

# Water Resources, Floods, and the Agro-Environment of Monsoon Asia: Description and Future Applications of the DWCM-AgWU Model

Takao Masumoto

*National Institute for Rural Engineering (NIRE), National Agriculture and Food Research Organization (NARO)*

*2-1-6 Kan-nondai, Tsukuba Ibaraki 305-8609, Japan*

## Abstract

Agricultural water use plays important roles both in agriculture and in global water budgets. Simulation and visualization of the complicated processes involved in agricultural water use, an issue that has not been studied in sufficient depth, may reveal solutions to agro-environmental problems such as food security, climate change, the risks of flooding and drought, and water footprints. To address these issues, this paper discusses the DWCM-AgWU model and its use to model agro-environmental hydrology, possible coping mechanisms for problems related to water management, and future research challenges related to water resources in agro-environments. Three main areas are focused on: (1) “Simulation and visualization (process visualization)” of water circulation in agro-ecosystems. (2) Agro-environmental trials related to management of water resources, particularly in the context of big issues such as climate change (extremes), food security, energy shortages, and the catastrophic earthquake that affected Japan in 2011. Process visualization provides crucial clues to solving these problems. (3) Finally, the topic entails proposals for sustainable strategies to be derived in future agro-environmental research.

*Keywords:* agricultural water use, climate change, DWCM-AgWU, flooding, irrigation, visualization, water footprint

## 1. Introduction

Monsoon Asia is a part of the world that has distinct wet and dry seasons, with high vulnerability to extremes (drought and flooding), and with agriculture that depends heavily on irrigation, particularly for paddy rice, one of the dominant crops in the region. Rice cultivation in paddies in Monsoon Asia offers high productivity, but it can also be a sustainable and environmentally friendly economic activity that is well suited to the climatic and topographical conditions of this region. This economic activity has evolved for hundreds to thousands of years in various regions of Monsoon Asia, as witnessed by 7000-year-old archaeological evidence of rice cultivation in China.

On the other hand, agriculture accounts for about 70% of the total water use in Monsoon Asia

and similarly high proportions elsewhere in the world, so this water use must be managed wisely to ensure that it is sustainable (Masumoto, Toritani et al., 2008). Because agricultural practices are human activities, it is necessary to account carefully for anthropogenic practices in models intended to support agricultural water resources management. However, such modeling is difficult, since both the human and environmental components of the system are complicated. In large river basins in Japan, for example, many irrigation facilities have typically been established. Once irrigation water has been withdrawn from the river at a diversion weir, the water is delivered to paddy plots. However, some of the water is not utilized and most of the unused water enters drainage channels and returns to the main river. This process is repeated along the main river, leading to a high degree of recycling of the water. Unfortunately, this recycling makes it difficult to grasp the details of this agricultural water use. Fortunately, simulation and visualization techniques offer a solution that will help managers to grapple with these complicated processes.

In this paper, I will discuss how a visualization process can improve our understanding of the complicated agricultural water use patterns in Monsoon Asia and provide insights into how to cope with agro-environmental problems caused by climate change, climate variation (extremes), food security, energy shortages, and the effects of natural disasters such as catastrophic earthquakes. Based on this discussion, I will propose challenging agro-environmental research topics that should be addressed in the future to help managers use water resources more sustainably.

## **2. Methods and Visualization Approaches**

Simulation and visualization processes (process visualization) have been achieved by developing the Distributed Water Circulation Model Incorporating Agricultural Water Use (DWCM-AgWU), which combines hydrological, water-allocation, and water-management sub-models (Masumoto et al., 2009; 2016; Yoshida, 2015). The key aspect of this modeling process is that it covers anthropogenic activities (e.g., artificial activities such as agriculture) as well as hydrological phenomena. In this section, a brief description of the model is presented.

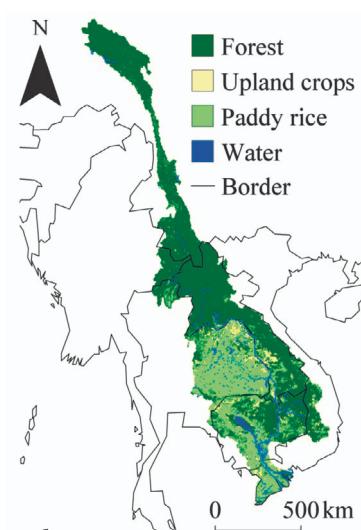
### **1) Targeted Basins for the Process Visualization**

The development of DWCM-AgWU began with researchers who were using the Mekong River Basin (800 000 km<sup>2</sup>) as a research target basin. The model was then extended to the Seki River Basin (1140 km<sup>2</sup>) in Japan for further development; in recent year, it has been subsequently applied to basins throughout Japan.

The Mekong River is an international river that flows through or along the borders of six countries. It is the largest river in Southeast Asia and the 12th longest (at 4200 km) in the world. The Mekong River has distinctive features that have been used to divide it into six sections (Masumoto, 2001): the 1st section extends from the mouth of the Mekong River to Stung Treng, the 2nd section extends from Stung Treng to Savannakhet, the 3rd section extends from Savannakhet to Vientiane, the 4th section extends from Vientiane to Luang Prabang, the 5th

section extends from Luang Prabang to Tan Ho, and the 6th section extends from Tan Ho to the source. Figure 1a shows the land-use patterns within the Mekong River Basin. The figure was derived from United States Geological Survey 1-km mesh land-use data obtained by reclassifying approximately 250 types of vegetation and land uses into five categories: irrigated and rain-fed paddy fields, irrigated and rain-fed upland fields, and others (mainly forest). Based on this data, agricultural land occupies 43% of the basin, of which rain-fed areas account for 90%. In addition, paddy rice is grown in 90% of the rain-fed areas. Therefore, agricultural production in the basin depends heavily on rice production in rain-fed areas, and rice production in rain-fed paddies will continue playing an important role in the future food supply in the basin (Shimiuzu and Masumoto, 2006).

In contrast, the Seki River basin in Central Japan (Fig. 1b) is 64 km long, and its catchment area is 1140 km<sup>2</sup>. The land cover is predominantly forest (79%), but 17% of the land area is agricultural land (mainly rice paddies). The Seki River originates in the Myoko Mountains (where the highest peak is about 2400 m asl). The climate of the basin is humid cold-temperate, typical of the Japan Sea area, and snowfall is heavy in the winter. Average annual precipitation is more than 3000 mm, more than half of which falls as snow. The total irrigated area of the basin is approximately 9000 ha, and it is mostly used for rice paddies. There are two major irrigation systems on the eastern side of the Seki River: one based on the Sasagamine Dam ( $9.2 \times 10^6$  m<sup>3</sup>), and the other based on the Itakura Diversion Weir. River discharge is observed at the Takada flow gauge station (Fig. 1b). There are three major irrigation blocks (areas), for which water is diverted at the Itakura weir and two other diversion weirs. DWCM-AgWU has also been used to model this basin.



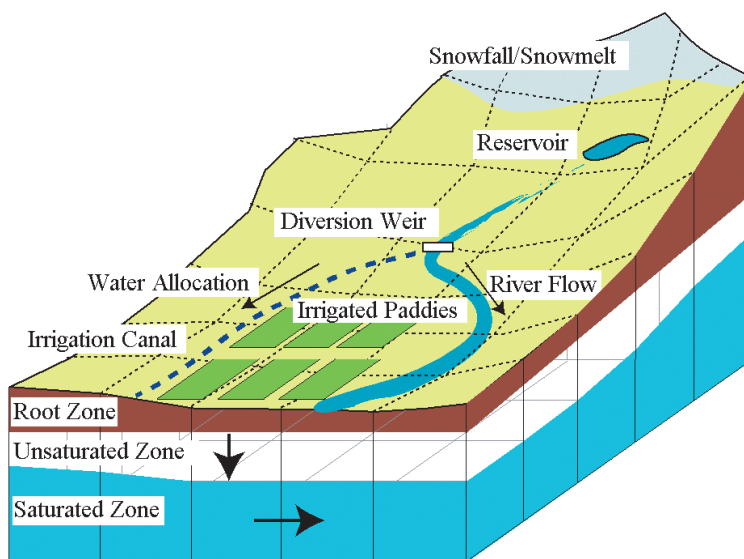
**Fig. 1** Maps of two basins that have been studied using the DWCM-AgWU model. (a) The Mekong River Basin. (b) The Seki River Basin in Japan.

