Modeling of Interaction between Flood and Agricultural Water Use in the Chao Phraya River Basin

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ABSTRACT

A prototype Seamless-DIF model was developed for visualizing the interaction of agricultural water use and flood by integrating flood and inundation processes into a model like the Distributed Water Circulation Model incorporating Agriculture Water Use (DWCM-AgWU). This prototype model was applied to the delta plain of the Chao Phraya River basin for the year of 2011, during which there was record flooding (70-year return period). The Seamless-DIF model uses a quasi-two-dimensional analysis by using river-land and land-land connections in order to model the flow of floodwaters in low-lying areas. Non-uniform flow analysis was used to simulate the effect of backwater flow in rivers. The model also takes into account the effects of elevated roads and railways on inundation during flooding and estimates overflows by replicating such roads and railways as weirs. The calculation methods of the Seamless model are divided into explicit and implicit schemes. A new seamless model could simultaneously simulate water distribution by considering agricultural water use through the river basin, regardless of flood and/or drought.

As the first step in developing the Seamless-DIF model (Seamless calculation model among Distributed water circulation (i.e. DWCM-AgWU), Inundation and Floods), the current DWCM-AgWU model's limitations were assessed by modifying it for the Chao Phraya River Basin and applying it for the period from 2008 through 2011, which includes drought and flood years. During the modification process, water allocation/management models were developed and special treatment of flood peaks was added in consideration of human activities, such as agricultural practices. Water in the middle and lower areas of the Chao Phraya River Basin is used for agricultural purposes and is controlled by dams and other irrigation facilities and systems. Two large

dams, the Bhumibol and the Sirikit, are the main sources of irrigation water for the middle and lower areas in the dry season, and both dams are also used to control floods in the downstream part of the basin in the rainy season.

Four major irrigation projects are located downstream from the Bhumibol and Sirikit dams. One is situated in the Ping River Basin, which is irrigated by the Bhumibol Dam, and two are in the Nan River Basin, which is irrigated by the Sirikit Dam, in the middle part of the Chao Phraya River Basin. In the lower part of the basin below the point where the four main tributaries meet, the area covered by the Greater Chao Phraya Irrigation Project lies along the western and eastern sides of the Chao Phraya River and is irrigated by both the Bhumibol and Sirikit dams. A cooperating reservoir management model was developed to incorporate the two dams with several remote irrigation areas for water allocation/management by considering the storage volume of the two reservoirs and the size of the irrigation areas.

Flood peak treatment was also introduced to enable the calculation of discharge. The original model is unable to cope with flooding processes, especially the flood peaks of river discharge. For the middle reaches of the Chao Phraya River Basin, A simple modification was carried out as a measure to calculate discharge by considering the maximum capacity of the river channel at several points. Moreover, for the lower reaches of the basin from Nakhon Sawan to the sea, special water management was applied for rainy days in response to the Thai Royal Irrigation Department (RID) report that the release at the Chao Phraya Diversion Dam would be controlled at a threshold such as 1,500 m^3/s. When the flow volume is higher than the control volume, RID will consider diverting water to connecting irrigation canals on the western and eastern sides of the Greater Chao Phraya Irrigation Project by considering the maximum capacity of the irrigation canals. However, in the delta plain area located in the lower reaches of the Chao Phraya River Basin, modeling of simple flood peak treatment in the DWCM-AgWU was not adequate for carrying out flood analysis given that the delta plain is a large, gently sloping area influenced by tidal effects.

Flood and inundation processes were introduced in the DWCM-AgWU for the development of a Seamless-DIF model. The calculation methods of the seamless model are divided into explicit and implicit schemes. In the calculation process, the cells that originated in the application of the DWCM-AgWU are temporarily defined as flooded and non-flooded cells. In non-flooded areas, river discharge is calculated by using the kinematic wave method in the DWCM-AgWU (explicit scheme solution), and the calculated discharge is used as inflow into the flooded cells.

The new seamless model could simultaneously simulate water distribution by considering agricultural water use throughout the river basin, regardless of flood and/or drought. The simulation of flood and inundation processes (implicit scheme solution) starts when the river discharge calculated by the explicit scheme exceeds the assumed capacity, which is estimated by considering cross-sectional areas under uniform flow. Flow routing between river cells in flooded areas to the boundary (river mouth) is expressed as nonuniform flow to reflect the effect of backwater flow such as that resulting from tidal effects. Moreover, flood routing over land is incorporated with the calculation of water balance in the cells, which takes into consideration rainfall, evapotranspiration, infiltration, irrigation water, soil moisture and groundwater flow.

The Seamless-DIF model was applied to the 2011 flood in Thailand, and an average relative error of 21% was obtained between the calculated and actually measured daily flow volume at the Nakhon Sawan station, which is located downstream from where the four main tributaries converge in the upper part of the Chao Phraya River. The calculated discharge at this point is used as inflow discharge into the lower areas that are specified as the maximum flood areas in the prototype model.

As a result of introducing the inundation and flood processes, a comparison of the simulated and observed water levels at the Sing Buri and Ayutthaya hydrological stations revealed simulation errors of 21% and 32%, respectively. The total extent of flooded areas simulated by our model was only 41% of that observed from satellite data. In the simulation, the total volume of floodwater in inundated areas between the Chainat-Pasak Irrigation Canal and the Chao Phraya River at its peak was 3,750 MCM, whereas the observed volume estimated from satellite data was 2,795 MCM.

With further refinement as specified in this dissertation, our prototype Seamless-DIF model will allow effective simulation of water circulation throughout the Chao Phraya River Basin by simultaneously incorporating agricultural water use and flood and inundation processes. A Seamless-DIF model will facilitate the development of adaptation measures against extreme events including floods and droughts, and enable the evaluation of their effectiveness in the Chao Phraya River Basin.

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ABBREVIATIONS

Organization

BMA	Bangkok Metropolitan Administration
DOH	Department of Highways
EGAT	Electricity Generating Authority of Thailand
GISTDA	Geo-Informatics and Space Technology Development Agency (Public Organization)
LDD	Land Development Department
MOAC	Ministry of Agriculture and Cooperatives
NOAA	National Oceanic and Atmospheric Administration
RID	Royal Irrigation Department

Model

DWCM-AgWU	Distributed Water Circulation Model incorporating Agriculture Water Use
A Seamless-DIF	A Seamless calculation model among Distributed water circulation, Inundation, and Floods

Unit

ha	Hectare (10,000 square meters)
km	Kilometer
km^2	Square kilometer
m	Meter
m/ha	Meters per hectare
m^3	Cubic meter
m^3/s	Cubic meters per second
MCM	Million cubic meters
mm	Millimeter

Chapter 1

Introduction

1.1 Background

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. 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 irrigation 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.

In 2011, both irrigation and urban areas in the Chao Phraya River Basin were damaged by flooding with a return period of 70 years. Flooding started in July in the upper part of the basin, reflecting a large inflow of water, especially in the Sirikit Dam. Flooding also occurred in the middle reaches, especially in the Yom and Nan sub river basins. During August through October, four major storm events caused a large inflow of water into the huge dams and flooding in the upper and middle reaches of the basin. As a result, storage in the dams exceeded the upper rule curves and nearly reached the maximum capacity. 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 through 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. In the analysis of floods, it is important to consider agricultural water use as human-controlled activities. In other words, the main method of flood management in Thailand culminates in the management of irrigation water through facilities such as the Bhumibol and Sirikit dams.

Furthermore, as a risk prevention strategy, countermeasures and/or adaptation measures for extreme events such as floods and droughts must be proposed and evaluated. An integrated distributed hydrological model combining the catchment-scale natural hydrological cycle with the impact of human activities, e.g., water management through irrigation facilities, and incorporating inundation and flood processes is required to facilitate the development of adaptation measures against floods and droughts and to evaluate the effectiveness of such measures.

The Distributed Water Circulation Model Incorporating Agricultural Water Use (DWCM-AgWU) was 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 using the large dams in northeastern Thailand. In the modified model, the management of irrigation systems and dam operations was introduced systematically. In addition, *Yoshida et al.* [2012] introduced a scheme that incorporated inundation processes in a basin-wide hydrological model for lowland rivers. The model was applied to a river basin in the Lao PDR.

As the first step in developing the Seamless-DIF model (Seamless calculation model among Distributed water circulation, Inundation, and Floods), which was to assess the limitations of the current model, *Vongphet et al*. [2014a, b] modified the DWCM-AgWU of *Yoshida et al*. [2012] and applied it to the Chao Phraya River Basin in Thailand to assess water use during 2008–2011, a period that includes both drought and flood years. The characteristics of the Chao Phraya River Basin are quite different from those in the above examples. Specifically, there are two huge dams, the Bhumibol and the Sirikit, which are connected to remote irrigation areas and a large, gently sloping plain in the lower basin where the channel networks are denser. The modeling emphasized the importance of dams and irrigation systems for agricultural water resource management, especially in the middle and lower reaches of the basin affected by the 2011 flood. However, the modified model cannot fully simulate flood and inundation processes, especially those in the low-lying areas.

Therefore, this dissertation presents the development of a Seamless-DIF model, which expands on the DWCM-AgWU by incorporating inundation and flood processes. Assessment of the Seamless-DIF model is carried out through its application to the Chao Phraya River Basin, against extreme events such as the flood in 2011. Moreover, modification of the DWCM-AgWU and its application to the Chao Phraya River Basin for the assessment of model limitations is presented as the first step in the development of a seamless model.

1.2 Literature reviews

1.2.1 Distributed hydrological models and their application

In order to analyze the effect of water circulation changes on flood production and the effect of extreme events on agricultural water use, it is essential to utilize an area-specific runoff model. Maps describing the spatial distribution of regional geographical features are used in developing distributed runoff models, and the introduction of the geographic information system (GIS) accelerated the development of various types of distributed runoff models. *Kampf et al.* [2007] summarized a framework for classifying existing distributed hydrologic models in the field of hillslope and catchment hydrology. The development of distributed models began by combining storage-type runoff models according to planes and channel segments [*Hayakawa et al.*, 1996; *Fukushima et al.*, 2003; *Oudin et al.*, 2004; *Moussa et al.*, 2007], and then evolved into grid-type models [*Matsui*, 2003; *Kim*, 2003; *Alam et al.*, 2006; *Gotzinger*, 2007].

The distribution models [*Beven et al.*, 1992, 2001; *Peters et al.*, 2003; *Pradhan et al.*, 2006; *Wang et al.*, 2007] are derived from the variable-source-area concept and TOPMODEL. However, TOPMODEL is a lumped conceptual model that uses a topographic index of hydrologic simplicity to estimate the characteristics and conditions within a basin. Similar quasi-distributed (semi-distributed) hydrological models have also been developed and utilized, particularly the VIC model [*Wooldridge et al.*, 2001; *Kavestski et al.*, 2003] that adopts a statistical distribution of storage elements for small-scale variables of soil, vegetation, and topography. In recent years, greater emphasis has been placed on research work on scientific, physically based distribution models. The advances made in GIS techniques and software packages (e.g., Arc/INF, Arc/GIS, and GRASS) have contributed to the development of such models. As for new algorithms and skills for determining digital elevation, flows and paths have been proposed [*Reed*, 2003; *Soille et al.*, 2003; *Soille*, 2004; *Pan et al.*, 2004]. *Nardi et al.*

[2006] proposed a hydrogeomorphic floodplain delineation that enables the development of spatially distributed models of runoff formulation. In line with the ongoing development of GIS technology and remote sensing techniques, particularly the linkage of GIS [*Liu et al.*, 2004; *Seibert and McGlynn*, 2007; *Pradhan et al.*, 2006] and remote sensing [*Moran*, 1997; *Takeuchi et al.*, 2004] with hydrologic modeling, flood prediction using distributed models is becoming increasingly advantageous and more reliable.

However, the models mentioned above deal with groundwater flow as a lumped flow, and applying these models to the analysis of large basins is subject to limitations.

A new physically based, distributed-parameter hydrologic model that uses irregular spatial discretization was subsequently introduced [*Ivanov et al.*, 2004]. This distributed model divides the domain into separate model elements based on a triangular irregular network (TIN). *Nawahda et al.* [2005] combined the groundwater process with a distributed runoff model, and *Saitou et al.* [2006] proposed a water cycle analysis program using a quasi-three-dimensional model that improves the accuracy of groundwater and saturation surface flow. *Ludwig et al.* [2000] linked an atmosphere transfer model with distributed runoff models. This physically based SVAT model incorporates an extended version of the conceptual TOPMODEL, and is known as PROMET (PRocess-Oriented Model for EvapoTranspiration].

Model sensitivity analysis is a valuable tool for identifying, improving, testing, and calibrating a hydrological model. *Sieber et al.* [2005] applied both regional sensitivity analysis (RSA) and regression-based sensitivity analysis. Model calibration and verification play important roles, but this process of using physically based, distributed parameters and models requires better field observation and more complicated identification procedures. Some trials have been conducted for spatial variability in terms of both land surface characteristics and precipitation on runoff [*Senareth et al.*, 2000], and for a large-scale, spatially distributed vadose zone [*Vrugt et al.*, 2004]. Moreover, a distributed-parameter, large-basin runoff model was developed [*Croley II et al.*, 2005a; *Croley II*, 2005b] whereby a watershed is divided into 1-km^2 grids with parameters used for elevation, slope, land cover, flow roughness, upper soil-zone depth, upper soil permeability, lower soil-zone depth, and lower soil permeability.

Giannoni et al. [2003] also examined a semi-distributed approach to rainfall-runoff modeling by using commonly available distributed information (on digital elevation, rainfall data, soil characteristics, and land use) to check whether the behavior of different basins can be described by the same model's set of parameters, which are closely related to the TOPMODEL application. The impact of the spatial aggregation of inputs and parameters on the efficiency of a rainfall-runoff model was examined [*Andreassian et al.*, 2004], with the conclusion that the use of spatially distributed rainfall data is more important than the disaggregation of watershed (land-surface) parameters.

Examples of distributed hydrological models being put to practical application include flood forecasting [*Vieux et al.*, 2004; *Liu et al.*, 2005], assessment of flood control using dams [*Sayama et al.*, 2005a, 2005b], environmental assessment [*Park et al.*, 2003; *Kojiri*, 2006], agricultural water management [*Al-Khudhairy*, 1999], and agricultural landscape modeling [*Molling*, 2005].

However, none of the models proposed or used in the studies above included the components of agricultural water use in a specific area or the mechanism of the water cycle in agricultural land, even though the dominant or most significant sector for the usage of water is agriculture.

Another important target of using hydrological models is the analysis of human interaction with water resources, as shown by a condition study based on the analysis of historical records on human influence compared with natural variations through climatic impact [*Ye*, 2003]. Apart from the modeling, *Potter* [2006] proposed small-scale, spatially distributed water management practices instead of using centralized facilities in terms of implications for research in the hydrologic sciences. *Reed et al.* [2006] suggested and outlined instrumentation platforms for point, plot, reach, and hillslope scales as the basis for forecasting water resources at the river basin scale. Direct human interaction with hydrologic systems is characterized through the concept of water use regimes [*Weiskel et al.*, 2007]. The impact of climate and landscape changes on water resources was examined in terms of climate controls such as the type of weather, rainfall, and evapotranspiration [*Fowler et al.*, 2003], soil profiles regarding water storage and permeability, and vegetation regarding surface coverage and water use [*Farmer et al.*, 2003].

Although extensive research has been conducted on irrigation and agricultural water use [i.e., *Watanabe*, 2001; *Bastiaanssen et al.*, 2003; *Cai et al.*, 2004a, 2004b; *Loomis et al.*, 2005; *Marques et al.*, 2005; *Yu et al.*, 2006], the research is not linked. On the contrary, this body of research relied on hydrologic modeling technology, especially for detailed descriptions of the water cycle, and entailed socioeconomic analyses that largely ignored the hydrologic factors.

1.2.2 Flood models and flood mitigation by using paddies

The increasing number of natural or man-made disasters has resulted in varying degrees of damage in areas around the world. Along with climate change, extreme weather events have become more frequent and intense [*Tezuka et al.*, 2014; *Madsen et al.*, 2014; *IPCC*, 2012]. The increase in agricultural expansion and deforestation due to population growth and land use change has a significant effect on global resources [*Nejadhashemi et al.*, 2012; *Canters et al*., 2014]. As climate change becomes more prevalent globally, the future availability of resources, especially water resources for human consumption, agricultural production, and manufacturing, becomes more uncertain. By the end of the 21st century, the global temperature is predicted to increase relative to 1980–1999, depending on greenhouse gas emissions [*Solomon et al.*, 2007; *Knutti et al*., 2008; *Gobiet et al*., 2014]. Climate change has a powerful impact on water resources, including changes to the frequency of rainfall events [*Strauch et al.*, 2015; *Beniston et al*., 2012; *Xu et al*., 2009]. Studies on the impact of climate change on water resources have investigated historical trends in stream flow, precipitation, and other variables [*Regonda et al.*, 2005; *Hamlet et al.*, 2005, 2007; *Mishra et al.*, 2010; *Sinha et al.*, 2010]. Relatively few studies have focused on extreme events. *Markus et al.* (2007, 2012) concluded that with global warming, some types of extreme weather have become more frequent and severe in recent decades, with increases in extreme heat, intense precipitation, and drought. Recent decades have also seen a greater frequency and intensity of extreme events due to climate change and global warming [*Dastagir*, 2015; *Milagros Skansi et al*., 2013; *Huntington et al*., 2010; *Zhang et al*., 2015]. *Markus et al.* (2009) studied the frequency of flooding as a result of the increasing intensity and frequency of heavy storms and the growth in urbanization. *Juckem et al.* (2008) discussed a climate-related step change in precipitation and base flow around 1970. A number of studies have attempted to understand the effects of climate change on water resources.

The increase in temperature due to global warming has led to more intense extreme events, especially floods. Floods are frequently occurring disasters that come at the high cost of human hardship and economic loss [*Monirul Qader Mirza*, 2002; *Tapash et al*., 2013; *Güneralp et al*., 2015]. The average annual economic loss due to natural disasters worldwide has been estimated at about 42 billion dollars [*Münich et al.*, 2003]. In a condition study on flood damage, this event not only depends on precipitation amounts but is also a consequence of geomorphological factors and human influences. Flooding that occurs as the result of a prolonged rain event, river overflow, or dam failure is relatively gradual, predictable, and long lasting. On the other hand, flash flooding that occurs during heavy rain events happens very quickly. High-velocity runoff in small basins, short lead times, fast-rising water, and transport of sediment make flash floods extremely dangerous to property, infrastructure, and human lives [*Špitalar et al.*, 2014; *Creutin et al.*, 2013]. However, they also end quickly. Flash floods cause extensive disruptions to a diverse range of living, working, societal, and spatial environments. However, several methods, using different approaches, can be used to prevent or mitigate flood damage.

Flooding is one of the most damaging natural disasters, having a negative impact on society, the economy, and the environment. Global climate change has the potential to accelerate the hydrological cycle, which may further increase the temporal frequency of regional extreme floods [*Li et al.*, 2013; *Strauch et al.*, 2015; *Beniston et al*., 2012; *Xu et al*., 2009]. In many developed cities, the drainage and flood defense infrastructure systems are aging, and may be inadequate to cope with possible increases in rainfall and river flow resulting from global and local climate change [*Yazdi et al*., 2014; *van Herk et al*., 2013; *Nam et al*., 2015; *Xia et al*., 2012]. Increasing intensity and frequency of extreme flood events as a consequence of global warming pose significant challenges. It is well recognized that adaptive and flexible flood management strategies are necessary for the future. The effects of climate change on flooding are complicated but researchers are working to identify the most appropriate set of mitigation or intervention measures [*Yazdi et al.*, 2014; *Lawrence et al.*, 2013; *Iglesias* and *Garrote*, 2015]. Adaptive flood management is necessary to reduce the consequences of flooding as well as the probability of flooding by considering a mix of options that extends beyond traditional engineering measures such as flood defenses [*Dawson et al.*, 2011]. The commonly adopted measures for flood mitigation are classified into structural and nonstructural measures.

Structural measures refer to any physical construction to reduce, avoid or prevent possible impacts of disasters, or to achieve disaster resistance and resilience in the structure or system, while nonstructural measures refer to any measure not involving physical construction by using knowledge, practice, policies and laws, public awareness raising or agreement to reduce risks and impacts [*Luo et al*., 2015; *Dawson et al*., 2011; *Chau et al*., 2014; *Faisal et al*., 1999]. Structural measures normally utilized for disaster risk reduction include dams, flood levees, ocean wave barriers, earthquake-resistant construction, and evacuation shelters. Nonstructural measures include building codes, land use planning laws and their enforcement, research and assessment, information resources, and public awareness programs [*Tucci et al.*, 1999; *Braga*, 1999].

Structural and nonstructural measures were studied for adaptive flood management. Various structural measures are used to prevent flooding on a floodplain. For example, reservoirs reduce peak flows; levees and flood walls confine the flow within predetermined channels; improvements to channels reduce peak stages; and floodways help divert excess flow. These measures include the possible prevention of the more frequent smaller floods that on many floodplains cause a large proportion of flood losses [*Baeta et al*., 2011; *Chow*, 1959; *Lind*, 1967]. Hence, structural measures affect flood losses by reducing both the expected value of flood damage and the cost of risk-taking. However, some of the characteristics of structural measures must be noted. First, structural measures do not provide complete protection against flooding; they only reduce the expected value of losses. Second, structural measures can create a false sense of security, with no permanent flood protection [*Krutilla*, 1966; *White*, 1964]. Nonstructural measures include efforts to manage flood-prone land so as to reduce the damage from floods that are expected to occur, and are based on a longer-term and more holistic view of flooding. Nonstructural measures are considered as a highly effective, low-cost method of damage prevention [*Dawson et al*., 2011]. In many communities, development in flood-prone areas can be completely prevented, which may return similar or increased benefits to the nation and community without the cost and consequences of flood impact [*Tucci et al*., 1999; *Braga*, 1999; Faisal, 1999; *Dawson et al*., 2011].

Flood protection can be achieved through various structural measures such as dikes, diversion channels and reservoirs, or nonstructural measures such as flood warnings and mass evacuation [*Gilbuena et al.*, 2013; *Qi et al.*, 2011]. However, the increase in population and economic activities near rivers has also caused an increased flood risk to urban regions. Computer simulation and modeling help to manage flood risk [*Morales-Hernández et al.*, 2013]. The estimation and prediction of floods using flood models is an essential theme in hydrologic engineering [*Swain et al*., 2004; *Reed et al*., 2007; *Looper* and *Vieux*, 2012; *Park et al*., 2014]. Flood models provide a framework for flood forecasting with high spatial and temporal resolution. Researchers investigate the models for hydrologic forecasting applications [*Reed et al.*, 2007], which have two purposes in hydrology. First, flood models help to explore the implication of making assumptions about the nature of the real-world system. Second, models can predict the behavior under the occurring circumstances (*England Jr. et al.*, 2007; *Beven*, 1989]. The use of flood models has become a highly prevalent method for simulating expected floods due to its ability to process more detailed floods [*Yan et al*., 2015; *Madsen et al*., 2014; *Meesuk et al*., 2015].

There are various approaches to creating flood models. One-dimensional hydrodynamic (1D) models are widely used in modeling flood flows [*Yoshida*, 2002; *Helmio*, 2002; *Masood*, 2012]. This type of model is considered for dealing with large river/channel systems and several hydraulic structures. However, when modeling floodplain flows, the accuracy and appropriateness decrease. This model requires that variables such as velocity and depth change predominantly in one defined direction along the channel. Due to the rarely straight condition of a channel, the computational direction is along the channel centerline. Two-dimensional hydrodynamic (2D) models compute the horizontal velocity components (V_x and V_y) or, alternatively, the velocity vector magnitude and direction throughout the model domain. Depth-integrated 2D models have long been used for predicting free surface flows, but they are generally more computationally expensive when dealing with channel networks and hydraulic structures. The increasing availability of digital topographic data in recent years provides this type of model with a wider scope of application. 1D approximation models require less information and are computationally time saving while 2D models, used when the real flow pattern does not correspond with a 1D model, give more precise results but are time consuming and more topographically demanding. Under certain conditions, with the need to improve model accuracy and gain computational time, coupled 1D and 2D models are modified [*Costabile and Macchione*, 2012; *Leandro et al*., 2014; *Bohorquez et al*., 2008; *Caviedes-Voullième et al*., 2014; *Bladé et al*., 2012; *Fernández-Nieto et al*., 2010].

However, 1D models are too restricted to capture the spatial differentiation of processes within a polder or system of polders, and 2D models are too demanding in terms of data requirements and computational resources [*Lindenschmidt et al*., 2008]. Quasi models have been developed for this situation, in which the floodplain is discretized into a network of virtual river branches and spills linked with the main river channels [*Castellar et al*., 2011; *Lindenschmidt*, 2008; *Meire*, 2010]. Although this approach has been successfully utilized for many flood studies, the initial setup of this type of model is time consuming and the accuracy of predictions varies with the way in which the floodplain is discretized [Morales-*Hernández et al*., 2013; *Fernández-Nieto et al*., 2010; *Caviedes-Voullième et al*., 2014; *Bladé et al*., 2012].

