IRRIGATION AND DRAINAGE
Irrig. and Drain. **(2016)**
Published online in Wiley Online Library (wileyonlinelibrary.com) **DOI**: 10.1002/ird.2013

MODIFICATION OF DWCM-AgWU MODEL APPLIED TO A PADDY-DOMINANT BASIN WITH LARGE DAMS†

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ABSTRACT

The Distributed Water Circulation Model incorporating Agricultural Water Use (DWCM-AgWU) was modified and the revised model was applied to assess water use in the Chao Phraya River basin in Thailand for the years 2008–2011, during which there were droughts and floods. A reservoir management model was introduced to incorporate two large dams (Bhumibol and Sirikit dams), with several remote irrigated areas in water allocation/management, and performed special treatments of flood peaks to account for agricultural practices. In the system, the two dams are the main sources of irrigation water during the dry season and they are used to control floods during the rainy season. Moreover, for the lower Chao Phraya River from Nakhon Sawan to the sea, another special water management was applied on rainy days to keep the release at the Chao Phraya Diversion Dam at or below a certain threshold. That is, when discharge exceeded the threshold, water was diverted to main irrigation canals on the western and eastern sides of the Greater Chao Phraya Irrigation Project. According to the simulation, the average relative error between the calculated and observed daily discharge was 21% at the Nakhon Sawan station, which is located below the confluences of the four main tributaries of the Chao Phraya River. The modified model will enable continuous calculations for mitigating the impacts of extreme events, such as the 2011 flood in Thailand, managing the use of irrigation water, and proposing adaptive countermeasures to climate change.

KEY WORDS: paddy-dominant basin; large-scale dam; remote irrigated area; water management; flood

Received 29 July 2014; Revised 19 February 2016; Accepted 20 February 2016

RÉSUMÉ

Nous avons modifié le modèle (DWCM-AgWU) de circulation et de distribution de l'eau avec intégration de l'utilisation de l'eau agricole, et appliqué ce modèle modifié en vue de l'évaluation de l'utilisation de l'eau dans le bassin versant de Chao Phraya en Thaïlande pendant les années 2008 à 2011 et durant lesquelles des sécheresses et des inondations se sont produites. Nous avons introduit un modèle de gestion de réservoir afin d'intégrer deux grands barrages (barrages de Bhumibol et de Sirikit) comportant plusieurs zones d'irrigation éloignées pour la répartition et la gestion de l'eau et eu recours à des traitements spéciaux des pointes de crue pour représenter les pratiques agricoles. Dans ce système, les deux barrages représentent les sources principales de l'eau d'irrigation pendant la saison sèche et sont utilisés afin de contrôler les crues pendant la saison des pluies. Par ailleurs, nous avons appliqué aux biefs inférieurs du bassin, de Nakhon Sawan jusqu'à la mer, une gestion de l'eau spéciale pour les jours de pluie afin de conserver la surverse au niveau du barrage de diversion de Chao Phraya autour d'une certaine valeur seuil; ainsi, au-delà de cette valeur, l'eau était détournée vers les canaux d'irrigation principaux des bordures occidentales et orientales du projet d'irrigation de Chao Phraya. D'après la simulation, l'erreur relative moyenne entre les rejets quotidiens calculés et observés était de 21% à la station Nakhon Sawan à l'aval de la confluence des quatre principaux affluents de la rivière Chao Phraya. Le modèle modifié va permettre des calculs continus en vue de l'atténuation des impacts d'évènements extrêmes tels que les inondations de 2011 en Thaïlande et de proposer des contre-mesures adaptatives au changement climatique.

MOTS CLÉS: bassin essentiellement rizicole; arrage à grande échelle; zone irriguée éloignée; gestion de l'eau; inondation

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†Modification du modèle DWCM-AgWU appliqué à un bassin essentiellement rizicole et équipé de grands barrages.

INTRODUCTION

The Chao Phraya River basin is the largest and most agriculturally productive basin in Thailand, especially for rice cultivation. This basin has more agricultural land under irrigation (34%) than any other basin in the country (Royal Irrigation Department (RID), 2011). Two huge multi-purpose dams, the Bhumibol and the Sirikit, are located in the upper part of the basin. These two dams supply the water for remote irrigated areas in the middle and lower basin, particularly in the dry season (around November to April), and they are also used for flood control in downstream areas during the rainy season. In the lower reaches of the basin is the Chao Phraya Diversion Dam, a major irrigation weir equipped with a series of flood control gates. The two multi-purpose dams and the diversion dam are mutually managed and controlled to supply large areas of land with irrigation water and to control floodwaters in the lower part of the basin (RID, 2012).

In 2011, irrigated and urban areas in the Chao Phraya River basin were damaged by a flood with a return period of 70 years (Komori *et al.*, 2012). The flood started in July in the upper part of the basin and expanded to the middle part by August. During this period, the water stored in the Bhumibol and Sirikit dams increased nearly to the dams' maximum capacities. Flooding spread to the lower parts of the basin, composed of irrigated and urban areas, from August to November. In order to maintain the stability of the Bhumibol and Sirikit dams, a management decision was made to release the inflow through the emergency spillways. At almost the same time, during September to November, flooding extended to the irrigation and urban areas in the lower basin, due to dike breaches along the main river. Thus, the floods in the middle and lower reaches were closely linked to the management of the two huge dams.

Climate change is predicted to result in an increased frequency of extreme weather events such as floods and droughts (Intergovernmental Panel on Climate Change (IPCC), 2012). Furthermore, as a risk prevention strategy, countermeasures and/or adaptation measures for these extreme events must be proposed and evaluated. In other words, the main method of flood management in Thailand is the management of irrigation water through facilities such as the Bhumibol and Sirikit dams. In the analysis of floods, therefore, it is important to consider agricultural water use as human-controlled activities.

