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RESEARCH ON DEVELOPING FARMLAND IRRIGATION WATER MANAGEMENT MODEL IN TAIWAN

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ABSTRACT

The agricultural water usage accounts 70% of total nation's water consumption in Taiwan, which paddy field irrigation have the largest proportion. When the drought occurs, the allocation and utilization of water usage become an important issue, especially in agriculture, farmer pump ground water to supply the irrigation deficit from surface water which may impact regional groundwater level and cause more problem in strata subsidence. Generally, the irrigation water intake from channel and groundwater depends on the weather condition and the crop planting period, such as crops planting ratio and the growth stage of crops. Farmers choose to irrigate crops with water extracted from irrigation channel or pumped groundwater. To the need for calculating field water assumption and irrigation water, system dynamic model was used to establish irrigation water management model for mixed cropping fields. The second crop simulation in 2016 shows that when the ratio of water irrigated on paddy to upland is 0.5 to 0.5 (about 104.5 hectares for both paddy rice and upland crops), the ratio of total pumping volume to total channel water during simulated crop growth is about 46% and 54%; when the ratio of water irrigated on paddy to upland is 0.9 to 0.1 (about 188 hectares of paddy and about 21 hectares of upland crops), the ratio of total pumping to total channel water intake during simulated crop growth is about 51% and 49%. It can be understood that the ratio of rice to upland crops farming will significantly affect the irrigation water situation. When the rice area increases, the irrigation water demand will also increase. As the scenario simulated when paddy area increased 40%, the water demand increased 11%. Meanwhile, under insufficient canal water supply, the groundwater pumping will be increased up to 5%. Through the integrated irrigation system of surface water and groundwater to explore the situation of agricultural water use, the water source allocation efficiency of agricultural water can be upgraded, and the space for the allocation of water for people's livelihood and industrial water can be further improved.

Keywords: System dynamic model; Farmland irrigation; Mixed crop, Taiwan.

1. INTRODUCTION

The climate in Taiwan is subtropical monsoon with an average annual rainfall about 2,510 mm. Although the wet season is abundant, the difference between the dry season and the wet season is greater than 2,000 mm. Moreover, due to climate change the rainy and dry season ratio in Northern Taiwan is 6:4, while it is 9:1 in Southern area. This dramatic distribution difference makes it extremely difficult to store and utilize water resources effectively. Drought is a kind of water stress [1,2] and has a direct impact on agriculture [3]. During the drought period, some of the allocated agricultural water transferred to the domestic and industrial sector, resulting in a lack of irrigation water for farmers. Therefore, how to enhance the water use efficiency (WUE) of agricultural water resources is a crucial issue.

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Simulation or optimization approaches are mostly used for water distribution system [4]. Precision irrigation by using a smart simulation system is a possible approach of enhancing WUE and maintaining crop growth conditions to ensure productivity. Therefore, this study uses the system dynamics software VENSIM to establish a smart irrigation water management system. Compared with other conventional methods, the smart system exhibited excellent performance with its reliable digital technology [5]. System dynamics firstly developed by Jay W. Forrester, used to analyse the modelling system changes and dynamic behaviour based on the linkage and response mechanism among models [6]. It is a computer-aided approach to evaluating the interrelationships of components and activities within complex systems [7], which is very useful in management and planning. Wu et al. applied the VENSIM model to a paddy rice field in Central Taiwan [8]. Luo et al. applied system dynamic model for time varying water balance in aerobic paddy fields [9]. The main objective of this study is to develop a smart irrigation system using the water balance method with the help of the VENSIM simulation tool.

2. METHODOLOGY

The VENSIM simulation tool was formulated for time variant field water balance analysis using mathematical governing equations. Various water balance components were analysed and simulated on a daily basis using feedback relations in the model. The simulated results were validated with the observed discharge data.

2.1 Field Water Balance Theory

The study is based on the water balance method. A water balance theory was applied in a control volume under the condition of mass conservation to evaluate the overflow discharge from paddy fields. Through the three-dimensional microcosmic view (Figure 1), the porosity medium flow condition can be given as in Equation (1):

q_in-q_out=ds/dt (1)

where q_in is inflow, q_out is outflow, ds is the change in storage of control volume with in a time t.

