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Modeling of Paddy Water Management with Large Reservoirs in Northeast Thailand and its Application to Climate Change Assessment

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Abstract

We developed a water circulation model that incorporates paddy water management, including reservoir operation and water allocation schemes, which is applicable to extensive and well-developed irrigation areas. First, reservoir operation and water allocation and management models were introduced into the water circulation model previously developed by the NIRE. Subsequently, we applied the developed model to assess the impact on irrigation reservoirs of climate change in the Mun River basin of northeast Thailand. As a result, taking into consideration the fluctuation in rainfall, the developed model reproduced the seasonal changes in storage water and water release at two large reservoirs, and monthly diverted water at a major diversion weir. Moreover, introducing the operation of reservoirs and diversion weirs improved the simulation accuracy of river discharges, particularly in dry seasons. According to climate change projections, the impacts of climate change on reservoir operations differed in each reservoir, although the reservoirs are in the same basin. This means that the impacts of climate change on the operation of water-use facilities should be individually assessed. Since the developed model requires only basic information and assumes simple operation rules, this model is useful for assessing impacts on the operation of numerous water-use facilities simultaneously at the macro level.

Discipline: Watershed and regional resources management
Additional key words: anthropogenic flow regulation, atmospheric general circulation model, reservoir operation model, water allocation and management model, Monsoon Asia

Introduction

Rice farming is a staple industry of Asian countries and comprises 94% of the world's rice harvest (Forster *et al.* 2012). Most paddy fields in the region are rain-fed without irrigation facilities. In parts of Monsoon Asia (e.g. Thailand), however, with climates characterized by rainy summers and dry winter monsoons, a number of irrigation facilities have been constructed for paddy irrigation. Although these facilities allow dry-season cropping, they alter the hydrological environment of river basins dramatically. For example, irrigation systems with large reservoirs strongly regulate river flow regimes by damming river discharges for several months, releasing stored water in response to water demand in downstream areas and diverting river flow into irrigation areas (Vörösmarty *et al.* 1997, Eskew *et al.* 2012, McCarthy *et al.* 2008, Forster *et al.* 2012). To quantify the hydrological cycle and available water resources, particularly in river basins with well-developed irrigation areas, it is therefore important to consider the effect on agricultural water use alongside natural hydrological processes.

Significant fluctuations in annual rainfall in Monsoon Asia lead to highly variable rice yields, which implies that changes in precipitation characteristics caused by climate change will significantly impact on agriculture in this region. Accordingly, the impact of climate change on agricultural water use is one of the critical issues facing Monsoon Asia (Eastham *et al.* 2008, Kiem 2008, MRC 2009, Ministry of Foreign Affairs of Japan). The impact of

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climate change typically needs to be assessed by simulations driven by climate change scenarios.

For these reasons, a grid-based water circulation model incorporating various paddy water uses has been developed by the National Institute for Rural Engineering (NIRE) research team to assess (1) the interaction between paddy irrigation and the hydrological environment, and (2) the impact of climate change on paddy water use in the Mekong River Basin (Taniguchi *et al.* 2009a, 2009b, 2009c, Masumoto *et al.* 2009). This water circulation model estimates the irrigation process for a small irrigation area, taking into consideration the various types of irrigation (e.g. small weirs, pumps, groundwater etc.) and rice cropping patterns (irrigation and rain-fed paddies) varying by region. However, in this model the water use process is confined to the supply and demand for water within a grid, the result being that an extensive irrigation system that covers several model grids is spatially decoupled and modeled as if the water resource were managed independently within each small area. Moreover, this model does not consider anthropogenic flow regulation by reservoirs and thus does not represent dry-season irrigation reasonably. In practice, extensive and well-developed irrigation regions (with areas exceeding tens of thousands of ha) are managed in an integrated manner, from upstream water sources to individual downstream paddies through various water-use facilities (i.e. reservoirs, diversion weirs, canals, etc.). Such extensive water management has a considerable effect on water circulation in river basins. Modeling of paddy water management can therefore be essential to represent water circulation accurately in highly developed basins.

The purpose of this study was to develop a water circulation model that takes into consideration paddy water management, including issues not previously addressed, such as reservoir operations and water allocation schemes for extensive irrigation areas. First, we modeled the processes involved in paddy water use: reservoir operations, diversions of river flow and allocations of irrigation water to each paddy plot. We integrated these processes into the previous water circulation model and subsequently investigated the applicability of this model by applying it to the Mun River basin in northeast Thailand, where numerous irrigation projects have been carried out. Finally, we used the developed model and a climate change scenario simulated with a General Circulation Model (GCM) to address the impact of climate change on irrigation reservoirs.

Study area and materials

1. Description of the study basin

The Mun River in northeast Thailand is a tributary of the Mekong River (Fig. 1). The area of the drainage basin is 119,700 km^2 and accounts for about 15% of the watershed of the Mekong River. The climate of the region undergoes distinct changes between dry and rainy seasons. Because of the Asian Monsoon, approximately 90% of annual rainfall is concentrated during the rainy season (May to October) and this seasonality results in an uneven temporal distribution of water resources between rainy and dry seasons. The annual rainfall fluctuates year to year, from 900 to 2,000 mm/y. This significant fluctuation in annual rainfall also intensifies the vulnerability of water resources.

Over 50% of the land in this region is farmland, while rain-fed paddies occupy about 90% of the farmland. This dependence on rain causes unstable rice production. Since the 1970s, a number of large irrigation projects have been carried out to increase agricultural productivity. These involved constructing a number of irrigation facilities such as reservoirs, diversion weirs and irrigation canals, to mitigate the impact of the uneven seasonal distribution of water resources and provide a reliable supply of water during dry seasons. This more reliable water supply has facilitated the practice of double cropping (cropping during both rainy and dry seasons).

Within the Mun River basin there are now 10 large reservoirs, with total storage capacity exceeding 100 million cubic meters (MCM) and 150 medium reservoirs with a total capacity exceeding 1 MCM (Fig. 2). Table 1 shows the main features of the 10 large reservoirs, each of which provides water for an extensive irrigation area exceeding 10,000 ha. In addition to providing irrigation water, some reservoirs also provide water for multiple purposes, such as domestic and industrial use and hydroelectric power. Because the main source of water during the dry seasons is the water stored in reservoirs during rainy seasons, reservoir management is an important issue in this region.

