A Simulation Model for Investigating the Effects of Rice Paddy Fields on Runoff System

Ray-Shyan Wu, Wen-Ray Sue, and Jia-Shien Chang
Department of Civil Engineering, National Central University
Chung-Li 32054, Taiwan

Abstract In Taiwan, the increase of the industrial demand on water resources and the free trading policy resulting from joining the World Trade Organization would most likely lead to a reduction of rice production. However, rice paddy fields are regarded as important in the conservation of water resources. Besides rice production, the effects of paddy fields on the environment include the increase of groundwater recharge and the remediation of floods. Unlike the rice production, the value of the conservation of the environment is difficult to quantify. This study investigates the effects of paddy fields on groundwater recharge and flood remediation. For the long-term estimation study, a model based on hydrologic equilibrium was employed to explain the performance of rice paddy fields to the promotion of groundwater recharge. According to the case study, the amount of the runoff from a rice paddy field is about 27% of the amount of the precipitation. Compared with the amount of the runoff from dry farming field being as high as 55% of the amount of the precipitation, it is clear that a significant increase in runoff and a decrease in groundwater recharge can be expected when a rice paddy field is converted into other uses. Moreover, an event-based simulation study is conducted to investigate the effects of rice paddy fields on the flood peak. Due to the detention capacity of the paddy field, the flood peak can be reduced to 1/3 of its quantity from a dry farm. Therefore, it is suggested that these positive effects of rice paddy fields on runoff should be considered in deciding upon the reduction of rice cultivation.

Keywords: Rice paddy field, Runoff system, Water balance, Traffic pan

1. Introduction

The increase of the demand of water resources for the industry in Taiwan limits the quantity of the agricultural water use. Furthermore, the join of the World Trade Organization would probably lead to a reduction of rice in Taiwan. However, paddy field plays an important role in the conservancy of water resources. Besides rice production, the effect of paddy field on environment includes the increase of groundwater recharge and the remediation of floods. However, it is difficult to quantify the value of the rice paddy to the conservancy of the environment.

Rice is a kind of crop that requires a certain depth of water in the paddy field during the growing season. According to the field data, the best rice production can be realized by keeping the paddy field as a pool with about 30 mm deep of water in the surface. About 20 to 40 cm beneath the soil surface, there exists a hard pan which minimizes leakage and keeps the water in the paddy filed to ensure a shallow water pond in between irrigation practices. To reduce surface runoff, the ridge is carefully maintained in a certain height. The higher the ridge is, the more the rainfall is kept in the paddy field.

It is noticed that the existence of rice paddy bring forward three major kinds of benefit: the rice production, the upholding of living environment, and the maintenance of the ecological system balance [Tsai, 1994]. The balance of the ecological system is achieved through the ability of rice paddy fields to provide groundwater nourishment, river flow and storm water regulation, drainage peak flow reduction, local weather stabilization, and wildlife shelter.

2. A Hydrologic Simulation model for Rice Paddy Fields

During the initial period of a rainfall event, there is no surface runoff from a rice paddy field because all the rainfall is impounded given the ridge as barrier. As the rain continues to fall, runoff may occur when the depth of the water excesses the height of the ridge. After the cease of the rain, part of the water trapped in the paddy field evaporates into atmosphere, part of the water infiltrates into the ground, and the rest of the water stays on the surface. It is shown as figure 1.

In this study, a hydrologic continuity model that describes surface runoff, evaporation, and infiltration, as shown in Figure 1, is developed. The model consists of the following modules. The Hamon equation is applied for estimating potential evapotranspiration. Then, evaporation is estimated by the crop coefficient. The

Horton equation [Aron, 1992] is employed to estimate infiltration. In the meantime, the effect of soil moisture content on percolation and infiltration is considered. Runoff is calculated by applying the weir function.

