IJERD – International Journal of Environmental and Rural Development (2023) 14-1

Research article

Development of a Simple-Concept Water Allocation Model at the Farm-Block-Level for Efficient Water Management

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Received 4 February 2023 Accepted 8 May 2023 (*Corresponding Author)

Abstract It is crucial to establish appropriate water management in agriculture. Due to financial difficulties, it is also necessary for farmers to work together with government agencies in water management. Existing water allocation models, however, require much effort to collect data. They are also black boxes difficult for farmers to understand, which may discourage farmers from participating in irrigation planning. In this study, we attempted to construct a farm-block-level water balance model with a simple tank model concept and easily collectible data. The model consists of two parts that reproduce the water distribution process from the farm block intake to each field (Canal Tank Model; CTM) and the water balance process in the paddy field (Paddy Tank Model; PTM), respectively. The model coefficients were identified using data from 2002 to 2003, and the model validity was evaluated using data from 2004 and 2005. The CTM coefficients were identified for 2002 and 2003 because of the different land use patterns. The CTM runoff coefficients and hole heights were changed on days when the farmers were considered to have operated diversion ratios significantly. The PTM coefficients were identified using the SDFP method and trial and error referring to the groundwater level. However, the PTM seepage holes were fixed to the corresponding values that the vertical seepage was approximately 5 mm/d based on the on-site survey. As a result, despite the arbitrary water manipulation by farmers, the same CTM coefficients for 2002, 2003, 2004 and 2005, when the land use pattern was similar, were able to reproduce the water allocation well. This water allocation model can be used to estimate the optimal delivery water management rate and to quantitatively evaluate the excess water withdrawal resulting from the labor reduction in water management.

Keywords water balance model, excess water withdrawal, participation irrigation management (PIM), prediction of water demand

INTRODUCTION

More than 90% of the total irrigation water is used for rice production (Khepar et al., 2000). However, the Organization for Economic Cooperation and Development (OECD) has addressed the idea that irrigation water is consumed unproductively and inefficiently (Fujimoto and Tomosho, 2003). On the other hand, recently, participation in irrigation management (PIM) is under great practice around the world. This method is for all farmers to get enough water, which is difficult to achieve with a top-down system, because of the financial pressure to maintain the irrigation system and the difficulty of taking care of fringe in the system by only the government (Saito, 2010). Yamamoto (2005) recommended that water use efficiency during abnormal dry spells should be improved by promoting PIM in paddy field irrigation in the Asian monsoon region. Irrigated water allocation models or water balance models become one of the decision-making support systems for SVP (Shared Vision Planning) in PIM. Murase and Kawasaki (2004) suggested that when consensus gets formed, optimization and equity become essential factors. Trade-offs achieve equity among the interests of stakeholders under optimized conditions. It suggests that equity is only contented once optimization is contented for water allocation. Then, the water balance components need to be quantified through field experiments. However, quantifying water balance components are often complicated because of the excessive time and expenditure involved in the execution (Khepar et al., 2000), especially in developing countries where water scarcity is a common phenomenon and optimized water allocation is strongly demanded.

In addition, the water balance model in a small district at the end of an irrigation system in which farmers' water demand finally needs to be met should be simulated to make satisfactory decision-making. In the case of open ditches, taking water into paddy fields is related to each other field. Thus, the degree of freedom of water management in each paddy field declines (Toyota et al., 1984). Toyota et al. (1984) declared that this agreement between water management in ditches and fields greatly affected water intake into paddy fields. Hence farm-block-level analysis was necessary. The smaller the analysis area, however, the more significant the impact of human disturbance, making it difficult to simulate water allocation in small-scale fields. The delivery water requirement would differ from the degree of each farmer’s diverging operation at a small canal (Furuki et al., 1979). This large human activity impact caused a few model developments of simulating water allocation at a farm-block level.

To explain human activity with a physical model could be a fault, but a statistical model might be acceptable. The tank model could reproduce this uncertainty, described as a semi-physical and semi-statistics model.

OBJECTIVE

This paper aims to develop a conceptual water allocation model acceptable to some land-use and irrigation systems changes and access to understanding decision-making processes. This model calculates the water balance and allocating process in the small-scale paddy fields area through the semi-physical and semi-statistic tank model.