## 2) Components of Runoff and the Water Allocation and Management System

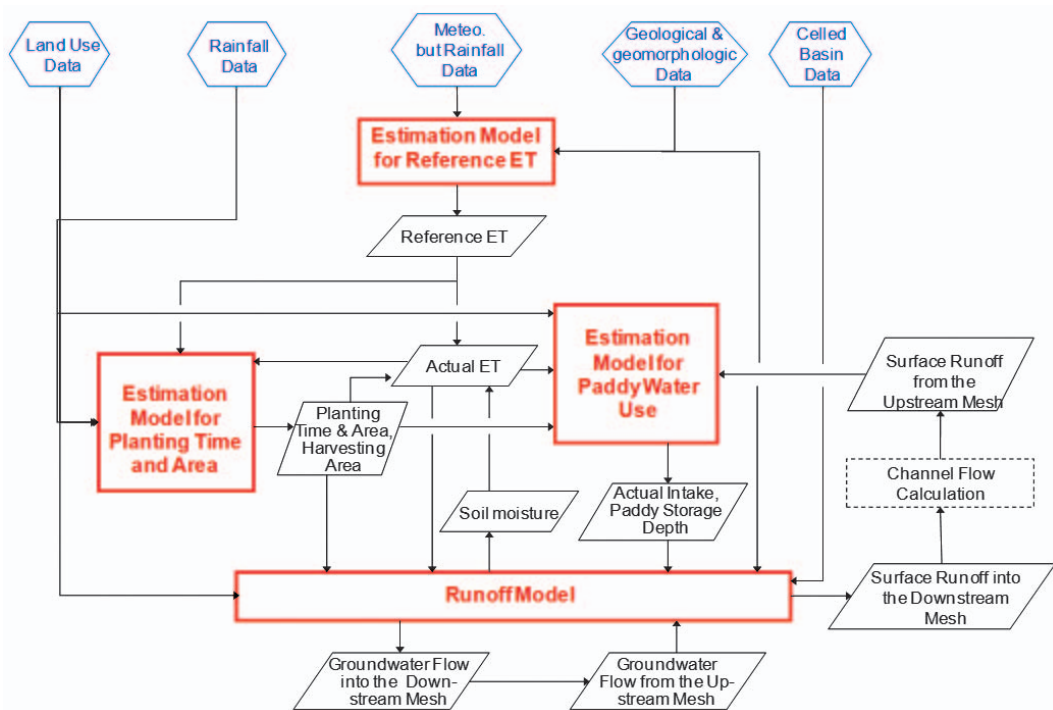
DWCM-AgWU consists of three main components: basin-wide runoff, parts of which are commonly obtained in any runoff model; reservoir management to let managers compare the river's discharge (i.e., available water) at the diversion weir with the water requirements in irrigated paddies so they can plan to release sufficient water for irrigation; and water delivery to irrigated paddies to decide the intake, water allocation, infiltration, and drainage.

Figure 2 illustrates the physical model for how a basin is divided into cells before the water balance of each cell and the movement of water between connected cells is calculated (Masumoto et al., 2009; Taniguchi et al., 2009). The overall model consists of four sub-models: an evapotranspiration sub-model that provides the foundation for estimation of actual evapotranspiration; a crop cultivation period and area sub-model that estimates the progress of crop growth in paddy fields based on the paddy type and rainfall; a paddy water-use sub-model that evaluates the use and control of water; and a runoff sub-model that accounts for water circulation between cells (Fig. 3).

The model takes a variety of agricultural water uses into consideration, and thereby allows us to forecast the water requirements of the crop at each phenological stage. This makes it easy to take measures to protect against the effects of changes in land use because each cell has its land uses defined as a percentage of the total area. Agricultural water use is categorized into two types: rain-fed and irrigated. However, rain-fed agriculture is subdivided into three types: only rainfall, rainfall plus supplementary water stored in small ponds, and using flooding water. The land-use data can be used to account for situations such as when soils are excavated to construct local roads, or when efforts are made to harness floods, as occurs in Cambodia within the Mekong River Basin. In the case of irrigated paddies, water use is subdivided into six categories: gravity-fed water, pumped water, reservoirs, impounding of silty water (colmatage), release of



**Fig. 2** Illustration of the physical basis for the DWCM-AgWU model.



**Fig. 3** Summary of the input data and calculation procedures for the DWCM-AgWU model. ET, evapotranspiration. The four main components of the model are highlighted in red.

river water into coastal wetlands and near-shore waters by managing controlling tides, and groundwater (Taniguchi et al., 2009).

In addition, the distributed runoff model can approximate the real irrigation status and respond to the repeated use of irrigation water in a paddy area because it determines the actual intake by comparing it with the paddy's water demand, irrigation facility capacity, and possible intake. Using this model allows us to estimate agricultural water use at an arbitrary date and location by accounting for the cultivated area, water intake, and soil water content. Furthermore, we can evaluate and project the effects of various human activities (e.g., changes in agricultural activity, global warming) on water circulation within the basin.

### 3) DWCM-AgWU Algorithms

The runoff sub-model has a completely distributed runoff structure in which adjacent cells are connected, which allows us to determine the water balance of each cell. We can estimate the runoff, groundwater movement rate, and changes in soil water content by inputting estimates from the other sub-models into the runoff sub-model. The soil is subdivided into three layers: a root zone that affects evapotranspiration, a saturated zone that affects groundwater movement rates, and an unsaturated zone that connects the root and saturated zones (Fig. 2). Note that the boundary between the saturated and unsaturated zones is not fixed; it moves in response to

changes in water inputs and outputs for a cell. Based on the assumption that the thickness of the whole soil layer is constant in a given cell, the daily water balance is calculated for each layer.

The cultivation period and area forecast sub-model estimates the planting date for all crops as well as its cultivation and harvest areas, which vary depending on the location and year. These areas are determined based on the field type using detailed land-use information about cultivated fields and account for differences in field types and annual changes in cultivation periods. The area in which yield decreases due to a water shortage is estimated by defining the actual evapotranspiration as a proportion of the available water (i.e.,  $ET/\text{available water}$ ). In addition, the agricultural water-use sub-model estimates the cultivation area, possible intake of water, and actual evapotranspiration based on the cultivation period and area using the runoff sub-model (Fig. 3). In many other runoff models, evapotranspiration and runoff mechanisms are included, but DWCM-AgWU combines agricultural water use with these processes by modeling planting and harvesting dates and areas, as well as water use.

#### **4) Modeling of the Water Release and Delivery System and Verification of the Results**

Another difficulty in modeling agricultural water use is how to model timely water releases through reservoir operation and water delivery for irrigation areas composed of many cells, each with different water needs.

A reservoir such as a dam or irrigation pond can be placed between two cells in the distributed runoff model. The runoff from the upstream cells serves as the reservoir's inflow in the dam control model. The reservoir release calculated by the model is the outflow from the upstream cells, which becomes the input for the downstream cell. Water releases from the reservoir for irrigation are calculated based on the gross water requirements derived from the paddy water-use model. When the runoff from the downstream part of the reservoir (which equals river discharge at the intake point if no water is released from the reservoir) decreases, resulting in a shortage of water (i.e., less than the required intake), supplementary water is released from the reservoir to compensate for the shortage.

A water distribution and control sub-model for a large irrigation area was also developed and integrated with DWCM-AgWU. This sub-model forecasts the actual intake at a given point and the water supply to a paddy field within an irrigation district. Irrigation water taken from the river is distributed to the district to meet its needs.