The Distributed Water Circulation Model incorporating Agricultural Water Use (DWCM-AgWU) was originally developed for water use analysis in the Mekong River basin (Masumoto *et al.*, 2009; Taniguchi *et al.*, 2009). The original model targeted river basins dominated by paddies over a continuous series of years that included droughts. Kudo *et al.* (2013) modified the model to reproduce the paddy irrigation processes with large dams used in north-eastern Thailand. In that modified model, the management of irrigation systems and dam operations was introduced systematically. Vongphet *et al.* (2014) previously applied the model of Kudo *et al.* (2013) to the Chao Phraya basin. However, this basin has characteristics that are quite different from the one in north-eastern Thailand. Specifically, it has two huge dams, the Bhumibol and Sirikit dams, and a major irrigation weir referred to as a diversion dam, the Chao Phraya Diversion Dam, which are mutually managed and controlled to supply irrigation water to several remote irrigated areas and to control floodwaters in the lower part of the basin where the slopes are gentle and channel networks denser. Those characteristics could not be considered in the model of Kudo *et al.* (2013).

To facilitate the development of adaptation measures against floods and droughts and to evaluate the effectiveness of these measures, we ultimately aim to develop a Seamless-DIF model (Seamless calculation model among Distributed Water Circulation, Inundation, and Floods) that expands on DWCM-AgWU by incorporating flood and inundation processes. Furthermore, the Seamless-DIF model will be applied to the Chao Phraya River basin for continuous calculation of water circulation throughout the basin, including extremes such as the 2011 flood, in which the interaction between floods and agricultural water use is a main factor in watershed management.

In the present study, the DWCM-AgWU was modified and applied to assess water use in the Chao Phraya River basin in 2008–2011, during which there were droughts and flooding. Water management related to human activities, such as management through irrigation facilities, dams and/or irrigation intakes, is considered in this application. The results of this application were used to assess limitations on flood and inundation processes of the present models as a first step in the development of the Seamless-DIF model.

AREAL MODEL

Target river basin

The study area is the Chao Phraya River basin, with an area of 160 000 km^2. There are four main tributaries in the upper and middle parts of the basin, the Ping, Wang, Yom and Nan rivers (Figure 1). These four tributaries converge at Nakhon Sawan. In this study, the basin is divided into upper, middle and lower areas, that is, the area above the Bhumibol and Sirikit dams, the portion from these dams to Nakhon Sawan, and the area from Nakhon Sawan to the coast, respectively. In the upper basin, rain-fed and irrigated paddy fields extend over arable areas. In the middle basin, there are floodplains along the four tributaries, and alluvial fans have formed where tributaries enter the floodplain. The floodplain is characterized by river channels, natural levees and their back marshes. The lower areas are defined as the

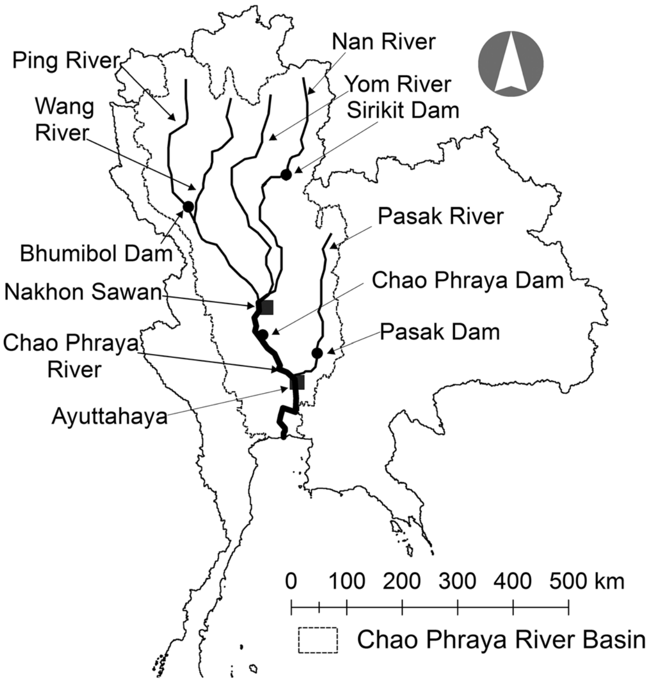

Figure 1. Outline of the study basin.

delta plain areas. The floodplain and delta plain along the lower reaches of the river, with an elevation of 20 m or less, act as a water diffusion and receiving area.

The Bhumibol and Sirikit dams are perennial-storage-type and multi-purpose reservoirs, being mainly used for irrigation and power generation. The Bhumibol Dam is on the Ping River and has a storage capacity of about 13.5 billion m^3, and the Sirikit Dam is on the Nan River and has a storage capacity of about 9.5 billion m^3. Both are managed by the Electricity Generation Authority of Thailand (EGAT). The most important irrigation facility is a weir including a series of large floodgates at Chainat (a little upstream of Station C.13 in Figure 2), called the Chao Phraya Diversion Dam. The RID uses this facility to regulate the intake of water to the irrigated area and to control floods in the lower basin. In the lower reach of the river at the city of Ayutthaya, the Pasak River (watershed area, 14 500 km^2) joins the Chao Phraya River from the left bank. The Pasak Dam is located 120 km upstream from this confluence; it is used for flood management and has a storage capacity of about 960 million m^3.

Hydro-meteorological data and treatment of cropping pattern

Hydrological data, including water level and discharge, were obtained from the RID for 135 observation points and 150 cross sections for the period from when each station was installed up to 2011. By using cross-sectional data, kinematic parameters were generated for a runoff model. Rainfall and other meteorological data (2007–2011) from the US National Oceanic and Atmospheric Administration were collected for the 43 stations. The data were interpolated into each cell in the target area by using the inverse distance weighted method. Meteorological data were used for calculating evapotranspiration based on the modified Penman–Monteith equation. Some additional data for water level and discharge in 2011 were collected for 100 stations after the last application of the model (Vongphet *et al.*, 2014).