For floodplains, the 1D, 2D and quasi models are compared in terms of the different uncertainties involved in each model. These include the influence on the results, the spill units, the hydraulic structures, etc. Studies show that the differences in the accuracy of schemes and the system features can be disregarded when compared with the uncertainties associated with the model parameters of the hydraulic structures (bridges, culverts and weirs) and the model input [*Villazon and Williem*, 2008; *Willems et al.*, 2002; *Hernández et al.*, 2013; *Zubova et al*., 2005].

Although there are several flood simulation models, agricultural water use is not widely considered. Especially in river basins that mainly supply water for agricultural activities, as in the case of the Chao Phraya River Basin, floodwaters are managed through irrigation facilities that are mainly used for irrigation purposes [*Falloon et al*., 2010; *Singh et al*., 2014]. Moreover, the Chao Phraya River Basin includes a large delta plain where most of the irrigation paddies are located. As the downstream area of the basin is influenced by tidal effects, flood simulation in the area should consider the function of paddies and irrigation versus the flood model and influence of tidal fluctuation [*Son et al*., 2014].

As mentioned earlier, irrigation facilities and irrigation areas play important roles in flood management, especially in the lower areas of the Chao Phraya River Basin. To mitigate flood damage due to the increasing frequency of heavy rainfall events, the use of paddy fields by installing runoff control devices in the drainage pits of paddy field plots has been highlighted. For example, the Kamihayashi district in Niigata prefecture, Japan, has undertaken flood mitigation that makes use of paddy fields as a flood control system [*Yoshikawa et al*., 2010]. The flood mitigation measures include the installation of runoff control devices in the paddy field drainage pits. This research evaluated the flood mitigation performance of paddy fields with runoff control devices by using combined hydrologic analyses and flood routing. The paddy fields are considered to have a function for mitigating heavy floods [*Abler*, 2004; *Matsuno*, 2006; *Groenfeldt*, 2006; *Kim et al.*, 2006]. Various studies have evaluated this flood control function. *Shimura* [1982], for the first time, estimated the floodwater storage capacity of all paddy fields at 8.1 billion m^3, which far exceeds 2.4 billion m^3, the total flood detention capacity of flood control dams in Japan. Most of the regional condition studies concluded that paddy fields play an important role in increasing the water storage capacity in river basins and lowering the peak flow of rivers to a certain extent, but not to the same degree as *Shimura* [1982] estimated. A study on the flood mitigation effect of the Paddy Field Dam project shows the quantification and evaluation of the effect of the Paddy Field Dam. Flood control measures using the ponding function of paddy fields, at the watershed scale, and combined hydrologic analyses and flood routing [*Yoshikawa et al.*, 2010]. *Sugono* [2010] concluded that paddy fields were very effective in flood reduction/rainfall retention. Flood reduction of paddy plots varies from 37.2% up to 55.7% depending on the water management technique used. Semidry cultivation was the most effective technique for flood reduction, with rainfall retention of up to 55.7%. Hence, these studies confirmed that the flood control measure is functioning effectively, as far as the study area is concerned. The effectiveness of water saving by paddy fields and irrigation techniques on flood reduction should be studied. The use of paddy fields for flood storage would be effective for the Chao Phraya River Basin, especially in the large irrigation and urban areas in the lower region.

1.3 Objectives of the study

The objectives of this study are to present the development of a Seamless-DIF model that expands on the DWCM-AgWU by incorporating flood and inundation processes, and to apply the new model to Thailand's Chao Phraya River Basin, in which the interaction between floods and agricultural water use is a main factor in watershed management. Specific objectives of the study are as follows:

1) To assess the limitations of the DWCM-AgWU, which was originally developed for the Mekong River Basin and river basins in northeastern Thailand, by modifying the model and applying it to the Chao Phraya River Basin for the period of 2008-2011, which includes both flood and drought years. Water management

related to human activities, such as management through irrigation facilities, dams and/or irrigation intakes, is considered in this process.

2) To develop a Seamless-DIF model by modifying the DWCM-AgWU, characterized by the incorporation of flood and inundation processes. The Seamless-DIF model is applied to the Chao Phraya River Basin to assess the performance of the model, especially in the lower area of the basin, which was severely affected by floods. The target period of analysis is 2011.

1.4 Thesis outline

Chapter 2 presents an outline of the Chao Phraya River Basin, the target area. In the first part of the chapter, an overview of the basin, meteorological data, cultivation practices and cropping patterns, river and drainage systems, observation networks and fundamental data, such as digital elevation model data, Arc-GIS data and transportation system data, are explained to show the characteristics of the basin. Next, information on irrigation and water management through the irrigation facilities is presented to express the relationship between the natural water cycle and human activities in agricultural water use. Chapter 3 describes the features of the 2011 flood, including its cause and effect in the study area. Information from the 2011 flood survey is presented in order to analyze the cause of the flood. Floodwater management through irrigation facilities, such as the operation of dams and/or diversion weirs equipped with a series of flood control gates, is also explained for this purpose. The modification of the DWCM-AgWU and its application to the target area are presented in Chapter 4. Firstly, an areal model was constructed to explain the study area and data. Next, features of the original model [*Taniguchi et al.*, 2009; *Masumoto et al.*, 2009; *Kudo et al.*, 2013] are explained to check the characteristics and the limitations of the original model. Then, the modification of the original model and its application are shown, especially on agricultural water use and floodwater management through irrigation facilities in the basin. In this chapter, the importance of irrigation as well as agricultural water use is emphasized and the limitations of the model are explained for the treatment of flood and inundation processes. Chapter 5 explains the development of the Seamless-DIF model and assesses the model performance, which are the essence of this study. The problems in applying the DWCM-AgWU, which lacks the flood and inundation processes, especially in the delta plain area, are solved by incorporating the runoff process with flood and inundation. The new model is verified by comparing the observed data with the calculated results on water levels, merging of flooded areas and flood storage in a specified paddy region in the lower area of the basin, which was severely affected by the flood in 2011.

Chapter 2

Features of Agricultural Water Use and Water Management in the Chao Phraya River Basin

2.1 Overview of the Chao Phraya River Basin

The Chao Phraya River Basin is located in the north and central regions of Thailand. The size of the basin is approximately 160,000 km^2, which is about one-third of the whole area of Thailand. This is the most important river basin in Thailand; about 40% of the country's population lives here and about 66% of the gross domestic product (GDP) is generated here [*ONWRC of Thailand*, 2003]. **Figure 2.1** shows the schematics of the basin including its important facilities. Within the Chao Phraya River Basin are eight sub-basins: the Ping, Wang, Yom, Nan, Pasak, Sakae Krang, Chao Phraya and Tha Chin. The main river, Chao Phraya, originates in the mountains in the four northern sub-basins (the Ping, Wang, Yom and Nan). These four main tributaries converge at Nakhon Sawan, and below this point is the Chao Phraya delta plain with a maximum elevation of 20 m.

When considering the importance of irrigation facilities and irrigation areas in this study, the basin is divided into the upper, middle and lower areas, that is, the area above the Bhumibol and Sirikit dams, the area from these two dams to the confluence at Nakhon Sawan, and the area below the confluence to the sea, respectively, although the basin is usually divided into upper and lower areas by the confluence of the main tributaries at Nakhon Sawan (**Fig. 2.1**).

The upper basin is almost completely covered by forests in mountainous areas. Rain-fed and irrigated paddy fields extend over the intermontane basin. There are four large storage dams in the upper basin: the Maengat Sombulchol and the Maeguang Udom Thara in the Ping River sub-basin, and the Kew Kohmah and the Kewlom in the Wang River sub-basin. The four dams are individually linked to irrigation areas. However, as multi-purpose dams, they also release water for electricity generation and domestic use.

In the middle basin, there are floodplains along the four tributaries, and alluvial fans are formed where the tributaries enter the floodplain. The floodplain is characterized by river channels, natural levees, and their back marshes.

The lower basin is defined as delta plain areas. The floodplain and delta plain along the lower reaches of the river, with a maximum elevation of 20 m, act as water diffusion and receiving areas. The most important irrigation facility is the Chao Phraya Diversion Dam, a weir equipped with a series of large floodgates at Chainat (slightly upstream from Station C.13 in **Fig. 2.1**). The Royal Irrigation Department (RID) uses this facility to regulate the intake of water for the irrigation areas and to control floods in the lower basin.

In the basin area from Ayutthaya to the seacoast, the main rivers and tributaries have a gentle slope and are influenced by tidal fluctuations in the flood season. About 13% of the area is urbanized. The city of Bangkok is located along the Chao Phraya River and extends to the eastern and western sides of the plain. The urban areas have a dense network of drainage canals and dikes.

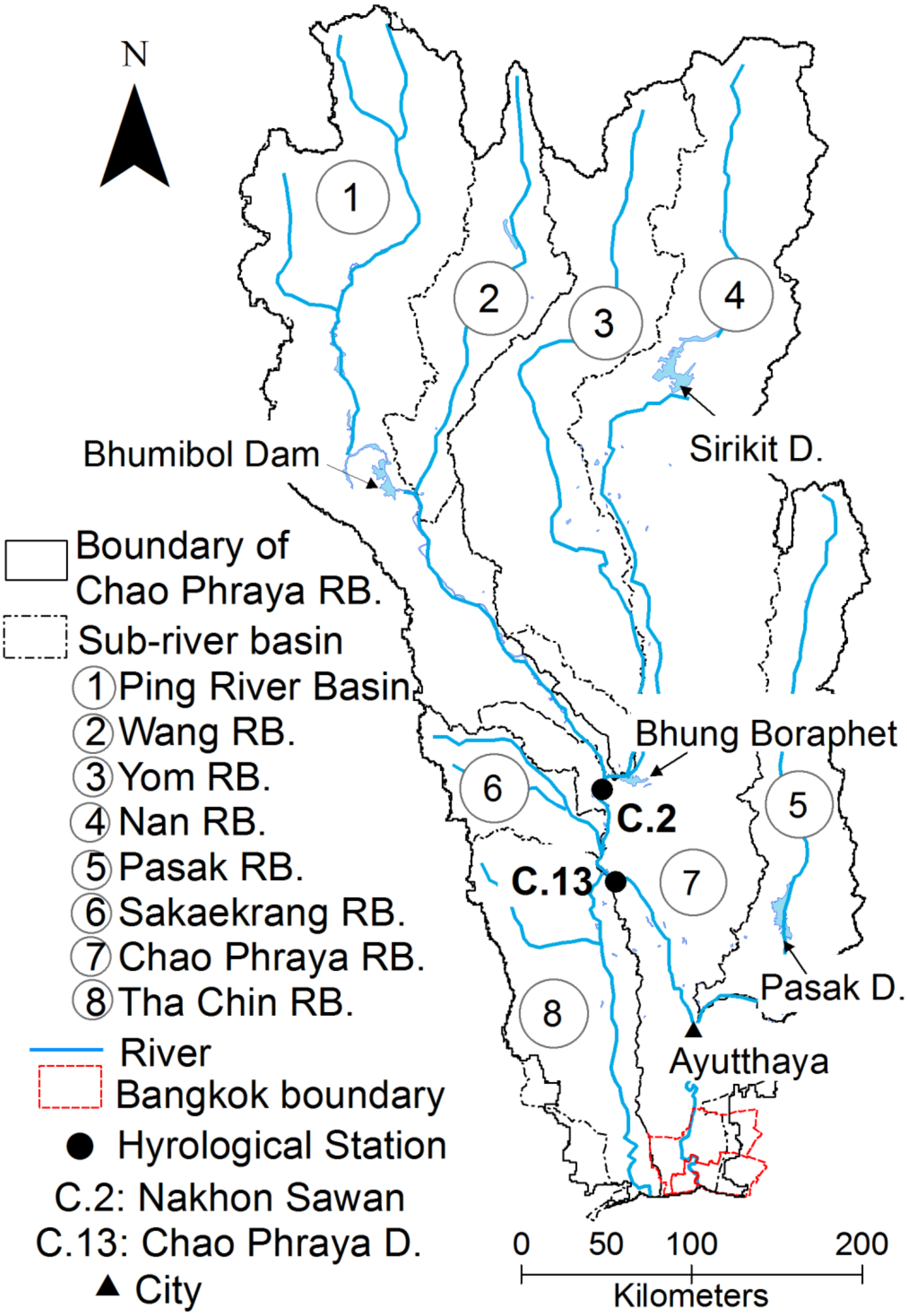


Fig. 2.1 Outline of the Chao Phraya River Basin

2.2 Hydrometeorological conditions

The Chao Phraya River Basin has a tropical savanna climate. There are essentially two seasons, based on rainfall amount. The rainy and dry seasons run from May through October and November through April, respectively. In the rainy season, southwest monsoon winds and tropical cyclones bring heavy rainfall to the basin. From mid-October through mid-February, the northeast monsoon brings cold, dry air from the anticyclone over mainland China. The average annual precipitation is shown in **Fig. 2.2**. The overall average annual precipitation is approximately 1,150 mm. Mean rainfall in the rainy season accounts for about 90% of the annual rainfall.

For example, at Station C.2 downstream from the confluence of the four main northern tributaries, the precipitation amount is approximately 118 billion tons per year given that the mean annual precipitation is 1,150 mm and the catchment area is 102,635 km^2, while the average total runoff amount is 25,000 MCM. Hence, the total runoff amount accounts for 20% of the total precipitation amount.

Meteorological and hydrological data is monitored by the Thai Meteorological Department (TMD) and the Royal Irrigation Department (RID), respectively. The meteorological data includes rainfall, maximum temperature, minimum temperature, average temperature, wind speed at 2 m, visibility and relative humidity. The hydrological data includes daily observed discharge and water levels. The hydrological and meteorological data was collected from the RID and the National Oceanic and Atmospheric Administration (NOAA), respectively. There are 42 and 135 observation stations for meteorological and hydrological data, respectively. **Figure 2.3** shows the location of the stations.

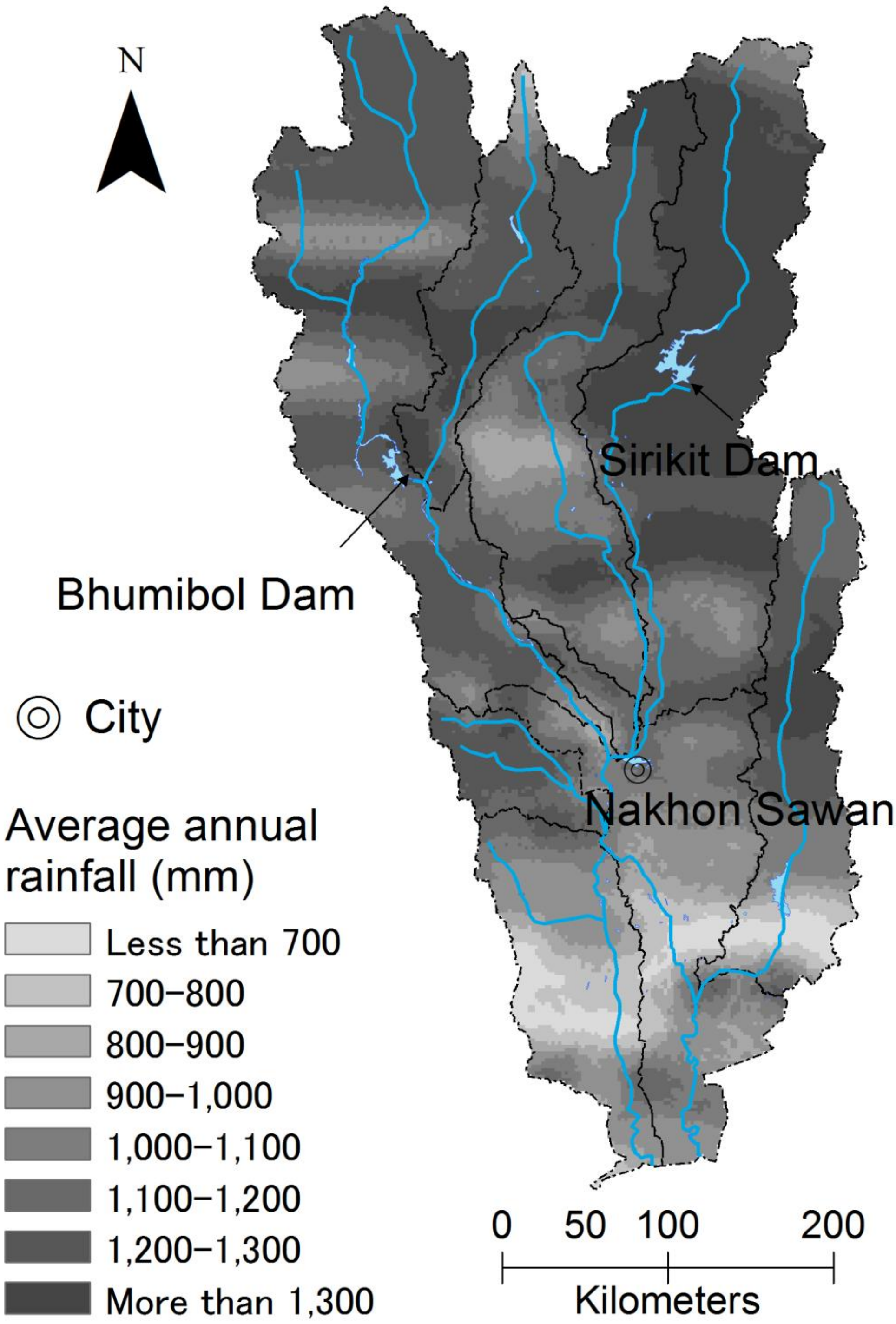


Fig. 2.2 Average annual precipitation in the Chao Phraya River Basin from 2004 through 2011

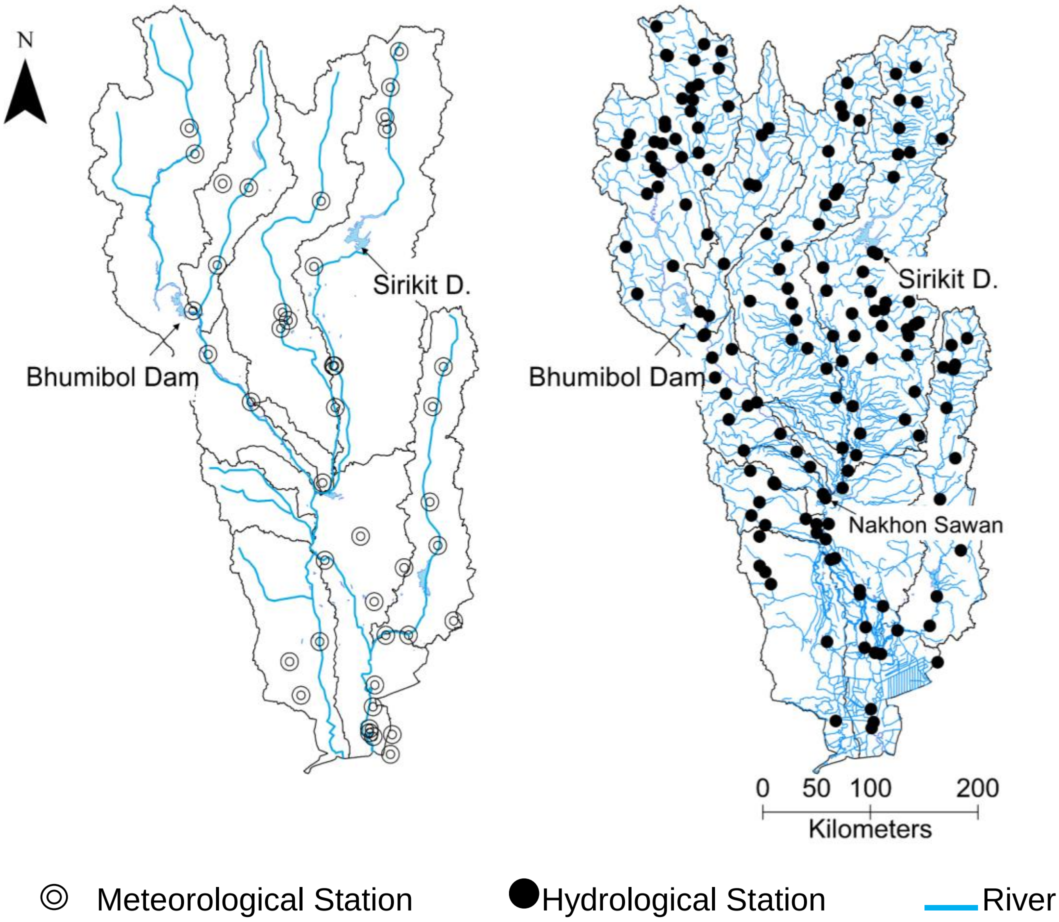


Fig. 2.3 Location of meteorological and hydrological stations

2.3 Agricultural farming and cropping patterns

Agricultural farming in the Chao Phraya River Basin is diversified, with differences in crops and cropping patterns. According to land use data from the Land Development Department (LDD), paddy fields account for approximately 46% of the total agricultural area and upland crops about 54%. Rice is the most important economic crop in Thailand.

Thailand produces two major rice varieties: one with photosensitive and the other without. Nowadays, due to the development of irrigation, farmers can cultivate two or three crops in a year. Hence, the non-photosensitive variety is popular. However, in regions suffering from damage due to the delay of rainfall or a flood, the variety with photosynthesis capability or deep-water resistance is used.

Figure 2.4 shows typical cropping patterns in the basin. The 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 and June 1 in the dry and rainy seasons, respectively. In addition, cropping patterns can be mixed, such as paddy cultivation in the rainy season and upland crops in the dry season.

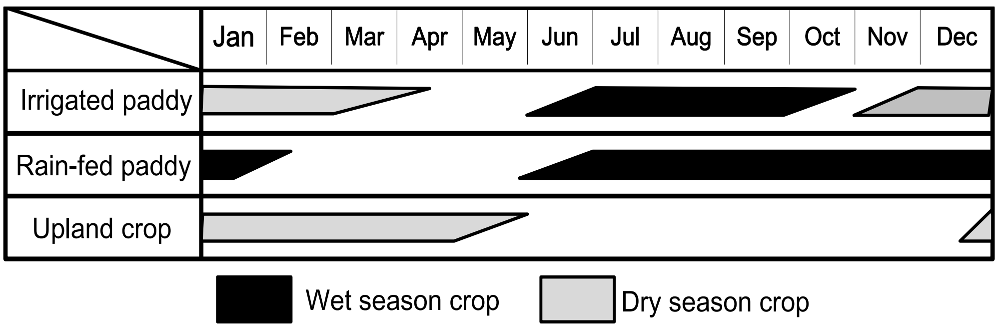


Fig. 2.4 Cropping patterns in the study basin

2.4 Schematics of river and drainage

Figure 2.5 shows the schematics of the river and drainage channel systems in the basin. The catchment area of sub-basins and the length of rivers are shown in **Table 2.1**.

In the middle basin, as defined in this study, the Wang River joins the Ping River downstream from the Bhumibol Dam, the Yom River joins the Nan River upstream from Nakhon Sawan, and the Ping and Nan rivers converge slightly upstream from Station C.2 (Nakhon Sawan). The Bhung Boraphet, a small sub-basin functioning as a wetland reservoir for the downstream area, connects with the Chao Phraya River upstream from Station C.2 after the confluence of the main tributaries in the upper part. The Chao Phraya River originates at this point and flows down to the gulf of Thailand. There are three artificial canals with control gates (**Fig. 2.5**). One is an irrigation canal and the other two are diversion canals. The RID uses these canals to supply irrigation water in the dry season and drain floodwater during high-flow periods. The irrigation canal is part of the Tha Thong Dang Irrigation Project and is used to divert water between the Ping and Yom Rivers. The diversion canals are the Hok Bath and Yom-Nan, which are used to divert water between the Yom and Nan rivers.

In the lower area, the Sakae Krang River joins the Chao Phraya River on the right bank between Station C.2 and the Chao Phraya Diversion Dam (**Fig. 2.5**). On the other hand, upstream from the Chao Phraya Diversion Dam, the Tha Chin and Noi rivers are diverted from the Chao Phraya River on the right bank by the Polthep and Baromathat intake gate facilities, respectively (**Fig. 2.5**). The Tha Chin and Noi rivers are used as the main irrigation and drainage canals at the same time. The Tha Chin River flows to the sea, while the Noi River rejoins the Chao Phraya River at Bangsai (south of Ayutthaya) (**Fig. 2.5**). Between the Chao Phraya Diversion Dam and Ayutthaya, the Lop

Table 2.1 Catchment area and river length

Sub-basin	Catchment area (km^2)	River length (km)
Ping	33,898	540
Wang	10,791	270
Yom	23,616	450
Nan	34,440	490
Pasak	16,292	360
Sakae Krang	5,191	135
Chao Phraya	20,125	270
Tha Chin	13,682	220

Buri River branches off from the Chao Phraya River by gate control and joins the Pasak River at around Ayutthaya. The Lop Buri River is the main drainage canal for the eastern irrigated areas inside the Chainat-Pasak Canal and the Pasak River. Then, the Pasak River joins the Chao Phraya River on the left bank at the city of Ayutthaya.