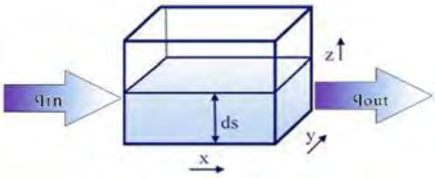

Figure 1. Microcosmic view of three-dimensional porosity medium flow condition

The Conceptual model (Figure 2) of field water balance was formulated by considering the field as a linear reservoir. Assuming that the paddy field is under cultivation and the plow sole exists, the water balance method is given by Equations (2). The decision criteria whether to irrigate or not is represented by Equations (3).

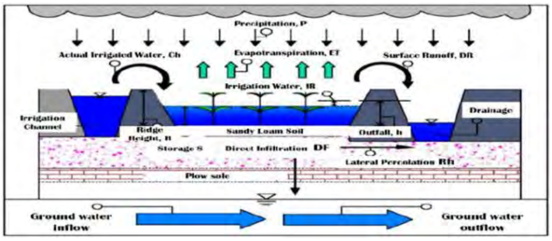

Figure 2. Conceptual model of field water balance

$$S_i = S_{i-1} + P_i + Ch_i + GW_i - ET_i - DR_i - DF_i - R_{hi} \qquad (2)$$

$$N_i = ET_i + DF_i + R_{hi}$$

$$If S_{i-1} + P_i < N_i\,,\;\; then IR_i > 0$$

$$If S_{i-1} + P_i \geq N_i\,,\;\; then IR_i = 0$$

$$IR_i = St_i - (S_{i-1} + P_i) + N_i \qquad (3)$$

$$If\ Ri_i \geq IR_i\,,\;\; then\ Ch_i = IR_i$$

$$If Ri_i < IR_i\,,\;\; then Ch_i = Ri_i$$

where the suffixes i and i-1 represent the day i and i-1. S is field storage, P is rainfall, Ch is channel irrigation water applied, GW is pumping of the groundwater, ET is actual crop evapotranspiration, DRis surface runoff/overflow from field, DF is vertical percolation, and Rh is lateral seepage inflow. N represents the field losses from the system, IR is the irrigation water requirement, Ri is channel water volume. The target depth of storage (S_t) equals the summation of ponding depth and soil saturation depth. All the components have same units (in terms of volume of water per unit area, or equivalent depth units).

2.2 Soil Water Balance Method

The water requirements of upland crops and paddy rice are different. Upland crops do not require the water storage. Therefore, this study uses soil water balance method to estimate soil water content. The water balance method is given by Equation (4)

$$SM_i = SM_{i-1} + P_i + IR_i + GW_i + CR_i - ET_i - DR_i - DP_i \qquad (4)$$

where SM is soil water content, P is rainfall, IR is the irrigation water requirement, GW is pumping of the groundwater, CR is the capillary rise from the underlying water table (The groundwater level in the study area is greater than 2 meters, so the CR is assumed to be zero.), ET is actual crop evapotranspiration, DR is surface runoff/overflow from field, DP is the sum of vertical percolation and lateral seepage inflow, the suffixes i and i-1 represent the day i and i-1.

The soil can store water, so the root zone in the upland crop field can be conceptualized as a box. The water content in the box fluctuates over time (Figure 3). The soil water content depends on the soil type. In the study area, soil type is sandy loam with average soil porosity of 43% and a coefficient of conductivity of 0.01158 (〖day〗^(-1)). The other characteristics include field capacity (14%) and wilting point (6 mm).

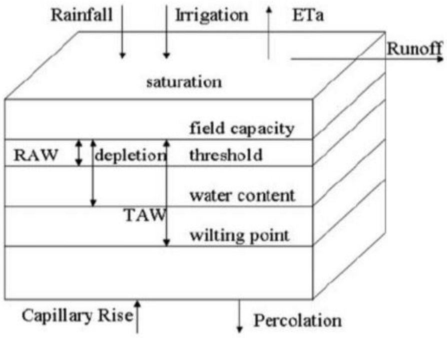

Figure 1. Conceptual model of the upland crop soil water balance adapted from Allen et al. (1998)[14]

In Figure 3, ETa is actual evapotranspiration, RAW is the readily available soil water in the root zone, TAW is the total available soil water in the root zone.