The outputs of the sub-models must be verified. This is done by comparing the calculated and observed discharges. Figure 4 illustrates the estimated flow of surface water at the Takada Observation Station on Japan's Seki River in 2005 and 2006 to provide examples of validation of the DWCM-AgWU model. The relative error between the observed and calculated discharges was 25%, which suggests relatively good estimation accuracy (Yoshida, Masumoto, Kudo et al., 2012). The same kind of verification was carried out for the Mekong River Basin, and the relative error (23–30%) confirmed the model's practical applicability (Taniguchi et al., 2009).

Conclusively, the process visualization performed by DWCM-AgWU lets water managers accurately assess the complicated phenomena involved in water circulation through an agricultural basin.

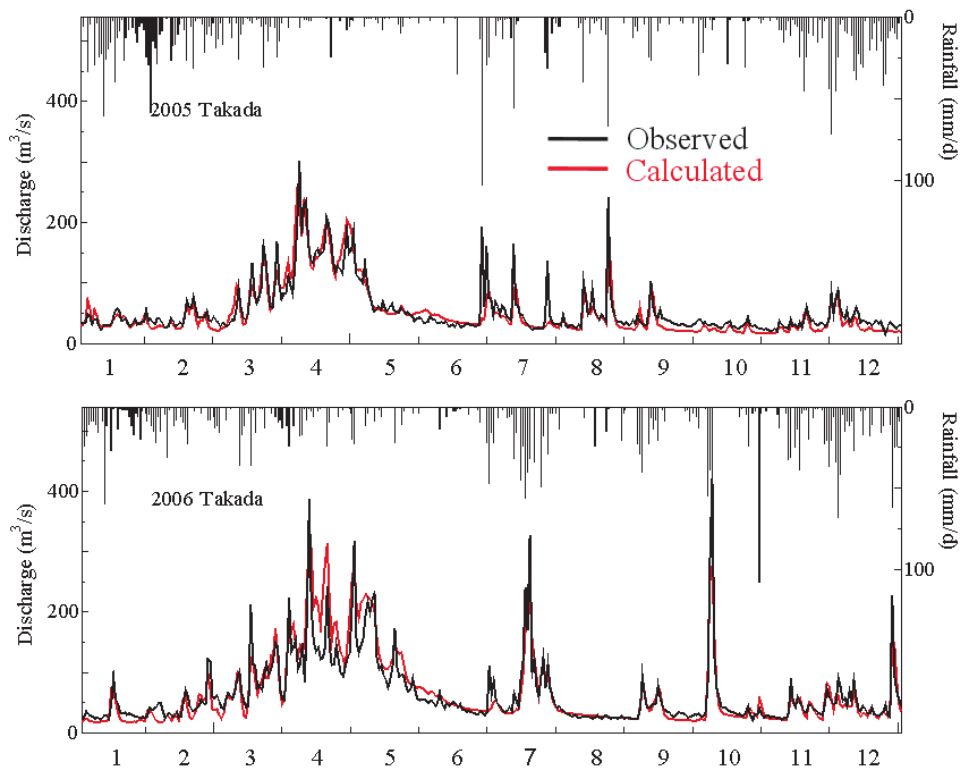


Fig. 4 An example of data used for validation of the DWCM-AgWU model. Data are for the Seki River Basin shown in Figure 1b.

### 3. Agro-Environmental Problems Related to Water Resources

The modeling of agricultural water use and water circulation provides a good tool for other simulation and visualization processes related to water resources and an important problem-solving tool. In this section, I will describe five applications for this kind of process visualization.

#### 1) Climate Change Issues

The first application is an assessment of the impact of climate change on agricultural water use. Figure 5 shows the components of a model for evaluating climate change impacts (Kudo et al., 2012). This evaluation system consists mainly of a downscaler that increases the resolution of climate forecast scenarios by using interpolated data, a bias corrector that corrects for differences (biases) between the climate forecast and the actual scenarios, and a distributed hydrological model that provides concrete information about agricultural water use. My research group used the estimation results from a global climate model to provide climate forecast scenarios and to evaluate the impacts of global warming. In this research, we used a scenario

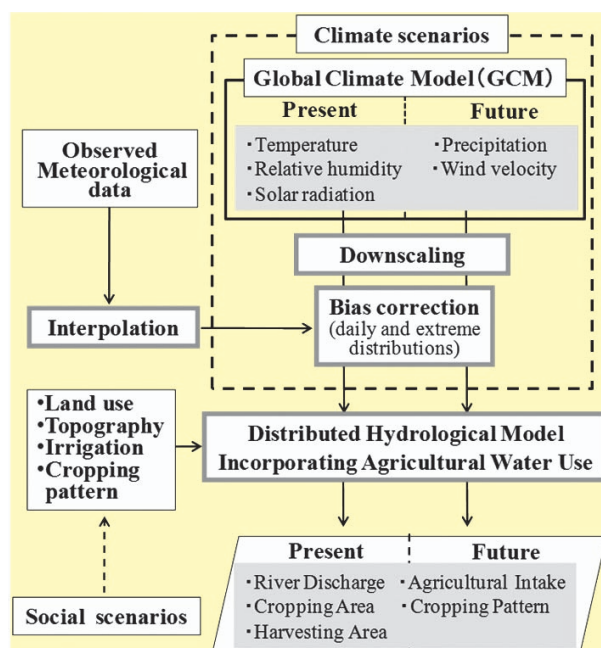
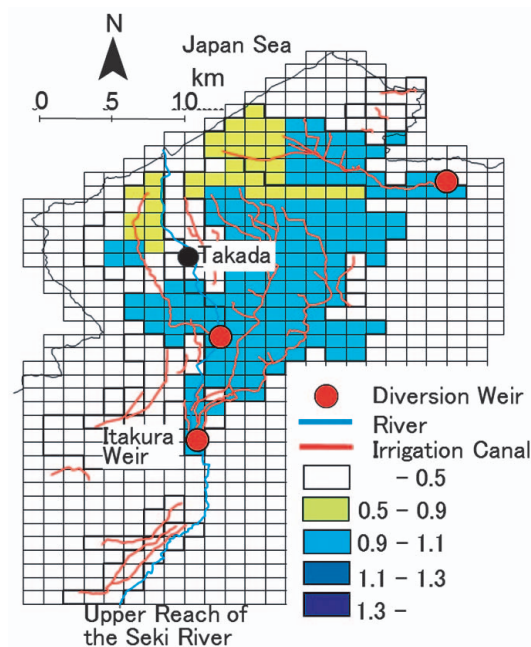


Fig. 5 Procedures for evaluating the impact of climate change.

resulting from the down-scaler and bias corrector as input for the distributed hydrological model, and compared the model's output with the actual hydrological data to evaluate the impact of climate change on agricultural water use. The core of this evaluation method is DWCM-AgWU, which we used for the process visualization because it accounted for a wide range of agricultural water uses, as described in the previous section.

We utilized the data produced by an ultra-high-resolution global atmospheric model (MRI-AGCM3.1S) developed by the Japanese Meteorological Research Institute under the Innovative Program for Climate Change Projection for the 21st Century to analyze the impacts for the Mekong River Basin, but used the MIROC3.2\_HIRES model (with 1.1° spatial resolution) under the IPCC SRES-A1B scenario to assess the impacts for all basins in Japan although I will only discuss the impacts for the Seki River Basin to provide an example.

This approach let us predict the future values of parameters such as the river water intake, water supply to paddy fields, crop cultivation period and area, and harvest date and area, based on a variety of social scenarios over an arbitrary period, but accounting for the impacts of climate change. Figure 6 shows the change in irrigation water requirements in the Seki River Basin under the IPCC SRES-A1B scenario. The data represents the ratio of irrigation water requirements during the puddling period in the future (2081–2100) to requirements in the present (1981–2000). In this example, we also assessed the effects of extremes (drought and flooding) to demonstrate concerns that there may be insufficient water to support future needs and that annual maximum discharges will need to increase (Kudo et al., 2012).