Figure 2.5 also shows the features of the drainage system in the areas from southern Ayutthaya to the sea including Bangkok. The RID operates the drainage system in the areas between southern Ayutthaya and the northern part of Bangkok, while the Bangkok Metropolitan Administration (BMA) operates the drainage system in the area inside Bangkok. In the eastern area from upper Bangkok, there are three main drainage canals: the Rapeephat, the Rangsit Prayulsak, and the Hok Wa. The Rapeephat Canal separates into two main canals: the first one, the Rapeephat Yak Tai Canal, drains water from the Pasak River to the sea, and the second one, the Rapeephat Yak Tok Canal, drains water to the Chao Phraya River (**Fig. 2.5**). The Rangsit Prayulsak and Hok Wa canals are parallel to the Rapeephat Yak Tok Canal. The function of the Rangsit Prayulsak Canal is to drain water to the Chao Phraya River; the pumping station is used when the water level of the river is higher than water level in drainage canal. The Hok Wa Canal is used to drain water to the Bangpakong River (outside the study area) using the pumping station.

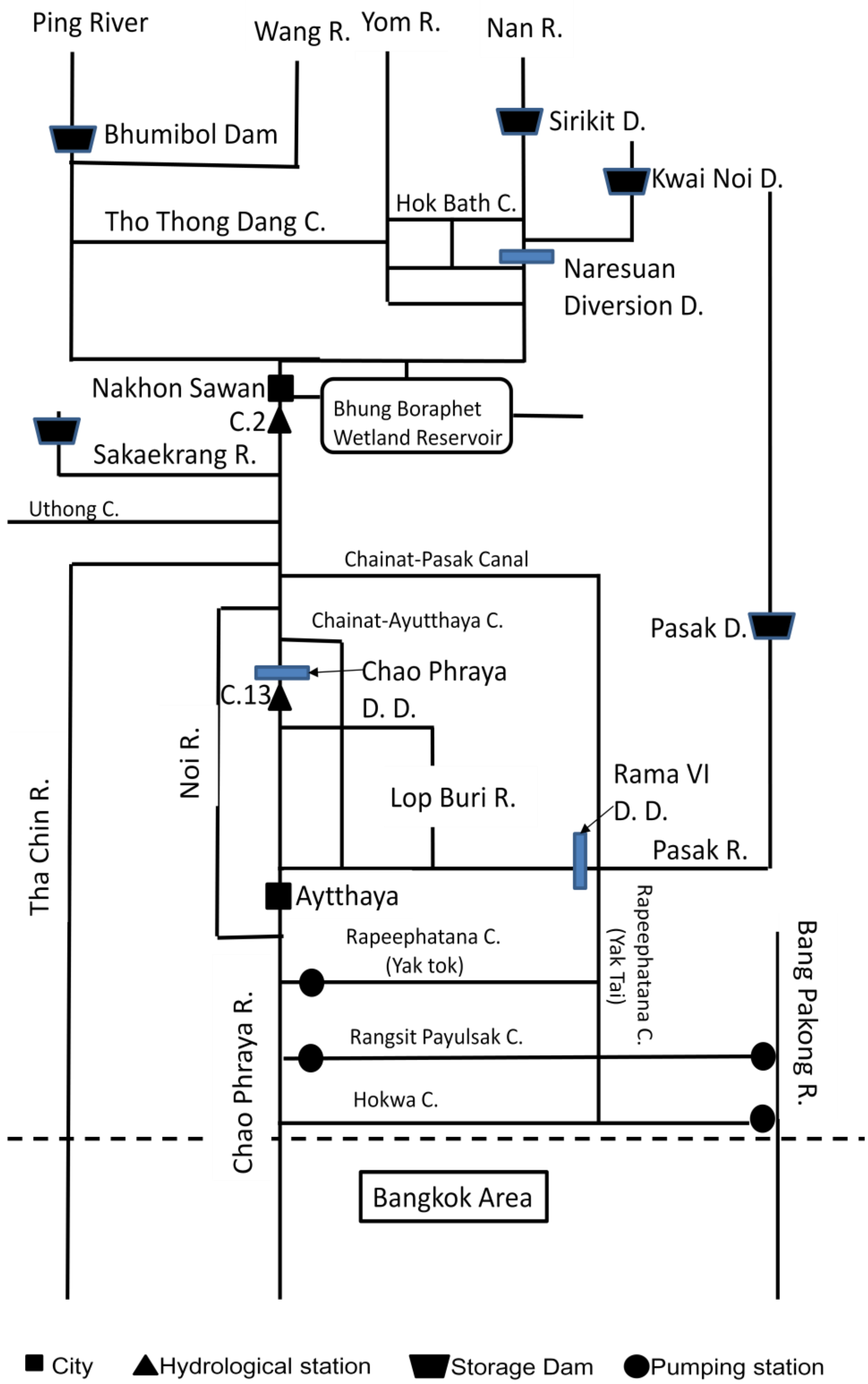


Fig. 2.5 Diagram of river and drainage systems in the Chao Phraya River Basin

In the Bangkok area (**Fig. 2.6**), the tidal conditions influence the drainage system and the Chao Phraya River, which contributes significantly to floods. The drainage system has been designed for rainfall intensity of 60 mm/h. There are 1,682 canals with 26 km of canal networks and 409 pumping stations with a total capacity of 1,638 m^3/s. In addition, the BMA uses seven drainage tunnels that drain water through a system of pipes. The total capacity of the tunnel systems is 155 m^3/s.

Figures 2.7 (**a**) and (**b**) show the daily seawater levels at the mouth of the Chao Phraya and Tha Chin rivers. The data is monitored hourly by the Thai Navy. The data was converted to daily values by averaging the maximum and minimum peaks in a day. The observed seawater level was compared with the mean seawater level. Daily fluctuations at the mouth of the Chao Phraya and Tha Chin rivers are approximately (−0.5)–0.5 and (−0.2)–0.75, respectively, and the maximum peak ranges are approximately 0.5–1.5 and 0.75–1.75, respectively. The elevation range of the areas between Ayutthaya and Bangkok is 0–5 m and the elevation range of the Bangkok area is lower than 0 to 2 m. Hence, the seawater level reflects the influence of tidal effects that action for drainage system (**Fig. 2.7**), as mentioned above.

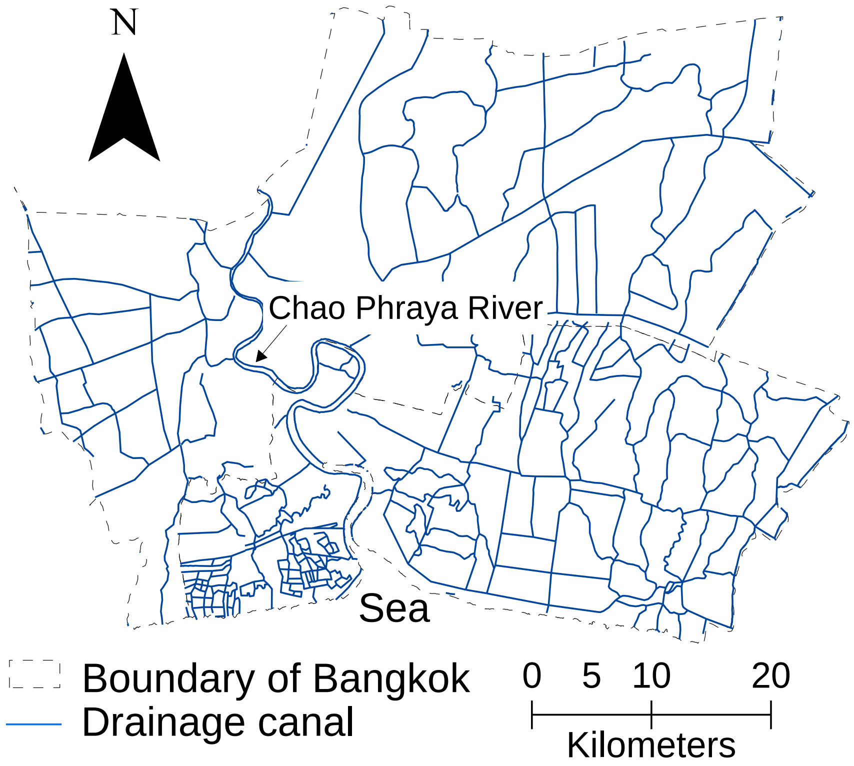
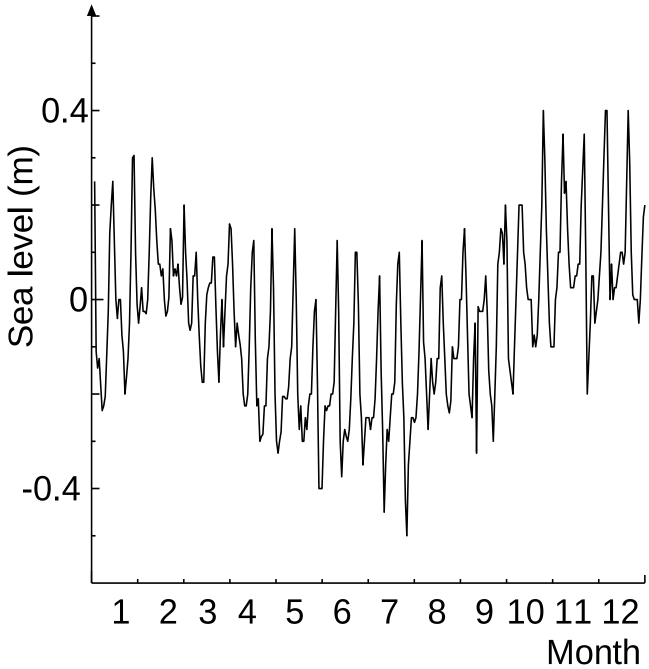
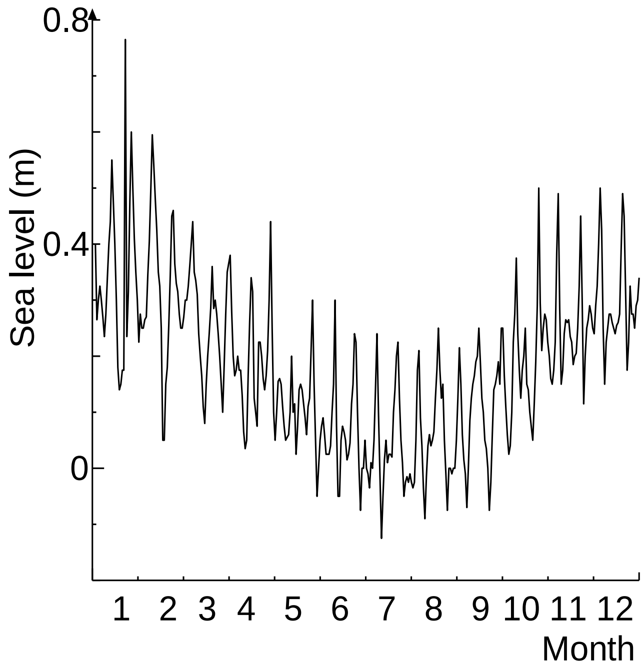


Fig. 2.6 Drainage system in Bangkok



a) Chao Phraya River



b) Tha Chin River

Fig. 2.7 Daily-averaged tidal water level at river mouths

2.5 Geomorphological and infrastructural features

2.5.1 Land use

Land use data was created in 2000 based on surveys carried out by the Land Development Department, Thailand. The data was collected from the Department of Irrigation Engineering, Kasetsart University as a GIS digital file.

Land use data was mainly classified into five categories: Forest, Agricultural, Water Body, Urban Area, and Others (e.g., mines). **Table 2.2** shows the area size of each land use in the sub-basins. Concerning sub-categories of agricultural areas, there are several types of agricultural land use, such as paddy fields, upland crop fields, and perennial crop fields. The land use classifications of the Chao Phraya River Basin are shown in **Fig. 2.8**. Four sub-basins have about 60% forest coverage in the upper part of the basins. However, agricultural land use is distributed in the plain areas on the intermontane sides. Areas in the middle basin are mostly covered by agricultural land and contain upland crops, and rain-fed and irrigated paddies. Irrigated paddies extend along the Ping and dams, respectively. Almost the entire lower area is covered with irrigated paddies.

Table 2.2 Land use in sub-area categories

Sub-basin	Forest	Rain-fed paddies	Irrigation paddies	Upland crops	Urban areas
Ping	25,000	1,681	1,653	5,696	90
Wang	7,864	700	430	1740	88
Yom	13,595	4,656	1,440	4.265	315
Nan	15,790	4,485	2,565	11,378	535
Pasak	3,395	2,360	600	9,090	3.3
Sakae Krang	2,420	1,510	20	950	0
Chao Phraya	970	3,860	7,520	7,810	1,630
Tha Chin	1,235	4,610	1,590	5,850	430
Total	70,269	23,862	15,818	42,518	3,091

Note: Unit in km^2

However, urban areas are expanding, including in Bangkok below Ayutthaya to the sea.

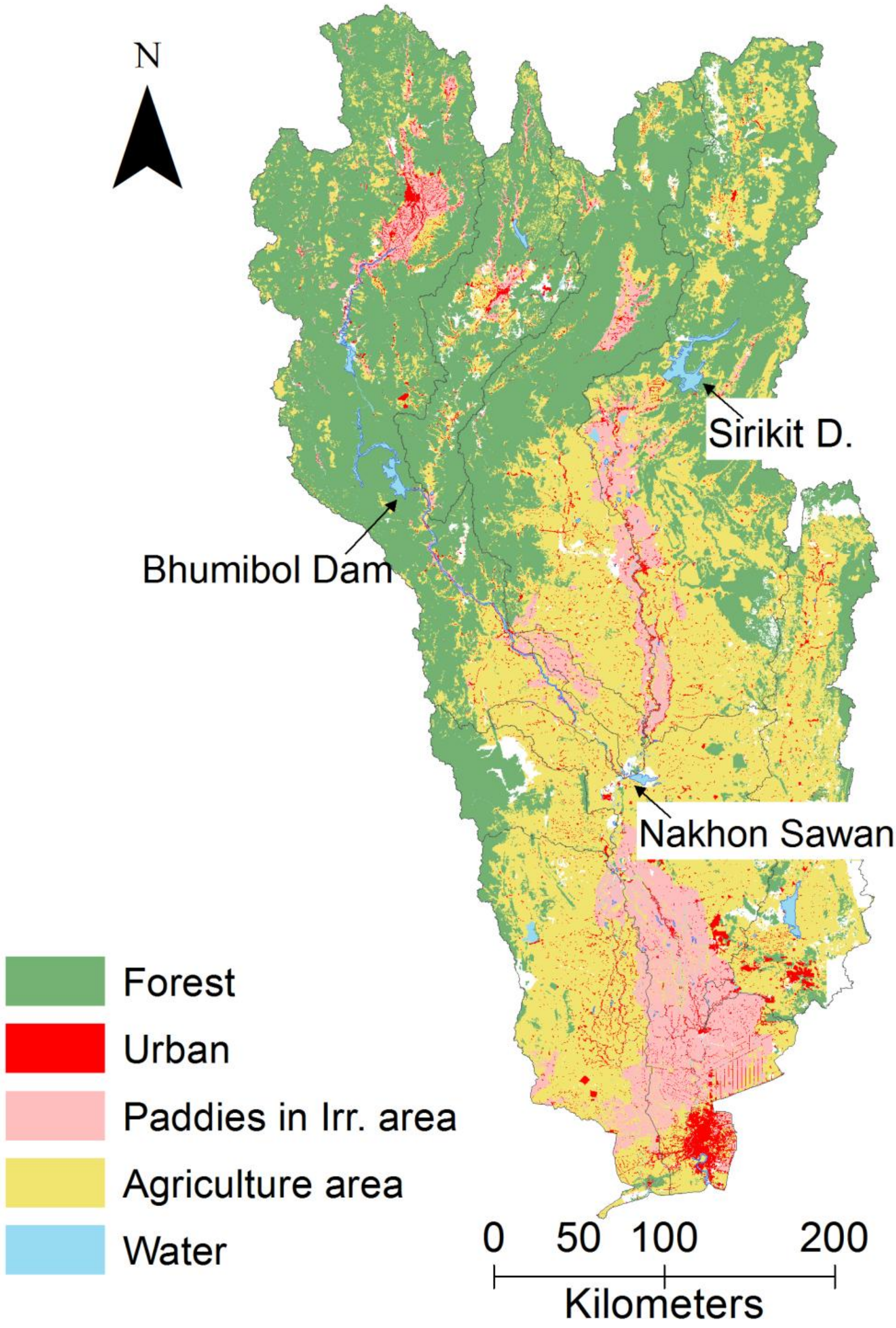


Fig. 2.8 Land use categories in the Chao Phraya River Basin

2.5.2 Topographic conditions

A digital elevation model provided us with three-dimensional elevation. The terrain elevation for ground positions is estimated at regularly spaced horizontal intervals. This data was obtained from the DIVA-GIS organization. The spatial resolution is 30 arc seconds (1-km grid), with a 1-m elevation interval.

As the next stage of data collection, GMTED2010 data was obtained from the USGS. Elevation was surveyed in 2010, with a 30-m grid and 1-m elevation interval. We also tried to collect LIDAR's profiler data for the delta plain areas from Nakhon Sawan to the sea. The survey was conducted by JICA and the data was published by the Thai government. However, our request is still being processed.

Figure 2.9 shows the topographical map of the Chao Phraya River Basin. The upper and middle basin areas have an elevation range of 150-1000 and 30-100 m, respectively. However, the areas along the main tributaries in the middle part have an elevation range of lower than 60 m. In the lower areas, the elevation range from the sea to Nakhon Sawan is 0-30 m. In the delta plain areas of the lower basin, there are three elevation classes: from Nakhon Sawan to Sing Buri, from Sing Buri to Ayutthaya, and from Ayutthaya to the sea, with elevation ranges of approximately 10-30, 5-10 and 0-5 m, respectively. Hence, the area from Ayutthaya to the sea is the most gentle in the delta plain, and is influenced by tides during floods.

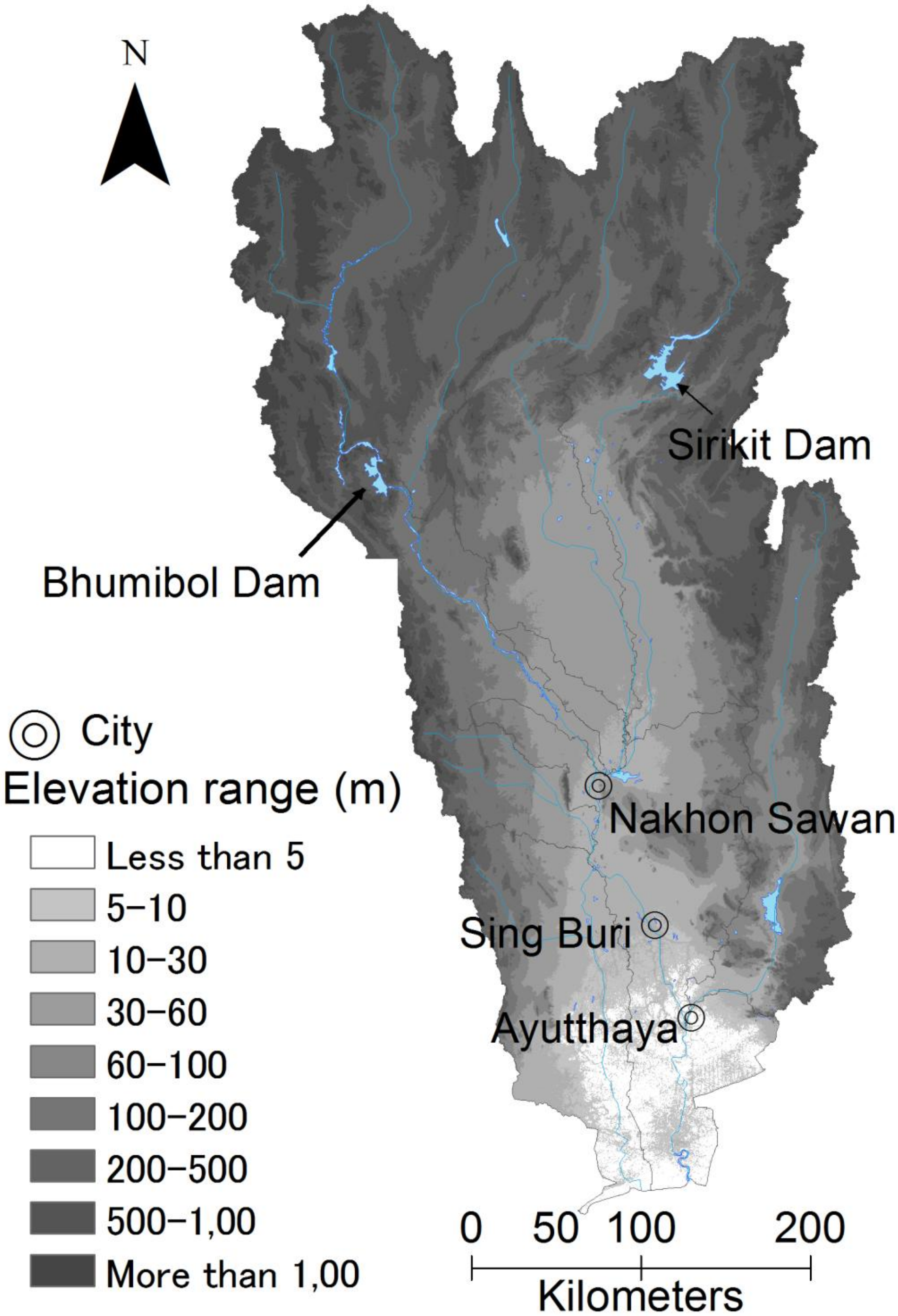


Fig. 2.9 Topographical map of the Chao Phraya River Basin

2.5.3 Transportation networks

Transportation networks are designated as roads and railways. These networks are managed by the Department of Highways (DOH) and the State Railway of Thailand (SRT), respectively. They are the main forms of transportation from the central to the northern and northeastern regions. **Figure 2.10** depicts the networks of roads and railways in the basin. The transportation network data was collected, which includes network location and elevation, from the DOH.

Road network

The main roads are Routes 1 (Pahon Yothin) and 2 (Mitraphap), connecting Bangkok to the northern and northeastern regions. Another important road is Route 32, which runs along the Chao Phraya River, beginning at Ayutthaya and meeting Pahon Yothin again at Nakhon Sawan. In addition, there are many roads in the irrigation areas. They run along the main tributaries in the lower basin and also function as dikes.

Railway network

There are two main railway lines, the Northern and the Northeastern. The Northern line begins at Bangkok and runs parallel to Pahon Yothin Road. At Ayutthaya, the Northeastern line branches off from the Northern line and runs through Sara Buri to the northeastern region.

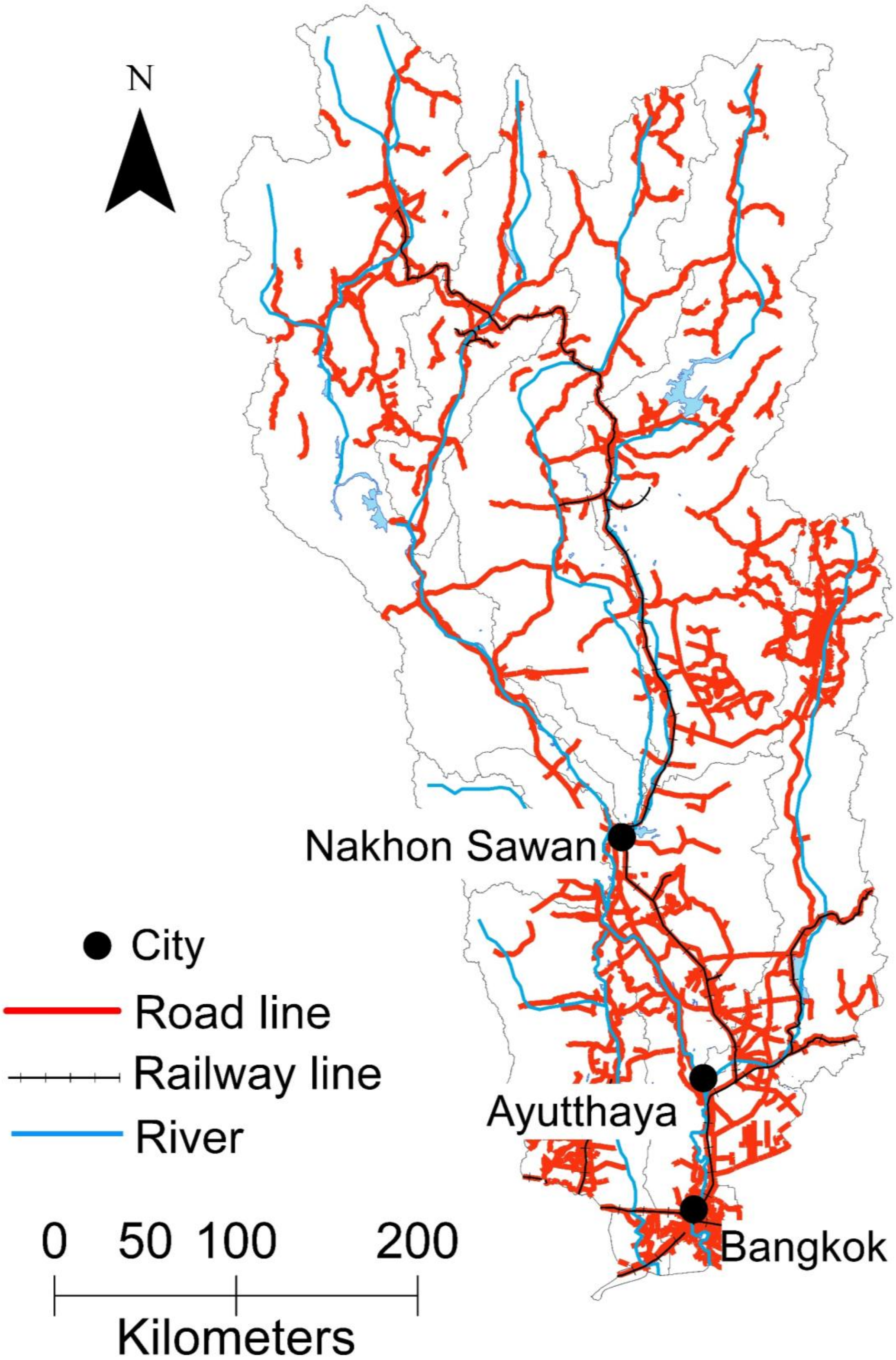


Fig. 2.10 Transportation networks along with river networks

2.6 Agricultural water use and water management

2.6.1 Practices in agricultural water use

1) Organization and policy

In Thailand, the RID is the main organization for managing water resources and operating the associated facilities such as irrigation storage dams, diversion dams and/or weirs. However, multi-purpose storage dams such as the Bhumibol, Sirikit and Kewlom, which also have the function of hydropower generation, are operated by the Electricity Generating Authority of Thailand (EGAT). Therefore, water management plans in Chao Phraya River Basin are carried out by a drainage committee. The committee consists of the RID, EGAT, and Ministry of Agricultural and Cooperation (MOAC). Water management plans differ between the dry and rainy seasons. Normally, the plans are set prior to the actual supply of water as 1) Domestic use, 2) Environmental use, 3) Agricultural use and 4) Industrial use. **Table 2.3** shows the water volume supplied for each type of use in the basin. According to the table, agriculture is the main water user

Table 2.3 Water supply during the dry season in sub river basins

Sub-basin	Domestic	Ecology	Agriculture	Industrial
Ping	16	24	1,421	0
Wang	12	21	126	0
Yom	19	0	333	1
Nan	77	0	1,389	0
Pasak	35	0	890	0
Sakae Krang	-	-	-	-
Chao Phraya	800	1,215	3,856	0
Tha Chin	50	375	1,753	0

Note: - No data

Unit in million cubic meters

Source: (RID, 2012)

in this river basin, although the number of agricultural areas outside the irrigation project is approximately 80% of the total agricultural areas in the basin.