Cropping patterns include two rice crops in irrigated paddies, one rice crop in rain-fed paddies, and upland crops. For irrigated paddies in the basin, the planting date depends on the availability of irrigation water and is specified as November 15 for the dry season and June 1 for the rainy season. In the model, however, planting was set to start on November 15 for the dry season and when cumulative rainfall since April 1 totals 275 mm for the rainy season, with the latter scenario also used for rain-fed paddies.

Irrigation facilities

The RID classifies dams as large, medium and small based on the storage capacity of their reservoirs. Large-scale reservoirs have a storage capacity of 100 million m^3 or more, medium-scale is 1 million m^3 or more, and small-scale is less than 1 million m^3. In the Chao Phraya River Basin, there are 10 large-scale reservoirs that have multiple purposes, including irrigation, domestic water supply or hydroelectric power generation, and 62 medium-scale reservoirs that are used mainly for irrigation. These reservoirs store water in the rainy season (May–October) and release water for their benefitting areas in the dry season (November–April), and also at the beginning of the rainy season. The total capacity of effective storage of large- and medium-scale reservoirs in the basin is approximately 27 billion m^3 (26 and 0.98 billion m^3 for large- and medium-scale, respectively). The average annual precipitation in the basin is 1200 mm, which is equivalent to an input of approximately 192 billion m^3. Therefore, the total storage capacity is about 14% of the annual precipitation. In this region, however, no rainfall is expected during the dry season, so water released from reservoirs is the main source of available water at that time. As a result, these reservoirs are extremely important for dry-season cropping in rice paddies.

MODIFICATION OF A COMBINED MODEL FOR THE ANALYSIS

Modelling of DWCM-AgWU

The original model and operation model. The DWCM-AgWU (Masumoto *et al.*, 2009; Taniguchi *et al.*,

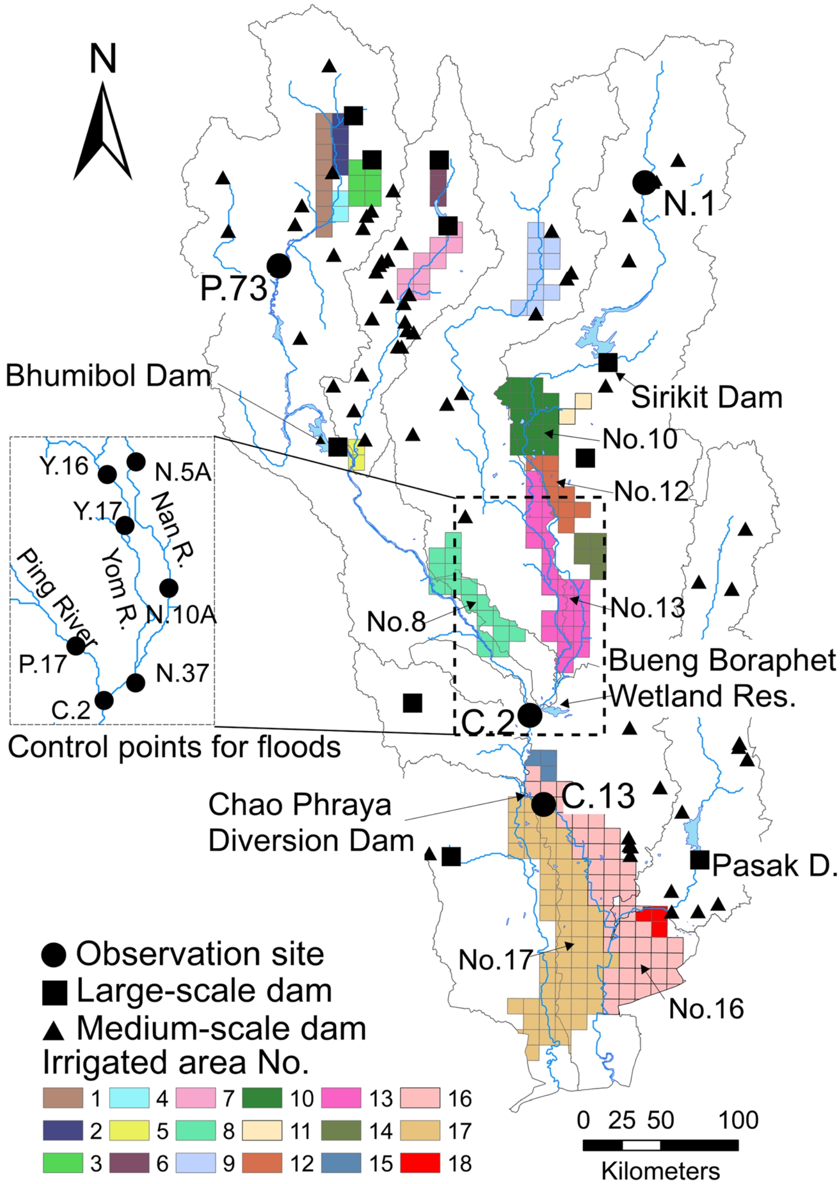

Figure 2. Location of large- and medium-scale reservoirs and irrigation areas in the target basin.

2009) was originally developed for the Mekong River basin. The model calculates the water circulation in each cell (dimensions of 0.1° in both latitude and longitude) by considering the component of agricultural water use via four submodels: (1) the Reference Evapotranspiration Forecast Submodel estimates the reference evapotranspiration based on the modified Penman–Monteith equation; (2) the Cropping Time and Area Forecast Submodel projects changes in the cropping area; (3) the Paddy Water Use Submodel calculates the amount of irrigation water used for the crops; (4) the Runoff Submodel forecasts the runoff and changes in soil water content. The model accounts for differences in agricultural water use, which allows us to estimate various data relevant to agricultural water use at an arbitrary time and place, such as the cropping area of paddy fields, actual water intake and the water content of the soil. Furthermore, it enables us to evaluate and project the effects on water circulation in the basin brought about by various human activities (e.g. changes in agricultural practices) and meteorological changes from global warming.