**Fig. 6** Illustration of the effects of climate change under the IPCC SRES-A1B scenario on irrigation water requirements in Japan's Seki River Basin. Values are the ratio of future water requirements during the puddling period (2081–2100) to current requirements (1980–2000) estimated using the DWCM-AgWU model.

## 2) Knowledge Transfer as Foreign Aid in Agro-Environments

As a second application of process visualization, my research group used DWCM-AgWU as a tool for foreign aid, including technical assistance. The target area was the whole Mekong River Basin, but used the following basins as examples: the Pursat River Basin (Cambodia) for irrigation development in an area with scarce data (Masumoto et al., 2014), the Nam Ngum River Basin (Lao PDR) for development of new water resources with hydroelectric power generation (Kudo et al., 2014), the Xe Bang Fai River Basin (Lao PDR) to annually flood rice paddies in the river's lower reaches (Yoshida, Masumoto, Horikawa et al., 2012), the Mun-Chi River Basin (northeastern Thailand) for irrigation management using large and medium dams (Kudo et al., 2014; 2015), and the Chao Phraya River Basin (Thailand) for flood control and agricultural water use in 2011 (Vongphet et al., 2014; 2015).

Based on those examples, an important application will be to use process visualization as a new basin-scale approach to generate long-term continuous data in areas with scarce data, especially in developing countries (Masumoto et al., 2014). The analysis presents the results of the application of process visualization to the Pursat River basin in Cambodia. Basic hydro-meteorological data are extremely scarce in this area, partly as a result of the Cambodian civil war, and agriculture today depends mainly on rainwater. Hydro-meteorological and other data (e.g., topographic and land-use data) were simulated using the procedure employed in the

climate change experiments of Masumoto (2010) and Kudo et al. (2012), and the simulation data were substituted for the observational data required for basin-scale irrigation planning. The input data for the model were the latest results from Japanese Meteorological Research Institute projects (MRI-AGCM3.1S; 2007–2011) for three 25-year periods: 1979–2003, 2015–2039, and 2075–2099. Daily values for precipitation, maximum and minimum temperatures, and maximum wind speeds were extracted from the MRI-AGCM3.1S simulation results. These data and the simulation data were input to the DWCM-AgWU model for the Pursat River Basin to allow an assessment of the effects of climate change. As one example, Figure 7 shows the simulated daily discharge at the Damnak Ampil weir on the Pursat River. These estimates represent quasi-observation data because they are simulations based on real input data, but they can still be utilized to plan future irrigation facilities (Masumoto et al., 2014).

This application showed that it is possible to use the model to generate basic data that can be used as a substitute for observational data, so that effective irrigation plans can be prepared that detail the specific processes and procedures needed to achieve them.

### 3) Extension to Food Security Issues

Application of the DWCM-AgWU model has been extended from the Seki River Basin to include all 336 Japanese river basins (Fig. 8) using 1- to 5-km cells. By examining individual basins, it was possible to validate the results for all of Japan. The results were satisfactory in terms of relative error checks of the simulated and observed discharges for many observation points, although some improvements are needed to account for water in industrial and domestic sewage in predominantly urban basins. Based on daily estimates for 5-km cells. Using the model, it was possible to estimate river flow (discharge) at any location and time throughout Japan. Moreover, an animation of planting dates for paddy rice and river flows is available for

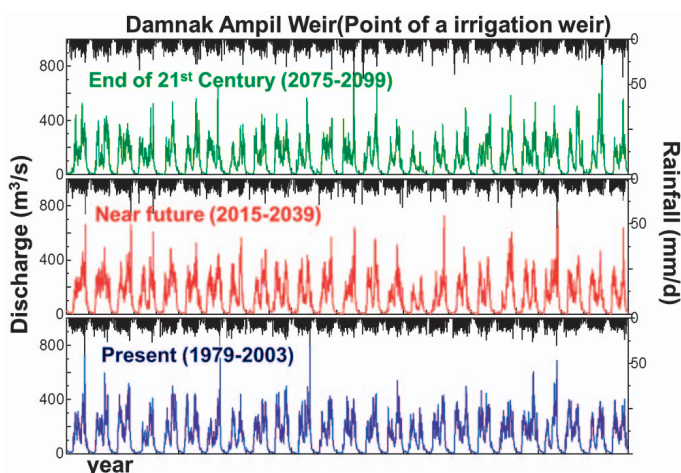
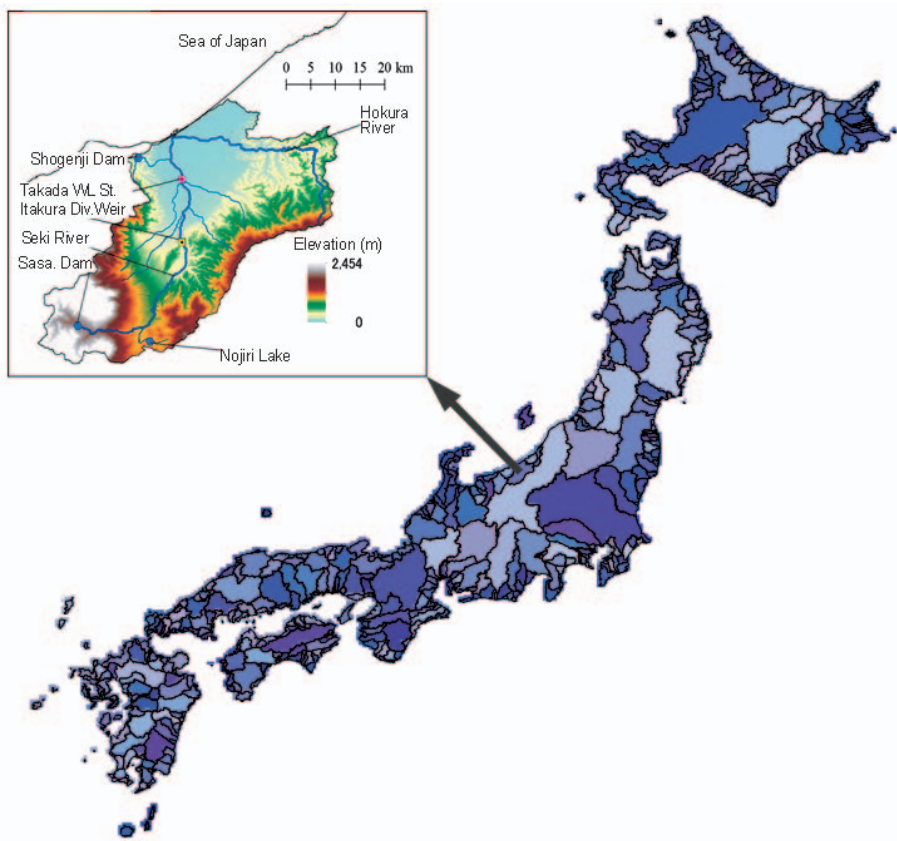


Fig. 7 Generation of quasi-observation data for the Damnak Ampil weir on the Pursat River (Cambodia) using the DWCM-AgWU model.



**Fig. 8** Division of Japan into river basins using cells with 1- to 5-km resolution (336 basins). The inset figure provides a more detailed result for the Seki River Basin.

demonstration of the model to Japanese stakeholders. The simulation results for all basins in Japan were utilized to support a socioeconomic model (Kunimitsu, 2011), which I will discuss in the rest of this section.

The socioeconomic assessment focused on food security and agricultural water use. The first application of the DWCM-AgWU model was to support development of the AFFRC Water–Food Model (Hayano et al, 2008), in which hydrology and water resources were combined with socioeconomic concerns. In developing the AFFRC model, my research group cooperated with several research organizations; we contributed the hydrology and water-use model (the National Institute for Rural Engineering, National Agriculture and Food Research Organization), the crop-production model was contributed by the National Institute for Agro-Environmental Sciences, the food security and food supply model was contributed by the socioeconomic research group of the Japan International Research Center for Agricultural Sciences, and the runoff mechanism was contributed by the Forestry and Forest Products Research Institute (Masumoto, Toritani et al., 2008). The resulting AFFRC Water?Food Model supported an analysis of the impact on food cultivated in areas dominated by rice paddies, the

proposal of counter-measures (e.g., land-use change, development, plant breeding, irrigation and water management), and the evaluation of effects of mitigation and adaptation methods in terms of “food politics.”