METHODOLOGY

Target Area

The study area is typical paddy fields (farm-block-level, about 30 ha) located in the middle area of the Chikugo River in Fukuoka Prefecture, Japan (Fig. 1).

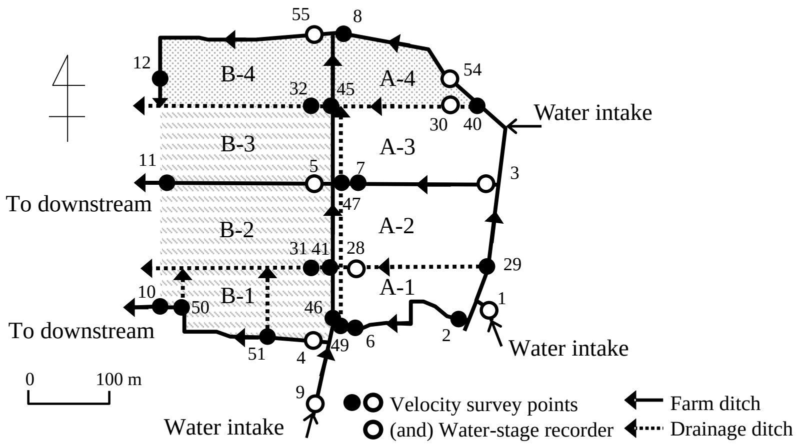


Fig. 1 The irrigation system and survey points in the study area

The number indicates each branch or release point. Irrigation started from three points (Nos.1, 3, and 9). The black and white circles show the survey points where water discharge was measured weekly. The water-stage recorders were installed at the white circle points. The different colored hatches describe the targeted areas for irrigation intakes water from three points.

The area was separated into A- and B-blocks by north and south roads. Moreover, each block was broken into four sub-blocks corresponding with field-block-level by north and south running farm roads and ditches. Each sub-block was regarded as one big paddy lot in this research. The study area had changed its crop planting (land-use) pattern. The land-use pattern was similar in 2002 and 2004 when the whole B-block cultivated the soya bean, and in 2003 and 2005 when part of the B-block (B-2 and B-3 sub-block) was used for the soya bean. The land-use changes made the water allocation complex and significantly affected the model parameters.

Measurement of Water Flow in Ditches

A propeller current meter and water stage recorders measured the water velocity and water level in only one direction in a branch point in the ditches (Fig. 1, B-direction). The former measurement was conducted once every week and the latter were recorded hourly. The scale observed the water level simultaneously with the propeller measurement, multiplied by velocity to estimate the observed discharge. The balance equation calculated the water discharge in the other direction (D-direction) in a branch point from the observed discharge, which is also considered an observed flow in the model. The water level measured hourly by the water stage recorder was converted to the discharge by using the following approximate formula obtained from the relationship between the weekly measured flow and the water level:

$$Q = \alpha h^{\beta} \tag{1}$$

where Q is discharged, h is measured water level, α and β are coefficients of approximate expression.