Dam management model. The storage $V_{\mathrm{res}}(t)$ [m^3] of a reservoir can be calculated from Equation (1), given the storage $V_{\mathrm{res}}(t-1)$ in the previous period:

$$V_{\mathrm{res}}(t) = V_{\mathrm{res}}(t-1) + (Q_{\mathrm{resin}}(t) - Q_{\mathrm{resout}}(t))\Delta t \qquad (1)$$

where Δt [days] is the duration of a single calculation step. The reservoir inflow Q_{resin} (t) is given by the Runoff Submodel and the reservoir outflow Q_{resout} (t) [m^3 day^{-1}] includes releases for irrigation, spillway overflow, domestic use and hydropower generation.

For irrigation, the reservoir releases supplementary water to compensate for the shortage of necessary intake based on a comparison of agriculture water demand and river discharge at the intake point. The reservoir is placed across the edges of two cells incorporated in the distributed water circulation model. The upstream cell runoff is the reservoir inflow, which is the input for the dam-control model. The reservoir release given by the model is the inflow to the downstream cell.

Furthermore, the amount of evaporation is calculated in the Reference Evapotranspiration Forecast and Runoff submodels by considering the proportion of approximated water surface area in a cell.

Water allocation model. The model estimates actual intakes at a specific point and the water supply to paddy fields in irrigated areas. Irrigation water taken from the river is distributed to the target region. The processes are independent of the mechanisms that determine river runoff and surface runoff in the water circulation model. At the same time, the irrigated area is classified into two types: one extending over two or more cells and the other situated within a single cell.

Irrigation command area occupying two or more cells. If a command area occupies multiple cells, it is necessary to model water intake, irrigated water distribution and return flow because the intake and drainage points are in different cells.

First, the water intake (Q_{div}) is calculated for the command area from the river discharge at the intake point and the region's water demand (e.g. gross water requirement of the region, capacity of the intake facility, and amount in water permits). That is, water to be taken and supplied to the area is the river discharge of the intake cell (Q_{riv}), the capacity of the facilities (Q_{cap}), or the water demand of the area (Q_{dmnd}), whichever is the smallest.

$$Q_{\text{div}} = \min\left(Q_{\text{riv}}, Q_{\text{cap}}, Q_{\text{dmnd}}\right) \tag{2}$$

The intake water is distributed to a cell in which the paddy water depth is lower than the control water level in the irrigated area, and priority is given to upstream paddy fields. The amount at which water is distributed to the cell is the projected gross water requirement, which accounts for the irrigated area of each cell and the irrigation efficiency. The water allocated to a cell is used to irrigate paddy fields and to meet the requirements for management in channels. For details of the water allocation management model for irrigation of multiple cells, see Vongphet *et al.* (2014).

The command area located in a single cell. If a command area is located in a single cell, the model compares the discharge at the upstream end of the river channel with water demand (considering the capacity of intake facilities and gross water requirements) of the cell to define the smaller demand as the share of the paddy field for actual water intake.

MODIFICATION OF THE DWCM-AGWU AND WATER MANAGEMENT MODEL

Incorporation of dam operation and water allocation/management models

Modelling of the reservoirs in the Chao Phraya River basin was carried out by targeting 10 large-scale and 62 medium-scale reservoirs (Table I). (Small-scale dams were not considered here because the total volume of those reservoirs was relatively small.) In modelling the water storage of the large-scale reservoirs, data on effective storage capacity,

Table I. Operational information on irrigation facilities in the target basin (10 large- and 62 medium-scale reservoirs)

No.	Dam name	Maximum storage(10^6 m^3)	Irrigated area(10^4 ha) [number of cells]
L.1	Mae Ngat Somboon Chon	265	2.8 [4]
L.2	Mae Kuang Udom Thara	263	2.0 [6]
L.3	Kew Khomah	170	3.2 [3]
L.4	Kew Lom	106	2.0 [9]
L.5	Bhumibol	13 462	30.0 [71]
L.6	Sirikit	9 510	27.0 [62]
L.7	Kwae Noi Bamrung Dan	939	2.5 [−]
L.8	Tab Salao	160	2.7 [−]
L.9	Kasaew	390	2.6 [−]
L.10	Pasak	785	4.6 [4]
M.1–62	Medium-scale reservoirs	985 (total)	10.3 [62]
S.1–347	Small-scale reservoirs	301 (total)	6.8 [347]

intake facility capacity at downstream intake sites (e.g. maximum intake, maximum discharge of irrigation canals) and the planned municipal water volume were collected from the RID and from meetings conducted locally.

Large-scale reservoirs in the Chao Phraya basin are located within separate cells, so special treatment was not required. For medium-scale reservoirs, however, the data on total storage capacity and command areas were collected from the RID. When several medium-size reservoirs existed within a single cell, the total storage capacity and benefitting land area of the reservoirs within the mesh were added together, and such reservoirs handled as a single dam.

With regard to the irrigation water allocation and management model, 18 irrigated areas were simulated; these were covered by large- and medium-scale dams. Under these conditions, data on irrigation facilities (point data), irrigation canal networks (line data) and benefitting land (polygon data) were obtained from the RID and used to specify irrigated areas. Figure 2 shows these areas in the Chao Phraya basin.

Runoff from the drainage canals to the river channels is slow, because the discharge facilities are relatively underdeveloped and the gradient of the discharge canals is low. To model this process, the possibility of hydrological tracking of the flow and modelling the storage process within a cell were considered; however, this process was simplified in this study by using a moving average, in a manner similar to calculating the overland flow in a runoff model. As a result, the moving average number of days for rice paddy runoff was added as a parameter.