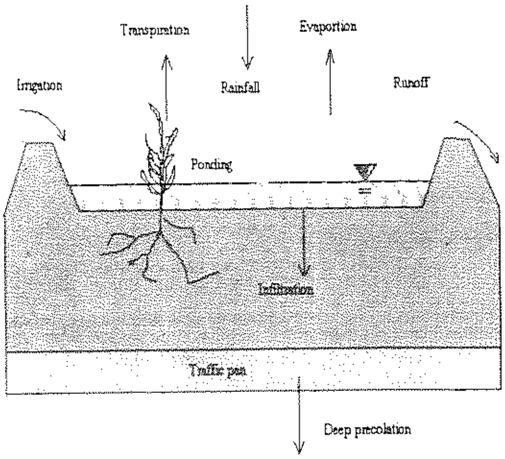

Figure 1:Inflow and outflow for paddy field

2.1 Evapotranspiration Module

To estimate the evapotranspiration, the Hamon equation [Hamon, 1961] is applied,

$$PE_t = \frac{0.021 H_t^2 e_t}{T_t + 273} \tag{1}$$

$$e_t = 33.8639\left[\left(0.00738T_t + 0.8072\right)^8 - 0.000019\left(1.8T_t + 48\right) + 0.001316\right], T \geq 0$$

where, PE_t : Potential evapotranspiration

H_t : hours of daylight

e_t : saturation vapor pressure (millibar)

T_t : temperature (${}^0C$)

and the evapotranspiration of the paddy is

$$ET_{crop} = PE_t \times K_c \tag{2}$$

where, K_c : crop coefficient

2.2 Infiltration Module

Infiltration, estimated by the Horton equation, is modeled as a function of time. The model requires three parameters: maximum infiltration rate f_0, stability infiltration rate f_c, and constant k. Furthermore, to take into account the effect of the underground percolation, the soil drainage function proposed by Bauer[1974] is used here,

$$d(t) = f_c\left[1 - \exp(-kt)\right] \tag{3}$$

where, $d(t)$: rate of percolation at time t

The initial conditions for dry soil can be regarded as the infiltration rate equals the maximum infiltration capacity, f_0, and no water percolates. As time goes by, the infiltration rate gradually decreases, while the percolation increases, as shown in Figure 2. According to the hydrologic continuity function, the change of the soil water storage equals the difference between infiltration and percolation.

$$\frac{ds}{dt} = f(t) - d = f_c + (f_0 - f_c)\exp(-kt) - f_c\left[1 - \exp(-kt)\right]$$
$$= f_0 \exp(-kt) \tag{4}$$

So the soil water storage at time t is:

$$S(t) = \frac{f_0}{k}\left[1 - \exp(-kt)\right] \tag{5}$$

When time t goes to infinity, the soil water storage reaches to its maximum :

$$S_c = \frac{f_0}{k} \tag{6}$$

That is, the percolation can be represented as:

$$d(t) = \frac{f_c S(t)}{S_c} \tag{7}$$

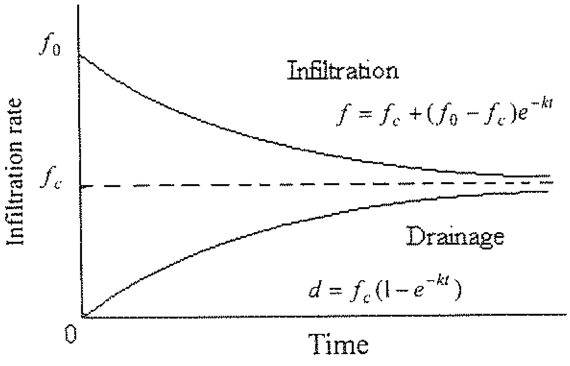

Figure 2: Relationship between infiltration and percolation

Horton equation relates the infiltration rate as a function of time. However, it is difficult to work in the time domain. Instead, in this study the equation proposed by Aron[1992] is applied:

$$f_p(t) = f_c + (f_0 - f_c)\left(\frac{S_s - S(t)}{S_s}\right) \tag{8}$$

where, f_p : potential infiltration rate (mm/hr)

f_0 : maximum infiltration rate (mm/hr), same as in Horton equation

f_c : stability infiltration rate(mm/hr), same as in Horton equation

S_s : soil water content at saturation (mm)

S : soil water content (mm)

Let it be noted that S_s is usually regarded as a basic soil property obtained in a standard laboratory test, but actually it is affected by the possible air trapped in the soil.

The potential infiltration limits the effective infiltration caused by rainfall depth and the flowage depth in the paddy field. That is, the effective infiltration is always less than the potential infiltration. Therefore, soil moisture content can be estimated by:

$$S(t+\Delta t) = (f_c - d - E_t)\Delta t + S(t) \tag{9}$$

where, Δt is 1hour.