Measurement of Water Balance in Paddy Fields

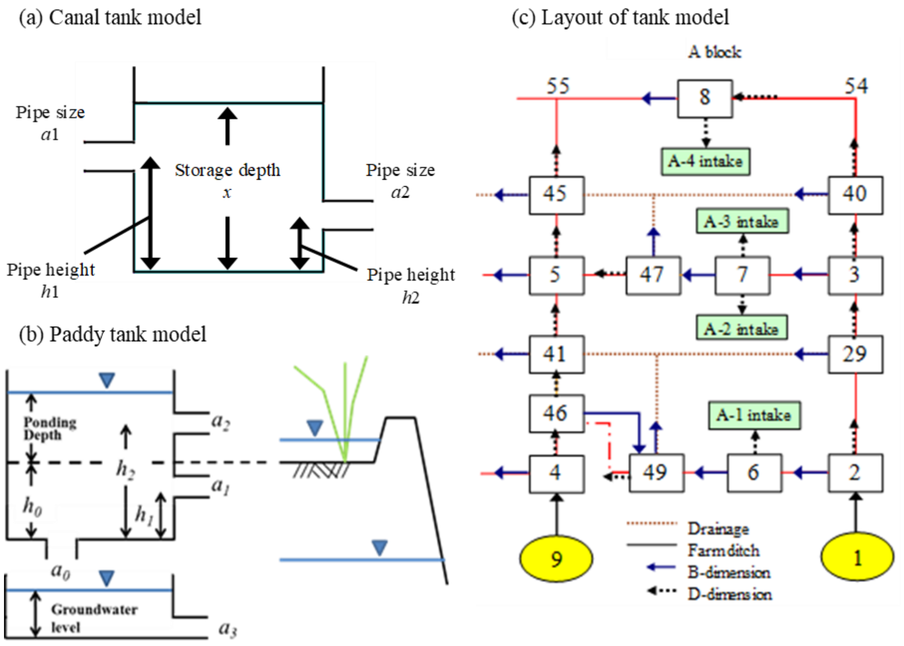


Fig. 2 The structure of the canal tank model (CTM, a), paddy tank model (PTM, b) and its layout in the allocation model (c)

Each CTM was installed at the branch point and PTM was placed in each block. B-direction was where water velocity was measured, and D-direction was where the water flow was calculated by water balance.

We targeted three paddy fields from A-2, B-2, and B-3 sub-blocks. The ponding water depth was measured hourly by a data logger. The precipitation (R) was observed at the nearby A-2 sub-block.

The elevation of the overflow weir at the outlet was measured weekly because a farmer did not frequently operate the outlet and used to calculate the amount of water release (Q_{out}) by overflow computing. Evapotranspiration (ET) was estimated by multiplying the ET ratio and potential ET by the Penman method from meteorological data. Percolation (P) was estimated by the water balance equation as:

$$P = Q_{in} + R - ET - Q_{out} + \Delta h \tag{2}$$

where Δh was a variation of ponding depth. All values were averaged or totaled daily. N-type water requirement survey evaluated the groundwater recharge from paddy fields. The vertical percolation was about 5 mm/d at the middle point in the field free from levee seepage. The groundwater level was measured hourly near No.1 (which was used to calibrate the paddy tank model). The amount of water runoff from paddy fields at block level was estimated from observed discharge in the drainage ditches (Fig. 1) by outflow minus inflow in the drainage.

Model for Water Allocation Through Ditches

The whole water distribution process in the study area was represented in two parts; in ditches and inside paddy fields. At the first step of computation of water allocation, the canal tank model (CTM, Fig. 2a) described the water distribution process through ditches, CTM installed at each branch point (Fig. 2c). The pipe size in CTM represented the water dividing rate at a branch for each direction, including wastewater ratio (e.g., branch point No.3). The outflow y_i from each i-th number of a pipe was computed as:

$$y_i = a_i(x - h_i)^{1.5} \quad (x \geq h_i) \tag{3}$$

where a_i is the coefficient of discharge, x is the storage water depth, h_i is the pipe height, and an output flow occurs only when the storage water depth is higher than the pipe height.

The parameters were calibrated manually but in a rational manner. The water-dividing operation depends on the land-use pattern and rice growth stage (e.g., rooting, ripening, etc.); thus, the pipe size parameter was determined by each period manual to consist of observed discharge. The biggest impacts on the water allocation operation were mid-summer drainage and water stopped before maturation. The timing of changing parameters was decided from the paddy water depth of the survey fields. The heavy rain causing excess irrigation water also changed the drainage operation at water release points. CTM parameters were calibrated in 2002 and 2003 (calibration period) and validated in 2004 and 2005. The parameter determined in 2002 was applied to 2004 with a similar land-use pattern year, and the parameter in 2003 was applied to 2005 for the same reason.

Model for Water Balance in Paddy Fields at Sub-Block-Level

The paddy tank model (PTM) structure is shown in Fig. 2 bottom left. The pipe of a_0 represented a vertical percolation reaching the groundwater: a_1 represented a lateral percolation through the levee draining to the drainage ditches: a_2 described water release from a surface and a_3 was for groundwater flow. The sum of lateral percolation and the water release defined the runoff from paddy fields. This simple model can adapt to a flexible scale. For example, Jayadi et al. (2000) applied one PTM to 300 ha paddies. In this study, PTM described block-level paddy fields, i.e., A-block and B-block.