2. Data

(1) Meteorological and hydrological data

We collected daily meteorological data (daily maximum/minimum/mean temperatures, daily mean relative humidity estimated from dew point temperature and daily mean wind velocity) from 13 stations in the Mun River basin for the period 1994-2003 from the Royal Irrigation Department of Thailand (RID) and NOAA web site (http://www7.ncdc.noaa.gov/CDO/cdo). We also collected daily precipitation data at 51 stations from the Mekong River Commission (MRC). To facilitate inputting of the meteorological data into a hydrological model, we interpolated the data onto 0.1° grids using the Inverse Distance Weighting (IDW) method, which produced a weighted average of inverse numbers of distances between a grid and meteorological stations.

For hydrological data, we used daily discharges at three stations (Fig. 1) and data on daily inflow, storage volume and water release of two large reservoirs (Ubolratana

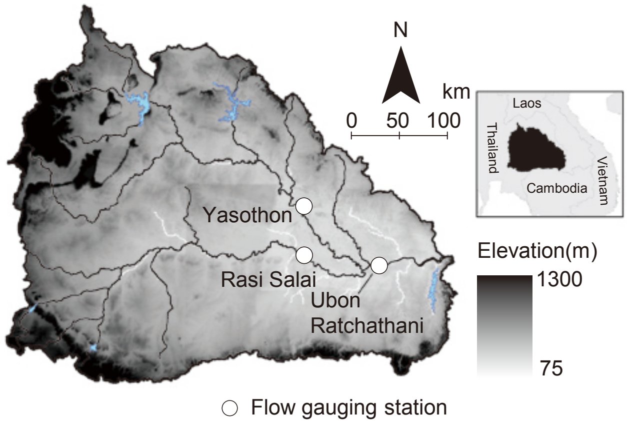


Fig. 1. Overview of the Mun River basin

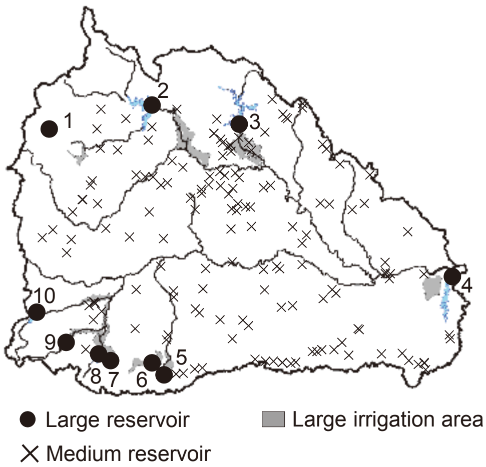


Fig. 2. Large/Medium reservoirs and large irrigation areas in the Mun River basin

Table 1. Features of large reservoirs in the Mun River Basin

No.	reservoirs	Total storage capacity (MCM)	Effective storage capacity (MCM)	Beneficial area (ha)
1	Chulabhorn	188	144	12,800
2	Ubolratana	2,264	1,854	42,240
3	LamPao	1,430	1,345	50,416
4	Sirindhorn	1,966	1,135	24,000
5	NangRong	121	118	10,944
6	LamPlaimat	98	91	3,200
7	LamSae	275	118	15,164
8	MunBon	141	134	7,636
9	PhraPhreong	110	109	10,096
10	LamTakhong	314	297	19,700

MCM : 10^6 m^3

and Sirindhorn) from the MRC.

(2) Climate change scenario based on GCM

We used the results of climate change simulations performed by the MRI-AGCM3.1S developed by the Meteorological Research Institute of Japan as part of the KAKUSHIN project (Kitoh *et al.* 2009). As a part of that project, time slice experiments were carried out with spatial resolution of 20 km under the SRES A1B scenario (Kusunoki *et al.* 2011) for three periods of time: present (1979-2003), near future (2015-2039) and future (2075-2099). The data we used were as follows: daily precipitation, daily maximum/minimum temperature, daily mean wind velocity and daily mean relative humidity estimated from specific humidity and sea level pressure.

Methods

1. Basic concept of the original water circulation model incorporating various paddy water uses

The framework of our analysis is a water circulation model incorporating various paddy water uses (Taniguchi *et al.* 2009a, 2009b, 2009c). An important characteristic of the model is that it takes into consideration various types of irrigation and provides quantitative estimates of paddy field irrigation (e.g. rice paddy cropping area, paddy water requirements and water withdrawals for each grid) as well as hydrological processes (e.g. runoff from adjacent areas, river flow, evapotranspiration and soil moisture). The model is a grid-based spatially distributed model and each grid is characterized by the ratio of five land-use categories: forests, rain-fed paddies, irrigation paddies, upland fields and bodies of water. The irrigation and crop patterns are also stipulated as agricultural conditions in each grid; irrigation water and actual evapotranspiration can be estimated from the growth stage of the rice, water depth and soil moisture in the paddy fields.

The model originally contains four sub models: a reference evapotranspiration model, a runoff model, a paddy water use model and a cropping pattern/area model. The reference evapotranspiration model estimates the reference evapotranspiration using the FAO Penman-Monteith equation (Allen *et al.* 1998) using crop coefficients and meteorological data. Based on the estimated reference evapotranspiration, actual evapotranspiration is calculated by taking into consideration the soil moisture and ponding depth of paddies which are obtained with the runoff and the paddy water use models. The runoff model calculates the surface runoff, groundwater runoff and the water balances of the root and saturated zones. In addition, the kinematic wave model (Chow *et al.* 1988) is applied to route river flow. The cropping pattern/area model estimates the starting date of rice planting and the planted area. Based on water use condition, paddy fields are classified into two categories: irrigation and rain-fed respectively. The irrigation paddies are cropped during both rainy and dry seasons, while the rain-fed paddies are cropped only during the rainy seasons. During the rainy seasons, rice planting starts after cumulative rainfall exceeds a certain threshold, which means the starting date of rainy-season cropping varies annually based on rainfall. This threshold needs to be set so that it is consistent with the actual date. In contrast, the starting date for dry-season cropping is determined by fixed irrigation schedules, because the available water resource is the water stored in reservoirs at the beginning of the dry season. Planted areas are determined based on the delay of the starting date of rice cropping from a specified date and the deficit in the soil water content (Taniguchi *et al.* 2009a). After estimation of the starting date and planted area, rice cropping proceeds according to the planting, growing and harvesting periods specified for each grid.

The paddy water use model simulates the water management of paddy plots by calculating the ponding depth, paddy water requirements and runoff from the paddies. First, the ponding depth of a paddy is calculated based on the water balance of a paddy plot, which is calculated from rainfall, paddy infiltration, evapotranspiration and irrigation water (irrigation paddies only) as follows:

$$H_{pad}(t) = H_{pad}(t-1) + (R(t) + Q_{supply}(t) - ET_a(t) - K_p - Q_{pad}(t)\Delta t \quad \text{for irrigation paddies}$$

$$H_{pad}(t) = H_{pad}(t-1) + (R(t) + ET_a(t) - K_p - Q_{pad}(t)\Delta t \quad \text{for rain-fed paddies} \tag{1}$$

where H_{pad} is the ponding depth of a paddy (mm), R is rainfall (mm/d), Q_{supply} is irrigation water (mm/d), ET_a is the actual evapotranspiration of the paddies (mm/d), K_p is the infiltration rate (mm/d), which is assumed to be constant during the irrigation period, Q_{pad} is the surface runoff from the paddies (mm/d) and Δt is the simulation time step (d). Irrigation water is supplied when the ponding depth is less than a target water depth.