2.3 Crop Evapotranspiration

The sum of evaporation and transpiration is called the crop evapotranspiration (ETc). Crop evapotranspiration and crop water requirement are the same because water loss by stomatal transpiration during plant growth is considered small and neglected. ET of paddy rice can be determined by Equation (5). When determining ET of upland crops, the soil moisture condition needs to be considered. Therefore, ET of upland crops can be determined by Equation (6). When the soil water content is lower than wilting point, evapotranspiration does not occur because the plants cannot obtain water from the soil.

$$ET_{paddy\ rice} = K_c \times ET_0 \quad (5)$$

$$ET_{upland\ crops} = K_c \times K_s \times ET_0 \qquad (6)$$

$$K_s = \begin{cases} 1 & D \leq RAW \\ \frac{TAW-D}{TAW-RAW} & RAW \leq D \leq TAW \end{cases} \qquad (7)$$

where K_c is the single crop coefficient, 〖ET〗_0 is the reference crop evapotranspiration, K_s is water stress coefficient, D is the root zone depletion. In this study, the K_c values of paddy rice were used from Yao et al. [15] and are listed in Table 1. The K_c values of upland crops were used from FAO and are listed in Table 2.[14]

Table 1. Paddy rice crop coefficient (K_c) for each growth stage adopted from Yao et al.[15]

Growth Days	Growth Stages	Growth Degree	Crop Season	
			1stCrop	2ndCrop
-	Ground	-	-	-
1~15	Seedling	185	0.92	1.01
16~30	Early tillering	381	1.00	1.11
31~45	End of tillering	589	1.00	1.11
46~60	Early flowering	808	1.13	1.23
61~75	End of flowering	1032	1.13	1.23
76~90	Early ripening	1259	0.89	0.93
91~105	Middle of ripening	1487	0.89	0.93
106~120	End of ripening	1715	0.89	0.93

Table 1. Upland crops coefficient (K_c)for each growth stage adopted from FAO

Crop	Initial Stage	Mid-season Stage	End of the late season stage
Cabbage	0.7	1.05	0.95

2.4 Irrigation Water Demand

Irrigation water demand is the amount of water that satisfies the normal growth of the plant. During irrigation periods, irrigation water demand should consider conveyance loss of field water and channel water. Therefore, the actual irrigation water demand is the sum of irrigation water demand and the conveyance loss, which can be described as in Equations (8) and (9).

$$\text{Water conveyance loss} = \frac{\text{Irrigation water demand}}{(1-\text{Water conveyance loss rate})} - \text{Irrigation water demand} \qquad (8)$$

$$\text{Actual irrigation water} = \text{Irrigation water demand} + \text{Water conveyance loss} \qquad (9)$$

The conveyance loss is calculated by the length of each channel from the intake gate to each sub-block. The conveyance loss rate is 10% per kilometer, as shown in Table 3.

Table 2. Water conveyance loss from the intake gate to each sub-block (unit: %).

Conveyance Loss (%) / Sub-Block	Block 1	Block 2	Block 3	Block 4	Block 5
No.1	8.15	13.15	20.23	21.16	28.50
No.2	8.15	13.15	20.23	24.93	28.50
No.3	10.45	11.90	22.01	24.93	29.33
No.4	10.45	11.90	22.01	33.33	29.33
No.5	11.71	19.08	22.85	–	30.38
No.6	11.71	19.08	–	–	30.38
No.7	12.74	21	–	–	–
No.8	12.74	21	–	–	–

2.5 Groundwater Pumping Calculation

The groundwater pumping calculations in this study are divided into two scenarios. The first scenario is to determine groundwater pumping. The amount of groundwater pumped is converted from the pumping time recorded by the farmer. If the amount of water is insufficient, it will be supplemented by channel water. Another scenario is to determine the channel water supply. If the amount of water is insufficient, the groundwater pumping will be automatically calculated by the model. The model sets the boundary conditions for channel water supply to be quantitative, and the boundary conditions for groundwater pumping are infinite. However, the current situation is closer to determining the channel water supply. When the channel water is insufficient, the farmers will start pumping groundwater. The pumping time is based on half an hour. If the pumping time is more than half an hour, but it is less than 1 hour, it is still calculated by taking 1 hour, and so on. The decision criteria of the model whether to pump or not is represented by Equation (10).

$$If Ch_i \geq IR_i,\ then Gw_i = 0 \ (10)$$

$$If\ Ch_i < IR_i,\ then\ Gw_i = (IR_i - Ch_i)_n$$

where Ch is channel irrigation water applied, IR is the irrigation water requirement, Gw is groundwater pumping, the suffixes i represents the day i, n is the time unit of groundwater pumping, n =1 is half an hour, n =2 is one hour, and so on. The average pumping discharge in the study area is 0.020 CMS (m3·sec-1).