Though there were several benefits of this holistic approach, it was not possible to modify the development of the socioeconomic component after the completion of the 5-year project term. It may be possible to solve this problem by bringing the socioeconomic experts in-house so they become part of the ongoing research program. An additional research direction will be to evaluate the impacts of water resources on socioeconomic risks using a socioeconomic model. Kunimitsu (2011) developed a model to analyze the factors that affect crop productivity; these parameters were estimated as panel data for 9 regions of Japan over 32 years. In addition, they introduced a Monte-Carlo simulation method within a prototype Applied General Equilibrium Model (Kunimitsu et al., 2015).

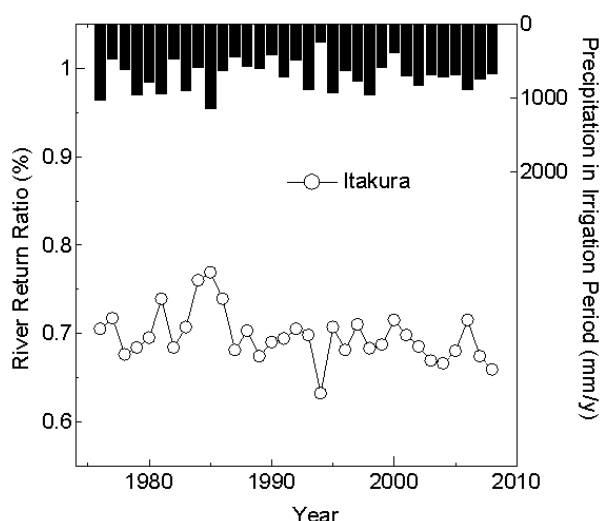
#### **4) Agricultural Water Rights**

Agricultural water use in Monsoon Asia is quite complicated. For example, there is a large difference between dry areas (irrigated field crops) and wet areas (paddy rice); the former require ongoing use of irrigation, whereas the latter require intermittent use of irrigation. Especially in paddy rice, some of the water obtained from a river is returned to the river, but it is difficult to determine what proportion is returned due to the complexity of agricultural water use. Fortunately, the DWCM-AgWU model can be used to determine the river return ratio (Yoshida, 2015; Yoshida et al., 2016).

To maintain agricultural water rights for different economic sectors, two Japanese government ministries (the Ministry of Agriculture, Forestry and Fisheries and the Ministry of Land, Infrastructure, Transport and Tourism) must negotiate the water rights for each use. Unfortunately, this is not feasible to estimate from observational data, as the overall water system is too complicated. Fortunately, the DWCM-AgWU Model can provide estimates that make it easier to determine the relevant water rights.

The procedure for allocating water follows two steps. First, managers select an irrigation area and search for inflow and outflow points. Second, managers estimate the return flow rate in an irrigation area based on discharges calculated by the model.

Figure 9 shows the results of this process for the biggest of the four irrigation areas in the Seki River Basin. This analysis revealed 37 inflow points and 23 outflow points, so it would clearly be impractical to observe all 60 points to obtain the necessary decision-support data. Instead, a case study used the mean results from daily calculations estimated by the model for a period of 33 years. The rice cultivation alone involved mean water flows from rainfall (888 mm during irrigation periods) and irrigation water (957 mm during irrigation periods) during the cultivation period. The DWCM-AgWU model also determined mean evapotranspiration from agricultural areas (510 mm during irrigation periods) and infiltration into groundwater (623 mm during irrigation periods). The net ratio of irrigation water to the total available water equaled 0.53, or 0.74 if using the mean gross estimate. Figure 9 reveals both the river return flow ratio and its inter-annual fluctuations. The overall average ratio of 0.70 shows that more than half of the



**Fig. 9** Estimated values of the river return flow ratio (i.e., the proportion of irrigation water returned to the river) at Itakura point in the Seki River Basin (Figure 1b).

irrigation water was returned to aquatic environments in the area and would have helped to regulate river flows. This ratio is larger than expected, but the results appear to be realistic, so this estimation method could be applied to other river basins in Japan.

### 5) Application of the ISO Water Footprint Method

In this application of the DWCM-AgWU model, the goal is to assess the ISO water footprint of agriculture (ISO, 2014; Masumoto and Yoshida, 2015), which is analogous to the carbon footprint; that is, it represents the impact of agriculture on the resource (here, water) that sustains it. This approach quantifies the interaction between the water cycle and anthropogenic practices as a result of agricultural water use and the recirculation of water through returning flows at the basin scale. The effect of such human activities on water availability is quantified based on land management practices that affect river flows and groundwater recharge, such as water use in forestry, agriculture, and wetland conservation.

Table 1 summarized the calculation results. The production of rough rice totaled  $5.39 \text{ t ha}^{-1}$  in the region (Masumoto and Yoshida, 2015). Although the apparent withdrawal of water for irrigation is  $9570 \text{ m}^3 \text{ ha}^{-1}$  ( $1780 \text{ L kg}^{-1}$  rough rice), evapotranspiration equaled  $5100 \text{ m}^3 \text{ ha}^{-1}$  ( $946 \text{ L kg}^{-1}$  rough rice), and the water consumed by evapotranspiration and seepage was  $11\,330 \text{ m}^3 \text{ ha}^{-1}$  ( $2200 \text{ L kg}^{-1}$  rough rice). The baseline values represent the natural system with rain-fed paddies rather than irrigation. The baseline production of rough rice without irrigation averages  $3.59 \text{ t ha}^{-1}$  in Monsoon Asia. Because the withdrawal of water for irrigation is zero in the baseline scenario, evapotranspiration totals  $2390 \text{ m}^3 \text{ ha}^{-1}$  ( $668 \text{ L kg}^{-1}$  rough rice), and the water consumed by evapotranspiration and seepage is  $7920 \text{ m}^3 \text{ ha}^{-1}$  ( $1480 \text{ L kg}^{-1}$  rough rice). Due in part to the  $1.83 \text{ t}$

**Table 1** Result of the ISO water footprint inventory analysis using the DWCM-AgWU model. The baseline values represent the natural system with rain-fed paddies rather than irrigation.

Items	Baseline		Irrigated rice paddies		Difference between Baseline and Irrigated rice paddies ( $\text{m}^3 \text{kg}^{-1}$ )	River Return Ratio (Return/Total Irrigation Water) <sup>‡</sup>
	Unit	( $\text{m}^3 \text{ha}^{-1}$ ) (rice yield = 3.59 t $\text{ha}^{-1}$ harvest <sup>-1</sup> )	( $\text{m}^3 \text{ha}^{-1}$ ) (rice yield = 5.39 t $\text{ha}^{-1}$ harvest <sup>-1</sup> )	( $\text{m}^3 \text{kg}^{-1}$ )		
Rainfall ( $R$ )		8 880	8 880	1.65		
Diverted water ( $Q_{\text{divert}}$ ) <sup>†</sup>		0	14 900	2.76		
Supplied water for irrigation <sup>††</sup>		(0)	(9 570)	(1.77)		
Inflows from residual areas ( $Q_{\text{res}}$ )		84 860 (surface) & 1 610 (groundwater)	23.6 (surface) & 0.45 (groundwater)	84 860 (surface) & 1 610 (groundwater)	15.7 (surface) & 0.30 (groundwater)	0.69
Returns flow into rivers ( $Q_{\text{out}}$ )		92 060 (surface) & 320 (groundwater)	25.6 (surface) & 0.09 (groundwater)	102 680 (surface) & 370 (groundwater)	19.0 (surface) & 0.07 (groundwater)	
Evapotranspiration ( $ET$ )		2 390	0.67	5 100	0.95	+0.28
Seepage ( $I_{\text{pad}}$ ) <sup>†††</sup>		(5 530)	(1.54)	(6 230)	(1.16)	(-0.38)
Storage change ( $\Delta S$ )		580	0.16	2 100	0.38	+0.22

All the values in this tableau were consistently normalized by the total area of grid cells covering the whole irrigation areas (127.0 km<sup>2</sup>).