2) Typical agricultural areas

Areas of irrigation and non-irrigation are shown in **Table 2.2**. The areas of rain-fed paddies and upland crops are approximately 28% and 54% of the total agricultural area, respectively. Rain-fed areas are mostly located in the middle basin area.

The total area of irrigated paddies is about 15,820 km^2, approximately 18% of the agricultural area. In the Chao Phraya sub-basin, there has been some change in land use from agricultural to urban. The irrigation facilities in those areas are still used for drainage purposes.

3) Irrigation areas

Figure 2.11 shows the location of large- and medium-scale dams and irrigation facilities in the basin. In the upper area, there are three main irrigation projects: The Upper Ping Irrigation Project in the Ping sub-basin, the Kew Lom Irrigation Project in the Wang sub-basin, and the Yom Irrigation Project in the Yom sub-basin. Water for the Upper Ping Irrigation Project is supplied by the Mae Ngat Sombulchol and Mae Guang Udom Thara dams, for the Kew Lom Irrigation Project, by the Kew Lom and Kew Koh Mah dams, and for the Yom Irrigation Project, by the Mae Yom Weir.

In the middle basin area, there are three main irrigation projects: the Utradit and the Pitsanulok Irrigation Project use water supplied from the Sirikit Dam, while the water for the Kham Phangphet Irrigation Project is supplied by the Bhumibol Dam.

In the lower basin area, the Greater Chao Phraya Irrigation Project is supplied with water from the Bhumibol and Sirikit dams. Irrigation areas in the lower eastern part, such as those below the Pasak River to the sea, use water from the Pasak Cholasit Dam and irrigation areas in the lower western part are supplied with water from the Mae Klong River Basin (outside the Chao Phraya River Basin)

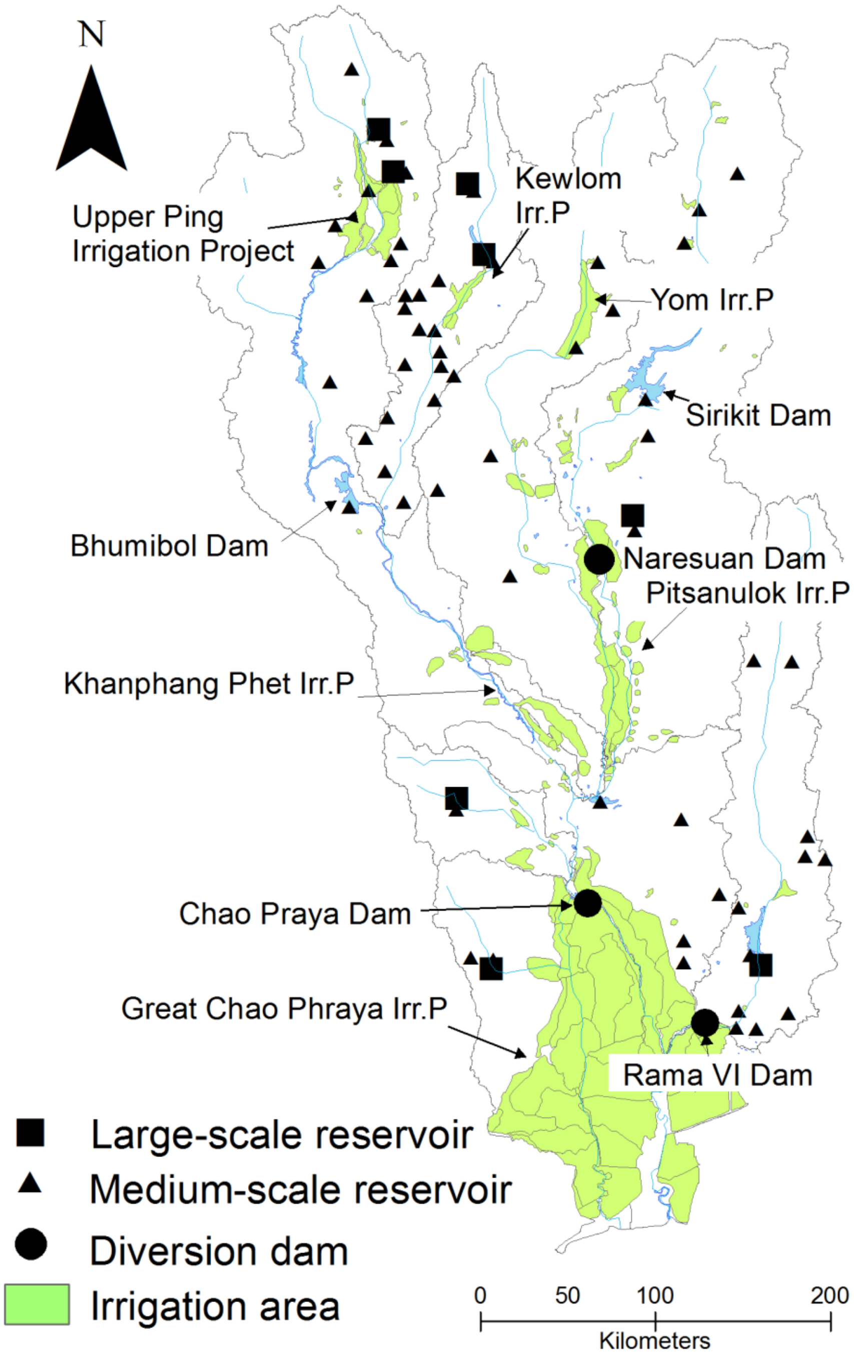


Fig. 2.11 Location of large- and medium-scale dams and irrigation facilities in the Chao Phraya River Basin

2.6.2 Irrigation facilities

1) Dams

The RID classifies dams as large, medium, and small based on the storage capacity of their reservoirs. The 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 beneficial 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 1,150 mm, which is equivalent to an input of approximately 192 billion m^3. Therefore, the total storage capacity is about 15% 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.

2) Diversion dams

The RID defines a barrage that has a series of flood control gates as a diversion dam. It is operated in tandem with intake facilities to regulate the water level and discharge at the main stream and to divert water into the irrigation canals in the dry season, as well as to control floods in the rainy season. There are three important diversion dams, which are shown in **Fig. 2.10** and described below.

The Narasuan Dam

The Narasuan Dam was built across the Nan River 180 km downstream from the Sirikit Dam in the middle area of this study basin (**Fig. 2.11**). It is equipped with five flood control gates measuring 12.5×6 m. The gates have a release capacity of 1,550 m^3/s. Two intake facilities are managed with this dam to supply water for the Pitsanulok Irrigation Project, which has a total irrigation area of about 91,000 rai.

The Chao Phraya Dam

The Chao Phraya Dam, the most important irrigation facility in the lower area, was constructed in the Chao Phraya River (**Fig. 2.11**). It has a series of 16 flood control gates, which have a release capacity of 3,300 m^3/s. This dam controls the water level to divert water to the Greater Chao Phraya Irrigation Project on the eastern and western sides through five intake facilities. There are two intake gates on the eastern side and three on the western side with a total capacity of approximately 300 and 500 m^3/s, respectively. The two on the eastern side are the gates of the Chainat-Pasak and Chainat-Ayutthaya canals, and the three on the western side are the Baromathat Gate on the Noi River, the Polathep Gate on the Tha Chin River and the gate on the Uthong Canal (**Fig. 2.11**).

The Rama VI Dam

The Rama VI Dam was constructed in the Pasak River to divert some of the water from the Pasak River and the Chainat-Pasak Canal to irrigation areas in the lower eastern parts of the Greater Chao Phraya Irrigation Project through the Rapeephat Canal (**Fig. 2.11**). This facility is indispensable for controlling the discharge from the Pasak River to Ayutthaya. The dam is equipped with a series of six flood control gates measuring 12.5×7.8 m and its total capacity is 1,800 m^3/s

2.6.3 Specific water management

1) Bhung Boraphet wetland reservoirs

Bueng Boraphet, the largest shallow reservoir and wetland complex in Thailand [*Sriwongsrithanon et al.*, 2009], is located on the Chao Phraya River slightly upstream from Nakhon Sawan **(Fig. 2.1)**. 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 reservoir to irrigate the surrounding paddy fields, which requires reversing the flow into the wetland and maintaining the reservoir water level. Due to irrigation in the dry season, the reservoir takes water from the Nan River in order to maintain the water level in the reservoir for ecology preservation such as fisheries.

2) Co-operation of the Bhumibol and Sirikit dams

The Bhumibol and Sirikit dams are perennial storage-type, multi-purpose reservoirs, mainly used for irrigation and hydropower generation. The two dams are operated by the Electricity Generating Authority of Thailand (EGAT). The Bhumibol is a concrete arch dam on the Ping River, with a storage capacity of about 13.5 billion m^3. The Sirikit is an embankment dam on the Nan River, with a storage capacity of about 9.5 billion m^3. They are the main sources of water for the middle and lower basin areas in the dry season, and they also play an important role for flood prevention in downstream areas in the rainy season. The water required from these dams is mostly for irrigation, ecology and domestic use. Although hydropower generation is one of the functions of these dams, hydropower is a by-product of the release of water; there is no release for hydropower itself. EGAT releases water from the Bhumibol and Sirikit dams by

Table 2.4 Water requirements in the downstream areas of the Bhumibol and Sirikit dams and release in the dry season

Use	2006	2007	2008	2009	2010	2011
Irrigation areas in the middle	2,340	2,905	2,550	2,800	2,350	2,345
Greater Chao Phraya Irrigation Project	3,750	5,140	3,770	4,520	3,370	4,375
Ecology	600	405	480	480	480	480
Domestic	750	600	750	750	800	800
Release from the Bhumibol and Sirikit dams						
Planned	6,890	8,500	7,000	8,000	6,000	6,800
Actual	7,662	9,648	9,530	9,152	7,678	6,867

Note: Unit in million cubic meters

Source: (RID, 2012)

considering the remaining storage in each dam due to keeping water levels in the reservoirs for hydropower generation. **Table 2.4** shows the water requirements in the downstream areas for type of use and the release amount. Releases are mainly for irrigation, especially for the Greater Chao Phraya Irrigation Project.

3) Flood prevention in the low-lying areas

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 to prevent flooding in the downstream areas, especially in the city of Ayutthaya. In this process, the RID regulates the discharge at two points: one at Station C.2, and the other at Station C.13 (Nakhon Sawan) located downstream from the Chao Phraya Diversion Dam (**Fig. 2.1**). At C.2, the discharge is restricted to 1800 m^3/s, which accounts for the total discharge from the Ping and Nan rivers, and the excessive discharge drawn from the Nan River is released into the Bueng Boraphet wetland reservoir when the total flow exceeds the control target. The Chao Phraya Diversion Dam is a weir structure with 16 large floodgates used for flood control and irrigation, as mentioned previously. Flows are stored in the upstream part of the dam and are also diverted to irrigation areas through the irrigation canals by considering the maximum capacity of the canals as well. In other words, for controlling the total discharge, the diverted volume is determined based on the capacity of the 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.

Chapter 3

Recent Floods in the Basin and the 2011 Flood

3.1 Overview of large floods

3.1.1 Historical floods

The Chao Phraya River Basin, particularly the delta plain area, experienced floods in 1983, 1995, 1996, 2002 and 2006 [*DHI*, 2012]. The return periods were estimated from records of the annual maximum water levels at the Ayutthaya Hydrological Station. Record floods occurred in 1995 and 2006, with return periods of 30 and 20 years, respectively. The 1995 flood affected an area of 15,000 km^2 and the 2006 flood affected 19,000 km^2 [*Vongvisessomjai*, 2007].

The 1995 flood [*Siripong et al.*, 2000] began with heavy rainfall from Tropical Storm "Luis" that hit the upper part of the basin. Water was released from the Sirikit Dam through the emergency spillway and a large discharge from the Nan and Yom rivers caused flooding in the plain areas of the middle part of the basin and subsequently in the delta plain of the lower area. The main cause of flooding was assumed to be the small capacity of river sections in the lower part. Overflow from the main rivers inundated mostly agricultural areas in the delta plain for 2–3 months. However, Bangkok was not affected due to flood mitigation structures that had been built and strengthened by 1984.

The 2006 flood was mainly caused by the small conveying capacity of the Chao Phraya River in the lower sections, considered to be a bottleneck [*Vongvisessomjai*, 2007]. The crucial flooded areas were agricultural areas upstream from Ayutthaya. The floodwaters reached Ayutthaya, causing damage to urban areas with industrial factories.

3.1.2 Development of master plans for flood mitigation

The first master plan was set up and implemented after the 1983 flood. His Majesty the King Bhumibol Adulyadej recommended the King’s dike project for the areas surrounding Bangkok, especially along the northern and eastern boundaries [*Vongvisessomjai,* 2007]. Dikes were also built along the Chao Phraya River in the Bangkok area. Thanks to these measures, Bangkok was not affected by the 1995 floods. The second master plan was created after the 1995 flood. The King recommended the construction of flood retention ponds, known as “monkey cheeks”. Based on that recommendation, the RID developed eight water storage areas in the Chao Phraya River Basin and the BMA constructed 21 temporary retention ponds within Bangkok, which are used to temporarily store water during high tides. Incorporating the function of monkey cheeks, several flood mitigation measures were implemented by the RID, such as an increase in the height of flood barriers, river and drainage improvements, a loop cut (short cut) into the Bangkok Port and construction of multipurpose dams [*Siripong et al.*, 2000]. Bangkok and the neighboring areas were safe from the 2006 flood due to these improvements.

However, even with the development of master plans for flood mitigation, the 2011 flood brought damage to urban areas, including Bangkok, as well as agricultural areas. Economic zones in Bangkok and even the Don Muang International Airport were inundated and heavily affected by the 2011 flood.

3.2 Flood surveys for the 2011 flood

A team from the National Institute for Rural Engineering (NIRE) surveyed the 2011 flood three times. The team’s mission was to collect information on the 2011 flood in the Chao Phraya River Basin, such as flood management and flood mechanism, and to collect hydrological and meteorological data and data on irrigation facilities. The first visit was in December 2011, with the main target being to assess the flood situation and to collect the necessary data through interviews. For the upstream survey, the team visited the Bhumibol and Sirikit dams to learn about their operation during floods. Then, the team visited the central RID office at Bangkok to interview engineers about the flood situation and flood management, and they also visited the Chao Phraya Diversion Dam, an important facility for managing floods in the lower area of the basin. The team also surveyed the impacted areas, such as the irrigation areas on the eastern side of the Chao Phraya River and the Nava Nakhon Industrial Park area situated downstream from Ayutthaya. In addition, to check the drainage system in Bangkok, the team visited the pumping station downstream from the Rangsit Payulsak Canal, which is used for draining floodwaters to the Chao Phraya River when the water levels in the Chao Phraya River are higher than those in the drainage area. The second and third missions focused on monitoring and collecting hydrological and irrigation data. During the third visit, in which the author participated, we found the importance of the main roads for floodwater storage; accordingly, we visited the central DOH and a branch office at Lop Buri to collect information on the roads, such as elevations and line networks. Moreover, the author visited the Department of Water Resource Management, EGAT and the Chao Phraya Diversion Dam to learn about the operational rules for cooperative management between the Bhumibol and Sirikit dams in terms of supplying water to remote irrigation areas in the middle and lower reaches. The information obtained on water management including agricultural water use is summarized in **Section 2.6.3.**

3.3 Characteristics of the 2011 flood

In 2011, the largest flood ever recorded in Thailand (70-year return period) inundated both irrigation and urban land in the Chao Phraya River Basin, especially low-lying areas including the megacity of Bangkok and neighboring Ayutthaya. The flood severely affected agricultural production and manufacturing industries, as well as the Thai economy and human life. *The World Bank* [2012] estimated the cost of damage due to the 2011 flood at about 1425 billion baht (US$ 45.7 billion). The plain areas of the basin suffered from flooding for about five months, from July to November.

3.3.1 Climate-related factors

From June to October 2011, the Chao Phraya River Basin, particularly the upper and middle reaches, experienced heavy rainfall from five large tropical storms: Haima (June 24–26), Nock-ten (July 30–August 3), Haitang (September 28), Nesat (September 30–October 1), and Nalgae (October 5–6). **Figure 3.1** shows the average annual precipitation in 2011, which is an estimated 1.4 times higher than the average annual precipitation for 2004–2011 (**Fig. 2.2**). According to **Fig. 3.1**, high total rainfall occurs in the upper part of the Yom and Nan river basins as well as in the middle basin areas from the Bhumibol and Sirikit dams to Nakhon Sawan. This is considered as the main cause of the increased inflow into the large dams in the basin, especially the Sirikit Dam, and also the cause of the increased river discharge downstream from these dams. **Figure 3.2** shows the inflow discharge into the Bhumibol and Sirikit dams during the time of the five storms. It reflects that; those storms produce high inflows into both dams.

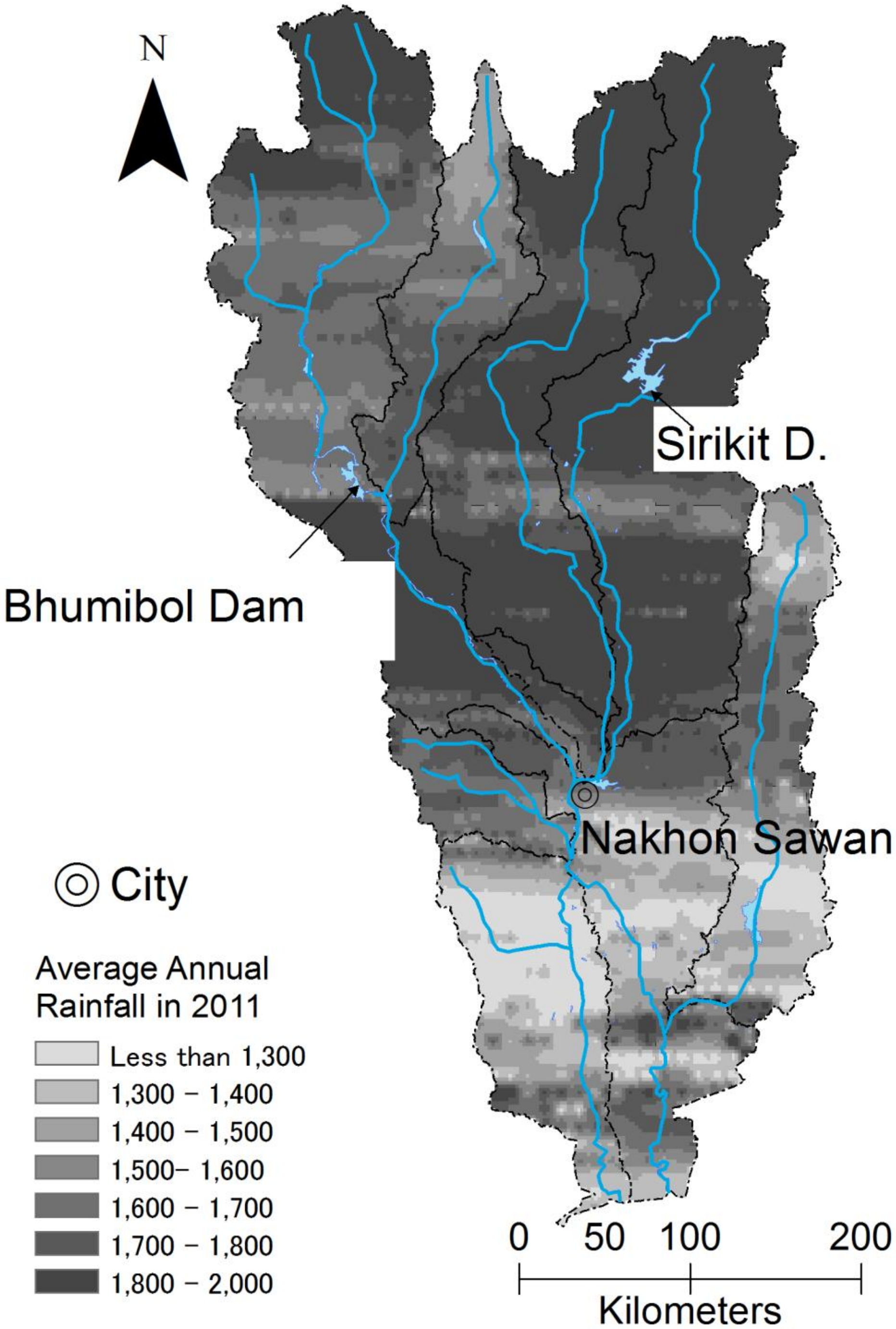
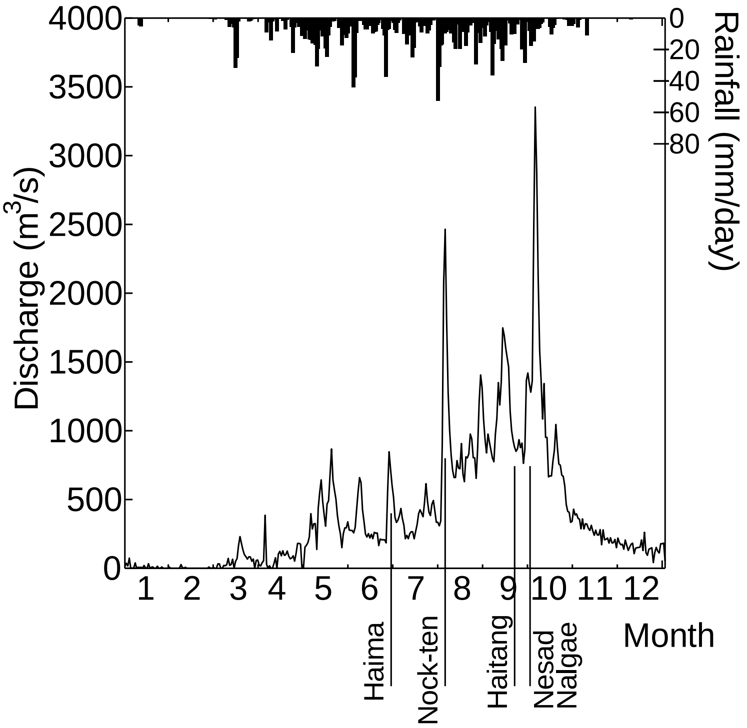
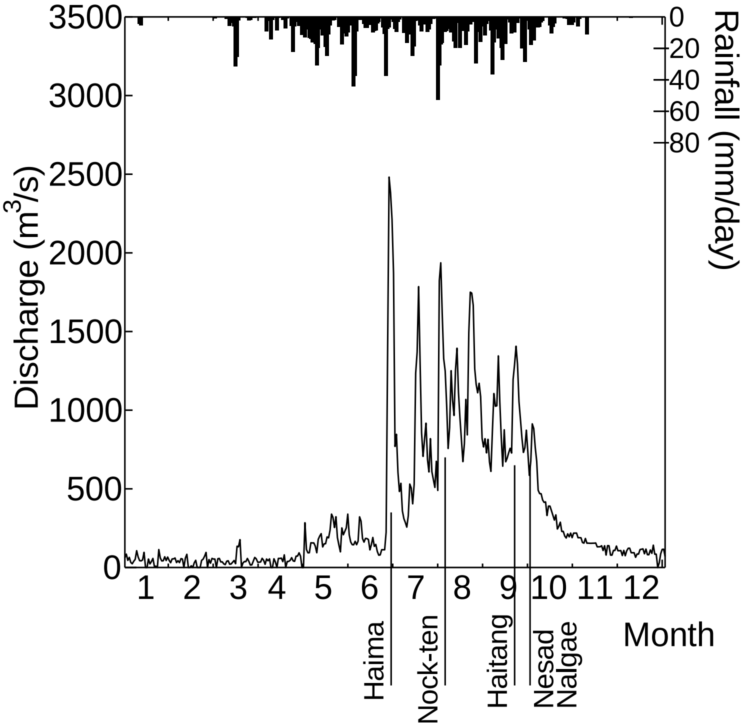