The input data for PTM were precipitation, ET, and paddy water intake calculated from CTM. The target output for determining parameters was the groundwater level (GWL). SDFP (Kadoya and Nagai, 1980) and the trial-and-error method decided the parameters. The vertical percolation a_0 was determined without the optimization method because the N-type water requirement was about 5 mm/d; therefore, a_0 was estimated at 0.070 or 0.075. The ponding depth, the height of the levee, and the outlet overflow weir height in the site were considered to decide the storage depth in the upper tank. The parameter calibrated by data in 2002 and 2003 was applied to data in 2004 and 2005 for testing the versatility. As with CTM validation, the identified model coefficients for 2002 were applied to the coefficients in 2004, when land use was similar, and the coefficients identified in 2003 were applied to the coefficients in 2005. Hereafter we call 2002 and 2003 a calibration period and 2004 and 2005 a validation period.

RESULTS AND DISCUSSION

Applicability of CTM

The simulated water allocation through irrigation ditches by CTM in calibration terms showed good agreement with the observed flows (Fig. 3a), especially at the endpoint of the irrigation system No. 55 (Fig. 2c) where recorded hourly flow (absolute errors was 5.5 mm/d). No. 46 reproduced reverse flow when a reversal of hydrodynamic gradient occurred between adjacent branches, and water flowed through the irrigation ditch opposite the normal flow direction.

CTM well-predicted water allocation in 2004 and 2005 (Fig. 3b, absolute error at No.55 were 6.3 and 18.0 mm/d, respectively), indicating that CTM has robust reproducibility to some extent regardless of drought season or rainy season because 2002 was drought and 2004 was rainy season. Also, good agreement suggested that water allocation operation was similar when the land use pattern was similar.

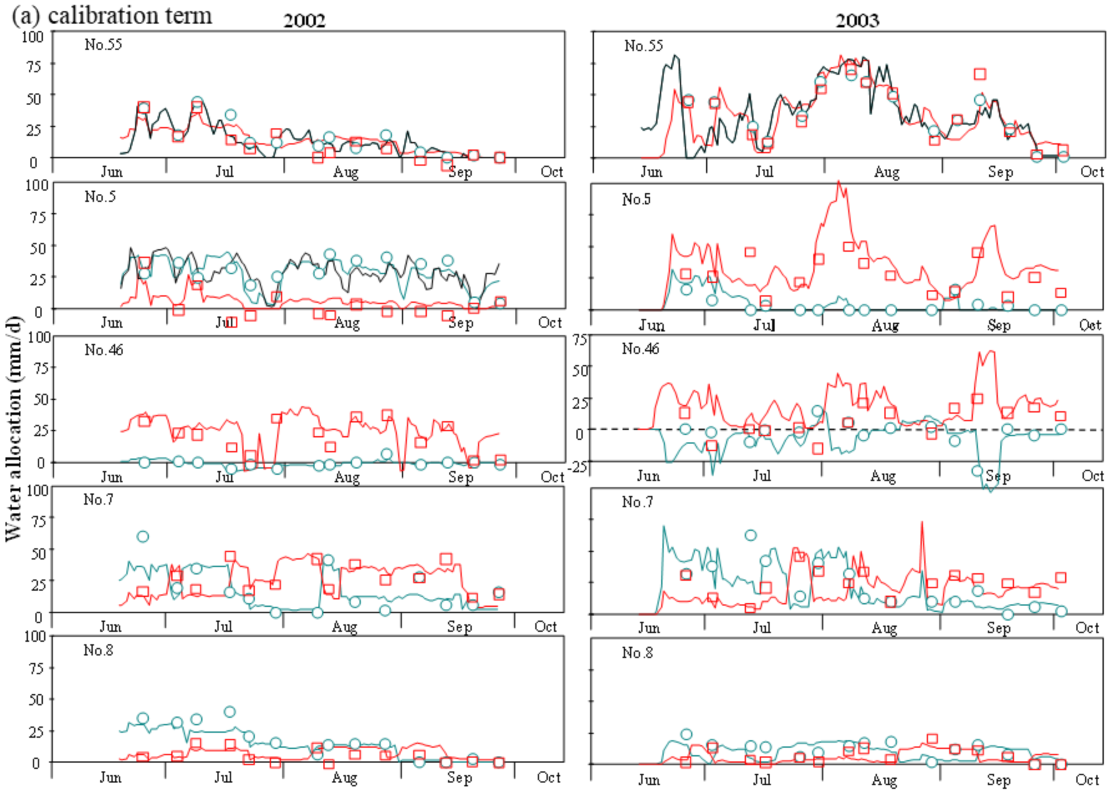
The CTM concept is apparent, simple, and easy to customize. CTM merely requires discharge data in irrigation ditches. Taniguchi and Satoh (2006) described that grasping the actual water usage required a series of observations of quantitative water allocation and enormous instruments and efforts. CTM can be one of the resolutions for these problems. Resource Division Planning Department Kyushu Agricultural Administration Office (1997) applied the CTM to about 4,600 ha district in Kasegawa, Saga prefecture, to analyze water distribution. The more the command area becomes extensive, the more the number of operation points changing the water-diverging ratio increases. Consequently, diversion operation increases its randomness and decreases the effect on the tank parameters, leading the parameters to be decided at one value. CTM has to be improved in the following two aspects. First, the present CTM could not precisely explain the reverse flow that occurred frequently and extensively. Second, long-term data needs to be collected to increase the accuracy of CTM's prediction.