2.6 Percolation Calculation

Percolation is the downward movement of water towards the horizontal hydraulic gradient and the vertical direction through porous media up to the groundwater table [10]. It is the sum of vertical percolation and lateral seepage.

2.6.1 Vertical Percolation

Experimental results under different irrigation conditions indicated that the plow sole leads to a decrease in the vertical and lateral percolation [11,12]. Therefore, water falls to the groundwater level after passing through the plow sole. The percolation of paddy rice fields consists of three different stages, as shown in Figure 4[13]. The procedure for estimating the percolation at different stages is different. Darcy's law is used to calculate vertical percolation. The occurrence of vertical percolation depends on the comparison of field capacity (FC) and the previous field storage, as given in Equations (11)–(13).

$$DF_i = \begin{cases} P_t if S_{i-1} > FC \\ 0 \quad if S_{i-1} \leq FC \end{cases} \qquad (11)$$

$$FC = Soil\ depth\ \times\ Field\ capacity \qquad (12)$$

$$P_t = k_p \times \frac{h_t + l_m}{l_p} (13)$$

Assume $C_p = k_p / l_p$,$P_t$can be converted to Equation (14).

$$P_t = C_p \times (h_t + l_m) \qquad (14)$$

where P_t is the percolation (mm·day-1), FC is the depth of field capacity (mm), k_p is the coefficient of hydraulic conductivity (mm·day-1), h_t is the previous ponding depth (mm), l_m is the thickness of muddy layer (mm), l_p is the thickness of plow pan (mm), which set as 7.5 cm [13]. C_p is the coefficient of conductivity (day-1).

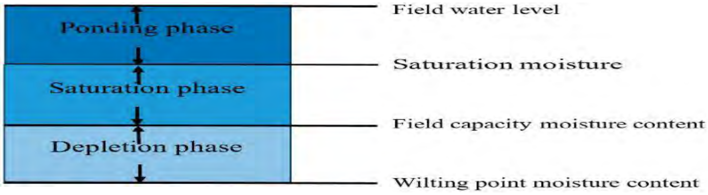

Figure 4. Schematic of the three stages of water balance calculation

2.6.2 Lateral Seepage

Lateral seepage is the horizontal loss sideways into the bunds or field boundaries, which varies with the initial soil water content. It is considered as additional field loss because under the bund of field there is no continuous plow pan layer. Therefore, the water movement is easy into and down through the bund to underlying water table. The schematic of ridge lateral seepage is shown in Figure 5.

This study assumes that the lateral seepage occurs under saturated conditions, and the terminal of seepage should be the groundwater level. The transmission mechanism of lateral seepage is derived from the Dupuit equation, as shown in Equation (15).

$$L_t = \frac{l_g}{A} \times k_L \times \frac{(h_t^2 - h_0^2)}{2L} \qquad (15)$$

where l_g is the length of the ridge near a drainage (m) and is set as the side length of each paddy block in this study. A is the area of the paddy field (m2), k_L is the hydraulic conductivity of the ridge (mm · day-1), set as five times k_p, h_t is the ponding depth (mm), h_0 is the water level of the irrigation channel (mm), set as 0 cm. L is the width of the ridge (mm), set as 50 cm. The decision criteria whether to occur seepage or not is represented by Equations (16).

$$R_{hi} = \begin{cases} L_t if S_{i-1} > FC \\ 0 \quad if S_{i-1} \leq FC \end{cases} \qquad (16)$$

where R_h is the lateral seepage of the ridge (mm · day^{-1}), L_t is the lateral infiltration (mm · day^{-1}).