Fig. 3.1 Annual precipitation in 2011



a) Bhumibol Dam



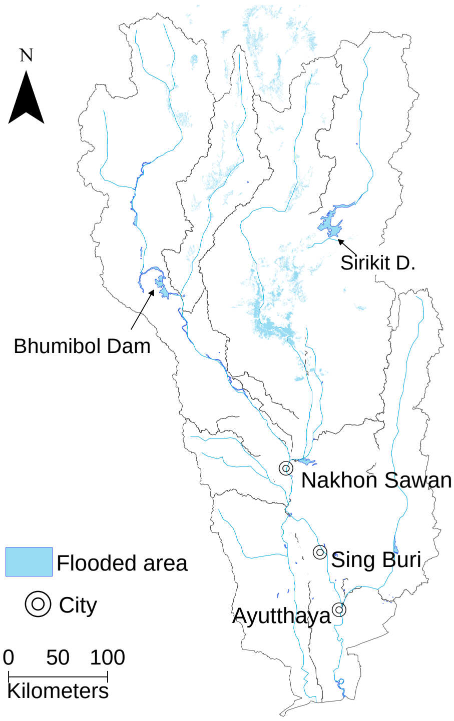
b) Sirikit Dam

Fig. 3.2 Strom water inflow into the Bhumibol and Sirikit dams in 2011

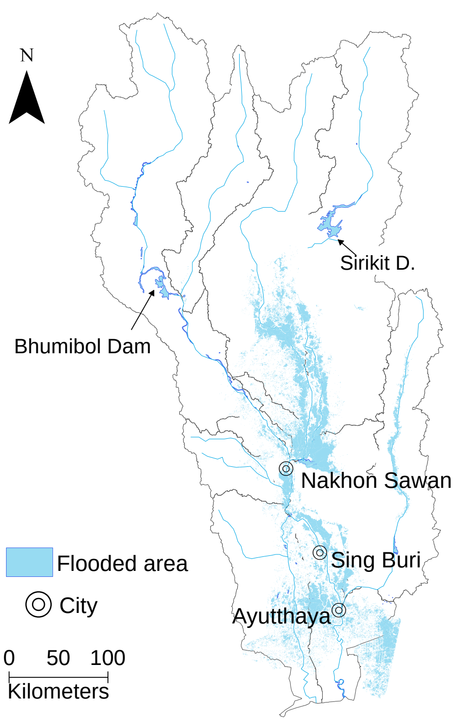
3.3.2 Flooding situation

Figure 3.3 shows the transition of areas inundated by floods (August–November) in the basin according to the data observed by satellite and normalized by GISTDA. *Komori et al.* [2012] concluded that flooding started around July in the upper reaches of the basin. These floods also reflect the large inflow into the Bhumibol and Sirikit dams, as mentioned earlier. In addition, floods occurred around the confluence of the Yom and Nan rivers in the middle part of the basin. These floods reached the upstream part of Nakhon Sawan, which is the confluence point of the four main tributaries. However, there were no large storm events in August. From September through October, after the Haitang, Nesat and Nalgae storms, inflow into the Bhumibol and Sirikit dams rapidly increased, as shown in **Fig. 3.2**. Consequently, both reservoirs reached their storage capacity, while flooding occurred in the lower reaches after the breach of dikes along the Chao Phraya River between Nakhon Sawan and the northern part of Bangkok. The RID reported the breach of 28 dikes (17 on the eastern bank and 11 on the western bank) (**Fig. 3.4**). The first breach occurred around the middle of September near Sing Buri (**Fig. 3.4**) after which the breach points increased from late September to mid-October. However, the breaches were not repaired until the last week of November.

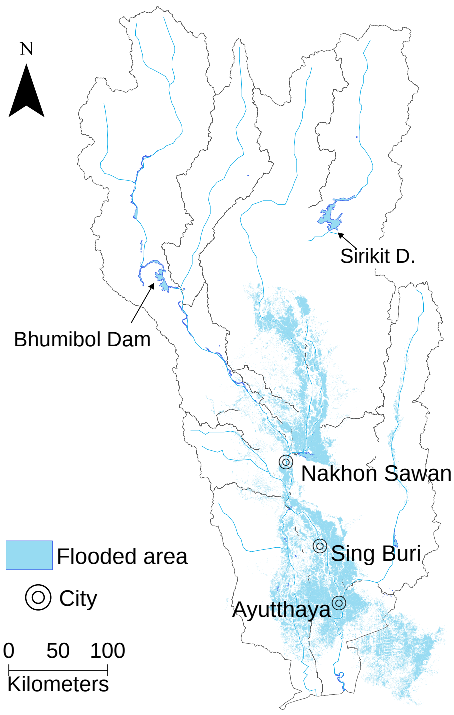
Floodwaters initially inundated low-lying irrigation areas bounded by elevated main roads and railways, and then overflowed to flood surrounding areas. These floods reached Ayutthaya in October and hit the urban areas around Bangkok in November.



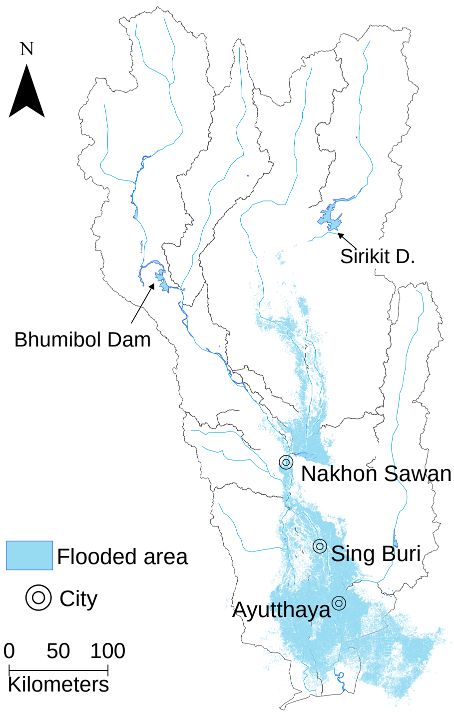
(a) August 7



(b) September 21



(c) October 17



(d) November 15

Fig. 3.3 Transition of flooded areas from August through November in 2011

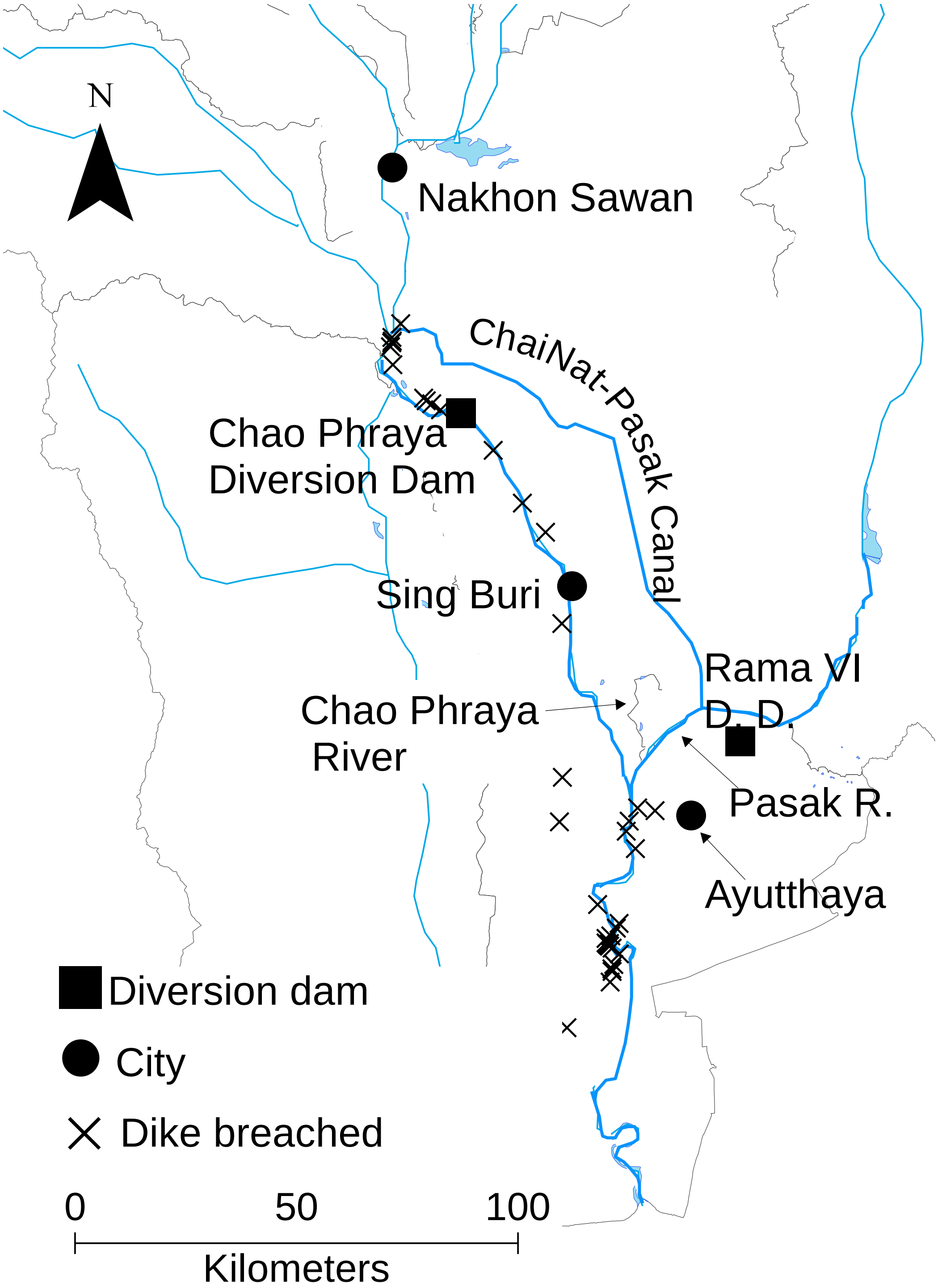


Fig. 3.4 Location of dike breach points

3.4 Floodwater management carried out during the 2011 flood

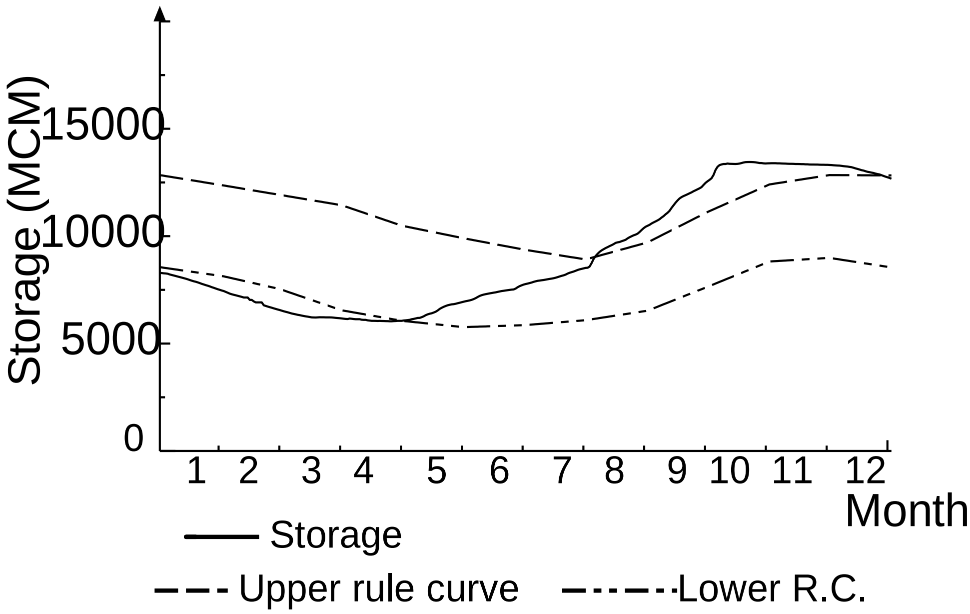
During the flood, the Thai government set up an ad hoc task force to oversee the flood operation, although the situation changed rapidly and communication seemed to be unreliable and muddled [*Koontanakuvong*, 2012]. The task force committee, which included several organizations in the water management sections in Thailand, such as RID, EGAT, BMA, TMD and GISTDA, carried out floodwater management as an integrated organization.

3.4.1 Management of the Bhumibol and Sirikit dams

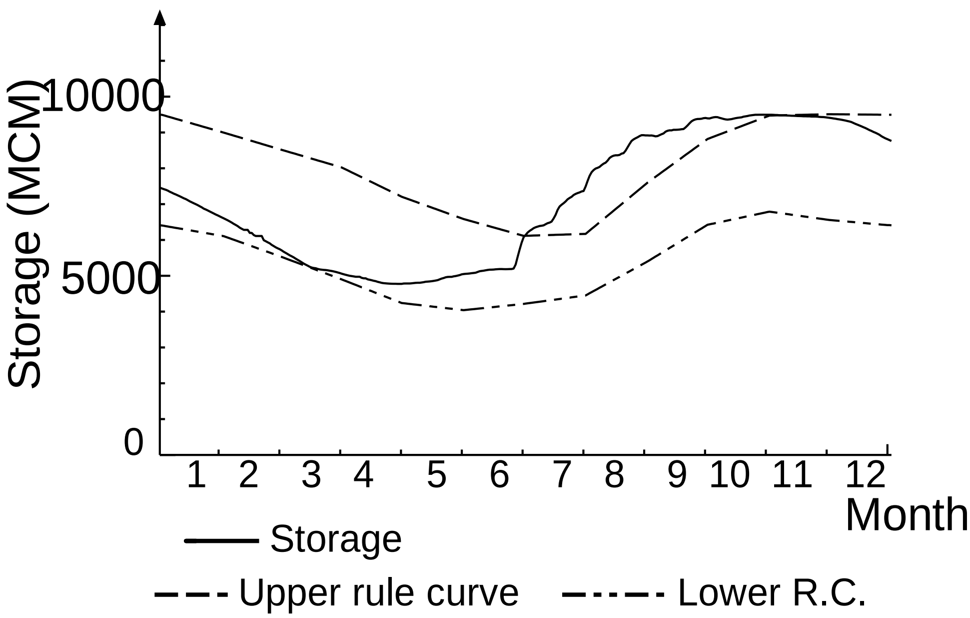
EGAT is responsible for floodwater management related to the Bhumibol and Sirikit dams. The storage capacity of these two dams in 2011 and their operation rule curves are shown in **Figs. 3.5** (a) and (b), and their release of water during that time is shown in **Figs. 3.6** (a) and (b). Under normal conditions, EGAT controls the storage in both reservoirs at a level between the upper and lower rule curves.

From September through October, EGAT tried to reduce the volume of water released from the Bhumibol and Sirikit dams due to the flood situation in the middle and lower parts of the basin (**Fig. 3.3**), while there was large inflow into the reservoirs during the same period. As a result, storage in the Bhumibol and Sirikit dams exceeded the upper rule curves and reached maximum capacity in October to early November. Of course, there was a difference in their operation: inflow was stored in the Sirikit Dam in July and in August, earlier than that in the Bhumibol Dam due to the direction of storms and the rainfall amount in the upper areas, so the Sirikit Dam reached its storage capacity in mid or late September, while the Bhumibol Dam had more room to store water during the same period.

In November, to maintain the stability of the Bhumibol and Sirikit dams, floodwaters were released via the emergency spillways, which exacerbated flooding in the lower reaches. Thus, flooding in the lower reaches was considered to be directly affected by the operations of both dams, as explained in **Section 3.3.2**, so floodwaters were still lingering in the lower areas by November (**Fig. 3.3**).

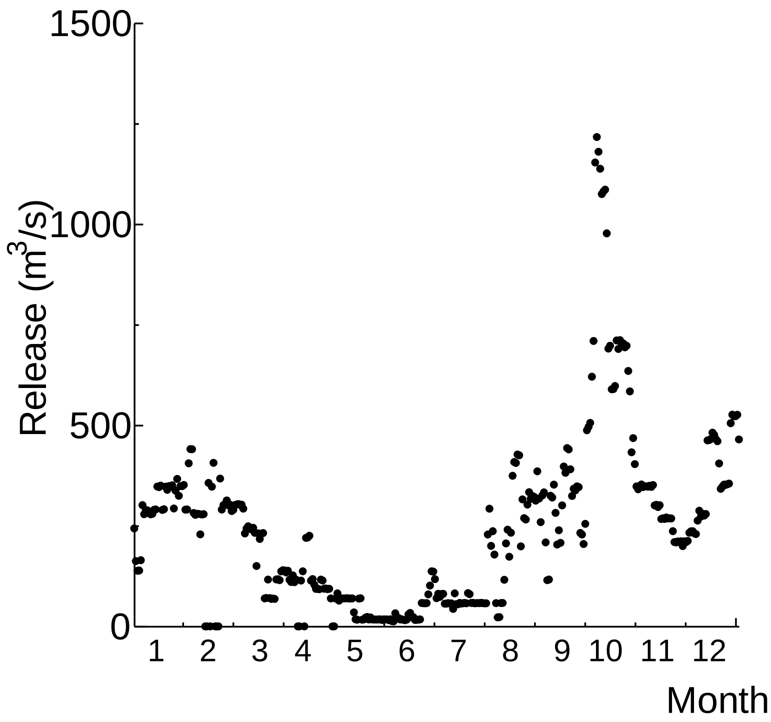


(a) Bhumibol Dam

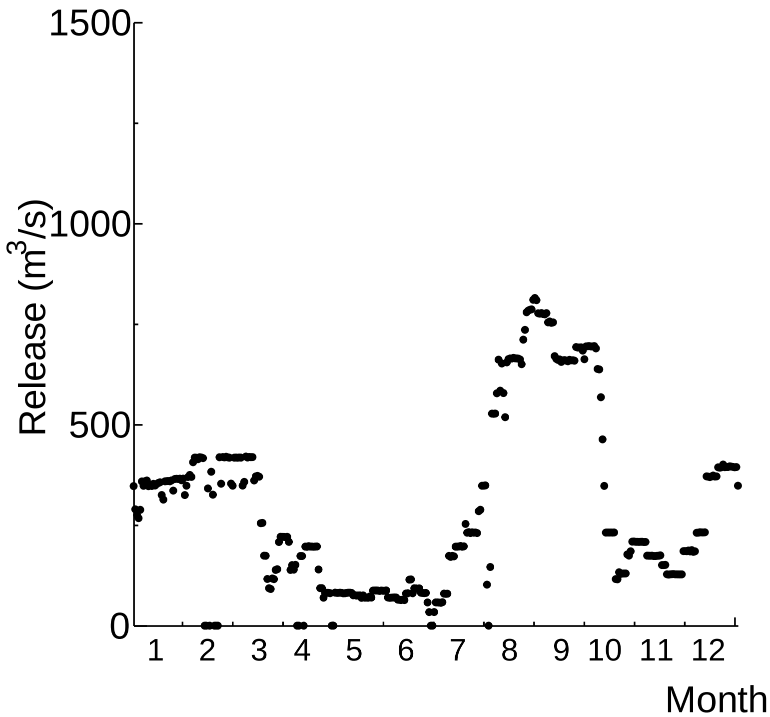


(b) Sirikit Dam

Fig. 3.5 Storage hydrograph of the Bhumibol and Sirikit dams with their rule curves



(a) Bhumibol Dam



(b) Sirikit Dam

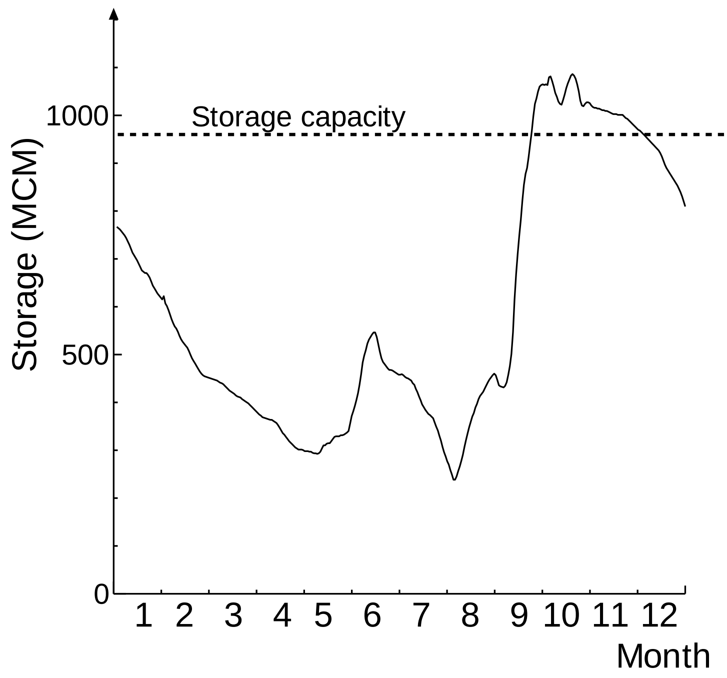
Fig. 3.6 Release of water from the Bhumibol and Sirikit dams

3.4.2 Management of the irrigation facilities in lower areas

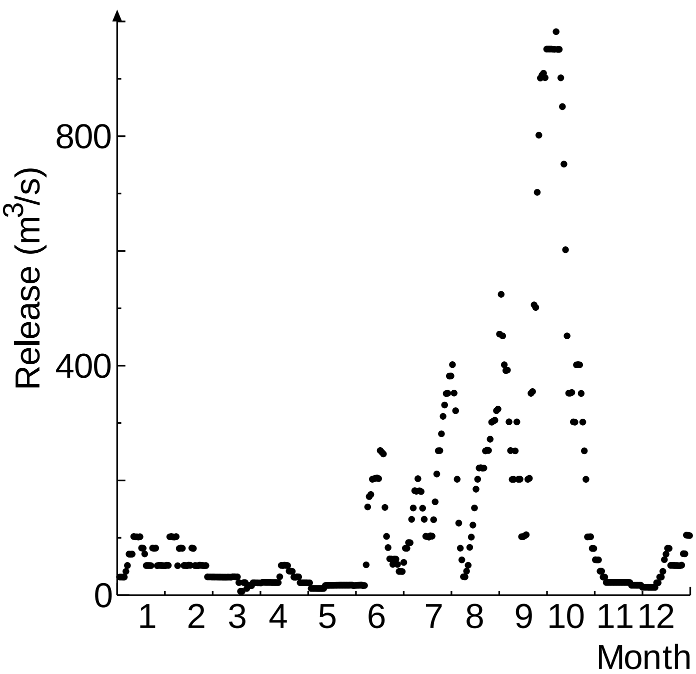
The RID controls the release of water from the Chao Phraya Diversion Dam at 1,500 m^3/s, as the first target, to prevent floods in the lower reaches of the basin, especially at Ayutthaya. At this point, the RID regulates the water level upstream from the Chao Phraya Diversion Dam by using a series of flood control gates, and diverts water to the irrigation canals through intake facilities, as mentioned in **Section 2.6.3 (3).**

Discharges observed in 2011, which were diverted through intake facilities to the eastern and western irrigation areas of the Greater Chao Phraya Irrigation Project, are shown in **Fig. 4.7** (b), as a comparison of calculated and observed diversion water, which is explained in **Chapter 4**. From September through October, however, the RID did not adjust the intake facilities on the western side by considering their capacity, even though the release of water from the Chao Phraya Diversion Dam exceeded the first control target (**Fig. 4.6 (b)**) and floods had already started due to dike breaches at several points in the lower areas from the Chao Phraya Dam (flooded areas around Sing Buri in **Fig. 3.4**).

Figures 4.7 (a) and (b) show the operation of the Pasak Dam including storage and release, respectively. In analogous contents for the Bhumibol and Sirikit dams, the Pasak Dam released water from September through November to maintain its stability (**Figs. 3.7 (a)** and **(b)**), while floods continuously affected the lower areas especially in Ayutthaya (**Fig. 3.3**). The maximum release is approximately 1,000 m^3/s. As one of the causes for the highest flood on the eastern side of the lower basin, it would be important to take release from the Pasak Dam.