2.3 Runoff Module

To investigate the remediation of floods during some possible storm events, this study assumes that the excess of water is drained through the weir in paddy fields, and the paddy field is a dew pond. The paddy field storage after rainfall is shown as:

$$S = Ay^{n_1} \tag{10}$$

where, S : storage

A : area of paddy field

y : depth of water in the paddy field

n_1 : assume to be 1 for water level almost horizontal

The outflow from paddy fields can be calculated as,

$$Q = C_w \cdot W \cdot h^{3/2} \tag{11}$$

where, Q : outflow

W : the effectual width of the weir

h : the hydraulic head

C_w : constant (C_w =1.838 rectangle weir)

If the bottom of the weir is located at a height d, the outflow is,

$$Q = C_w \cdot W \cdot (y-d)^{3/2} \tag{12}$$

Therefore, the height of the water in the paddy field is,

$$y = d + \left(\frac{Q}{C_w \cdot W}\right)^{2/3} \tag{13}$$

Thus,

$$S = A \cdot d + A\left(\frac{1}{C_w \cdot W}\right)^{2/3} \cdot Q^{2/3} \tag{14}$$

From the continuity of mass,

$$\frac{Q_{t+\Delta t} - Q_t}{\Delta t} = K_w\left(\frac{I_{t+\Delta t} + I_t}{2} - \frac{Q_{t+\Delta t} + Q_t}{2}\right)\left(\frac{Q_{t+\Delta t} + Q_t}{2}\right)^{1/3} \tag{15}$$

where, I : inflow to paddy field (cms), which can be obtained as $I = iA \times 0.001/3600$, where i is the rainfall depth(mm/hr) and A is the area of paddy field (m^2)

From Equation 15, one can compute the outflow at any given time period. In this study, the time period, Δt, is chosen as 1 hour.

3. Application of Model

3.1 Case Study Area

Chiai County in the central part of Taiwan is chosen as the case study area. Figure 3 shows the average monthly temperature from 1981 to 1990. Figure 4 shows the average monthly rainfall from 1981 to 1990. It is apparent that a year can be divided into a dry season and a wet one. In fact, paddy fields get more rainfall on the second tillage than that on the first one. Rice is cultivated in both seasons.

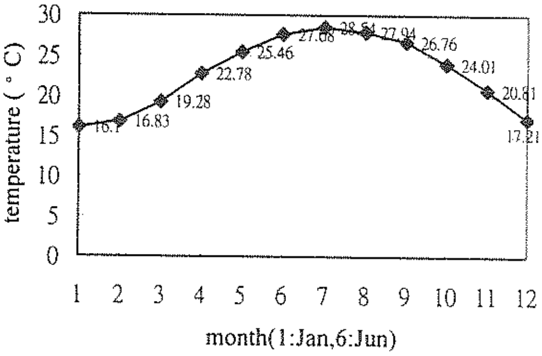

Figure 3: Average monthly temperature from 1981 to 1990

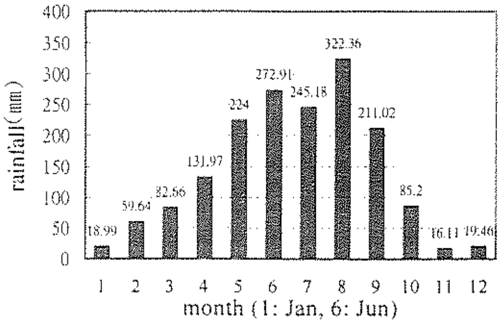

Figure 4: Average monthly rainfall from 1981 to 1990

In the experimental study of the effects of rice paddy filed on the local hydrologic balance, a period of 10 year data (1981-1990) is chosen as the weather input. The growing season of rice in this area is from March to October. And the submergence depth of water is 30 mm. Farmers irrigate when the soil moisture content is below field capacity. The water depth during each rotation of irrigation is 45mm. The ridge is set to be 100mm. Three types of cultivation, namely, growing rice, fallowed, and changed to dry farming, are simulated. When paddy field is in fallow, the ridge height maintains the same but the field is not irrigated. In the case of dry farming, no water would be kept in the surface for there is no ridge. Although there are many kinds of dry farming crop, the crop coefficient is set to be an average value about 0.5. The initial soil moisture for paddy field and for fallow is set to be the field capacity, 72.9 mm, and that for dry land is the wilting point capacity, 70.2 mm.