The amount of irrigation water for a grid is determined based on the paddy water requirement WD (mm/d), which is estimated with the following equation:

$$WD(t) = ET_a(t) + K_p - R(t) \tag{2}$$

Subsequently, the gross water demand Q_{gw} (mm/d) of each paddy is estimated as follows:

$$Q_{gw}(t) = \frac{WD(t)}{1000 \times IE} A_{ir} \quad WD(t) > 0$$
$$= 0 \quad WD(t) \leq 0 \tag{3}$$

where A_{ir} is the area of the irrigation paddy in each grid (m^2)

and *IE* is irrigation efficiency (-).

Finally, the supply water to each grid (Q_{supply}) is determined as follows:

$$Q_{supply}(t) = \min(Q(t), Q_{gw}(t)) \quad (4)$$

where Q is the river discharge in each grid.

When the ponding depth exceeds the height of an outlet weir in a paddy plot, surface runoff Q_{pad} is calculated from the weir formula (Hayase & Kadoya 1993). This surface runoff Q_{pad} is assumed to drain directly into a river in the grid and represents the return flow from the irrigation area to the river system. Consequently, river discharge in each mesh is somewhat affected by the extraction of irrigation water and drainage of excess water, even though these processes are limited within a grid.

2. Modeling of water use processes, including reservoir operation and water allocation, in extensive irrigation areas

Generally, several types of water management exist via water-use facilities in areas with extensive and well-developed irrigation systems (Fig. 3): 1) reservoirs (impoundments and releases), 2) diversion weirs (extraction of water from rivers), 3) irrigation canals (allocation of extracted water), 4) paddy fields (regulation of water depth) and 5) drainage canals (return flow to river channels). In this list, management types 4) and 5) can be regarded as water management within individual paddies and are represented in the original model. However, modifications of the original model are required to simulate management options 1) to 3) so as to represent paddy water use processes in more extensive and well-developed irrigation areas, spreading over several model grids. The required modifications involve introducing a reservoir operation model and a water allocation and management model into the original water circulation model.

(1) Reservoir operation model

To represent river flow management, we employed a reservoir operation model developed by Horikawa *et al.* (2011). To apply this model, a few basic features of reservoirs (e.g. effective storage capacity, maximum hydropower release and beneficial area of irrigation) are required as input data. This model assumes simple operating rules without local rules. The simplicity of the model and the generalization of operating rules facilitate the analysis of large regions (e.g. large rivers or a regional/national scale simulation) where a number of reservoirs are in operation, or an analysis of the hydrological impact of the construction of new reservoirs, specific rules for which are not yet available.

The continuity equation of a reservoir can be expressed as follows:

$$V_{res}(t) = V_{res}(t{-}1) + (Q_{in}(t) - Q_{out}(t))\Delta t \quad (5)$$

where V_{res} is the reservoir storage (m^3), Q_{in} is the reservoir inflow (m^3/d) and Q_{out} is the water release from the reservoir (m^3/d). In equation (5), inflow (Q_{in}) is calculated with the water circulation model. Accordingly, estimation of the reservoir release (Q_{out}) is a key role of the reservoir model. The reservoir model estimates the supply of water based on domestic and industrial use, hydroelectric generation and irrigation.

First, domestic and industrial water (Q_{di}) is estimated from the design water supply (Q_{dplan}).

$$Q_{di}(t) = Q_{dplan} \quad (6)$$

For hydropower generation, the model releases water in proportion to the ratio of current water storage to effective storage as follows:

$$Q_{pw}(t) = OR(t) \times Q_{pwmax}$$
$$OR(t) = \frac{V_{res}(t-1)}{V_{resmax}} \quad (7)$$

where V_{resmax} is the effective storage capacity (m^3) and *OR*

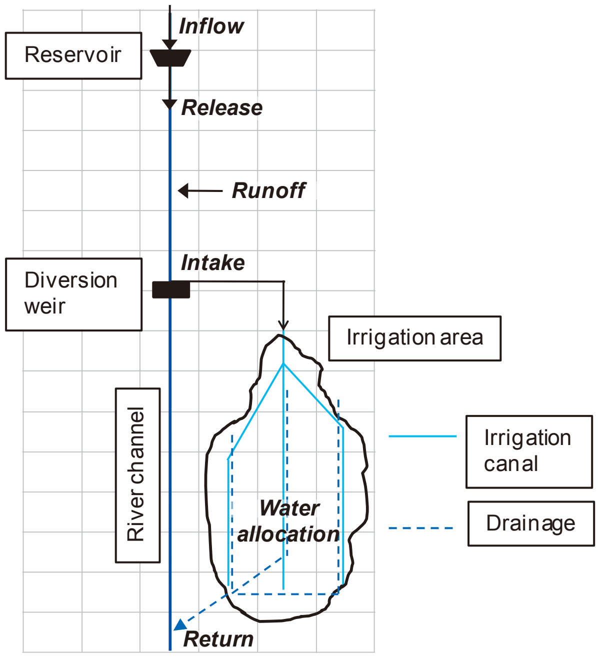


Fig. 3. Conceptual diagram of water management in an extensive and well-developed irrigation system with a reservoir
Note: Squares denote the grids of a water circulation model.

is the coefficient of hydropower release (the ratio of current storage to effective storage capacity).

For irrigation purpose, the reservoir model releases supplemental water to compensate for shortages of river discharges at a target diversion weir when the runoff amount from the downstream area of a reservoir is less than the water demand of the irrigation area (Fig. 4).

$$Q_{ir}(t) = Q_{dmnd}(t-1) - Q_{rsf}(t-1) \qquad Q_{dmnd}(t-1) > Q_{rsf}(t-1)$$
$$Q_{ir}(t) = 0 \qquad Q_{dmnd}(t-1) \le Q_{rsf}(t-1) \tag{8}$$

where Q_{ir} is the irrigation release (m^3/d), Q_{dmnd} is the demand for water for the irrigation area (m^3/d) and Q_{rsf} is the runoff from the downstream area of a reservoir (m^3/d), which is calculated as follows:

$$Q_{rsf}(t-1) = Q_{riv}(t-1) - Q_{out}(t-1) \tag{9}$$

where Q_{riv} is the river discharge at a diversion point (m^3/d). To estimate the irrigation release, it is necessary to specify a target diversion point associated with a reservoir. If relevant diversion points cannot be specified due to lack of information, irrigation water release can be estimated alternatively as follows:

$$Q_{ir}(t) = C_{resrt} Q_{gw}(t-1)$$
$$C_{resrt} = \frac{A_{bf}}{A_{ir}} \tag{10}$$

where C_{resrt} is the irrigation area coefficient, which is equated to the ratio of the irrigation area of a reservoir (A_{bf}) to that in a grid (A_{ir}) to adjust the difference between the two irrigation areas. This calculation is based on the assumption that water demand for beneficial areas can be estimated from demand in a paddy field of a reservoir grid.