(a) Storage of the Pasak Dam



(b) Release from the Pasak Dam

Fig. 3.7 Operation of the Pasak Dam during 2011

3.4.3 Management of drainage system in urban areas

The RID drained floodwaters into the lower areas from Ayutthaya to the northern part of Bangkok through three main drainage canals and through the lateral canals as mentioned in **Section 2.5**. Pumping stations at the edge of the Rapeephat Yaktok and Ransit Payulsak canals were used to drain floodwaters into the Chao Phraya River. On the other side, floodwaters were drained into the Bangpakong River (outside the Chao Phraya River Basin) by using a pumping station at the Hokwa Canal. Temporary embankments and sand bags were used to increase the height of dikes along the streams and temporary flood retention walls were also used in urban areas.

The BMA used their drainage facilities, such as the tunnel pumping stations, to drain floodwaters into the sea, and they used sandbags to prevent water from entering the pipeline.

3.5 Damage caused by the 2011 flood

3.5.1 Damage to agricultural sector

The total area of affected farmland was approximately 17,500 km^2, mostly located in the delta plain areas of the lower basin and in flat areas in the Yom and Nan sub-basins in the middle basin area [*Haraguchi*, 2013]. The estimated agricultural damage and loss was approximately 1,008.9 million US$ [*World Bank*, 2012]. Paddy fields suffered the highest loss, estimated at 70% of the total agricultural loss.

3.5.2 Damage to industrial sector

Seven industrial parks were severely affected by flooding: Bang Pa In, Bangkadee, Factory Land, Hi-tech, Nava-Nakhon, Rojana, and Saha Rattana. These are located in the lower areas from Ayutthaya to the northern part of Bangkok on the eastern side of the Chao Phraya River. Inundation depth was reported as about 2–4 m. The highest number of those affected were Japanese manufacturers, at about 450 in total. The World Bank reported that the overall damage due to floods in the industrial arena sector was approximately 7.4 billion US$.

3.5.3 Damage to urban areas and infrastructures

The Thai government reported that about 1.5 million houses and other structures were impacted throughout the duration of floods with nearly four million total structures estimated to have sustained affects [*Aon Benefield*, 2012]. The World Bank reported an economic loss of about 2.7 billion US$ for this sector.

Transportation infrastructures were heavily impacted during the floods. According to the DOH report, rural roads, highways and bridges were affected by flooding at about 1,700 points in total. The DOH estimated the cost of loss and damage at 4.5 billion US$. The International Don Muang Airport was also affected by flooding from October through November. After the floodwaters were drained from the airport, the terminal buildings and runways had to be renovated; they re-opened in March 2012. Moreover, multiple railway lines were submerged, especially in the lower areas of the basin.

3.6 Evaluation of flood storage function by paddies

3.6.1 Features of the 2011 flood and further analysis

Due to the continuous heavy rainfall mentioned above, low-lying areas in the upper and middle reaches of the Chao Phraya River Basin suffered from inundation. Heavy rainfall continued through to mid-October, so floods extended to paddy areas and to industrial and residential areas in the northern and central area of Bangkok. Total precipitation was 1.2 to 1.8 times (1/50-year return period) that of a normal year, as mentioned earlier. Given the nature of the large floods, which were intensively covered by the mass media as disastrous events, and which caused urban inundation damage according to the heavy rainfall at the time, the role of flood storage in paddy regions was analyzed in the total flood processes.

3.6.2 Targeted paddy-dominant areas

The target area is an irrigated paddy region surrounded by the main stream of the Chao Phraya River, the Chainat-Pasak Canal and the Pasak River (**Fig. 3.8**). In the course of flooding, overflows and/or dike breaks/breaches occurred in the upper and lower reaches from the Chao Phraya Diversion Dam. Discharge at the point of the Chao Phraya Diversion Dam exceeded 3,700 m^3/s on September 21, 2011 Dike breaks started in the order of 1, 2, 3, ….., 12, etc., as shown in **Fig. 3.9**, from September 14 to October

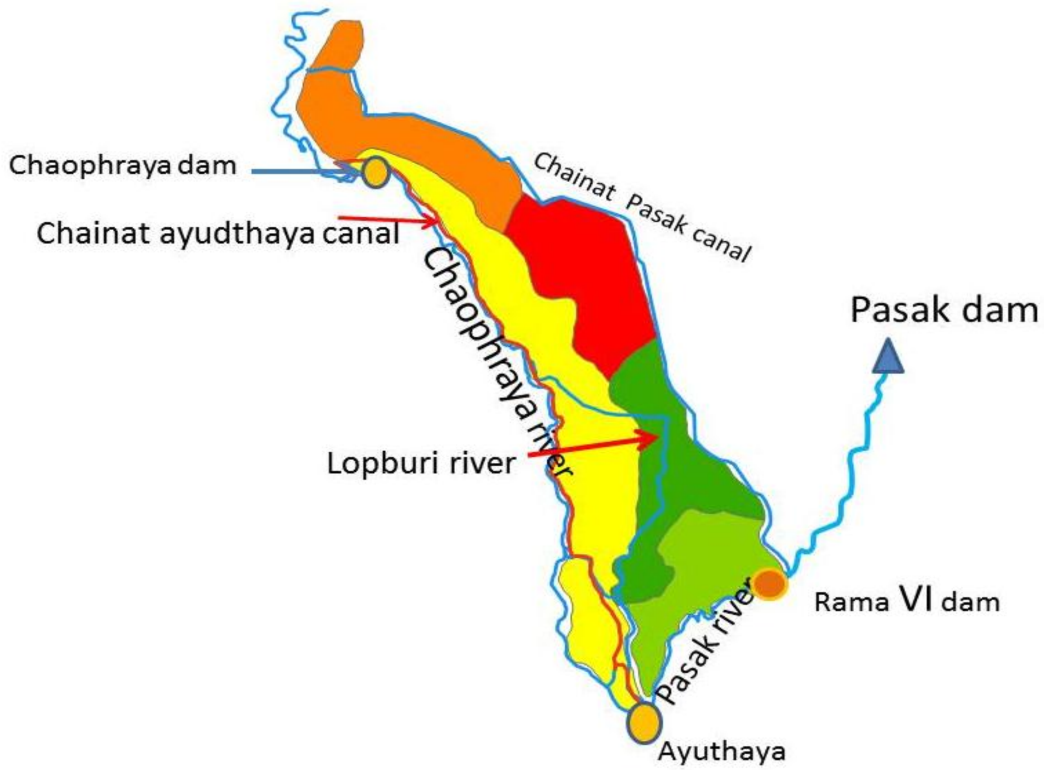


Fig. 3.8 Division of the target area surrounded by irrigation and drainage canals/rivers

7, 2011. As a result, a large amount of floodwaters moved into the paddies on the left side of the Chao Phraya River. In addition, floodwaters arrived at Bangkok and caused severe damage, affecting 71 provinces, 4 million people in 1.37 million houses, 18,000 km^2 of agricultural land, 32 urbanized areas (Ayutthaya to Bangkok) and so on.

3.6.3 Flooding in paddy areas and the effect of flood storage by paddies on the whole delta

1) Estimation method for evaluating the process and amount of paddy inundation

Floodwaters due to the dike breaks were stored in the paddy areas surrounded by main road networks and river dikes (serving as roads under certain conditions) (see **Fig. 3.10**). In the process of floodwater movement, floodwaters were stored in the paddy areas until the storage capacity was reached, and then the excess floodwaters moved over the crest of downstream roads. This cascade runoff process was repeated. The data required for the analysis included the starting time of the dike break at each point, the width of breached dikes, the elevation of breached dikes, details of elevations in flooded paddies, elevations of main roads and/or river dikes, and rainfall data for the area. Furthermore, for the drainage from the last sub-area (lower left in **Fig. 3.9**), most of the water returned to the Pasak River, which faces the edge of the downstream line, and the remaining water is assumed to have flowed over the left and right dikes of the Pasak River.

2) Relationship among flooding processes in paddy regions, release from the Pasak Dam and floods near Bangkok

Figure 3.10 shows the hydrographs (temporal transition, daily) of the estimated flood volume in each block (sub-area in **Fig. 3.9**). The figure compares the total volume of the estimated floodwater with the flood volume calculated from satellite data obtained by GISTDA (Geo Informatics Space Technology Development Agency) in Thailand. The comparison matches quite well, which verifies that the estimation is reliable. As a result, the maximum storage volume in the target region was estimated as 3,660 MCM (averaged flood depth of 1.68 m). Furthermore, the time from the start to the peak volume in each block was calculated as Upper: 8 days (Sep. 21, 2011), Upper Right: 3 days (Sep. 18), Central: 20 days (Sep. 14), Lower Left: 10 days (Oct. 3), Lower Right: 5 days (Oct. 12). The values in parentheses represent the starting time of the floods. On the other hand, the release from the Pasak Dam turned out to be quite large in spite of the storage conditions for maintaining the safety of the dam, so it is considered that the release affected the floods in the downstream area.

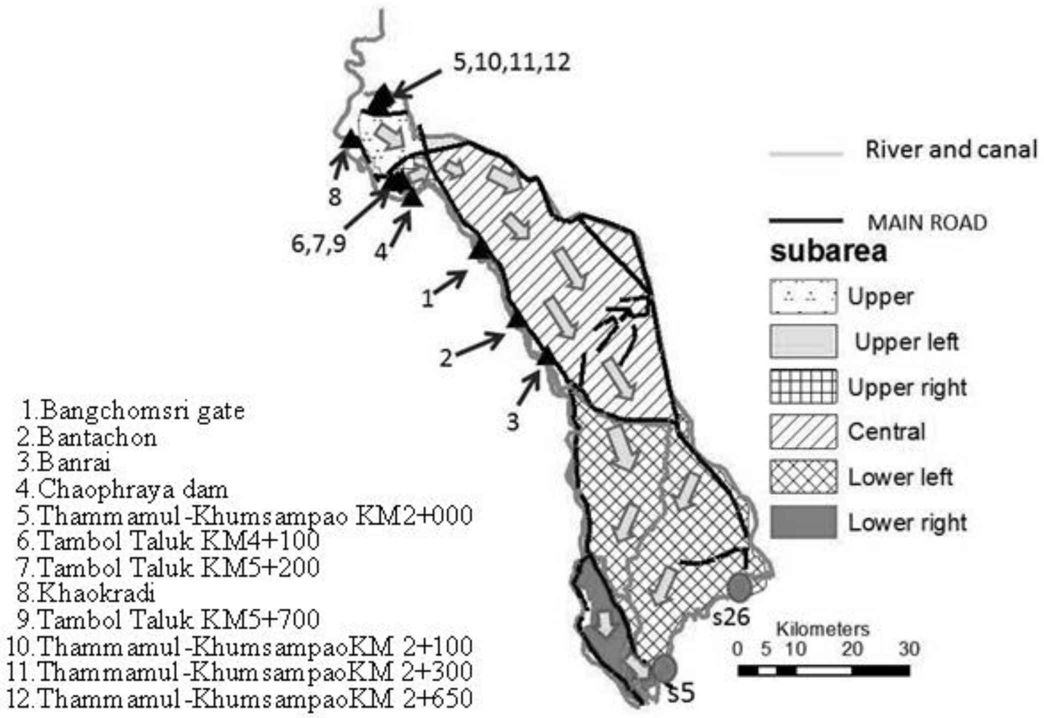


Fig. 3.9 Division of flooded paddies surrounded by the Chao Phraya River and the Chainat-Pasak Canal

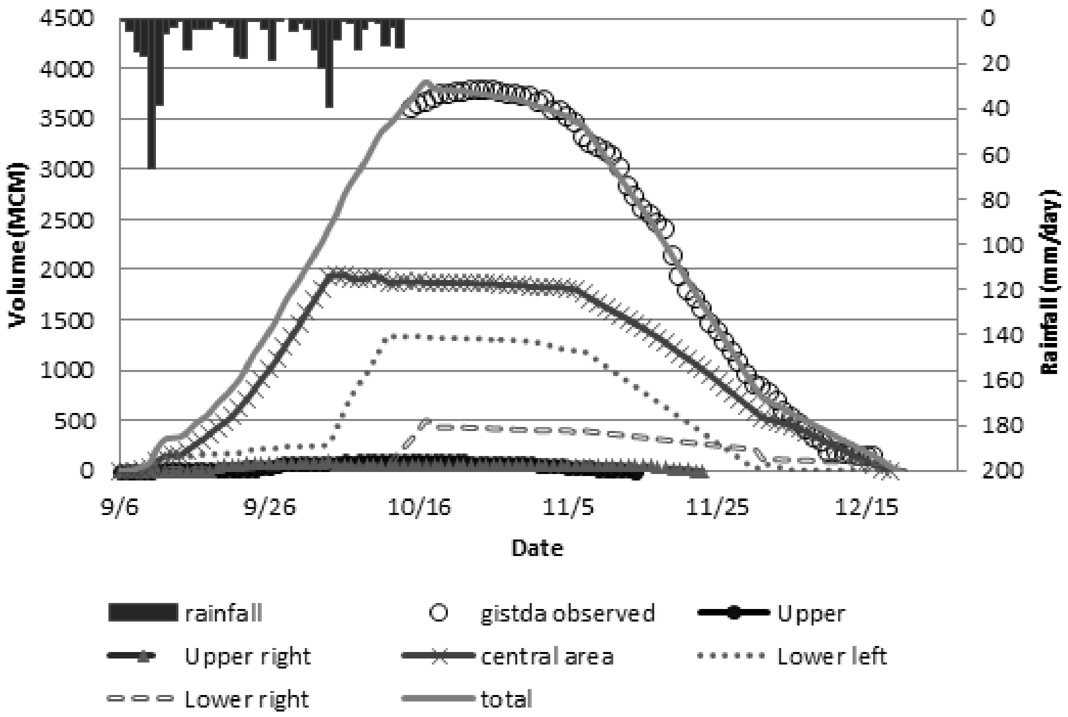


Fig. 3.10 Estimation of flood volume in the target paddy areas during the flood in 2011

3) Discussion

According to the hearing from Thai RID officials during the survey visit by NIRE staff, the maximum flood volume in the whole country was estimated as 10,000 MCM. Although the timing differs for each peak flood volume, the flood storage in the target area contributed greatly to the overall storage of floodwaters and the delay of runoff, reducing the damage in Bangkok.

Chapter 4

Application of DWCM-AgWU to the Chao Phraya River Basin with Large Irrigation Paddy Areas and Dams

4.1 Introduction

Water used for irrigation in the Chao Phraya River Basin is controlled by facilities such as dams and the irrigation infrastructure. Releases for irrigation were calculated by comparing the gross water requirements of irrigation areas, the discharge at intake points and the irrigation canal capacity based on the incorporation of the reservoir operation and water allocation/management models.

This chapter presents the modification of the DWCM-AgWU (Distributed Water Circulation Model Incorporating Agricultural Water Use) and the application of the revised model to an assessment of water use in the Chao Phraya River Basin for the period of 2008–2011, during which there were both drought and flood years. The results were used to determine the limitations of the present models as a first step in the development of a Seamless-DIF model.

4.2 Data input procedures

4.2.1 Normalization of topographical data and its use

Digital elevation model (DEM) data was normalized to a 10-km grid using the averaging method in the statistics function of ARC-GIS software to represent the elevation for a cell. The data was used to generate the flow direction and estimate the gradient of rivers by considering the distance between cells. River flow direction was generated up to the steepest direction by comparing eight surrounding cells.

4.2.2 Estimation of observed meteorological values

Hydrological data, including water level and discharge, was obtained from the RID of Thailand for 135 observation points and 150 cross sections for the period from when each station was installed through 2011. By using cross-sectional data, kinematic parameters were generated for a runoff model. Rainfall and other meteorological data (2007–2011) from the U.S. National Oceanic and Atmospheric Administration was collected for the 43 stations. The data was interpolated into each cell in the target area by using the inverse distance weighted method. Meteorological data was used for calculating evapotranspiration based on the Penman-Monteith equation.

4.2.3 Treatment of cropping patterns

Cropping patterns include two rice crops in irrigated paddies, one rice crop in rain-fed paddies, and upland crops, as shown in **Fig. 2.4**. As mentioned in **Section 2.3**, 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.

4.2.4 Incorporation of dams and irrigation areas

Modeling of the reservoirs in the Chao Phraya River Basin was carried out by targeting 10 large-scale and 62 medium-scale reservoirs (**Table 4.1**). Small-scale dams were not considered here because the total volume of those reservoirs was relatively small. In modeling the water storage of the large-scale reservoirs, data on effective storage capacity, intake facility capacity at downstream intake sites (e.g., maximum intake, maximum discharge of irrigation canals), and the planned municipal water volume was collected from the RID and from meetings conducted locally. Large-scale reservoirs in the Chao Phraya River 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 was collected from the RID. When several medium-size reservoirs existed within a single cell, the total storage capacity and beneficiary land area of the reservoirs within the mesh were added together, and such reservoirs were handled as a single dam.

With regard to the irrigation water allocation and management model, 18 irrigation areas were simulated, which were covered by large- and medium-scale dams. Under these conditions, data on irrigation facilities (point data), irrigation canal networks (line data), and beneficiary land (polygon data) was obtained from the RID and used to specify irrigation areas. **Figure 4.1** shows those areas in the Chao Phraya River Basin.

The 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 modeling 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.

Table 4.1 Operational information on irrigation facilities in the model (10 large- and 62 medium-scale dams)

No.	Dam name	Maximum storage (MCM)	Beneficiary irrigated area (ha) [Number of cells]
L.1	Maengat Sombulchol	265.0	28,000 [4]
L.2	Maeguang Udom Thara	263.0	19,710 [6]
L.3	Gewkhomah	170.0	3,200 [3]
L.4	Gewlom	106.2	22,052 [9]
L.5	Bhumibol	13,462.0	300,400 [71]
L.6	Sirikit	9,510.0	270,200 [62]
L.7	Kwae Noi Bamrungdan	939.0	24,800 [-]
L.8	Tabsalao	160.0	26,713 [-]
L.9	Khaseaw	390.0	26,376 [-]
L.10	Phasak Cholasit	785.0	46,179 [4]
M. 1–62	Medium-scale reservoirs	984.7 (total)	102,841 [62]
S. 1–347	Small-scale reservoirs	300.9 (total)	67,648 [347]

Note: The letters L, M and S in the 'No.' column denote large-, medium- and small-scale dams, respectively.

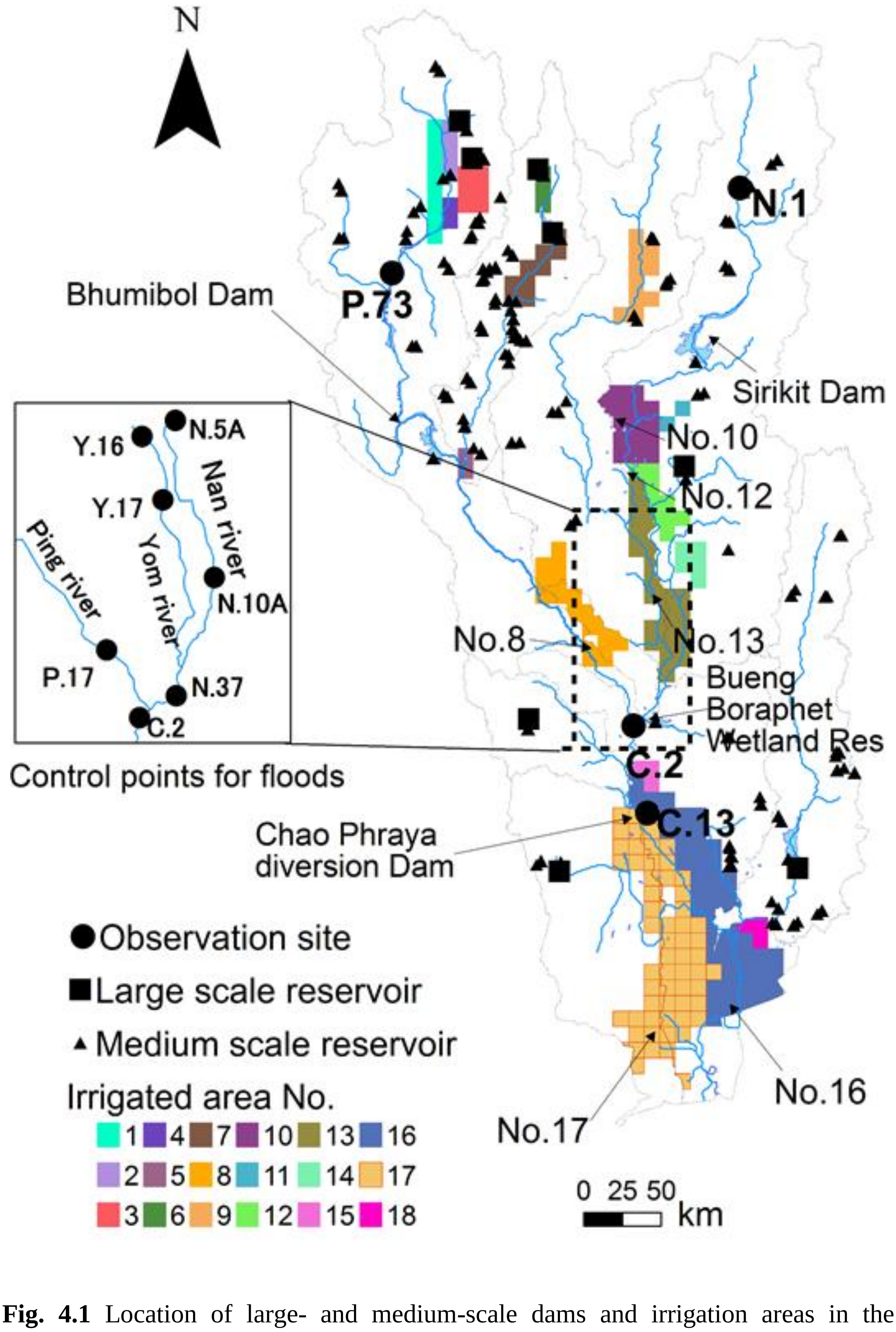


Fig. 4.1 Location of large- and medium-scale dams and irrigation areas in the modeling

4.3 Modification of DWCM-AgWU for the analysis

4.3.1 Modeling of DWCM-AgWU

1) The original model

The DWCM-AgWU [*Masumoto et al.*, 2009; *Taniguchi et al.*, 2009] was originally developed for the Mekong River Basin. The model calculates the water circulation in each cell (dimensions 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; and (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.

2) Dam management model

Storage calculation

The storage $V_{res}(t)$ [m^3] of a reservoir is given by the following equation having the storage $V_{res}(t-1)$ in the previous period (or the previous day if the calculation step is a day), the reservoir inflow $Q_{resin}(t)$ [m^3/d], and the reservoir outflow $Q_{resout}(t)$ [m^3/d]:

$$V_{res}(t) = V_{res}(t-1) + \left(Q_{resin}(t) - Q_{resout}(t)\right)\Delta t \tag{4.1}$$

where Δt [days] is the time of a single calculation step. The storage $V_{res}(t)$ was set at a minimum level (so-called dead water level) at zero (0).

The reservoir inflow $Q_{resin}(t)$ is given by the Runoff Submodel while the storage V_{res} $(t-1)$ in the previous period is already known. Therefore, we can solve the water-balance equation by finding the reservoir outflow $Q_{resout}(t)$.

In this model, it is assumed that the reservoir outflow consists of the irrigation release $Q_{resout}(t)$ [m^3/d], which is described later, the full-water release (spillway overflow), and the discharge for river maintenance. In addition, the necessary release for domestic use and for hydropower generation having the maximum power generation release, are considered.

Release for irrigation

In general, a reservoir-dependent irrigation region is targeted for irrigation by river discharge at the intake point for the irrigation area. Then, when there is a decrease in the runoff from the residual area downstream from the reservoir, resulting in a shortage of the necessary intake amount, supplementary water is released from the reservoir to compensate for the shortage. Accordingly, the discharge given by subtracting the dam release was defined on the previous day from the river discharge at the intake point on the previous day as the remaining area runoff. Then the difference between the runoff from the remaining area and the water demand at the intake point were estimated, and water was released to compensate the shortage.

In the reservoir-dependent irrigation areas in Southeast Asia, the ratio of irrigated area to beneficiary area differs between the rainy and dry seasons because the irrigated area varies seasonally. In the rainy season, most of the beneficiary area is irrigated, so it is equal to the reservoir-dependent beneficiary area. In the dry season, the irrigation area is sometimes given by the storage of the reservoirs at the beginning of the season. These are also considered in the model.

Incorporation into the distributed water circulation model

A reservoir such as a dam or an irrigation pond is placed on the edge between two cells in the distributed water circulation model. The runoff coming from the upstream cell is the reservoir inflow that is input into the dam control model. The reservoir release given by the model is the outflow from the upstream cell, which is input into the downstream cell. This means that in the downstream cell, the surface inflow to the cell is replaced with the reservoir release. The release for irrigation from the reservoir is given by using the gross water requirements derived from the paddy water use model. As a result, the necessary information (parameters) on the reservoir consists of the following six values: i) Cell number having an intake point; ii) Period-by-period effective storage; iii) Reservoir-dependent beneficiary area; iv) Design capacity of the domestic water requirement; v) Maximum power generation release; and vi) Reservoir functions.