In the experimental study of the effects of rice paddy filed on the remediation of flood resulting from a short-term storm, the area of the paddy fields are 1 ha and 0.25 ha. The storm on September 2, 1981 is chosen. The duration of the storm is 15 hours and the total amount of precipitation is 372.9 mm. It is also assumed that there is no surface water storage and the soil moisture is saturated. Two types of outflow mechanisms are studied. One is that the water crosses the top of the ridge, and the other is that the water flow out paddy field through the in the ridge.

3.2 Runoff Simulation in A Short-term Storm

For the short-term storm, this study is assumed that the paddy fields are 1 ha and 0.25 ha. The storm, which have rainfall duration time 15 hours and precipitation 372.9 mm, is applied on Sep. 2 1981. It also considers that there is no storage and the soil moisture is saturation. Two outflow method is consulted, one is that the weir width is equal to the ridge width, another is the weir width is equal to the actual paddy field weir width.

4. Results and Discussion

4.1 Long-term Simulation

Figure 5 shows the result of the long-term simulation. There is no runoff from October to January. This observation reflects the fact that it is very dry in winter on Chiai. Due to the detention storage provided, the runoff from paddy fields is only one half of that from dry farming land. In terms of evapotranspiration, there are two peak periods in May and August for rice paddy field. This is due to massive irrigation in these two periods to grow rice. For fallow field, most of the precipitation is in June, July, and August. Therefore, evapotranspiration is utmost in this three months. However, the evapotranspiration of fallow field is still less than that of paddy field in all year round. It is clear that paddy fields provide the greatest amount of deep percolation among three types of land use. This is due to the ponding of water almost all year round in paddy fields and subsequently soil moisture is kept saturated. In other words, there is no lack of the supply of water and the path of percolation. The percolation of dry farming field is large than that of fallow field.

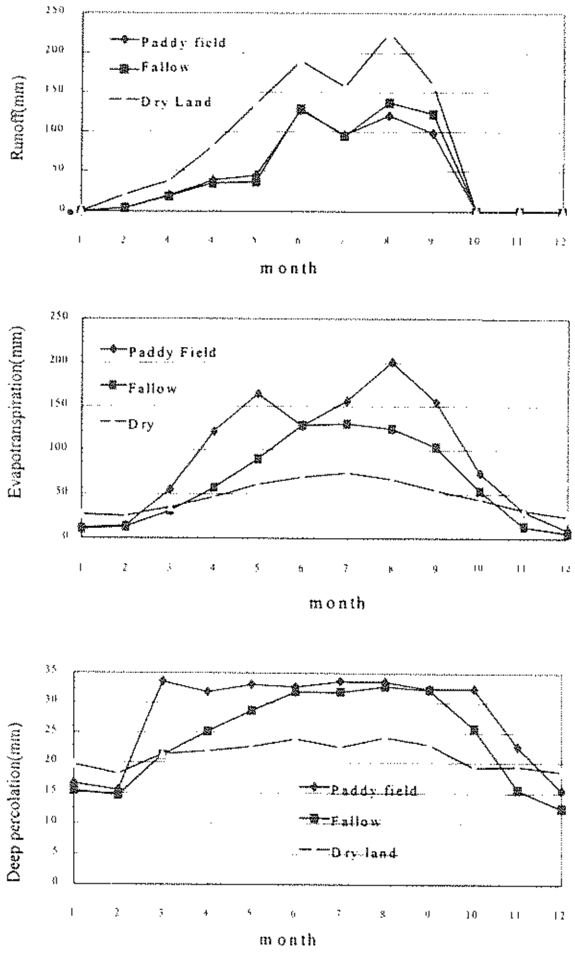

Figure 5: Water balance for three types of land uses

Let percolation denote groundwater recharging, runoff denote floods, and evapotranspiration denote the regulation of the local climate. The results show that paddy fields provide positive effects for all three aspects. Fallow fields that keep the ridge decrease runoff significantly. The effects of dry farming fields on these three aspects are not apparent, it there is any. According to the case study, the amount of the runoff from rice paddy field is about 27% of the amount of the precipitation. Compared with the amount of the runoff from dry farming field being 55% of the amount of the precipitation, it is clear that a significant increase of runoff and a decrease of groundwater recharge can be expected when rice paddy field is converted into other uses.