Applicability of PTM

The estimated GWL from PTM demonstrated well fitted with the observed value, shown in Fig. 4a. PTM also simulated the water runoff from A-block and its relative error was around 50% and 28% in 2002 and 2003, respectively (Fig. 4b). An unsteady flow and seepage from the weir shutter were an obstacle to measuring the drainage discharge, causing some outlier values, and leading to the fitting error being worse. However, the calculated flow reproduced the other observed trend well, and the identified parameters could be used for prediction.

The prediction of GWL and runoff from paddy fields, shown in Fig. 4, demonstrated good agreement with observed values and proved PTM’s versatility. However, although simulated GWL in 2004 well matched with observed GWL, the predicted runoff had difficulties at reproducibility. The relative error of runoff in 2004 was about 200% due to the failure to reproduce the small observed values in the denominator of the relative error equation. The high error in 2004 was caused by using the same parameter through 2004 and 2005 even though the land use pattern changed. However, the prediction in 2005 showed good fitting simulation both for GWL and runoff.

Future development was that the model's sensitivity to land use should be improved. In this study, the block level was considered to be one paddy tank. However, the sub-block could be regarded as one paddy tank to improve sensitivity, and the model would deal with various land use patterns in more detail. Furthermore, the paddy lot management schedule should be taken for calibrating PTM parameters into account. The PTM coefficient could be changed according to the rice growing stage or water management schedule.