In addition to the release for water utilities, outflow from a spillway (Q_{spill}) occurs when water storage in reservoirs exceeds effective storage capacity.

$$Q_{spill}(t) = 0 \qquad V_{res}(t-1) + Q_{in}(t)\Delta t < V_{res\max}$$
$$Q_{spill}(t) = Q_{in}(t) + \frac{V_{res}(t-1) - V_{res\max}}{\Delta t} \qquad V_{res}(t-1) + Q_{in}(t)\Delta t \ge V_{res\max} \tag{11}$$

Finally, water release from a reservoir is given by equation (12):

$$Q_{out}(t) = Q_{di}(t) + Q_{pw}(t) + Q_{ir}(t) + Q_{spill}(t) \tag{12}$$

(2) Water allocation and management model

The water allocation and management model estimates the amount of water diverted at weirs and allocated the diverted water to each paddy field in a beneficial area. First, the minimum value among water demand for irrigation (Q_{dmnd}), river discharge at a diversion point (Q_{riv}) and capacity of the water facility (Q_{if}) is employed as the amount of water diverted at weirs (Q_{div}).

$$Q_{div}(t) = \min(Q_{riv}(t), Q_{if}, Q_{dmnd}(t)) \tag{13}$$

Q_{if} is defined as the upper limit of diversion water, and Q_{riv} is regarded as the maximum amount of available water at the diversion point. Q_{dmnd} equates to the sum of gross water demand (Q_{gw}) in an irrigation area and fluctuates according to meteorological conditions, as is obvious from equation (2).

The diverted water is then delivered to each grid in the same irrigation area based on a conceptual approach rather than hydraulic approach. A schematic diagram of the water allocation process (Fig. 5) shows that in the sub-model, water is delivered sequentially from the nearest grid to the furthest grid, based on the distances between the weir and grids. For grids that lie equidistant from a weir, grids with major irrigation canals or with the highest elevation are prioritized for water allocation. Through these processes, irrigation water is distributed based on the water use conditions and water demands of each grid.

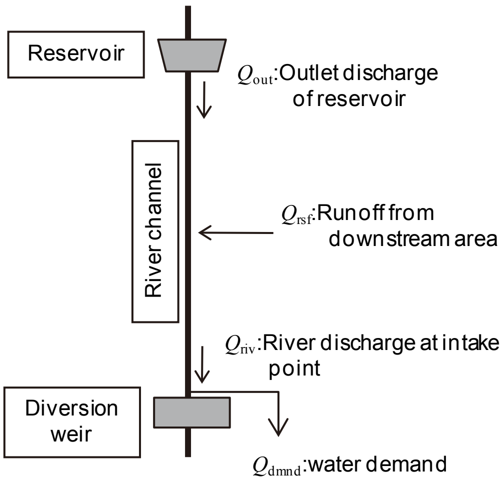


Fig. 4. Conceptual diagram of irrigation release by a reservoir operation model

3. Impact assessment of climate change on paddy irrigation

The procedures to assess the impact of climate change based on the water circulation model and climate change scenarios derived from the simulation with the Atmospheric-Ocean Coupled General Circulation model (GCM) are shown in Fig. 6 (Kudo *et al.* 2012).

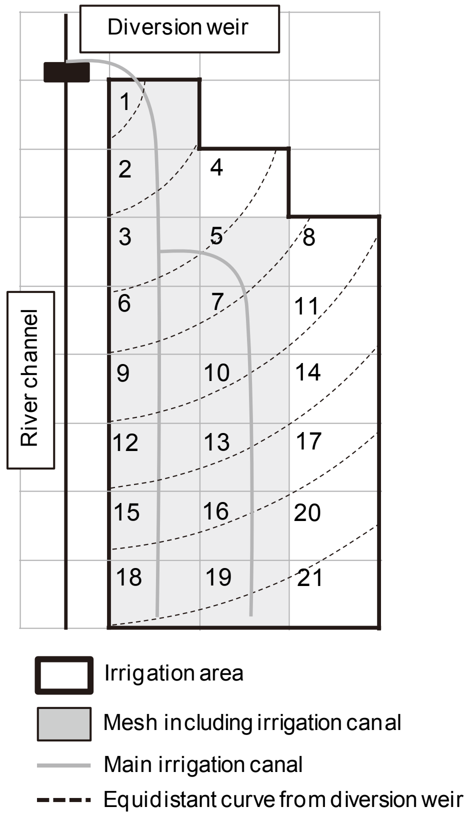


Fig. 5. Conceptual diagram of a water allocation and management model

Note: Numbers in grids denote order of water allocations.

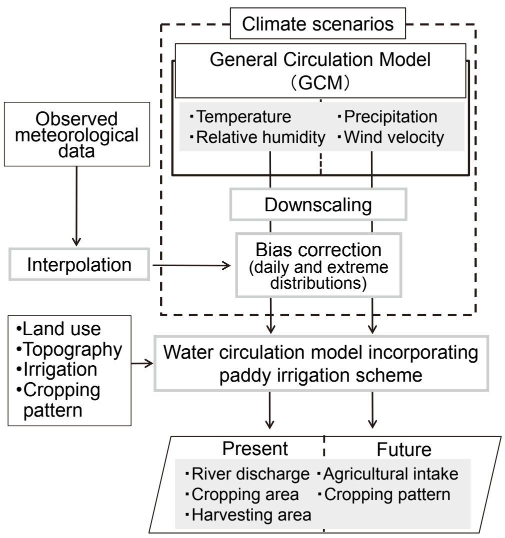


Fig. 6. Procedure to assess climate change on water resources using a water circulation model and climate scenarios (Kudo et al. 2012)

First, to bridge the resolution gap between the GCM and water circulation model, the GCM outputs are interpolated onto finer resolution grids using the IDW method. Subsequently, we correct the bias between observed climatology and the output of the GCM, most of which is caused by incomplete modeling of terrain conditions and mesoscale phenomena because of the coarse spatial resolution of the GCM. The bias correction method that we used is often referred to as the 'CDF-mapping method' (e.g. Li *et al.* 2010). In this method, the Cumulative Distribution Function (CDF) of the GCM output (F_{gcm}) and the CDF of observations (F_{obs}) are used and the CDF of the GCM is fitted to the CDF of the observations with the following equation:

$$x'_{gcm} = F_{obs}^{-1}\left[F_{gcm}(x_{gcm})\right] \qquad (14)$$

where x_{gcm} and x'_{gcm} are the raw and corrected GCM outputs, respectively.

