax_{out} utcm)a_{in} ntcm)a; (full tank and inflow directly overflows out).

---

**Table 1 | Summary of the processes and their functions in the RSD system of the rainwater system and rice paddy**

<table>
<thead>
<tr>
<th>Process</th>
<th>Rainwater system</th>
<th>Rice paddy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall</td>
<td>Building roof surface &lt;br&gt; Roof drain facilities</td>
<td>The area of rice paddy (A)</td>
</tr>
<tr>
<td>Storage</td>
<td>Rainwater tank</td>
<td>The area and height of rice paddy (RSD system)</td>
</tr>
<tr>
<td>Pump</td>
<td>Pump (Rainwater usage)</td>
<td>Infiltration</td>
</tr>
<tr>
<td>Discharge</td>
<td>Rainwater sewer pipes</td>
<td>Stream levee</td>
</tr>
<tr>
<td>Operation control</td>
<td>Rainwater tank ( h_0 ), constant</td>
<td>Levee ( h_0 ), variable</td>
</tr>
</tbody>
</table>

---

**Figure 5 | Flow conditions of a retention tank and rice paddy field**
$Q_{\text{in}}$ is the quantity of water flowing into the rice paddy field. $Q_{\text{out}}$ is the overflow from the rice paddy field. $Q_{\text{inf}}$ is the infiltration of the floor of the rice paddy. In this study, $Q_{\text{out}}$ is calculated using Equation (4) from the design inflow rate curves for Korea and the given conditions. The maximum value of the calculated outflow rate is the controlled peak runoff rate according to the rice paddy area. Figure 6 shows the outflow hydrograph according to the decrease in the rice paddy area and the impact of the inflow for a 100-year period and 90-min rainfall duration.

**Variation of duration time and rice paddy area**

Figure 7 shows the rice paddy area versus the peak outflow rate for the design inflow of a 100-year return period in Seoul. Dotted lines connect the peak runoff flow values, following the variation of the rice paddy area calculated using Equation (4), to the corresponding rainfall durations. Each line follows the standardized rainfall for a specific duration. The thick black line shows the maximum peak outflow with respect to the rice paddy area, which is the relationship between the rice paddy capacity and the maximum outflow for the 100-year storm period in Korea.

It is assumed that the rainfall process for an RSD system has no time of concentration, which means that the peak intensity time is the same as the time of the peak runoff flow. An RSD system will take into account all rainfall events having a duration of less than 24 h. The thick black curve shown in Figure 8 represents the predicted maximum outflow for the design inflow curves of all durations of less than 24 h for a 100-year return period. For a case study on practical design, each duration of less than 24 h is calculated for several return periods. Figure 9 shows the rice paddy area versus the peak outflow for the runoff of 5-, 10-, 30-, 50-, and 100-year return periods. The graph shows the 10,000-m² rice paddy area with respect to the peak outflow.

Figure 8 shows that rice paddy can reduce the peak runoff flow from rainfall. The line connecting points A, B, and C indicates the rice paddy area required to reduce the peak runoff flow for a 100-year rainfall event to that of a 5-year rainfall event. Point A represents the rice paddy area of a 5-year rainfall event. Point B indicates the same runoff value point as point A on the line of a 100-year return period. Point B also denotes the controlled peak flow of a 100-year rainfall event with respect to the rice paddy area volume at point C. The rice paddy area of
5,000 m²/10,000 m² can reduce the runoff of a 100-year rainfall event to the peak runoff value of a 5-year rainfall event. This means that, in an RSD system with a rice paddy area of 5,000 m²/10,000 m², a discharge pipe for a 5-year design period would provide protection from flooding for a 100-year rainfall event.

When a rice paddy field is developed into an impermeable layer, a rainwater harvesting facility can replace the field from the perspective of the runoff reduction. Figure 9 shows the rainwater storage tank design according to the decreasing rice paddy area. Further, Kim (2008) reported that the size of a rainwater tank can be designed efficiently when pumping the stored rainwater. Therefore, on the basis of Kim’s study, the appropriate size of rainwater storage facilities for the runoff reduction is calculated considering the decrease in the rice paddy area and the use of a pump in a rainwater tank (Figure 10). The appropriate capacity of rainwater storage is 2,000 tons when the rice paddy field is 10,000 m² in area. However, it can be reduced to 1,400–1,800 tons when rainwater is used for another purpose.

**CONCLUSION**

The RSD system is a type of onsite structure for rainwater management. In this study, the area of rice paddy was assumed to be 10,000 m²; the rice paddy also performed the storage and catchment functions of a rainwater harvesting system. The RSD system was used for analyzing the outflow rate according to the rice paddy area and the peak outflow curves for a 100-year period and its effectiveness in reducing the final water discharge rate through a rice paddy.

We studied the effects of the flood control and groundwater recharge functions of a rice paddy field and a rainwater harvesting facility for finding a replacement that performed the environmental protection functions of a rice paddy field. The simulation results indicated that a rice paddy field controlled floods at the rate of 3 tons per 10,000 m² and 4.1 tons per 108 day⁻¹ per 10,000 m². Further, it was found that the most economically efficient way of calculating the storage tank volume was multiplying the roof area (m²) by 0.1 m for the flood control function.

The overflow from a rainwater tank is also treated by infiltration. Moreover, the surplus rainwater is discharged to the fourth groundwater flow under 5.5 m from the surface. Such a rainwater treatment method leads to a tax saving of 1.3 euro/m by using exiting sewerage arrangements. Hence, this method has become a standard rainwater utility method in Munich. Likewise, Korea needs to come up with a political system to substitute the environmental protection functions of the rice paddy field with a rainwater harvesting facility.

**ACKNOWLEDGEMENT**

This research was supported by the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (20120008986).
REFERENCES

Kim, Y. J. 2008 A Design Method of Rainwater Tank Retention Volume for the Control of Runoff from Building Rooftop. Seoul National University, Korea.


First received 11 November 2012; accepted in revised form 14 February 2013. Available online 14 September 2013.