(a) calibration term

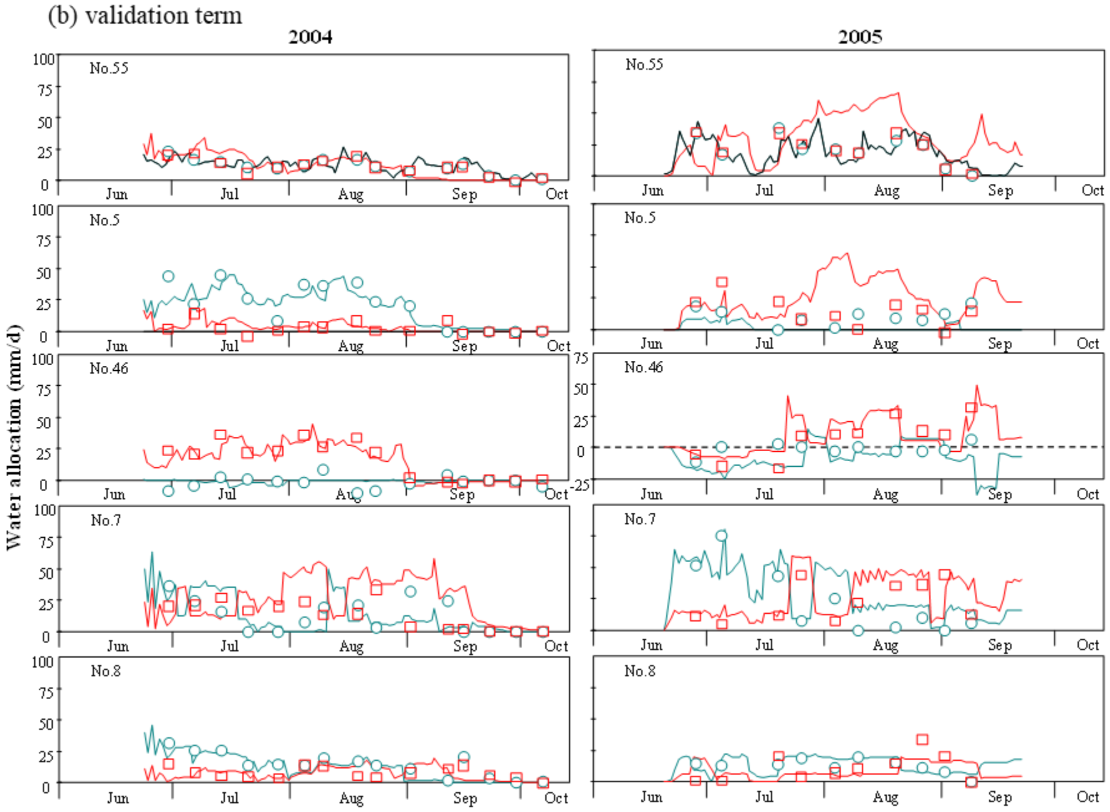
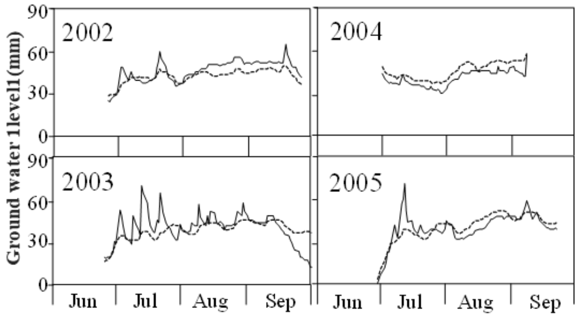

(b) validation term

Fig. 3 Water allocation in ditches

The black solid line, outline of a green circle, and red square stand observed flow in the B-direction and D-direction, respectively. The green and red solid lines represent CTM's simulated values in B- and D-direction, respectively. The minus value at No.46 demonstrates the reverse flow.

In this study, the simulation model was developed to predict water allocation and balance with easily available data at the farm block level. Kuo et al. (2006) calculated the water demand of paddy and upland crops by CROPWAT designed by Smith (1991) at the ChiaNan Irrigation Association that could estimate the soil moisture but not include the paddy lot water management or delivery water management, thus could not evaluate the water productivity. The present model in this study can estimate and consider both lot water management from PTM and delivery water management from CTM. The proposed model can also apply to farm and large-scale levels, including complex land use areas.

(a) Ground Water Level (GWL)



(b) Runoff

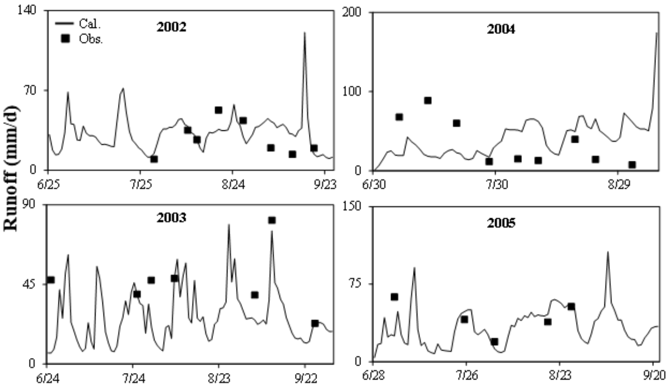


Fig. 4 Comparison between calculated and observed GWL (a) and water runoff (b) from paddy fields in the calibration term (2002-2003) and validation term (2004-2005)

Solid lines are calculated and dotted lines are observed values (a).

The developed model becomes a decision-making support system for SVP (Shared Vision Planning) in PIM. Murase and Kawasaki (2004) suggested that optimization and equity were essential for forming consensus. The equity is comforted by trade-offs among stakeholders' interests under optimized conditions. This model can optimize water management or land use patterns by simulating the water balance and allocation process. Thanks to the tank model's semi-physical characteristics, the participant intuitively understands the operation of the water diversion and water balance component to which the model parameters correspond.