Treatment of remote areas irrigated from large dams (Bhumibol and Sirikit dams)

There are four irrigation projects supplied with water by the Bhumibol and Sirikit dams, even though they are all located in remote areas from the dams (RID, 2011). These projects are: (i) the Khamphaeng Phet Irrigation Project along the Ping River (irrigated area No. 8 in Figure 2), which is supplied by the Bhumibol Dam; (ii) the Utaradit Irrigation Project along the Nan River (No. 10), supplied by the Sirikit Dam; (iii) the Pitsanulok Irrigation Project, also along the Nan River (Nos. 12 and 13) and supplied by the Sirikit Dam; and (iv) the Greater Chao Phraya Irrigation Project in the lower part of the Chao Phraya River basin (Nos. 16 and 17), which is supplied by both the Bhumibol and Sirikit dams and a water intake upstream of the Chao Phraya Diversion Dam (weir, Figure 2).

Given that both large dams and the diversion dam are mutually managed and controlled, a cooperating reservoir management model was developed to incorporate the Bhumibol and Sirikit dams with these four remote irrigation projects as a water allocation/management model. The area on the eastern side of the Chao Phraya River (No. 16), irrigated by means of two main canals with a total capacity of 285 $m^3\ s^{-1}$, and the area on the western side of the river (No. 17), irrigated by three main canals with a total capacity of 615 $m^3\ s^{-1}$, were linked to both large dams (Visutimeteegorn *et al.*, 2007). As the first step, the irrigation water requirement for release of water (Irr.Req.) from each dam was determined by considering the ratio of the remaining storage in each dam to the total remaining storage. In addition, the water requirements of the irrigated areas in the middle part of the basin were estimated as the ratio of total remote irrigated areas to irrigated area in the lower part, as the first term in Equation (3):

$$\mathrm{Irr.Req.}_{\text{The Bhumibol or Sirikit dam}} = \frac{\sum \text{Area of all remote irrigated area}}{\sum \text{Areas (Nos.16, 17)}} \times \sum \text{irr.requirement (Nos.16, 17)} \times \frac{\text{Storage in the Bhumibol or Sirikit dam}}{\sum \text{Storage in the Bhumibol and Sirikit dams}} \quad (3)$$

Handling flood peaks

The modelling of floods and inundation was not included in the original model. A simple modification for flood treatment was subsequently applied to calculate discharge by considering the maximum capacity of the river channel at several control points. That is, discharge exceeding the maximum capacity of the channel was assumed to flow into the connecting cells on both sides of the channel and return to the river via runoff mechanisms. The control points were seven observation points located where extensive floodplains occur along the river, as shown in the lower middle part of Figure 2.

Modification of water management. There are two modifications for water management in the model.

Treatment of dry season flow by the Bueng Boraphet wetland reservoir. Bueng Boraphet, the largest shallow reservoir and wetland complex in Thailand (Sriwongsrithanon *et al.*, 2009), is located on the Chao Phraya River a little upstream of Nakhon Sawan on the Chao Phraya River (Figure 2). It has multiple functions, serving as a habitat for fish, a source of irrigation water in the dry season for surrounding paddy areas, and as a means of controlling floods associated with inland water and excessive inundation from the Nan River during the rainy season. In the dry season, farmers use pumps to take water from the Bueng Boraphet Wetland Reservoir to irrigate the surrounding paddy fields, and this water use requires reverse flows into the wetland to maintain the reservoir water level.

In the modelling, paddy fields around the Bueng Boraphet Wetland Reservoir were identified as irrigated paddy areas with irrigation facilities, which apparently take water directly from the Nan River. It was assumed that the flow from these paddies returns to the Bueng Boraphet Wetland Reservoir in the normal runoff process. During the dry season, water is taken from the Nan River and diverted to the reservoir to maintain the wetland's ecological functions.

Prevention of floods downstream from the Chao Phraya River in the rainy season. When river channels have high flows during the rainy season, the RID controls the release from the Chao Phraya Diversion Dam at 1500 $m^3\ s^{-1}$ to prevent downstream flooding, especially in the city of Ayutthaya (RID, 2012). In this process, the RID regulates discharge at two points: at Station C.2 at Nakhon Sawan and Station C.13 located downstream of the Chao Phraya Diversion Dam (Figure 2). At C.2, the discharge is controlled at 1800 $m^3\ s^{-1}$, which accounts for the total discharge from the Ping and Nan rivers, and the excessive discharge withdrawn from the Nan River is released into the Bueng Boraphet Wetland Reservoir when total flows are more than the control target. The Chao Phraya Diversion Dam is a weir structure with 16 large floodgates that are used for flood control and irrigation. Flows are stored upstream of the dam and are diverted into irrigated areas (Nos. 16 and 17) through irrigation canals while considering the maximum capacity of the canals. To control the entire discharge, the diverted volumes are determined based on the capacity of diversion facilities (e.g. intake facilities and/or irrigation canals) and the flooding situation in the target area as well as in the downstream reaches of the Chao Phraya River.

Therefore, in the model river discharges at three intake points, the Bueng Boraphet Wetland Reservoir and the eastern (No. 16) and western (No. 17) irrigated areas (Figure 2), are regulated at the control targets. However, the flooding situation in the irrigated area of the Greater Chao Phraya Irrigation Project and the flow conditions at the Chao Phraya Diversion Dam floodgates are not considered in the model.

RESULTS AND DISCUSSION

Estimated parameters

The target period for the analysis was 2007–2011. However, 2007 was used as a spin-up period and was not used in validating the accuracy of the model calculations. Thus, the actual target period was 4 years. The model parameters were determined by trial and error. For details of the selected parameters, see Vongphet *et al.* (2014).