<sup>†</sup> The values of this row were calculated with the amount of diverted water from rivers.

<sup>††</sup> The values of this row were estimated with the supplied water for irrigation directly used for rice, so that they were included in those of diverted water ( $Q_{\text{divert}}$ ).

<sup>†††</sup> The values of seepage ( $I_{\text{pad}}$ ) were included in those of the return flow into rivers ( $Q_{\text{out}}$ ) plus storage change ( $\Delta S$ ).

<sup>‡</sup> The river return ratio combines the daily inputs and outputs considering the  $Q_{\text{res}}$  (at 37 points) and  $Q_{\text{return}}$  (at 23 points), which are obtained using only the model's calculations.

$\text{ha}^{-1}$  difference in rice yields between the irrigated and baseline systems, the total water consumption by evapotranspiration and seepage for an irrigation system decreases by 100 L  $\text{kg}^{-1}$  rough rice compared to the baseline (See Table 1). This suggests that irrigation is an efficient water use in terms of its water footprint.

In addition, the groundwater recharge function of rice paddies, shown as seepage in Table 1 was 1160 L  $\text{kg}^{-1}$  rough rice yield at the basin level. In terms of the global average water availability index (ISO, 2014), this means that rice production results in a burden on freshwater resources equivalent to an additional 2200 L  $\text{kg}^{-1}$  of direct water use. The major factor contributing to the increased water consumption in this example is irrigation. The water footprint of rice cultivation is high because irrigation occurs in addition to rainfall input. It is important to note that agricultural water, especially water used for paddy cultivation, should be evaluated at the basin scale and that the analysis should include times when water demand is low and recognize the other functions of agricultural water use, such as recycling of water for paddy cultivation, groundwater recharge, and reuse by river systems; that is, that not all water input to the irrigation area is lost from the basin

#### 4. Proposals for Future Research in Agro-Environmental Water Management

Among many interesting future research topics related to water resources in agro-

environments, I have chosen five challenging topics that range from observation and modeling to practical applications: (i) basic research on the relationships between climate and irrigation, with an emphasis on long-term observation to discover new phenomena; (ii) a redefinition of the concept of basins (e.g., to consider upland agriculture on the Kashima Plateau and seashore fishery management through ecological water releases); (iii) efforts to provide educational and technological assistance to developing countries such as Cambodia in Monsoon Asia; (iv) countermeasures against extreme events such as the 2011 flood in Thailand (including the development of an integrated model that combines irrigation and flood control); and (v) participatory disaster-prevention planning to reduce the risk of problems such as flooding by means of water management.

### 1) Basic Research on Water Resources Based on Long-term Observations

In agro-environmental research, continuous observation over long periods plays an important role because it provides the knowledge required to develop accurate models and sometimes reveals important new mechanisms. For example, my research group established an observation tower in Tonle Sap Lake, Cambodia, 12 years ago (Fig. 10). Our hydro-meteorological observations at Chong Khneas demonstrate that the longer the observation period, the more valuable the observed data become. For example, Figure 10 clearly illustrates the seasonal fluctuations in the lake's water level.

We used these data to investigate the seasonal variations in radiation and evaporation and their relationship to the diurnal distribution of rainfall (Tsujimoto et al., 2008). Contrary to expectations, we found something new: that the rainy and dry seasons had nearly the same amount of solar radiation in the Lower Mekong River Basin (Masumoto et al., 2007; Tsujimoto et al., 2008). This is because the Earth's axial tilt during the rainy season resulted in larger inputs



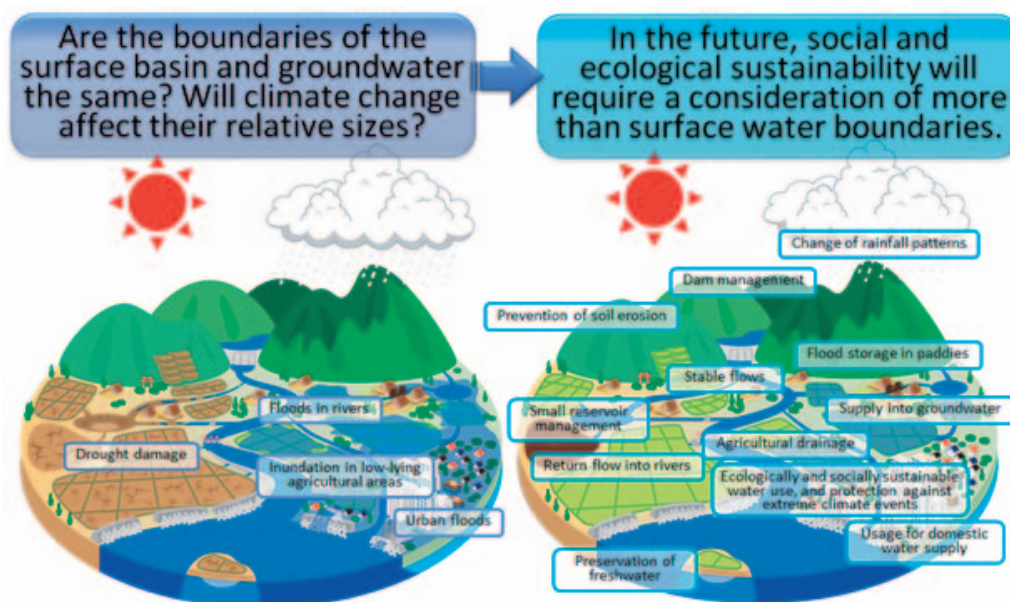
**Fig. 10** Hydro-meteorological observation tower at Chong Khneas in Cambodia's Tonle Sap Lake in (a) June and (b) November.

of solar radiation than during other seasons, no rain fell during nearly half of the days of the rainy season, and the amount of solar radiation on rainy days reached 88% of that on non-rainy days. The third factor can be attributed to the high frequency of evening rainfall. Furthermore, this rainfall?radiation relationship meant that during the rainy season, the land received a surprisingly large amount of net radiation because it received more sunlight than expected (including long-wave incoming radiation). Accordingly, evapotranspiration was high during the rainy season. Moreover, the rain-fed rice paddies that are the dominant form of agriculture in this region benefit from sufficient radiation to produce good crop yields.

These results will lead to future research on the mechanisms related to water resources that were revealed by these findings.

## 2) Change in the Basin Concept

Although the concept of a hydrological basin has been important and useful for many years, a paradigm shift in the concept may occasionally be necessary. The left side of Figure 11 depicts the current state of a conceptual basin. Until recently, the boundary of the groundwater catchment within a basin was assumed to be the same as the boundary of the surface water catchment. However, my research group found that the groundwater catchment boundary changes in response to changes in soil water. Yoshida et al. (2008) observed groundwater flow in boreholes and evaluated the water balance in four small watersheds on Japan's Kashima Plateau; they found that the boundaries of the groundwater catchment did not coincide with the corresponding surface boundaries (Yoshida, 2015). Hydrological and groundwater observations



**Fig. 11** Reimagining the concept of a hydrological basin. Note on the right figure: River transport of nutrients and eroded materials from farmland into coastal habitats.

in the Kashima-Kohoku watershed showed that the groundwater catchment was larger than the surface catchment, the groundwater potential may change after intense rainfall events (particularly with more than 50 mm of rain per event), and estimates of the long-term water balance confirmed that groundwater flowed into the surface catchment from the outside. Hydrologists have long known that tilted strata can intercept surface water in one surface catchment and direct it to the surface in neighboring catchments that are completely separate in their surface catchment boundaries. Our lead-in implies that our research group discovered this phenomenon about the divergence of groundwater and surface water catchment boundaries. The area of the Kashima–Kohoku groundwater catchment was 1.2 to 2.8 times the area of the surface catchment (Yoshida et al., 2008; 2009). They obtained similar results for two other watersheds.