To calculate the CDFs of meteorological elements, we applied the Gamma distribution to daily precipitation and daily mean wind velocity and applied the normal distribution to the daily maximum/minimum temperatures and relative humidity. In addition to correcting daily precipitation, we also applied the Gumbel distribution to the sequences of monthly maximum daily precipitation to improve the accuracy of bias correction, particularly for extreme hydrological events. Finally, the bias-corrected climate projections are input to the water circulation model and the simulation results between present and future climate conditions are compared.

Results and discussions

1. Application to Mun River basin

We applied the developed water circulation model to the Mun River basin in northeast Thailand. The simulation period was 1994-2003, including a 5-year spin-up period (1994-1998) to avoid artifacts associated with the initial conditions of the model. Irrigation and cropping information (e.g. crop and irrigation schedule) was specified based on the former study (Taniguchi *et al.* 2009b), with modifications based on our field investigations.

The reservoir operation model was applied to 10 large reservoirs and 150 medium reservoirs. We obtained the principal features of the reservoirs from the RID (Table 1). If several reservoirs were located in a same grid, their storage volumes and beneficial areas were integrated to simulate them as a single reservoir.

The water allocation and management model was applied to the beneficial areas of the 10 large reservoirs (almost 20% of all irrigated paddies estimated in this study). GIS data from the MRC was used to specify the attributes of the irrigation facilities and determine the order of water allocation based on the locations of irrigation canals and diversion weirs.

For the climate change assessment, we interpolated the projections of the MRI-AGCM3.1S onto 0.1º grids (approximately 10 km square grids) to be consistent with the resolution of the water circulation model. The interpolated raw outputs of the MRI-AGCM3.1S were subsequently corrected for bias with equation (14).

(1) Storage volume and water release from large reservoirs

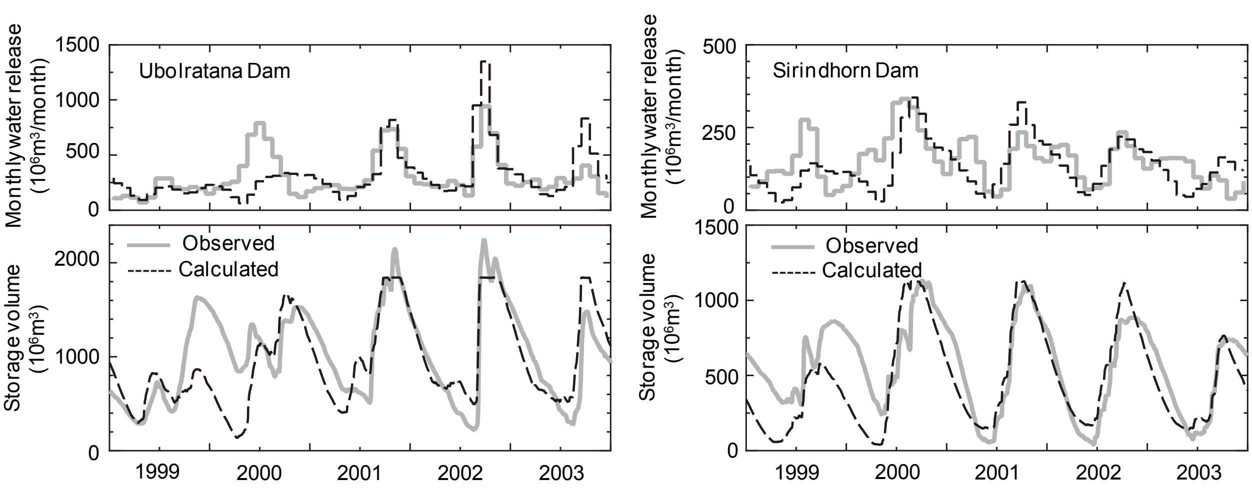
The simulation results for the storage volume and water release at the Ubolratana and Sirindhorn dams are illustrated in Fig. 7. These two reservoirs have the largest storage capacities in the Mun River basin and provide water for multiple purposes. Despite the simplicity of the assumed operation rules, the simulations by the developed model matched the actual values of the storage volumes and water releases at the two dams well; the simulations correctly described the retention of flood discharge during rainy seasons and the release of stored water during dry seasons. However, the simulated water releases for the first half of 2000 were underestimated compared to the actual values at both dams. One reason for these differences was a large flood in the early part of the rainy season. In practice, these two reservoirs seem to have been managed according to a specific rule that is not considered in this model. This model simply activates spillway discharges only when water storage exceeds effective storage capacity. Although the results of this model were good with respect to seasonal changes in storage water and water release, the incorporation of detailed rules for releasing water before the water level reaches a maximum level is required to improve model predictability.

(2) Estimation of water withdrawal at diversion weirs

The simulated monthly diversion water was validated by comparison with actual values at the Nonwai weir in two years (Fig. 8): 2000 (a relatively wet year with annual rainfall of approximately 1500 mm) and 2003 (a relatively dry year with annual rainfall of approximately 1000 mm). The Nonwai weir is a water facility in the irrigation system of the Ubolratana dam with a maximum intake capacity of 53 m^3/s.

According to the actual values, it is apparent that the diversion of water fluctuates widely from year to year during the rainy season (particularly during June, July and October), whereas only slight annual fluctuations are apparent during dry seasons (January through March). Basically, the main agricultural water resource in rainy seasons is rainfall and diversion water is a supplemental resource. In this sense, diversion water during rainy seasons varies considerably, depending on the rainfall. In contrast, regardless of rainfall, the water demand during dry seasons is related primarily to evapotranspiration and paddy infiltration, which do not change significantly from year to year. Accordingly, the amount of diversion water during dry seasons does not fluctuate considerably. This pattern of seasonal fluctuations of diversion water is characteristic of this region.

The developed model simulated the above-mentioned characteristics well. For example, the actual amount of diversion water differed significantly between the two years at the beginning of the rainy season in July and at the end of the rainy season in October and November, because of differences in rainfall (see the upper panels in Fig. 8).