CONCLUSION

This study calculated water balance through irrigation ditches and paddy fields in the area using understandability concepts and accessible collecting data by connecting the canal tank model (CTM) to the paddy tank model (PTM). An easily understandable and collectible data structure is essential for the decision-making process. The present model parameters are consistent and capable of predicting water allocation and balance with similar land use patterns. For example, a simulation by CTM and PTM under a scenario of saving irrigation water because of a lack of precipitation could predict how the groundwater level would change. If the groundwater level could be predictable, it could avoid wet or drought injury to the crop.

Using available data for this type of study is important because it is difficult to gather large amounts of actual data on water allocation at every branch of the irrigation system every week for several years. This paper aims to build a model based on a simple tank model concept and data that can be easily collected. The data used in this study spans from 2003 to 2005. Nonetheless, we have demonstrated that it is possible to develop an accurate model for our intended purpose, as the method of collecting actual data has remained consistent even today. In the future, the remaining issue is to accommodate the changing land use, and the PTM parameters should be calibrated at each paddy, upland, and greenhouse (Kato, 2005). To some extent, the tank model parameters have generality attributed to the semi-physical character, which means that human activity to change irrigation management can be reproduced by the present model.

REFERENCES

Fujimoto, N. and Tomosho, T. 2003. A viewpoint to apply water pricing to the Asian humid tropics. Paddy and Water Environment, 1 (2), 75-83, Retrieved from DOI https://doi.org/10.1007/s10333-003-0014-3

Furuki, T., Yamashita, A., Sato, H. and Ezaki, K. 1979. Studies on conveyance loss in paddy field irrigation. Bulletin of the National Research Institute of Agricultural Engineering, 1-30. (in Japanese)

Jayadi, R., Fukuda, T., Nakano, Y. and Kuroda, M. 2000. Deterministic optimization of irrigation water allocation in a low-lying paddy area with creek networks. Journal of the Faculty of Agriculture, Kyushu University, 44 (3-4), 419-429, Retrieved from DOI https://doi.org/10.5109/24343

Kadoya, M. and Nagai, A. 1980. Runoff analysis method, Optimize identification of storage function model by SDFP. Journal of JSIDRE, 48 (12), 65-70. (in Japanese)

Kato, T. 2005. Development of a water quality tank model classified by land use for nitrogen load reduction scenarios. Paddy and Water Environment, 3 (1), 21-27, Retrieved from DOI https://doi.org/10.1007/s10333-005-0069-4

Khepar, S.D., Yadav, A.K., Sondhi, S.K. and Siag, M. 2000. Water balance model for paddy fields under intermittent irrigation practices. Irrigation Science, 19, 199-208, Retrieved from DOI https://doi.org/10.1007/ PL00006713

Kuo, S.F., Ho, S.S. and Liu, C.W. 2006. Estimation irrigation water requirements with derived crop coefficients for upland and paddy crops in ChiaNan Irrigation Association, Taiwan. Agricultural Water Management, 82 (3), 433-451, Retrieved from DOI https://doi.org/10.1016/j.agwat.2005.08.002

Murase, M. and Kawasaki, H. 2004. Research on model for participation consensus formation in low-water management. Dam Engineering, No. 213, June 2004, 9-15. (in Japanese)

Saito, K. 2010. To think of irrigation management. Journal of JSIDRE, 1046-1048. (in Japanese)

Smith, M. 1991. CROPWAT manual and guidelines. FAO, Rome, Italy.

Taniguchi, T. and Satoh, M. 2006. Impact of irrigation water stability on on-farm water distribution in a paddy field. Journal of JSIDRE, 246, 17-23. (in Japanese)

Toyota, M., Suzuki. M., Nishiide, T. and Tomota, A. 1984. Characteristics of water management in paddy field open canal system. Journal of JSIDRE, 991-998. (in Japanese)

Yamamoto, K. 2006. Paddy field characteristics in water use, Experience in Asia. In Water and Agriculture, Sustainability, Markets and Policies, 287-315, OECD Publishing, Paris.