One problem that must be solved based on these findings is how to model the mechanisms responsible for variations in the groundwater boundaries and to obtain additional data and determine whether this phenomenon is widespread.

Another challenge is that the concept of a basin's boundary must be extended. For example, a cooperative project with a fisheries research group revealed that it may be necessary to include the seashore area in the watershed because agricultural practices produce important nutrients that are transported into the coastal area, thereby affecting aquatic resources in seashore areas. They may also affect sediment loads transported in river water. Thus, we must consider the concept that basins have wider boundaries than formerly believed. The right side of Figure 11 shows an expanded image of the basin concept.

### **3) Knowledge Transfer as Foreign Aid**

In recent years, the Japanese government has increased efforts to transfer state-of-the-art home-grown technologies to developing countries as well as developed ones; this is known as “packaged infrastructure export.” The government targets 11 fields in this program: coal power plants, the electrical grid, nuclear power plants, railroads, recycling systems, the aerospace industry, smart grids and smart communities, renewable energy, information and communication technology, urban development, and industrial complex development. Thus far, the nuclear, railroad, and smart community components have received the most attention. Though agricultural water and facilities related to agro-environments are not specifically included in this program, the related technologies are part of the rural infrastructure that is a target of this program (Taniguchi et al., 2009; Kudo et al., 2012; Yoshida et al., 2012; 2016; Masumoto et al., 2016).

In contrast, we can think of other forms of foreign aid. For example, it may be possible to help establish a research institute in Cambodia. Cambodia's Ministry of Water Resources and Meteorology (MoWRAM) is planning to strengthen its Technical Service Center (TSC), which is currently a MoWRAM department, into a full institute, namely the “Institute for Water and Crops” [proposed by France] or the “Institute of Soil and Water” [proposed by Cambodia], and thereby promote related research, the training of researchers, and in-house training of MoWRAM engineers. However, it is unclear whether this institute will be able to grant postgraduate degrees such as a PhD in Engineering. MoWRAM is seeking support from Japan

and France to transform TSC into an institute. The Minister responsible for MoWRAM has expressed his intention to ask Japan's Ministry of Foreign Affairs and Overseas Land Improvement Cooperation Office, Ministry of Agriculture, Forestry and Fisheries, to support this initiative by supplying Japanese researchers as lecturers. The roles of the new institute would expand to include irrigation and water resource management research, the training of researchers, and the training of engineers in Cambodia.

Japan's National Institute for Rural Engineering (NIRE), which is part of the National Agriculture and Food Research Organization, has supported Phases I, II, and III of the TSC project by dispatching several researchers to provide short-term expert services under schemes offered by the Japan International Cooperation Agency (JICA). Support for the new institute by NIRE has been proposed as follows:

1. JICA will support participation by lecturers at the institute for periods of 2 to 3 years; researchers are not necessarily required for these roles. In addition, short-term participation will be supported in the form of intensive lectures, joint research projects, and other activities.
2. If it is difficult to start this program or takes longer than planned to realize it, NIRE will provide competitive research grants through a joint program between JICA and the Japan Science and Technology Agency, with a duration of 5 years, for example. Based on this funding, while NIRE develops and conducts a joint research program with its Cambodian counterparts, lecturers will be provided to the institute.
3. A new "Basin-wide Irrigation Management" project began in the summer of 2014, following Phase III of the TSC program under JICA's assistance. In addition, an international assistance program to Myanmar is being planned; it will evolve a cooperative study to set up a higher-education organization for the broad field of agriculture. However, as in the case of transforming the Cambodian TSC into an institute, it will be necessary to concentrate on irrigation and management of water resources to obtain assistance from Japan.
4. The Vietnamese national research institutes managed by the Ministry of Agriculture and Rural Development can currently issue higher academic degrees (at the Master's and PhD level), but details of these programs must be confirmed. In addition, Thailand's Irrigation Institute of the Royal Irrigation Department offers 4-year undergraduate university programs. Further information should be collected to determine how Japan can participate in these programs.

The lecturers provided by Japan include scholars, researchers, and engineers who will be able to carry out joint projects and research with foreign colleagues in addition to delivering lectures and training ("one-way" activities). However, additional efforts will be required to find experts in the following fields:

- i) Irrigation and drainage management (Agricultural Hydrology, Irrigation Planning, Law & Rights for Water Use, Water Environment, Hydraulic Environment, Canal Systems, Geo-environment and Structures, Paddy Water Management, Crop Science, Dry Land

Irrigation, Socioeconomics).

- ii) Disaster management (Geographical and Geomorphological Classification, Morphology and Disaster, Remote Sensing, Soil Mechanics, Structural Engineering, Risk Management).
- iii) River engineering (River Hydrology, River Management, Terrestrial-aquatic Environmental Interactions)
- iv) Meteorology and climatology (Climatology, Agricultural Meteorology, Plant Cultivation).

#### **4) Countermeasures against Extreme Events**

Climate change will result in an increased frequency of extreme weather events such as floods and droughts. To prevent or at least mitigate the potential damage from such events, countermeasures and adaptation measures must be proposed and evaluated. Because the expanded concept of a basin discussed earlier in this paper includes many components that go beyond the traditional basin concept, the right side of Figure 11 reminds us of the need to consider sustainability and social safety.

Another challenging topic will involve the development of an integrated water-management model that also accounts for extreme events, such as unusually prolonged drought and “Frankenstorms.” We currently lack a model to support a comprehensive analysis of such situations, so a water circulation model and an inundation model will need to be refined and combined. The 2011 flood along Thailand’s Chao Phraya River emphasized the necessity of developing a model capable of integrating irrigation and flood management. Accordingly, Vongphet et al. (2014; 2015) developed a prototype simulation of water circulation in the river’s basin that can account for both floods and droughts. Moreover, the model accounts for agricultural water use and water management, including floodwaters.

The next step will be to focus on supporting efforts to propose and evaluate risk management strategies, countermeasures, and adaptation measures to cope with extreme events such as floods and droughts. Moreover, an integrated distributed hydrological model that combines catchment-scale natural hydrological cycles with the impact of human activities (e.g., water management through irrigation facilities) and inundation and flood processes will be required to facilitate the development of adaptation measures and to evaluate their effectiveness; such measures may include taking advantage of the flood prevention function of paddies (Masumoto, Pham Thanh et al., 2008).

#### **5) Participatory Disaster Management Planning**

Floods are one of the primary climate-related disasters, and within the context of climate change, both the size and the frequency of extreme floods are likely to increase in flood-prone regions of Monsoon Asia. Countermeasures and adaptations must be developed and evaluated to protect rural areas from such disasters. The goal will be to develop procedures for identifying and testing adaptation measures in rural areas based on participatory approaches that include both farmers and water managers. Examples include the use of irrigation facilities such as agricultural water gates and an early warning system that takes advantage of a hydrological observation network. In that approach, hydrological analysis is necessary to reveal both the

inundation processes and the factors that influence them to develop more effective operational management strategies. For example, one of my research group's large studies includes an investigation of the management of agricultural water gates for operational flood protection in low-lying paddies based on numerical simulations.

For instance, Yoshioka et al. (2015) chose the Nam Cheng River basin in the Lao PDR to assess the influence of water-gate operations on inundation processes during the wet season with the goal of mitigating inundation damage. Their trial included the development of a numerical analysis method using DWCM-AgWU to model regional drainage through water gates, the introduction of an inundation process using an  $H$ - $V$  (height–water volume) curve for the area, and application of the developed model to the basin's low-lying paddy areas. The basin's 14 agricultural water gates provide irrigation water during the dry season and flood protection during the wet season. Several feedback control strategies, combined with gate opening heights, the number of open gates, operation intervals, and differences in threshold inner and outer water levels were examined with a focus on inundation damage within the area and drainage volume through the gates.

Further development and extension of this research will include on-site flood-prevention practices based on the proposed countermeasures.