Estimated results for river flow and dam management

Discharge observation points and inflow into large-scale dams. Model accuracy was validated for data from 2008 to 2011. Through trial and error, the model parameters were determined such that calculated discharge matched measured discharge at Stations P.73 and N.1, located upstream from the Bhumibol and Sirikit dams, respectively. Figures 3, 4(a) show the comparison between the calculated and observed discharges at Station N.1 and inflows into Bhumibol Dam, respectively. The results indicate that the daily fluctuations of the discharge during the rainy and dry seasons are well reproduced by the model at both sites. However, there remain some discrepancies in the peaks.

For 2008–2011, the relative errors of the calculated values in relation to the observed daily discharge at Station N.1 and inflows into Bhumibol Dam were 34.8–41.2% (average, 38.0%) and 34.7–51.0% (average, 39.8%), respectively. Inflow into the Bhumibol Dam in 2009 (drought year) was not used for error estimation due to the exceptionally high peaks in the rainy season even compared to the flood year of 2011, suggesting that the 2009 observation data for reservoir water level was incorrect. Despite omitting these data, the average relative error for inflow into the Bhumibol Dam reservoir was nearly 40%, and the errors during low-flow periods in the dry seasons, especially in

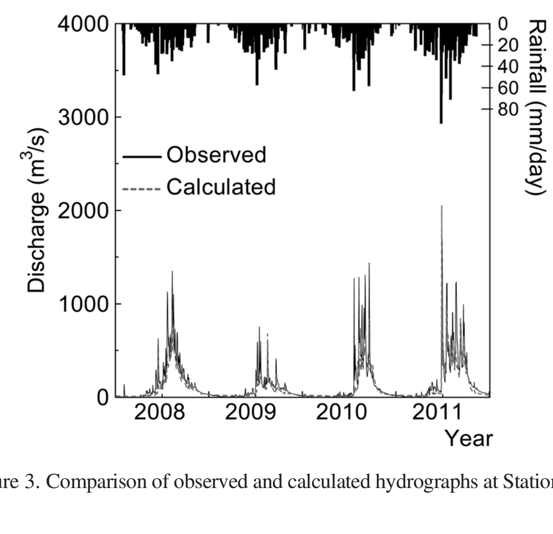

Figure 3. Comparison of observed and calculated hydrographs at Station N.1.

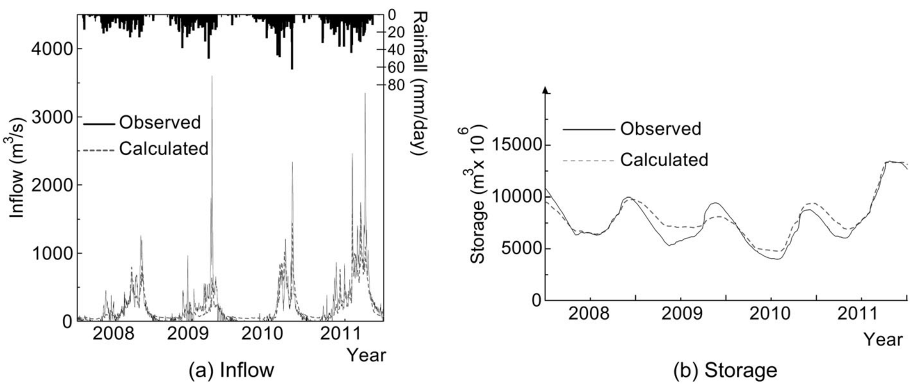

Figure 4. Comparison of inflow and storage volumes at the Bhumibol Dam, as an example of large dams.

2010, were large. The inflow into the Bhumibol Reservoir during the dry season was apparently affected by discharges from the dam into the upstream sector of the river, but because water is discharged from the Mae Ngat Somboon Chon Dam (L.1 in Table I) and Mae Kuang Udom Thara Dam (L.2) for hydroelectric power generation and domestic use as well as for paddy irrigation within the major irrigated areas in the model, the calculated flows during the dry seasons are high compared to the actual flows.

Dam storage and release. To illustrate the effectiveness of the reservoir management model, a comparison between the calculated and observed storage of the Bhumibol Dam is shown in Figure 4(b). Based on the inclusion of a management model for the two large reservoirs, Figure 5 shows the calculated results from 2008 to 2011 for releases from the Bhumibol and Sirikit dams. Releases in the dry seasons were mainly for irrigation, with cooperative management considering the remaining storage in each reservoir. In the rainy season of 2011, both dams released a large volume of water over their spillways, which is one of the release functions in the reservoir management model.

Estimated results of discharge and irrigation water in low-lying areas

River flow. To study the effect of a reservoir operation model on the estimation of river flow, the C.2 observation point (Nakhon Sawan) was selected. Figure 6(a) shows a comparison of the calculated and observed daily river flow at Station C.2 with the incorporation of a reservoir management model. In the dry seasons and latter half of the rainy seasons, the calculated river flow becomes closer to the observed values, thus improving the model's accuracy. The relative error of the calculated daily river flow in relation to the observed values was 21%. In the Chao Phraya River basin there is inadequate rainfall in the dry season, so the river flow in low-lying areas is mainly composed of releases from dams, with partial releases for irrigation. In addition, even a simple treatment of floods that accounted for the capacity of river channels in each year improved the accuracy of discharge around the peaks (Figure 6a).