(a) Ubolratana dam (b) Shirindhorn dam

Fig. 7. Simulation results of storage volume and water release at the Ubolratana and Shrindhorn dams

Note: The upper graphs denote monthly water release and the lower graphs depict daily storage volumes.

The developed model reproduced these fluctuations in the amount of diversion water because the estimates of the model are based on gross water demand (Q_{gw}), which is related to rainfall.

(3) River flows at major hydrological stations

The accuracies of the simulated river discharges at the Ubolratana dam and Rasi Salai, Yasothon and Ubon Ratchathani stations were estimated by the Root-Mean-Square Error (RMSE) and the Water Balance error (*WB*) (Table 2).

$$RMSE = \sqrt{\frac{1}{N}\sum_{j=1}^{N}(Q_{c,j} - Q_{o,j})^2} \quad (15)$$

$$WB = \frac{(\sum_{J=1}^{N} Q_{c,j} - \sum_{J=1}^{N} Q_{o,j})}{\sum_{J=1}^{N} Q_{o,j}} \times 100 \quad (16)$$

where Q_o is the observed discharge (mm/d), Q_c is the simulated discharge (mm/d), and N is the total number of simulation days. The RMSEs at the Ubolratana dam and the Yasothon station were larger than those at the other two stations. These differences were partly because the daily inflows at the Ubolratana dam fluctuate significantly from day by day and the discharges at the Yasothon station are markedly affected by the operation of two large dams, the Ubolratana and Lampao dams (see Fig. 2). The *WB* results showed that the total calculated discharges agreed well with the observed discharges, with differences ranging from -1.9 to 3.5% at the four stations.

The simulated river discharges at the Ubon Ratchathani and Rasi Salai stations are illustrated in Fig. 9. Although the developed model reproduced the observed discharges at each station in terms of seasonal variation, there were mismatches between the simulations and observations during the flow reduction period and the flood peak, particularly in 2002. According to the report of the Bank of Thailand (2002), significant inundation occurred in the Mun River Basin in 2002, which implies these errors were caused by the lack of a modeling of inundation phenomena which occur frequently in this region. Because we focused on modeling of paddy water management in this study, we did not account for inundation processes. These results indicate, however, that future studies should address inundation phenomena to improve the simulation accuracy in this region.

The flow duration curve for five years (1999-2003) at Ubon Ratchathani is shown in Fig. 10. The simulations by the developed model (calculated (developed)) were in good agreement with the observations over the entire range of exceedance probabilities, whereas the previous model (calculated (previous)) underestimated the discharges for exceedance probabilities by more than 50%. The discharges in this range occurred predominantly during dry seasons. Accordingly, this improved accuracy of simulated river discharges during the dry season indicates that the model-

Table 2. Accuracies of simulated river discharges at four stations

Station	RMSE (mm/d)	WB (%)
Ubolratana dam	1.06	-1.9
RasiSalai	0.47	3.5
Yashothon	0.72	-0.2
Uon Ratchathani	0.55	1.1

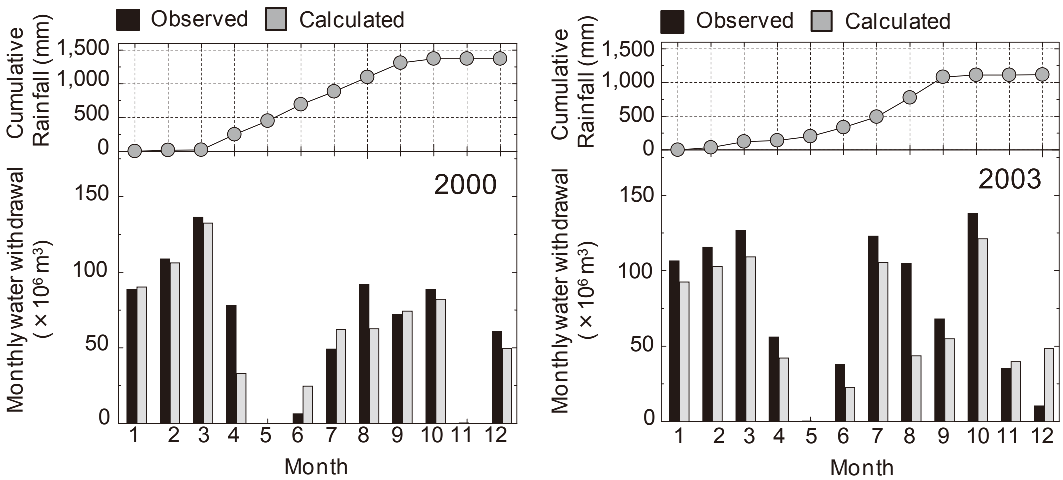


Fig. 8. Comparison between actual and simulated amounts of monthly diversion water at the Nonwai weir in 2000 and 2003

Note: The upper panels of the graphs denote the cumulative rainfall from 1 January and the lower panels show the monthly water withdrawals

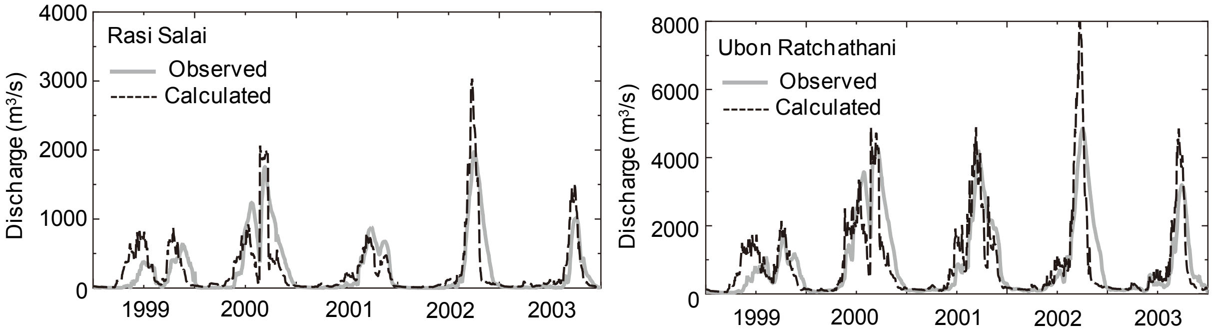


Fig. 9. Example simulation results of river discharges at the two hydrological stations

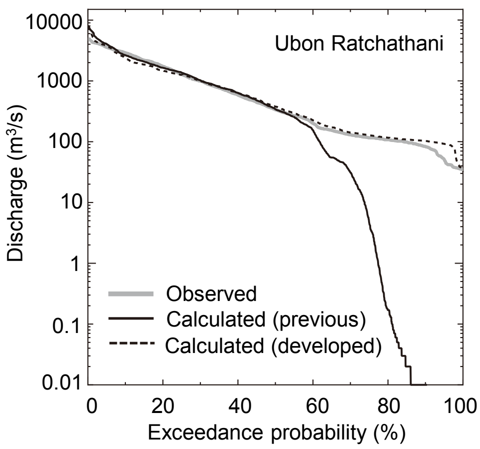


Fig. 10. Changes in the accuracy of simulated river discharges by incorporating the water management of reservoir irrigation systems

ing of flow regulation via paddy irrigation is essential in a region where numerous irrigation facilities dominate the hydrological conditions.