3) Water allocation model

This model estimates the actual intake 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 and these processes are independent of those for river and slope runoff in the water circulation model. At the same time, the irrigation area is classified into two types: one extending over two or more cells and the other situated within a single cell.

Irrigation district spreading over two or more cells

For an irrigation area of multiple cells, it is necessary to model a series of processes: water intake, irrigated water distribution, and return flow because the cell with the drainage points for the downstream beneficiary area differs from that with the intake point.

Firstly, the water intake for the irrigation area from the river discharge at the intake point and the region's water demand (e.g., gross water requirements of the region, capacity of the intake facility, and water-rights discharge) are calculated. That is to say, water to be taken and fed to the area is either the river discharge Q_{riv} of the intake cell or the water demand Q_{dmnd} of the area, whichever is smaller.

$$Q_{div} = \min(Q_{riv}, Q_{dmnd}) \tag{4.2}$$

The intake water is distributed to the cell in which the paddy water depth is lower than the control water level in the irrigation area, and priority is given to paddy fields in the upstream part. The rate at which the amount of water is distributed to the cell, is projected gross water requirements considering field-by-field water demand, the irrigated area of each cell, and the irrigation efficiency. However, no water is distributed to a low-priority downstream cell if the sum of the gross water requirements given on a cell basis exceeds the intake of the region, because the model does not consider water reuse in the region.

The cell's share falls into irrigated water as paddy field supply and management requirements in channels. Most of the water supplied to paddy fields except evapotranspiration goes into the drainage channels, so management requirements are regarded as the inflow to the river channel of each cell. If the sum of the cell's share is lower than the intake of the irrigation area, the difference is appraised as management water requirements, and water is fed to all the cells in the area according to their irrigated paddy field ratios (= cell-by-cell irrigated paddy field area/irrigation district area).

The following shows the procedure (two steps) for making the water allocation and management model of the irrigation area having multiple cells as mentioned above.

i) Use the spatial information on the facilities for agricultural water use and beneficiary areas to relate intake facilities to the area.

ii) Use the information on intake points, irrigation channels, and cell-by-cell elevation to determine the allocation order.

In Step i), databases related to agricultural water use facilities are used to select the irrigation facilities (e.g., headworks, irrigation and drainage channel networks, and discharge observation points) and beneficiary areas. These data do not relate to each other in the original database, so the intake points, irrigation channels, and beneficiary areas to each other are connected and they are integrated into a single irrigation system. In Step ii), the cell-by-cell distribution process of the irrigation area is modeled by using the single irrigation system in i). Specifically, the headwork point is defined as the top of the irrigation area, and determine the water allocation order according to the following rules:

- Water is fed to cells in ascending order of distance from the intake point. If two cells are at the same distance, priority is given to the cell having a main irrigation channel.
- If two cells are at the same distance from the intake point and neither cell has a main irrigation channel, priority is given to the higher cell (in land elevation).

Irrigation area located in a single cell

In an irrigation area that is situated in a single cell, the discharge at the upstream end of the river channel is compared with the water demand (considering the capacity of the intake facility and gross water requirements) of each cell to define the smaller one as the paddy field's share for actual water intake. Next, as mentioned above, the difference between the cell's share and the supply for paddy fields is defined as the management water at the rate of the water flow in the river channel in the cell.

Necessary input data

The basin to be analyzed is divided into arbitrary cells and give each cell various data, such as land use as well as geographical and topographical conditions. Time-series data for input includes daily rainfall and other factors such as temperature, humidity, and wind speed, to project the reference evapotranspiration. A submodel included in the DWCM-AgWU is used to estimate the cropping areas as paddy fields, actual evapotranspiration, irrigation rate, and runoff at an arbitrary time and point.

In addition, the factors related to paddy water use are classified in detail and they are supplied to the model as cell information. The cropping system consists of rainy-season and dry-season cropping patterns because the two seasons are clearly separated. In a region where the temperature is moderate and irrigation conditions are good throughout the year, triple cropping takes place. In another region, where flooding occurs, there is a rice cropping system in which floodwaters are used for irrigation. Different regions use different types of rice crops. In a region where farmers suffer from damage due to a delay in the rainy season or a flood, they use photosensitive or deep-water-resistant rice varieties, while in another region that does not have such damage, farmers use high-yield non-photosensitive rice. In countries with advanced irrigation facilities, modern high-yield rice is popular. These practices are input in the model.

4.3.2 Modification to the Chao Phraya River Basin

1) Treatment of remote areas irrigated by 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 downstream from the dams, as mentioned in **Section 2.6.2 (2) and 2.6.3 (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 295 m^3/s, and the area on the western side of the river (No. 17), irrigated by three main canals with a total capacity of 495 m^3/s, were linked to both large dams. In addition, the water requirements of the irrigation areas in the middle part of the basin were estimated as the ratio of total remote irrigation area to irrigation area in the lower part, as the first term in Eq. (4.3):

$$Irr.Req._{Bhumibol\,or\,Sirikit\,Dam} = \frac{\sum Area\,of\,all\,remote\,irrigated\,area}{\sum Areas\,(Nos.16,17)} \times \sum irr.Req\,(Nos.16,17) \times \frac{Storage\,in\,Bhumibol\,or\,Sirikit\,Dams}{\sum Storage\,in\,Bhumibol\,and\,Sirikit\,Dam} \tag{4.3}$$

As the first step, the irrigation water requirements (*Irr.Req.*) for release of water from each dam was determined by considering the ratio of the remaining storage in each dam to the total remaining storage.

2) Handling flood peaks

The modeling 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 **Fig. 4.1**.

3) 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

According to **Section 2.6.3 (1)**, irrigated areas around the Bueng Boraphet reservoir are supplied with irrigation water from the reservoir by using pumps. From this point, the reservoir takes water from the Nan River to maintain the water level for other purposes.

In the modeling, paddy fields around the Bueng Boraphet 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 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

According to **Section 2.6.3 (3)**, the following treatment is introduced in the water allocation model: the river discharge at three intake points, the Bueng Boraphet wetland reservoir and the eastern (No. 16) and western (No. 17) irrigation areas (**Fig. 4.1**), is regulated at the control targets. However, the flooding situation in the irrigation 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.

4.4 Results and discussion

4.4.1 Estimated parameters

The target period for analysis is the five years from 2007 through 2011. However, the first year (2007) was set as a spin-up period, and is not used in validating the calculation accuracy of the model. As a result, the actual target period is a four-year term. The grid size was set to 0.1°, and for land utilization, the land use classification map that was created in units of grids was reclassified into five types of land use (forests, upland crop fields, irrigation rice paddies, rain-fed paddy fields, water bodies) and utilized.

The model parameters were determined by trial and error such that the inflow of the Bhumibol and Sirikit dams for the four-year period from 2008 through 2011 matches the observed values as well as the flow volume of the P.73 and N.1 observation points **(Fig. 4.1)**, both of which lie in the upper stream of the above dams, respectively. The parameters that were decided on are shown in **Table 4.2**. In addition, the obtained values related to agricultural water use, which are required in the rice paddy water use model and the cropping pattern/area estimation model, are also shown in **Table 4.2**. These values were determined based on the values used when conducting the analysis of the Mekong and the Mun-Chi river basins [*Taniguchi et al.*, 2009; *Kudo et al.*, 2012] as well as hearings conducted locally. The parameters K and P for the kinematic wave model applied to the calculation of the river channel flow were estimated by using river channel cross-section information for 135 points obtained through the RID.

Table 4.2 Parameters used in the model

No.	Type	Parameter	Value
1	Division of the target basin	Divided meshes (cells)	2063
		Sub-basins	8
2	Calculation	Time step	1 day
		Starting year	2007
		Stopping year	2011
		Total years	5 years
		Spin-up year (initial)	1 years
3	Water allocation, management	Number of reservoirs	72
		Number of large irrigated areas	18
4	Paddy fields	Water depth management	10 cm
		Percolation rate in paddies	3.35 mm/d
		Accumulated rainfall at cropping start (rainy season)	275 mm
5	Runoff	Root zone thickness	
		(paddy fields)	150 mm
		(forest)	955 mm
		(upland crops)	450 mm
		Groundwater flow rate	(-)
		Base flow	(-)
		Infiltration parameter	(-)
6	Delay of runoff	Moving average for surface flow (slope)	5 days
		Moving average for paddy runoff (slope)	30 days
		Kinematic parameter (channel)	(-)

Note: (-) indicates that the parameter varies according to the area.

4.4.2 Estimated results for river flow and dam management

1) 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 the measured discharge at Stations P.73 and N.1, located upstream from the Bhumibol and Sirikit dams, respectively. According to the limited number of stations especially in forest areas, the author verified the water balance in the upper river basin at Stations P.73 and N.1 by considering rainfall, evapotranspiration, river discharge at target point, water storage in the area as changing of soil moisture, and water storage in large dams. The target of verification is yearly. Discrepancies are calculated as adjusted factor using for rainfall.

The areas upstream from Station N.1 are mostly forest, while those upstream from Station P. 73 are a mixture of forest, large irrigation areas and urban areas. The urban and irrigation areas upstream from Station P.73 are supplied with water from two large dams, the Maengat Sombunchol and Maeguang Udom Thara, L1 and L.2 in Table 4.1, respectively. Therefore, the model parameters at Stations N.1 and P.73 represent the simple areas as forest and the complex areas as forest, and irrigation and urban areas, respectively.

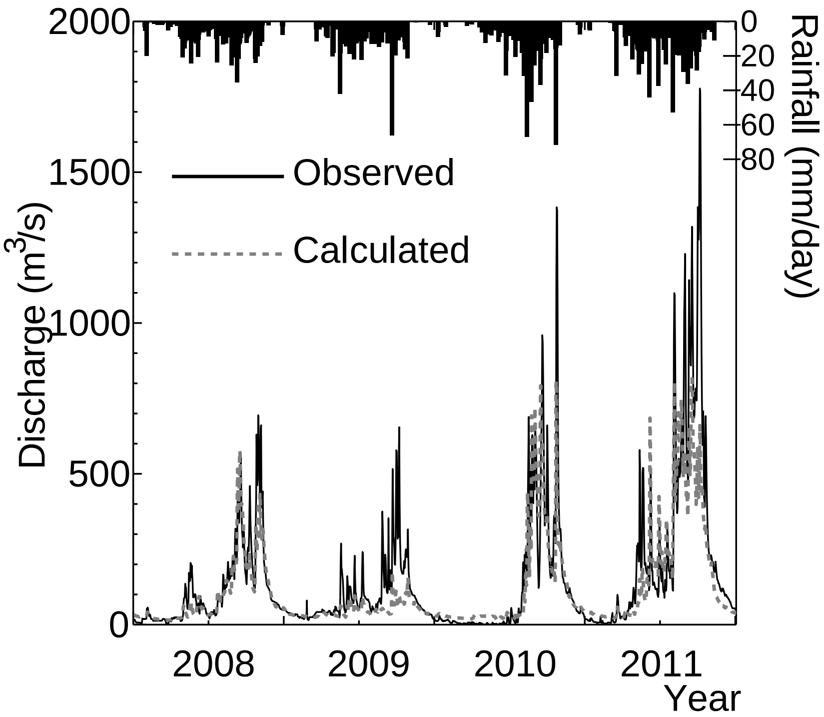
Calculated river discharge values at Stations P.73 and N.1 are selected to assess the accuracy of the model calculation for the upper parts of the basin. Moreover, inflow at the Bhumibol and Sirikit dams is selected to demonstrate the function of the dam operation models. A comparison of continuously simulated hydrographs is included for 2008–2011 as the whole target period and for 2009 and 2011 as typical years. The comparison of 2009 and 2011 represents the extreme events as drought and flood years, respectively.

Figures 4.2 and **4.3** show the comparison between the calculated and observed discharge at Stations P.73 and N.1, respectively. Furthermore, a comparison of the inflow into the Bhumibol and Sirikit dams is shown in **Figs. 4.4** and **4.5**, respectively. The results indicate that the daily fluctuations in the discharge during the rainy and dry seasons are well reproduced by the model at both sites. The hydrograph fluctuations at the upstream stations are almost the same as that for the inflow. However, there remain some discrepancies in the peaks.

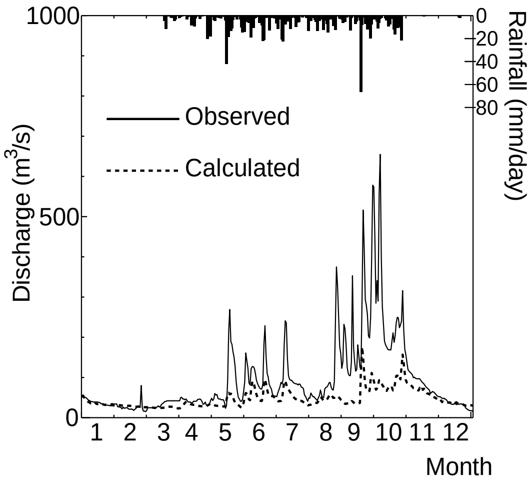
For 2008–2011, the relative errors of the calculated values in relation to the observed daily discharge at Stations N.1 and P.73 were 34.8–41.2% (average, 38.0%) and 34–45%, (average, 42%), respectively, while the relative errors of the calculated values in relation to the observed daily inflow into the Bhumibol and Sirikit dams were 34.7–51% (average, 39.8%) and 36.95–38.94% (average, 36.9%), respectively.

Inflow into the Bhumibol Dam in 2009 (drought year) was not used for the 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 the reservoir water level was incorrect. Despite omitting this data, the average relative error for the inflow into the Bhumibol Dam reservoir was nearly 40%, and the errors during low-flow periods in the dry seasons, especially in 2010, were large. The river discharge at Station P.73 and the inflow into the Bhumibol Dam reservoir during the dry season were apparently affected by discharges from the dam into the upstream sector of the river, but because water is discharged from the Maengat Sombulchol Dam (L.1 in **Table 4.1**) and Maeguang Udom Thara Dam (L.2) for hydroelectric power generation and domestic use as well as for paddy irrigation within the major irrigation areas in the simulation, the calculated flow during the dry seasons is high compared to the actual values.

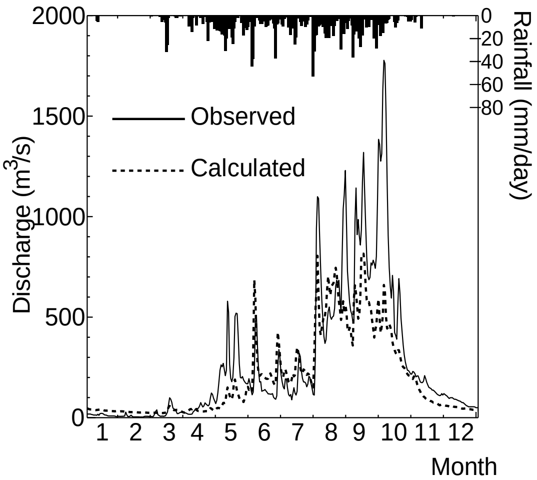
Moreover, the effect of the extreme drought event in 2009 reflects high discrepancies due to releases from the dams (L.1 and L.2) due to the supply of water exceeding the operating plan during the rainy season of 2009. However, the operator decided to reduce releases in the dry season of 2010 according to the water shortage of the previous year.



(a) a comparison for four years, 2008–2011

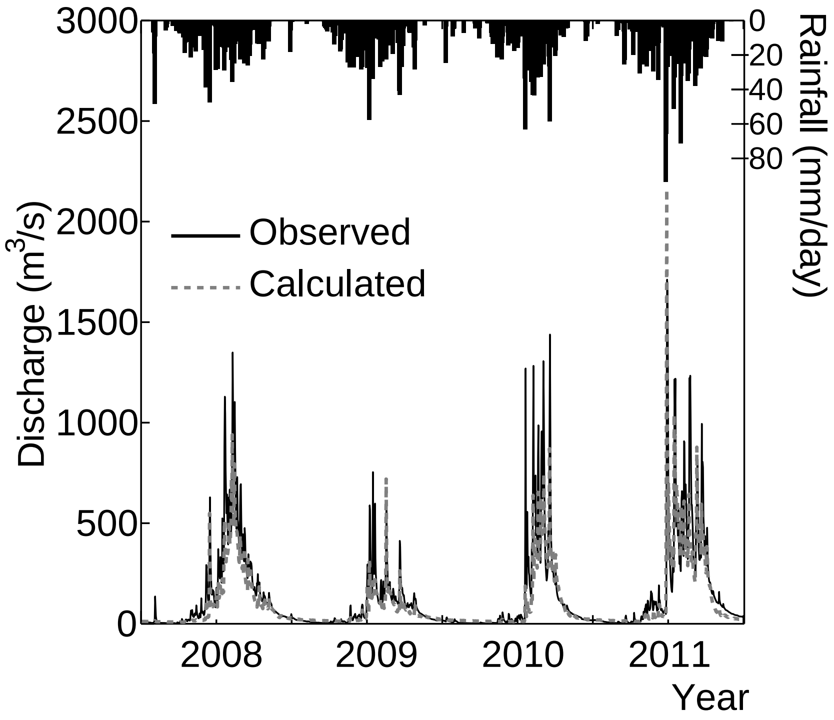


(b) 2009 (Drought)

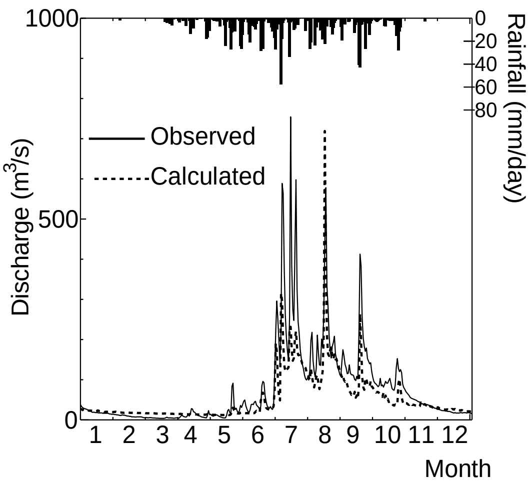


(c) 2011 (Flood)

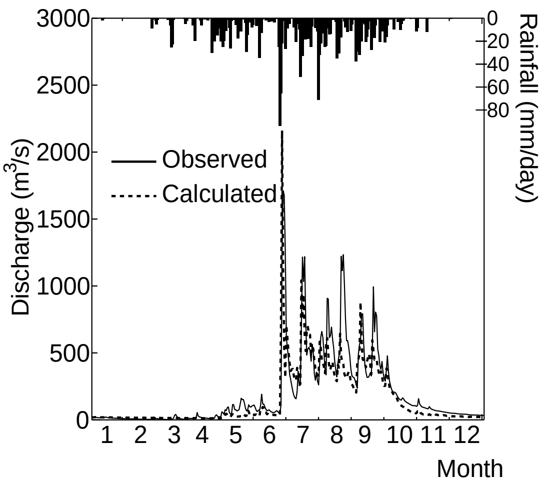
Fig. 4.2 Comparison of observed and calculated hydrographs at Station P.73



(a) a comparison for four years, 2008–2011

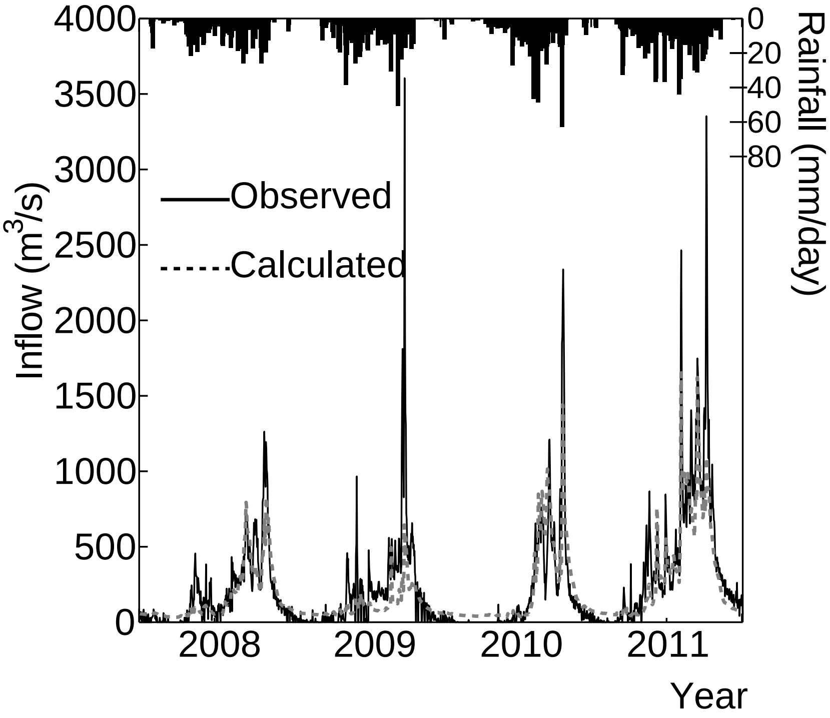


(b) 2009 (Drought)

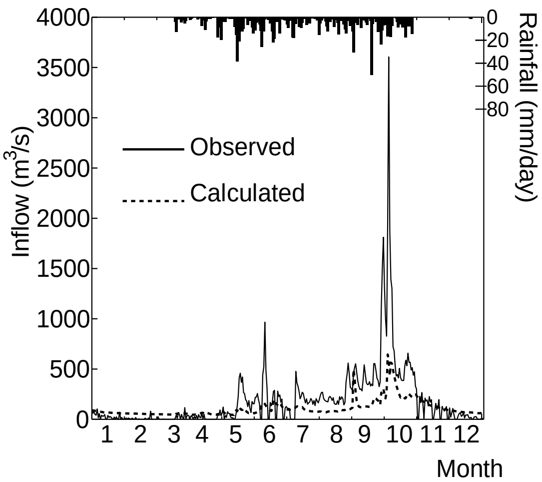


(c) 2011 (Flood)

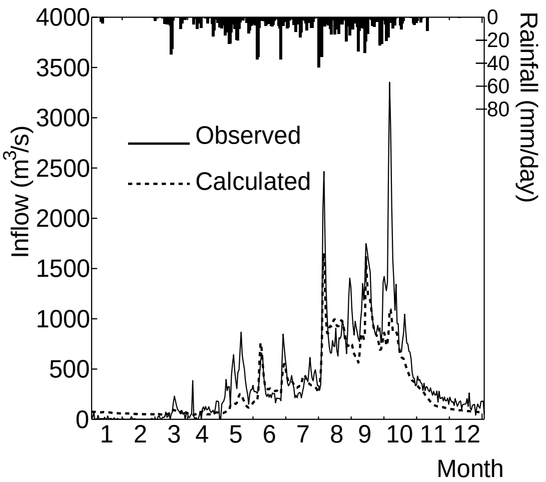
Fig. 4.3 Comparison of observed and calculated hydrographs at Station N.1



(a) a comparison for four years, 2008–2011

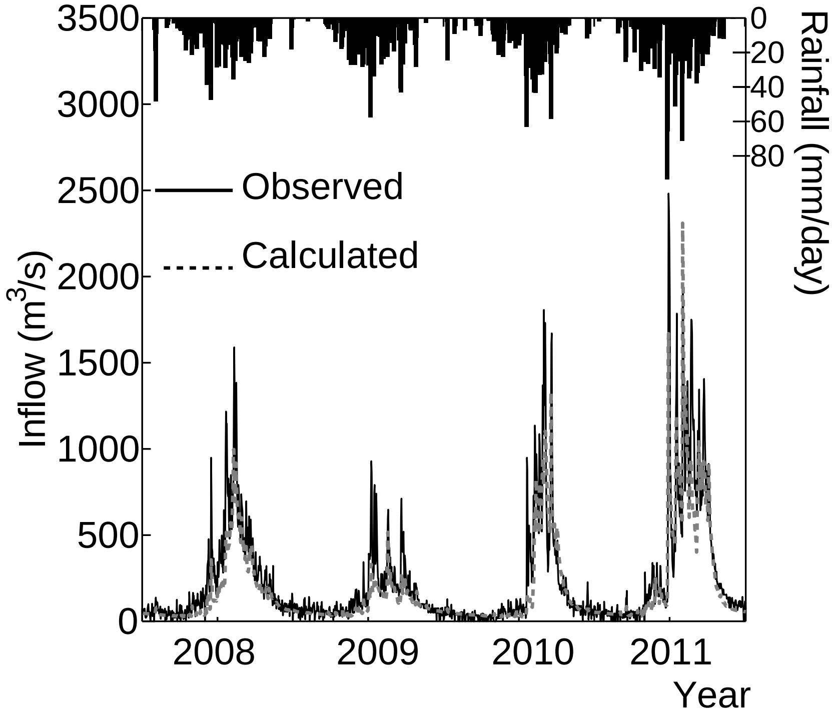


(b) 2009 (Drought)

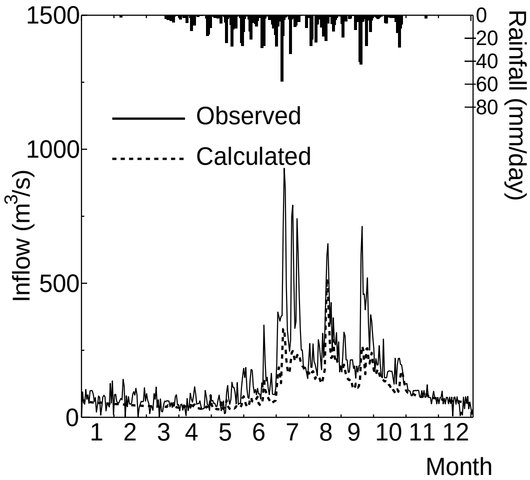


(c) 2011 (Flood)

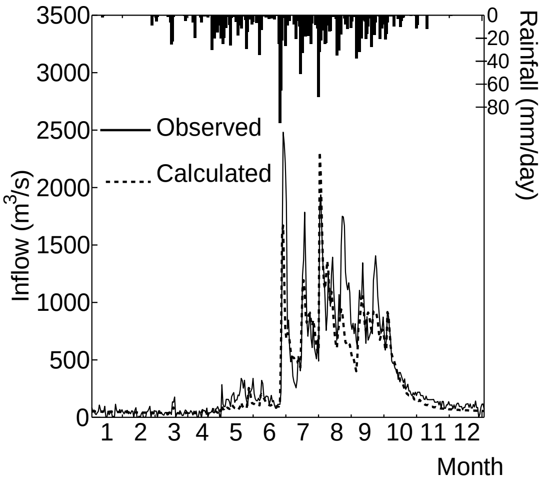
Fig. 4.4 Comparison of observed and calculated inflow into the Bhumibol Dam



(a) a comparison for four years, 2008–2011



(a) 2009 (Drought)

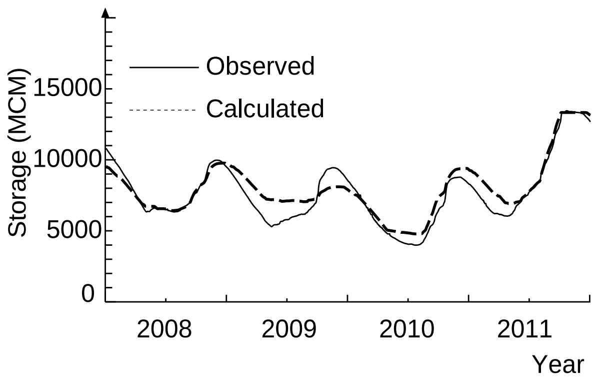


(b) 2011 (Flood)

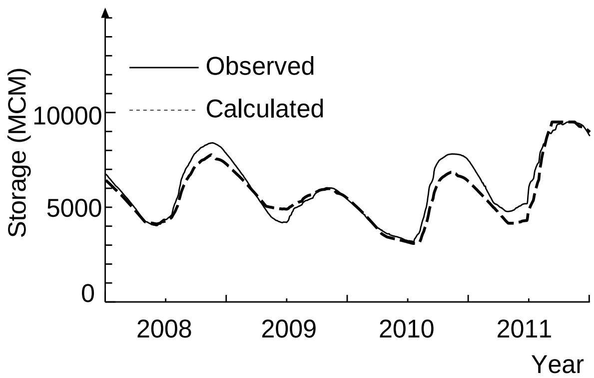
Fig. 4.5 Comparison of observed and calculated inflow into the Sirikit Dam

2) 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 **Fig. 4.6 (a)** and **(b)**. Based on the inclusion of a management model for the two large reservoirs, **Fig. 4.7** shows the calculated results from 2008 through 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.