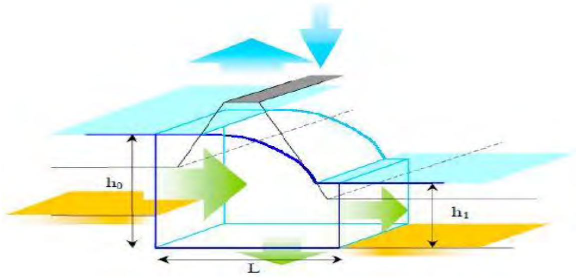

Figure 5. Schematic of the ridge lateral seepage

2.7 Field Surface Runoff Calculation

The ponding depth required for paddy rice must be adjusted suitably during different growth stages. It is controlled by the height of outfall on the ridge. The height of the outfall and ridge determines the magnitude of field storage. In saturated conditions, when the ponding depth is higher than the outfall or ridge, it will overflow to the drainage, as shown in Figure 6. The outflow of the field runoff can be represented as in Equations (17)–(19). The height of the outfall depends on the different growth stages of the paddy rice in Taiwan, as shown in Table 4.

$$if S_{i-1} + P_i + Ch_i - ET_i - DF_i - Rh_i > V_{fi}$$

$$DR_i = S_{i-1} + P_i + Ch_i - ET_i - DF_i - Rh_i - V_{fi} \qquad (17)$$

$$if S_{i-1} + P_i + Ch_i - ET_i - DF_i - Rh_i \leq V_{fi}$$

$$DR_i = 0 \qquad (18)$$

$$V_f = (h + Soildepth \times \varphi)(19)$$

where 〖V〗_f is the depth of field storage (mm), which is the total height of water in soil saturation and outfall. DR is the outflow of the field runoff (mm), h is the height of outfall (mm), φ is soil porosity (%).

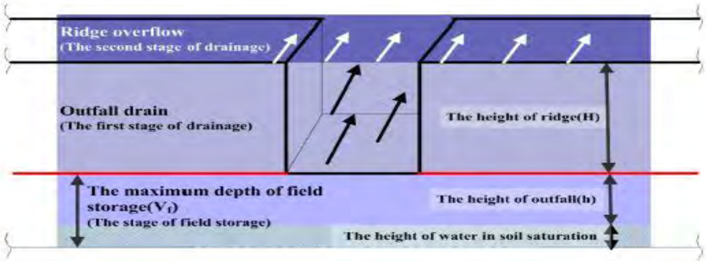

Figure 6. Two-way drainage stages in the paddy field

Table 3. Ponding depth of the paddy rice in Taiwan

Growth Stages	Seedling		Start of Tillering	End of Tillering	Young Panicle Differentiation		Young Panicle Formation	Booting Stage	Heading	Milk Ripe	Mature	Reaping
The day after transplanting	1	16	25	30	48	50	65	77	92	107	120	130
Ponding depth (cm)	5	5	5	5	5	5	10	10	10	3	3	0

If the duration of the rainfall is extended, the ponding depth may be higher than the height of the outfall. In order to avoid any impact on the growth of the crop roots, the maximum outflow of the ridge must be calculated. The average overflow discharge can be calculated using Equations (20)–(23).

$$if P_i > Q_i + ET_i + DF_i + Rh_i$$

$$Q_i = \frac{C \times R_D}{1000 \times D} \quad (20)$$

$$if S_{i-1} + P_i + Ch_i - ET_i - DF_i - Rh_i > V'_{fi}$$

$$DR_i = S_{i-1} + P_i + Ch_i - ET_i - DF_i - Rh_i - V'_{fi} \quad (21)$$

$$if S_{i-1} + P_i + Ch_i - ET_i - DF_i - Rh_i \leq V'_{fi}$$

$$DR_i = min\left[Q_i ;\ S_{i-1} + P_i + Ch_i - ET_i - DF_i - Rh_i - V_{fi}\right] \quad (22)$$

$$V'_f = (H + Soil\ depth \times \varphi) \quad (23)$$

Where V_f^' is the maximum depth of field storage (mm), which is the total height of water in soil saturation and ridge. Q is the outflow in unit area (mm · day-1), D is the crop soaking time (day), set as three days in this study. C is the runoff coefficient (C = 0.6), R_D is continuous rainfall in D days (mm), according to the Xi-Zhou rainfall station with a 10-year return period, which is 294.5 mm · day-1. H is the height of the ridge (mm).