## 5. Conclusions

This paper discussed how to address many agro-environmental problems by taking advantage of a powerful model (DWCM-AgWU) for process visualization of agricultural water use and the future research challenges to increase the model's usefulness in agro-environments. This model has been used both in Japan and in other parts of Monsoon Asia to improve the management of regional water resources, but also to provide protection against problems such as food shortages, climate change, energy shortages, and natural disasters. The examples I have provided illustrate the principle of “going with the flow” by adapting to changing conditions, in other word, the importance of not “swimming against the tide” when confronting changing conditions, a principle that especially applies to agricultural research.

## References

- Hayano, M., Horikawa, N., Kuwagata, T., Furuya, J., Ishigooka, Y., Hasegawa, T., Taniguchi, T., Shimizu, A., Toritanim, H., Tada, M. and Masumoto, T., 2008. Features of the AFFRC model for evaluating the relationship between the water cycle and rice production, *Paddy Water Environ.*, 6(1): 15–23.
- ISO 14046, 2014. Environmental management — Water footprint — Principles, requirements, and guidelines, *International Standard*: 1–33.
- Kudo, R., Masumoto, T. and Horikawa, N., 2015. Modeling of paddy water management with large reservoirs in northeast Thailand and its application to climate change assessment, *JARQ*, 49(4): 363–376.
- Kudo, R., Masumoto, T., Horikawa, N. and Yoshida, T., 2014. Modeling of paddy irrigation processes with large reservoirs and quantification of river flow regimes affected by anthropogenic activities, *J. Jpn.*

- Soc. Hydrol. Water Resour.*, 22(2): 101–113 [in Japanese with English abstract].
- Kudo, R., Masumoto, T., Yoshida, T. and Horikawa, N., 2012. Development of quantitative impact assessment method of climate change on agricultural water use in irrigation-dominant basins, *J. Irrig. Drain. Rural Eng.*, 277: 21–29 [in Japanese with English abstract].
- Kunimitsu, Y., 2011. Asset management of public facilities in an era of climate change: Application of the dynamic computable general equilibrium model, In: Sustainable Development and Planning V [C. A. Brebbia and E. Beriatos (eds.)], WIT Press, p. 553–562.
- Kunimitsu, Y., Kudo, R., Iizumi, T. and Yokozawa, M., 2015. Fluctuations in rice productivity caused by long and heavy rain under climate change in Japan: Evidence from panel data regression analysis, *JARQ*, 49(2): 159–172.
- Masumoto, T., 2001. Preliminary analysis of the 2000 flood in the Lower Mekong River Basin, *Ann. Rep. Jpn. Res. Soc. Prac. Hydrol. Syst.*, 4: 103–122.
- Masumoto, T., 2010. Impact of global warming on water circulation and food production, *J. Jpn. Soc. Irrig. Drain. Rural Eng.*, 78(1): 15–19 [in Japanese].
- Masumoto, T., Pham Thanh, H. and Shimizu, K., 2008. Impact of paddy irrigation levels on floods and water use in the Mekong River Basin, *Hydrol. Process.*, 22(9): 1321–1328.
- Masumoto, T., Taniguchi, T., Horikawa, N., Yoshida, T. and Shimizu, K., 2009. Development of a distributed water circulation model for assessing human interaction in agricultural water use, In: From Headwaters to the Ocean: Hydrological Changes and Watershed Management [M. Taniguchi, W.C. Burntt, Y. Fukushima, M. Haigh & Y. Umezawa (Eds.)], Taylor and Francis, p. 195–201.
- Masumoto, T., Toritani, H., Tada, M. and Shimizu, A., 2008. Assessment of changes in water cycles on food production and alternative policy scenarios, *Paddy Water Environ.*, 6(1): 5–14.
- Masumoto, T., Tsujimoto, K. and Somura, H., 2007. Hydro-meteorological observation and analysis of observed data at Tonle Sap Lake and its environs, Urban and Paddy Areas, Technical Report of the National Institute for Rural Engineering, No.206: 219–236 [in Japanese with English abstract].
- Masumoto, T., Yoshida, T. and Kudo, R., 2016. Basin-scale irrigation planning in areas with scarce data, *Irrig. Drain.*, (accepted)
- Masumoto, T. and Yoshida, T., 2015. Visualization of basin-wide agricultural water use in Monsoon Asia for water footprint inventory analysis, In: Sustainable Basin Water Management –Challenges of Supply and Demand Management at the Basin Scale, USCID Eighth International Conference on Irrigation and Drainage, Reno, Nevada, June 2-5, 2015, p. 65–77.
- Masumoto, T., Yoshida, T. and Kudo, R., 2014. Proposal of basin-wide irrigation planning based on climate change assessment in extremely data scarce areas, 22th International Congress on Irrigation and Drainage, 14-20 Sep. 2014, Gwangju, Korea, “Securing Water for Food and Rural Community under Climate Change,” Q.58 R.2.03: 1–11.
- Shimizu, K. and Masumoto, T., 2006. Classification and mapping of agricultural water use in the Mekong River Basin, *Trans. Jpn. Geomorphol. Union*, 27(2): 235–244 [in Japanese with English abstract].
- Taniguchi, T., Masumoto, T., Yoshida, T., Horikawa, N. and Shimizu, K., 2009. Development of a distributed water circulation model incorporating various paddy water uses, Part 1, 2, and 3, *J. Jpn. Soc. Hydrol. Water Resour.*, 22(2): 101–113, 114–125, 126–140 [in Japanese with English abstract].
- Tsujimoto, K., Masumoto, T. and Mitsuno, T., 2008. Seasonal changes in radiation and evaporation implied from the diurnal distribution of rainfall in the Lower Mekong, *Hydrol. Process.*, 22(9): 1257–1266.
- Yoshida, T., 2015. Dynamics of water circulation and anthropogenic activities in paddy dominant watersheds — From field-scale processes to catchment-scale methods —, *Bulletin of the National Institute for Rural Engineering*, No.54: 16–18
- Yoshida, T., Masumoto, T. and Horikawa, N., 2009. Identification of underground catchment area of plateau basin through observation of groundwater flow and water balance analysis, *Appl. Hydrol.*, 21: 28–37 [in Japanese with English abstract].

- Yoshida, T., Masumoto, T., Horikawa, N., Akatsu, H., Bounlom, V. and Koumphonh, B., 2012. Coupling scheme of inundation processes into a basin-wide hydrological model for low-lying rivers, *J. Irrig Drain. Rural Eng.*, 281: 27–31 [in Japanese with English abstract].
- Yoshida, T., Masumoto, T., Horikawa, N., Kudo, R., Minakawa, H. and Nawa, N., 2016. River basin scale analysis on return ratio of diverted water to irrigated paddy areas, *Irrig Drain.*, (accepted)
- Yoshida, T., Masumoto, T., Kubota, T. and Matsuda, S., 2008. Water balance characteristics of Kashima Plateau Basins assuming variable areas of underground, *Paddy Water Environ.*, 6(2): 189–198.
- [25] Yoshida, T., T. Masumoto, R. Kudo, T. Taniguchi, and N. Horikawa, 2012. Modeling of Basin-wide Water Circulation Incorporating Water Allocation and Management Schemes in Large Irrigated Paddy Areas, *J. Irrig Drain. Rural Eng.*, 277: 9–19 [in Japanese with English abstract].
- Yoshioka, Y., Masumoto, T., Maruyama, K. and Minakawa, H., 2015. Agricultural water-gate management for operational flood protection in low-lying paddies, *J. Teknologi*, 76:17: 37–44.
- Vongphet, J., Masumoto, T. and Minakawa, H., 2015. Development of a seamless model to simultaneously simulate agricultural water use and the effects of flooding, *Appl. Hydrol.*, 27: 29–37.
- Vongphet, J., Masumoto, T., Minakawa, H. and Kudo, 2 R., 014. Application of a DWCM-AgWU Model to Chao Phraya River Basin with large irrigation paddy areas and dams, *Appl. Hydrol.*, 26: 11–22.