2. Impact assessment of climate change on irrigation reservoirs

(1) Inflow of large reservoirs

Changes in the monthly inflows at the Ubolratana and Sirindhorn dams estimated by the developed water circulation model driven by the bias-corrected outputs of the MRI-AGCM3.1S are shown in Fig. 11. At the Ubolratana dam, the model projected a slight decrease in inflows in May and June and an increase from July to September. In addition, a decrease in the monthly inflow during October was also apparent. Although the inflow at the Ubolratana dam peaks twice per year at the present period (small peak in June and larger peak in September), the above trends seem to shift toward a single peak per year. This change in the monthly inflow pattern will affect reservoir operation, even though no profound changes in the annual inflows to the Ubolratana dam were projected; they were estimated to be 2,200 MCM for the present, 2,100 MCM for the near future and 2,200 MCM for the future.

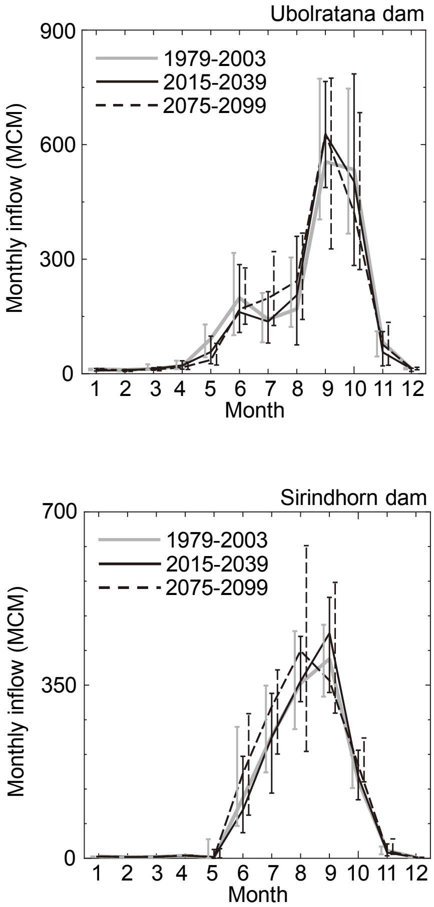


Fig. 11. Changes in monthly inflows at the Ubolratana and Shirindhorn dams

Note: The thick lines denote the 25-year median values of monthly inflow and error bars denote the range between the 25th and 75th percentiles of monthly inflows.

In contrast, at the Sirindhorn dam, an increase in inflows from June through August and a decrease during September were projected. In addition, the range between the 25th and 75th percentiles in August enlarged considerably. These results mean that the peak monthly inflow was projected to occur earlier than the present simulation. The annual inflows during the future period were estimated to increase by 10% compared to the present period. This projected pattern differs from the trend shown at the Ubolratana dam and will have potential impacts on dam operation in terms of both water use and flood mitigation.

(2) Reservoir storages and spillway discharges

We explored changes in reservoir storage and the days when the two reservoirs were empty (Fig. 12). At the Ubolratana dam, storage volumes started to recover in May from the lowest water level in the present period, whereas this recovery tended to be delayed until June in the future period. Because rainy-season cropping starts at the end of June, this delay will affect the irrigation supply during the beginning of rainy-season cropping. For example, the dam was projected to often empty from June to September in the future period, although it did not empty excepting the end of dry seasons in the present period. This change occurred because rainy-season cropping began despite insufficient restoration of water storage in drought years. Even during rainy seasons, irrigation water from reservoirs is indispensable in drought years. Based on these results, the delay in the timing of recovery at the beginning of rainy seasons will lead to a shortage of irrigation water at the beginning of rainy-season cropping in drought years.