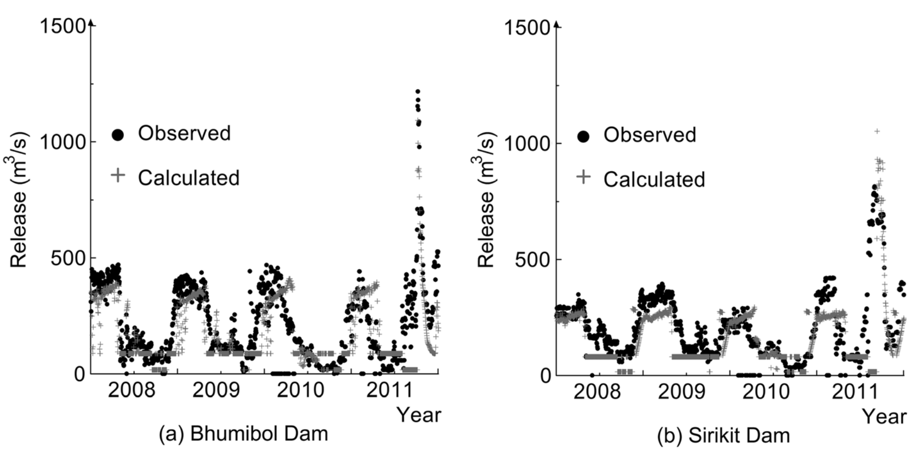

Figure 5. Calculated and observed releases at the large dams.

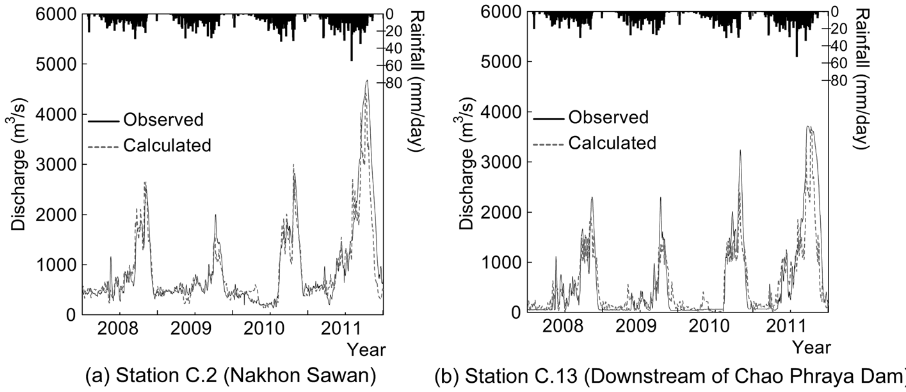

Figure 6. Estimated discharge before and after the intake of water for irrigation areas originally supplied by the Bhumibol and Sirikit dams.

Furthermore, the accuracy of the estimated river flow in rainy seasons was improved by accounting for the special treatment of water management at the Bueng Boraphet Wetland Reservoir, mentioned in the section 'Modification of water management', for flood prevention. However, the simple flood treatment could not improve calculation during the drainage stage of November to December in 2011 (Figure 6a).

Irrigation and water management. With regard to the effects of applying the water allocation and management

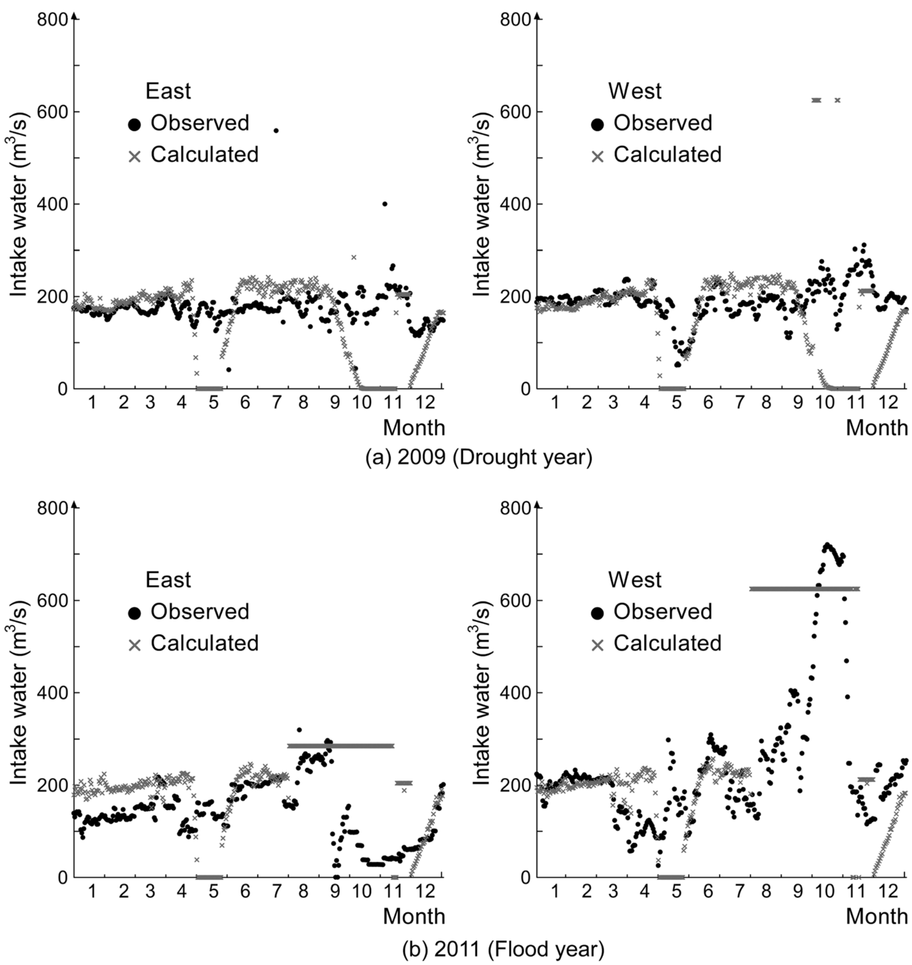

Figure 7. Calculated and observed water volume diverted to the eastern and western irrigation areas (Nos.16, 17 in Figure 2) of the Greater Chao Phraya Irrigation Project.

model, Figure 6 shows the change in river discharge before and after the intake of irrigation water from the weir between Stations C.2 and C.13. In the model, there are two intake facilities for the irrigated area the Greater Chao Phraya Irrigation Project. The supply of irrigation water from the eastern and western parts of the main irrigated areas (Nos. 16 and 17 in Figure 2, respectively) increased upon application of the irrigation water management model. During the dry season, the annual water supply increased by 400 $m^3\ s^{-1}$. Intake water for the eastern and western irrigated areas is compared in Figure 7 for the typical years, namely 2009 and 2011. The calculated results of intake water were estimated based on irrigation requirements and special water management in the rainy season. In the calculation, irrigation water was taken from the main stream in accordance with the pattern of cropping in both seasons. In the model, during the high-flow period (around September–November), excess water from the target control points is diverted to irrigated areas while considering the capacity of the irrigation facilities, such as irrigation intake gates or canals. However, estimation of release from the dam in the rainy season needs to be improved. In addition, for water intake during the transition from the end of the rainy season to the beginning of the dry season (November and December), estimation of operational results of intakes and releases was subject to large errors.