3. SYSTEM DYNAMIC MODE

The calculation of irrigation and drainage discharge are the prerequisite for the verification of the water balance approach. The irrigation and drainage channels in the study area are separate. In addition, the main drainage accommodates surplus water from each drain, which is helpful for calculating the total drainage discharge. Therefore, this study established a system dynamic model VENSIM to simulate the water demand and consumption of the study area in central Taiwan, and verified the relation between the observed outflow and the simulated outflow.

3.1 Study Area

The study area is located in Chang-Hua County, central Taiwan. The Zhou-Shui River is the main irrigation water resource. In order to conveniently control the quantity of irrigation water, this study selected a small area of 215 hectares under the San-Tiao-Zun channel irrigation region. There are five supplementary ditches in this area, corresponding to blocks 1 through 5, respectively. There are six field monitoring stations for water level monitoring, corresponding to blocks 1 through 5. The block 2 has two stations for data monitoring. The stations in the field are powered by solar panels, and the recorder transmits water level information to the data centred every 10 minutes. The layout of the study area is shown in Figure 7.

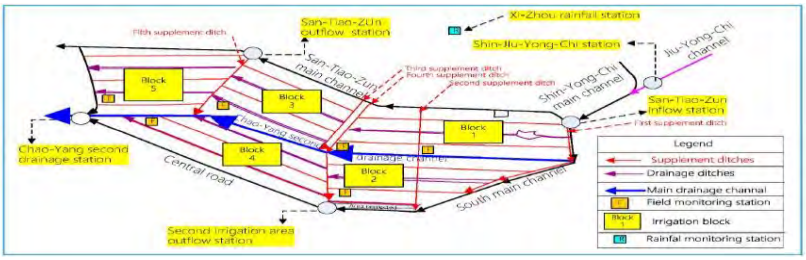

Figure 7. Layout of the study area

3.2 Model Establishment

The study area is divided into five irrigation blocks. Then, the five irrigation blocks are subdivided into 31 sub-blocks of paddy rice and 31 sub-blocks of upland crops. The sequence of irrigation water allocation is from the first irrigation block to the fifth irrigation block in the study area, as shown in Figure 8. The structure of the model is shown in Figure 9, where the boxes "1-1-1 irrigation area" and "1-1-2 irrigation area" mean the area of block 1-1 in paddy rice and upland crops, respectively. The sequence of flow in the individual irrigation sub-block is shown in Figure 10. The model is based on water balance theory to establish and estimate irrigation water, field drainage, channel water and groundwater. If the ponding depth reaches the target value, the model will stop supplying water. If the depth of the rainfall is more than the height of the outfall, the water will overflow to the nearby field drain ditches and converge to the main drain, Chao-Yang second drainage channel.

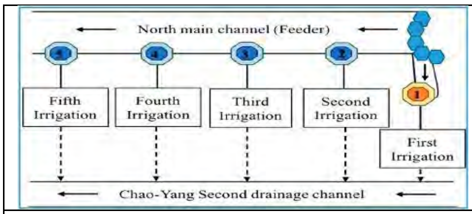	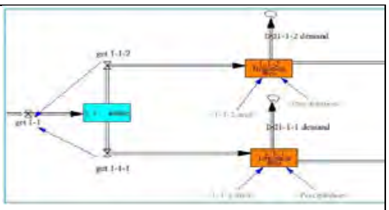
Figure 2. Direction and sequence of the irrigation and drainage in the study area	**Figure3.** Water usage sequence of model establishment