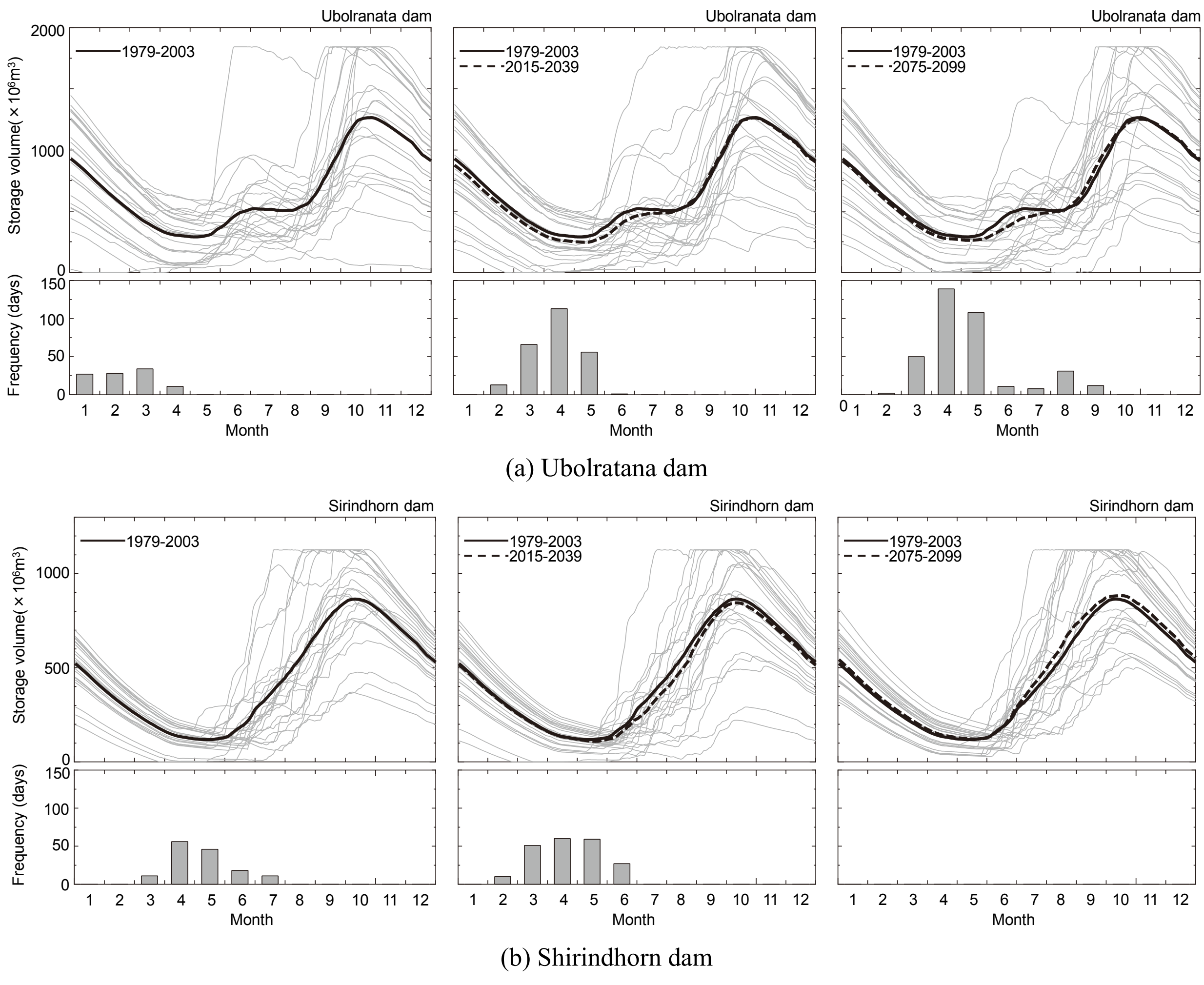


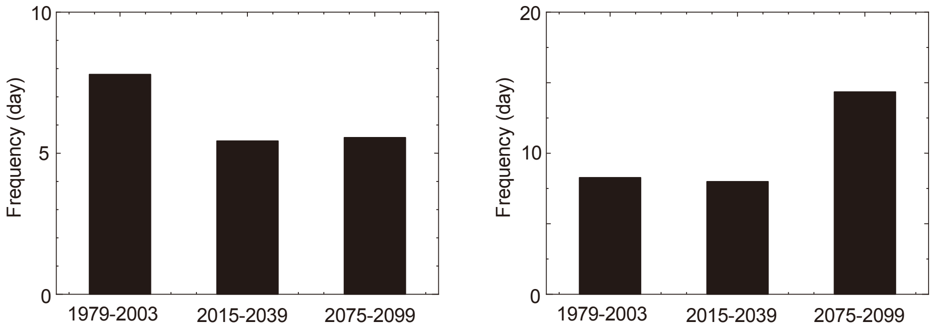
Fig. 12. Changes in storage volume and the frequency of empty days (no water storage) at the (a) Ubolratana and (b) Shirindhorn dams

Note: The thick lines denote the 25-year averages of daily reservoir storage and the thin gray lines denote the annual sequences of daily reservoir storage in each period. The bar graphs in the lower panels show the number of empty days in the reservoirs.

In contrast, a slight increase in reservoir storage was projected during the rainy seasons at the Sirindhorn dam. In addition, the empty days of storage were not apparent throughout the year in the future period, which would be advantageous for stabilizing water use.

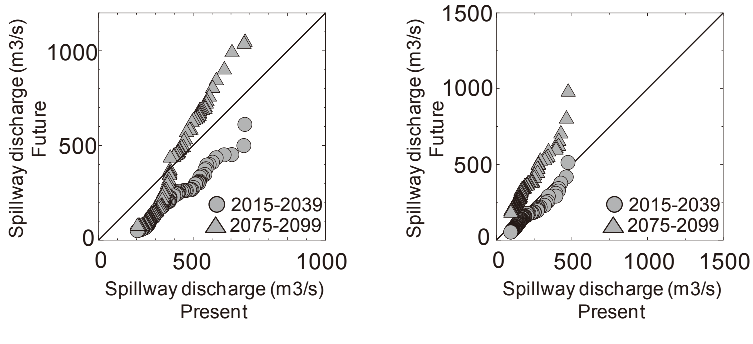
The increase in storage volume, however, could spark concerns with respect to flood mitigation and inefficient operation with increasing dead outflow from reservoirs. Changes in the frequency of occurrence of daily spillway discharges and the amounts of such discharges are shown in Figs. 13 and 14, respectively. The increase in the storage volume of the Sirindhorn dam led to an increase in the frequency and magnitude of daily spillway discharges in the future period. In contrast, because no marked increase in storage volume was projected at the Ubolratana dam in the near future and future periods, the frequency of spillway discharges decreased during both periods. However, some of the daily spillway discharges increased (Fig. 14), the implication being that it will be necessary to pay attention to flood management at the Ubolratana dam, despite the reduced frequency of spillway discharges.

As just described, the impacts of climate change on reservoir operation differed at these two dams although they are in the same river basin. Thus, climate change impacts need to be assessed explicitly through individual modeling of water-use facilities. Since the model developed in this study requires only basic information and assumes simple rules for reservoir management, this model is useful for assessing impacts on the operation of numerous water-use facilities simultaneously at the macro level.



(a) Ubolratana dam (b) Shirindhorn dam

Fig. 13. Changes in the frequency of occurrence of daily spillway discharge (total days during 25 years) at the (a) Ubolratana and (b) Shirindhorn dams



(a) Ubolratana dam (b) Shirindhorn dam

Fig. 14. Changes in daily spillway discharge at the (a) Ubolratana and (b) Shirindhorn dams

Conclusions

In the present study, we developed a water circulation model that incorporated paddy water management for extensive and well-developed irrigation areas. To develop this model, we introduced a reservoir operation model and a water allocation and management model into the water circulation model developed by the NIRE. The developed model was then applied to the Mun River basin in northeast Thailand, where a number of irrigation facilities exist. We also used the developed model and climate change scenario from the MRI-AGCM3.1S to assess the impact of climate change on reservoirs in the study basin. The results obtained in this study were as follows:

1) Despite the assumption of simple operation rules on various types of irrigation facilities, the developed model represented water management in extensive and well-developed irrigation areas spreading over several model grids and containing large reservoirs which was not simulated in the previous water circulation model.
2) Introduction of the reservoir operation and water allocation and management models improved the simulation accuracy of river discharges, particularly during dry seasons. This result indicates that modeling of flow regulation through paddy water management is essential in a region where a number of irrigation facilities affect hydrological conditions.
3) According to climate change projections, the impacts of climate change on reservoir operation differed at the two dams although they are in the same river basin. Thus, climate change impacts need to be assessed explicitly through individual modeling of water-use facilities. Since the model developed in this study requires only basic information and assumes simple rules for reservoir management, this model is useful for assessing impacts on the operation of numerous water-use facilities simultaneously at the macro level.

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