Remaining problems

At Station C.13 located downstream from the Chao Phraya Diversion Dam (Figure 6b), there were some discrepancies in river flow in the dry seasons, as indicated by the relative error of 39% for the calculated daily river flow in relation to the observed values, as well as discrepancies in the intake by water management practices for downstream flood prevention in irrigated areas in the rainy seasons (Figure 7). The Chao Phraya Diversion Dam stores water and releases it via 16 large floodgates in both dry and rainy seasons. As a result, discharge at Station C.13 is subject to operation of those gates. At present, our model is not able to account for gate operation at the Chao Phraya Diversion Dam.

CONCLUSION

In this study, a modified DWCM-AgWU was applied to the Chao Phraya River basin. The model allowed us to calculate water circulation, including agricultural water use. In the model, agriculture is the principal water use. Dams and irrigation systems are important for agricultural water resource management, especially in the middle and lower parts of the Chao Phraya basin, which were affected by floods in 2011. The Bhumibol and Sirikit dams are the most important facilities with respect to management of agricultural water use in remote irrigation systems in the middle and lower basin. However, a modified model could not carry out flood and inundation processes in the low-lying areas.

In the future, the DWCM-AgWU will be expanded by incorporating flood and inundation processes as a Seamless-DIF model. The model will allow us to simultaneously simulate water distribution through the basin even in extreme events. As the remaining points, operation of the large gates at the Chao Phraya Diversion Dam will be applied to the model. Furthermore, the planting start date for irrigated areas in the rainy season will be defined according to the RID or the actual situation. The results obtained by using this model will be fundamental for developing a Seamless-DIF model that uses the DWCM-AgWU framework to account for floods and inundation, which, in turn, will allow the development of adaptive measures (i.e. countermeasures) to mitigate the effects of extreme weather conditions. Application of this improved model should be helpful in the future management of water resources in the Chao Phraya River basin.

ACKNOWLEDGEMENTS

This work was supported financially by the Ministry of Agriculture, Forestry and Fisheries of Japan through a research project entitled ‘Impact of climate change on the vulnerability of agricultural and forestry, water/land resources’. The work was also was supported by a Japan Society for the Promotion of Sciences (JSPS) Grant-in-Aid for Scientific Research (B) (no. 26292129). The authors would also like to thank Mr. Naoki Horikawa, Japanese International Research Center for Agricultural Sciences (JIRCAS), Japan, for his useful comments, and Mr. Thada Sukhapunnaphan, RID, Thailand, and Mrs. Wanphen Kaewkamthong, EGAT, Thailand, for providing hydrological data and the Bhumibol and Sirikit dams operational data, respectively.

REFERENCES

Intergovernmental Panel on Climate Change. 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II. Cambridge University Press: Cambridge, UK, and New York, NY, USA.

Komori D, Nakamura S, Kiguchi M, Nishijima A, Yamazaki D, Suzuki S, Kawasaki A, Oki K, Oki T 2012. Characteristics of the 2011 Chao Phraya River flood in Central Thailand. *Hydrological Research Letters* **6**: 41–46.

Kudo R, Masumoto T, Horikawa N, Yoshida T 2013. Modeling of paddy water management in large-reservoir irrigation areas and its integration into distributed water circulation model. *Applied Hydrology* **25**: 61–70 (in Japanese with English abstract).

Masumoto T, Taniguchi T, Horikawa N, Yoshida T, Shimizu K 2009. Development of a distributed water circulation model for assessing human interaction in agricultural water use. In: Taniguchi M, Burnttt WC, Fukushima Y, Haigh M, Umezawa Y (eds), *From Headwaters to the Ocean. Hydrological Changes and Watershed Management*. Taylor and Francis, London: 195–201.

Royal Irrigation Department (Thailand) 2011. Irrigation and Water Management Plan in Dry Season of 2011–2012 , Bangkok (in Thai): Thailand.

Royal Irrigation Department (Thailand) 2012. Irrigation and Water Management Plan in Rainy Season of 2012 , Bangkok (in Thai): Thailand.

Sriwongsrithanon N, Surakit K, Hawkins P 2009. A water balance budget for Bung Boraphet—a flood plain wetland-reservoir complex in Thailand. *Water* **1**: 54–79.

Taniguchi T, Masumoto T, Yoshida T, Horikawa N, Shimizu K 2009. Development of a distributed water circulation model incorporating various paddy water uses. Part 3. Structure of the total model and estimation of agricultural water circulation. *Journal of the Japan Society of Hydrology & Water Resources* **22**(2): 126–140 (in Japanese with English abstract).

Visutimeteegorn S, Likitdecharote K, Vongvisessomjai S 2007. Effects on the upstream flood inundation caused from the operation of Chao Phraya Dam. *Songklanakarin Journal of Science and Technology* **29**(6): 1661–1774.

Vongphet J, Masumoto T, Horikawa N, Kudo R 2014. Application of DWCM-AgWU model to the Chao Phraya River Basin with large irrigation paddy areas and dams. *Applied Hydrology* **26**: 11–22.