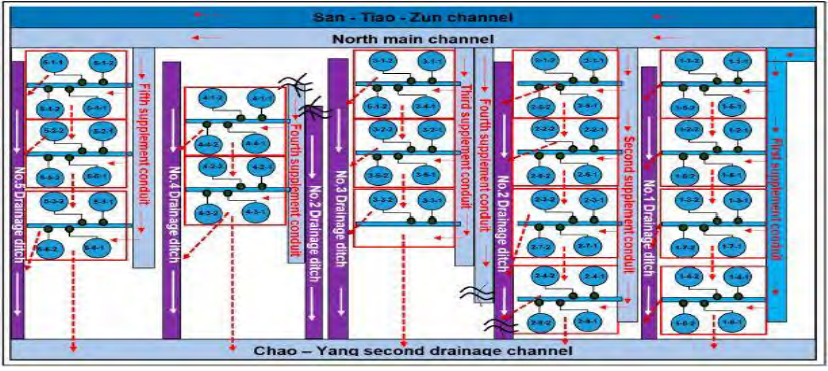

Figure 10. Flow direction of each sub-block in the study area

3.3 Model Validation

To validate the model, this study used the correlation coefficient (R^2) as a criterion. The discharge data was available during the experimental period ranges from 31 August 2016 to 24 September 2016. The correlation coefficient R2 is 0.72 in determining the groundwater pumping, as shown in Figure 11. The correlation coefficient R^2 is 0.80 in determining the channel water supply, as shown in Figure 12. The discharge of the observed and simulated shows a good fit with the correlation coefficient R^2.

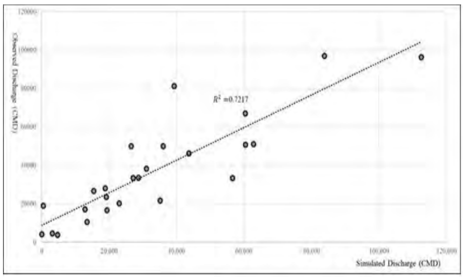

Figure 4. Schematic diagram of the correlation coefficient in determining the groundwater pumping(CMD: Cubic Meter per Day)

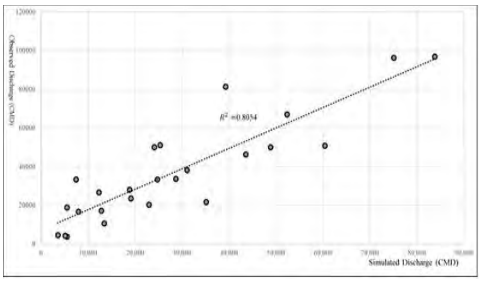

Figure 5. Schematic diagram of the correlation coefficient in determining the channel water supply(CMD: Cubic Meter per Day)

4. RESULTS A ND DISCUSSION

Irrigation water must be reduced during the drought. However, farmers will pump groundwater to supplement insufficient irrigation water. Under this premise, this study simulates crop water requirements, groundwater pumping, and channel water in different areas of paddy rice and upland crops. Finally, explore the effects of groundwater pumping and water use under different areas of paddy rice and upland crops.

Case 1: Area ratio in 50% Paddy Rice and 50% Upland Crops

Under the area of 50% paddy rice and 50% upland crops, the simulation results show that the maximum crop water requirement is about 15,500 CMD, as shown in Figure 13. Taking the second irrigation block as an example, the ratio of groundwater pumping to channel water is 46%: 54%, as shown in Figure 14. The depth of groundwater pumping in the study area is shown in Figure 15.