4.2 Storm Event Simulation

The result of the storm event simulation is summarized in Figures 6 and 7. Figure 6 compares the spilling outflow of different height of ridge in paddy field with the ridge width being 100 meters. It is clear that the higher the ridge is, the lower the peak of flood would be. However, the effectiveness of the reduction of the peak depends on both the size of the storm and the shape of the hyetograph. In this particular case, the peakflow can be reduced to less than 20% of the original peakflow by maintaining a 30cm high ridge. Figure 7 compares the outflow of different weir width ranging from 0 to 30 cm, with the width and height of the ridge being 50m and 0.2m, respectively. The results show that peakflow diminishes and the time to peak delays as a result of the ridge. It also indicates that the width of the weir affects both the peak of flow and the time to peak. In this case study, the wider the weir is, the greater the peakflow would be. Again, the impact on the hydrograph depends on both the size of the storm and the shape of the hyetograph.

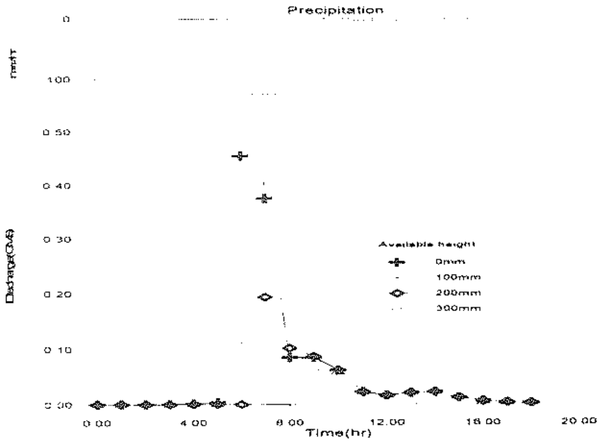

Figure 6: Compares the outflow in different storage height for paddy field

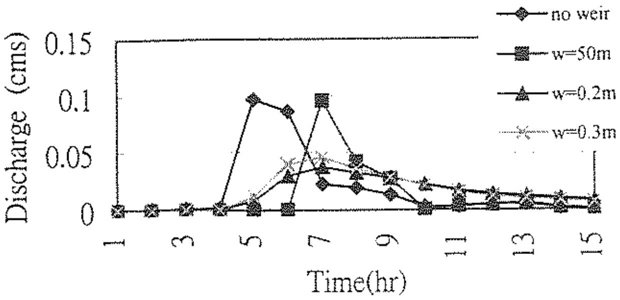

Figure 7: Discharge from three types of weir width

5. Conclusions

The simulation study described here is designed to explore the positive effects of rice paddy fields on the runoff system. In general, rice paddy fields promote groundwater recharge and reduce flooding. To quantify these effects, a long-term simulation and an event-based simulation are performed. The simulation model is based on the hydrologic equation and the weir flow equation. A paddy field in the central area of Taiwan is chosen as the case study. Three types of cultivation, namely, growing rice, fallowed, and changed to dry land farming, are simulated.

The result of the long-term simulation shows that the runoff from paddy fields is only one half of that from dry land farming. However, the evapotranspiration of rice paddy fields is the highest among all three land uses. Most importantly, paddy fields provide the greatest amount of deep percolation among all three types of land use. This is because water is kept in the paddy fields. As a result, the supply of water and the path of percolation is abundant. It is clear that paddy fields provide positive effects for groundwater recharge and flood remediation. It is clear that a significant increase of runoff and a decrease of groundwater recharge can be expected when a rice paddy field is converted into other uses.

The results of the event-based simulation show a significant decrease in the peakflow can be achieved when the ridge of paddy fields is well maintained. In fact, the higher the ridge is, the lower the peak of flood would be. Furthermore, the width of the weir affects both the peak of flow and the time to peak. This study indicates that the wider the weir is, the greater the peakflow would be. However, the effectiveness of the reduction of the peak and the impact on the hydrograph can vary for different storm and hyetograph.

However, we only analyses the runoff from the paddy field, without considering the hydraulic routing in the channel. The consideration of the channel networking would become important when a regional drainage system planning is performed. Moreover, the phenomenon of the traffic pan is another interesting topic in research and requires further study.

Finally, it should be noted that the positive effects of rice paddy fields on runoff system should be considered in deciding the reduction of the rice cultivation. Moreover, the broader ecological impacts of the transformation of land use of rice paddy fields may produce problems significantly more severe than the effects on the runoff system presented here.

6. Acknowledgements

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