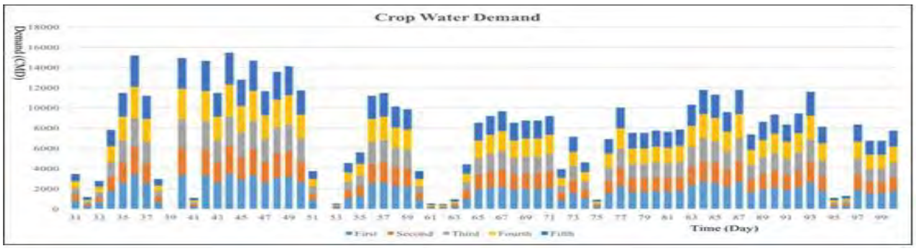

Figure 13. Crop water requirement for 50%paddy rice and 50% dryland crop area

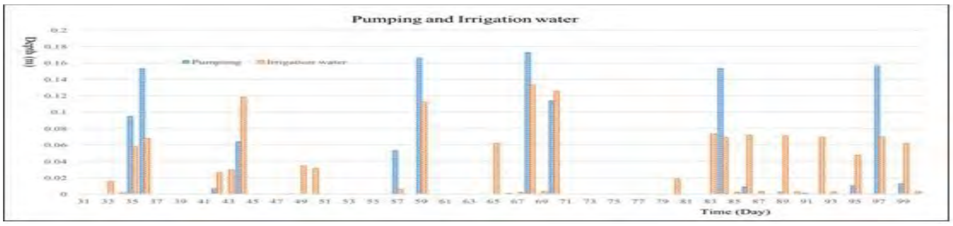

Figure 14. The ratio of groundwater pumping to channel water

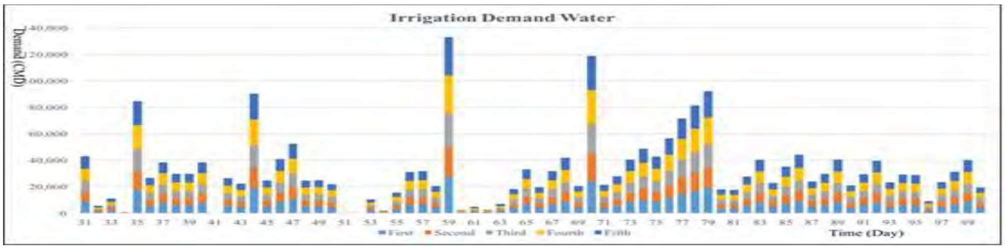

Figure 15. The depth of groundwater pumping in the study area

Case 2: Area ratio in 90% Paddy Rice and 10% Upland Crops

Under the area of 90% paddy rice and 10% upland crops, the simulation results show that the maximum crop water requirement is about 17,500 CMD, as shown in Figure 16. Taking the second irrigation block as an example, the ratio of groundwater pumping to channel water is 51%: 49%, as shown in Figure 17. The depth of groundwater pumping in the study area is shown in Figure 18.

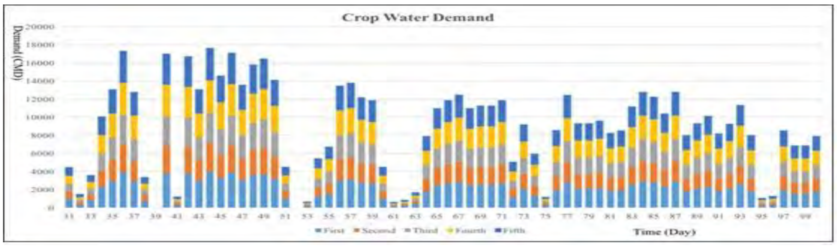

Figure 16. Crop water requirement for 90%paddy rice and 10% dryland crop area

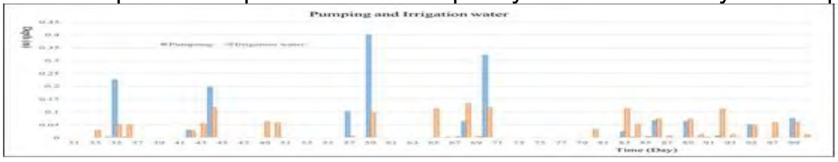

Figure 17. The ratio of groundwater pumping to channel water

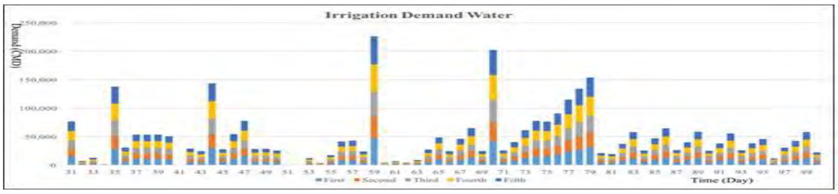

Figure 18. The depth of groundwater pumping in the study area

5. CONCLUSIONS

This study applied the water balance method to develop irrigation water management models and explored the effects of groundwater pumping and water use under different areas of paddy rice and upland crops. Moreover, the verification results of the model show that the discharge of the observed and simulated have a good fit with the correlation coefficient R^2. The simulation results of the case show that when the paddy rice planting area is increased, the crop water requirement will also increase, as the scenario simulated when paddy area increased up to 40%, the water demand increased 11%. Meanwhile, under the same scenario, when the channel water is insufficient, the groundwater pumping will be increased up to 5%with the increase of paddy rice planting area. From the above results, this study can be concluded that the increase or decrease in paddy rice planting area will directly affect water use and groundwater pumping in the study area.

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