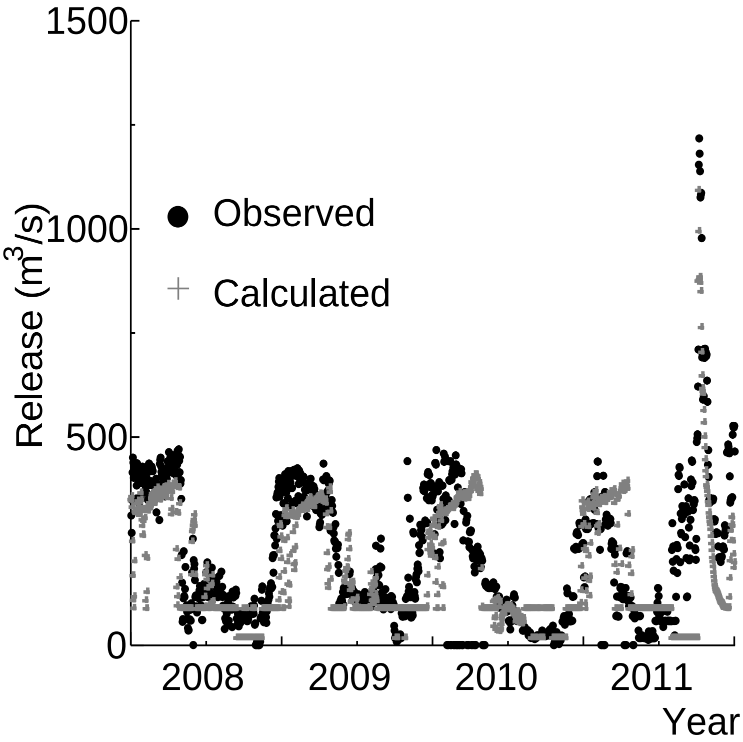


a) Bhumibol Dam

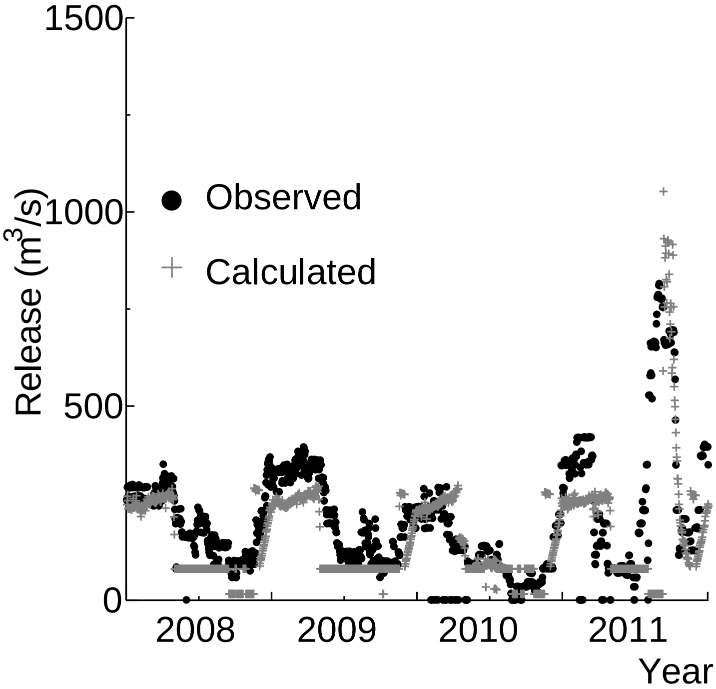


b) Sirikit Dam

Fig. 4.6 Storage at the Bhumibol and Sirikit dams as examples of large dams



a) Bhumibol Dam



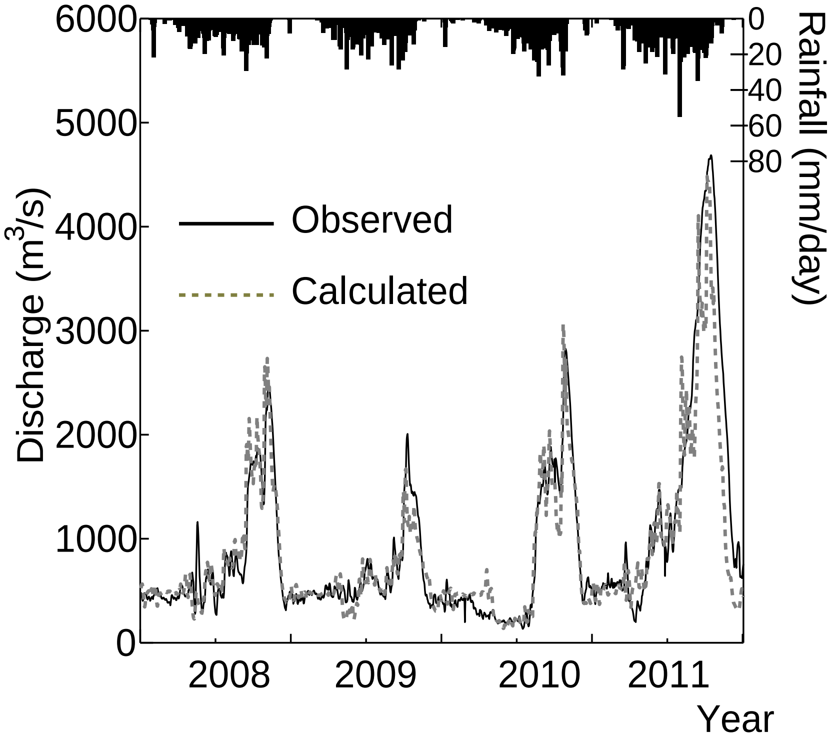
b) Sirikit Dam

Fig. 4.7 Calculated and observed release of water at the large dams

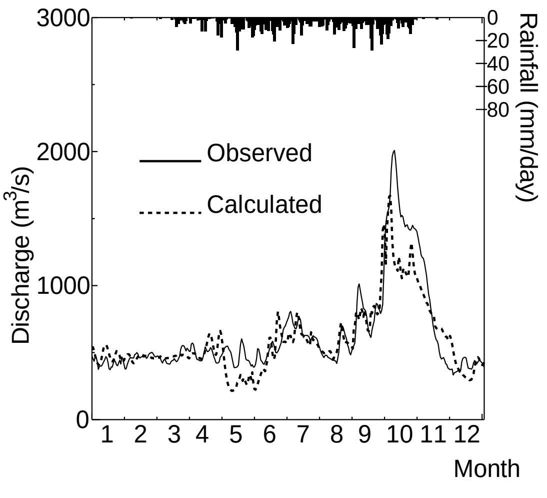
4.4.3 Estimated results of discharge and irrigation water in low-lying areas

1) River flow

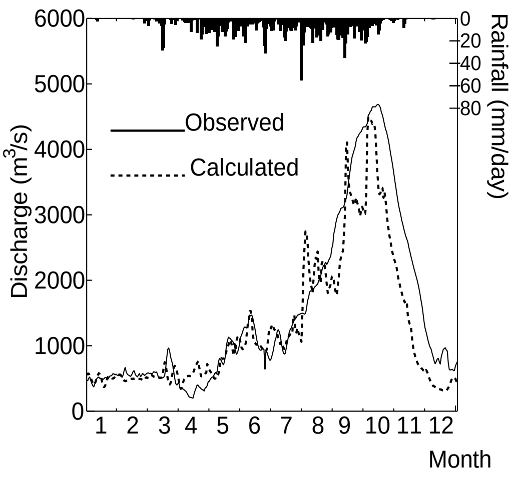
To study the effect of a reservoir operation model on the estimation of river flow, the C.2 observation point (Nakhon Sawan) was selected. **Figure 4.8 (a)** shows a comparison of the calculated and observed daily river flow at Station C.2 with the incorporation of a reservoir management model. In the 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 (**Fig. 4.8 (c)**). 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 reservoir, mentioned in "Modification of water management", for flood prevention. However, the simple flood treatment could not improve the calculation during the drainage stage of November through December in 2011 (**Fig. 4.8 (c)**).



(a) a comparison for four years, 2008–2011



(b) 2009 (Drought)



(c) 2011 (flood)

Fig. 4.8 Estimated discharge at Station C.2 before the intake of water for irrigation areas originally supplied by the Bhumibol and Sirikit dams

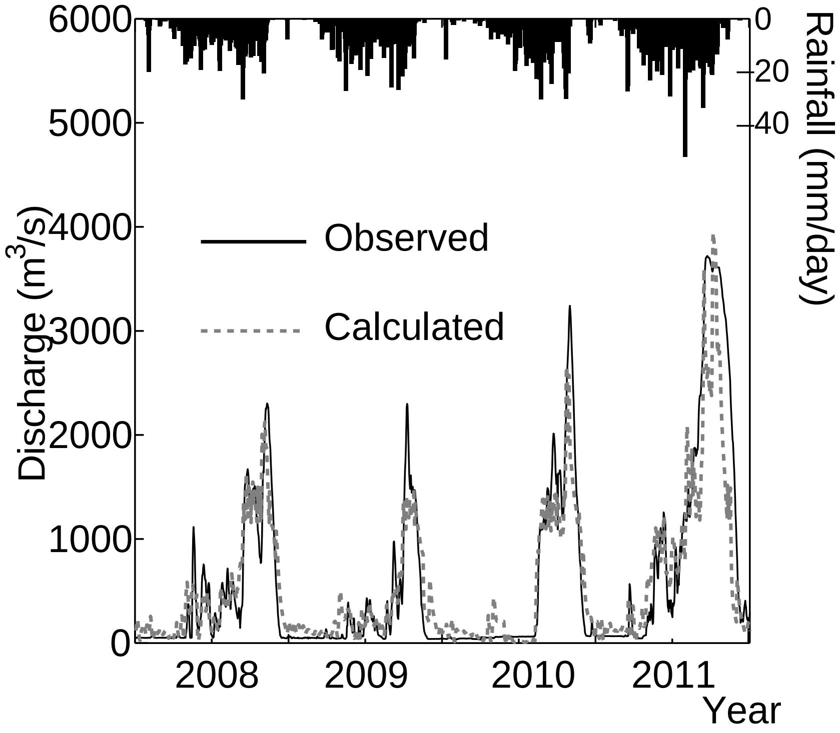
2) Irrigation and water management

With regard to the effects of applying the water allocation and management model, **Figs. 4.8 and 4.9** show the change in river discharge before and after the intake of irrigation water from the weir between Station C.2 and C.13. In the model, there are two intake facilities for the irrigation area of the main project. The supply of irrigation water from the eastern and western parts of the main irrigation areas (Nos. 16 and 17 in **Fig. 4.1**, respectively) increased upon application of the irrigation water management model. During the dry season, the annual water supply increased by 400 m^3/s.

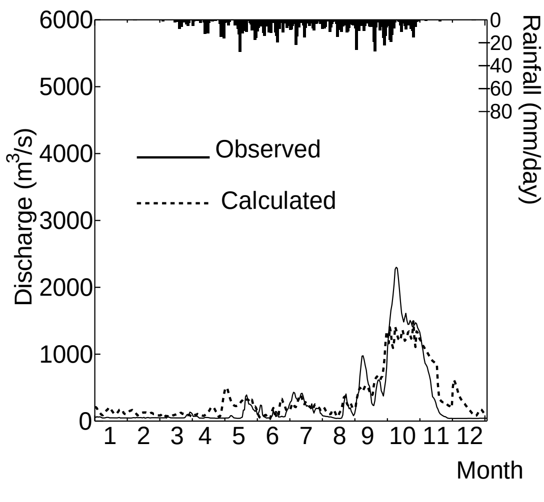
Intake water for the eastern and western irrigation areas is compared in **Fig. 4.10** for the typical years, namely 2009 and 2011. The calculated results of intake water were estimated based on irrigation requirements and special water management in the rainy season. In the calculation, irrigation water 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 irrigation areas while considering the capacity of the irrigation facilities, such as irrigation intake gates or canals. However, the estimation of release from the dam and amount of diverted water during high flow depended on the political decision of the Thai government, governors of provinces downstream and the RID.

The operation of two dams due to rule curves is not considered in the simulation because operators did not strictly manage dams by considering rule curves. So, in the simulation, there is no reduction of releases according to that operation. Moreover, during rice cultivation periods, RID regulates the amount of diverted water according to political decision as well as the situation of water availability in the main river and cropping areas which are decided differently each year. In the model, however, the amount of diverted water is calculated based on the latter condition

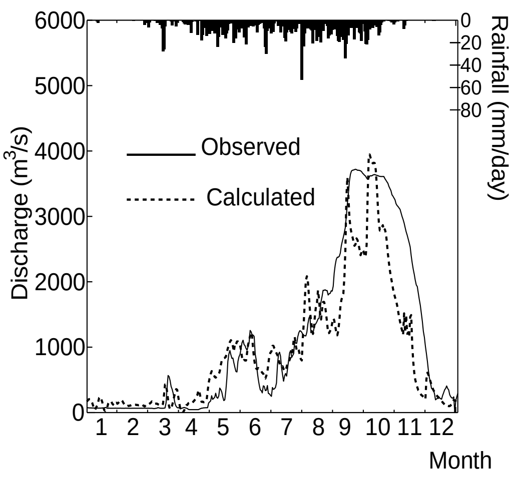
In addition, for water intake during the transition from the end of the dry season through the beginning of the rainy season (November and December), the estimation of operational results took into consideration cropping duration including double-cropping rice. However, in the Greater Irrigation Project, farmers would cultivate three rice crops in a year, as mentioned in **Section 2.3**. Therefore, the RID supplied water to irrigation areas simultaneously.



(a) a comparison for four years, 2008–2011

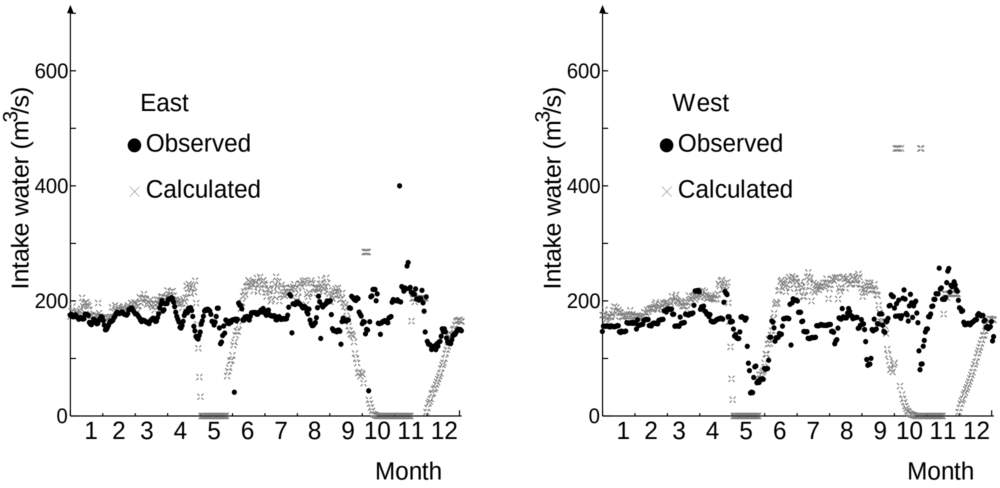


(b) 2009 (Drought)

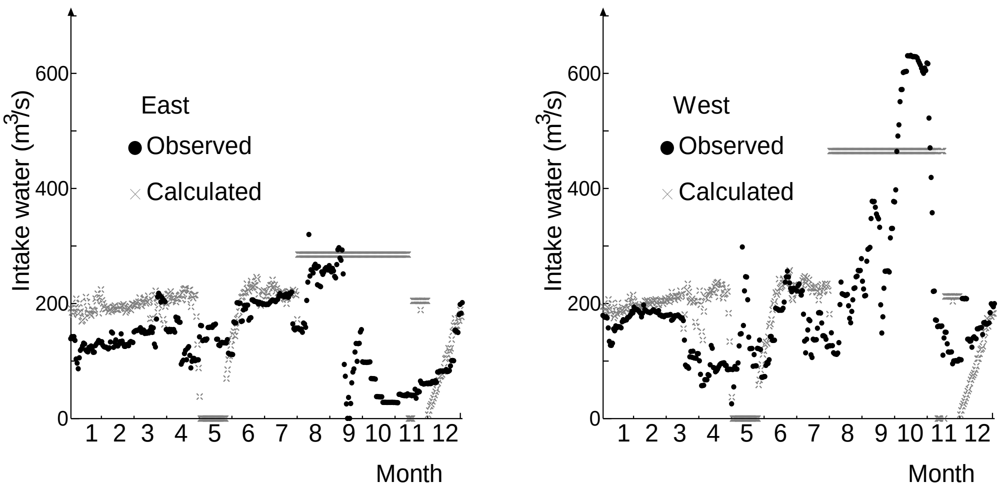


(c) 2011 (flood)

Fig. 4.9 Estimated discharge at Station C.13 after the intake for irrigation areas originally supplied by the Bhumibol and Sirikit dams



(a) 2009 (Drought)



(b) 2011 (Flood)

Fig. 4.10 Calculated and observed water volume diverted to the eastern and western irrigation areas (Nos. 16, 17 in **Fig. 4.1**) of the Greater Chao Phraya Irrigation Project

3) Remaining problems

At Station C.13 located downstream from the Chao Phraya Diversion Dam (**Fig. 4.9**), there were some discrepancies in the river flow in the dry seasons, as indicated by the relative error of 37% 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 (**Fig. 4.10**). The Chao Phraya Diversion Dam stores water and releases it via 16 large floodgates in both the dry and rainy seasons. As a result, discharge at Station C.13 is subject to the operation of those gates. At present, our model is not able to account for gate operation at the Chao Phraya Diversion Dam.

4.5 Summary

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 River Basin, which were affected by floods in 2011. The Bhumibol and Sirikit dams are the most important facilities with respect to the management of agricultural water use in remote irrigation systems in the middle and lower basin. However, a modified model could not carry out inundation and flood processes in the low-lying areas.

In the future, the modified 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 extremes 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 irrigation 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.

Chapter 5

Development of a Seamless Model to Simultaneously Simulate Agricultural Water Use and the Effects of Flooding

5.1 Introduction

In 2011, the largest flood ever recorded in Thailand (70-year return period) inundated both irrigation and urban land in the Chao Phraya River Basin, especially low-lying areas including the megacity of Bangkok and neighboring Ayutthaya. The flood severely affected agricultural production, manufacturing industries, the Thai economy and human life. *The World Bank* [2012] estimated the cost of damage due to the 2011 flood to be about 1425 billion baht (US$ 45.7 billion).

In this chapter, a prototype integrated approach is presented to modeling flooding by first using the DWCM-AgWU to develop protocols for a model that continuously calculates distributed water circulation, inundation and flooding (Seamless-DIF model), which are then evaluated by using it to model agricultural water use and flooding in the Chao Phraya River Basin in 2011, a year of extensive flooding.

5.2 New flood process model

5.2.1 Fundamental equations for distributed channel flow routing

The flow of water through the channels of a watershed is a distributed process because the flow rate, velocity, and depth vary in space throughout the watershed. Estimates of flow rate or water level at important locations in the channel system can be obtained using a distributed flow routing model. This type of model is based on a partial differential equation that allows the flow rate and water level to be computed as a function of space and time. The one-dimensional Saint-Venant equation (1871) describes unsteady flow in open channels [*Chow*, 1988].

1) Saint-Venant equation

Chow [1988] summarized the assumptions required for the derivation of Saint-Venant equations as follows:

1. The flow is one-dimensional; depth and velocity vary only in the longitudinal direction of the channel. This implies that the velocity is constant and the water surface is horizontal across any section.
2. Flow is assumed to vary gradually along the channel, and so hydrostatic pressure prevails and vertical acceleration can be disregarded.
3. The longitudinal axis of the channel is approximated as a straight line.
4. The bottom slope of the channel is small and the channel bed is fixed; that is, the effects of scour and deposition are negligible.
5 Resistance coefficients for steady uniform turbulent flow are applicable, and so a relationship such as Manning's equation can be used to describe the resistance effects.
6. The fluid is incompressible and of constant density throughout the flow.

Continuity equation

The continuity equation expresses the conservation of mass considering the elemental control volume in the specified area. As one of the assumptions in the Saint-Venant equation, the continuity equation is used for open channel flow (one-dimensional unsteady) and is governed by **Eq**. (5.1).

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \tag{5.1}$$

where Q is the inflow volume entering the control element at the upstream end, A is the average cross-sectional area, x is the control area distance, t is the calculation duration and q is the lateral inflow along the side of the channel entering the control volume.

The flow rate for the control volume is adjusted depending on the channel distance and considering the inflow volume from upstream (Q) and the distribution of lateral flow per unit length ($q\partial x$). The cross-sectional area rate is adjusted depending on the mass in the control volume for the duration of the calculation.

Momentum equation

As Newton's second law, the rate of change in momentum stored within the control volume plus the net outflow of momentum across the control surface equals the sum of forces acting on the control volume. For unsteady uniform flow, there are five forces acting on the control volume: gravity, friction, contraction/expansion, wind shear and pressure [*Chow,* 1988]. As in the above assumption, the momentum equation for the one-dimensional open flow can be expressed as **Eq**. (5.2)

$$\frac{\partial Q}{\partial t}+\frac{\partial\left(\beta Q^2/A\right)}{\partial x}+gA\left(\frac{\partial h}{\partial x}+S_f+S_e\right)-\beta q v_x+W_f B=0 \qquad (5.2)$$

where Q is the inflow entering at the upstream end, A is the average cross-sectional area, x is control channel distance, t is the calculation duration, h is the water surface elevation, S_f is the friction slope from the friction force term, S_e is the eddy slope from contraction/expansion force causing energy loss, β is the momentum coefficient, v_x is the flow velocity, W_f is the wind shear factor according to the wind force, and B is the width of the water surface.

2) Classification of the calculation for the distributed flow routing

Table 5.1 shows the variations of the Saint-Venant equation including the continuity and momentum equations in both the conservation and non-conservation forms, which are used to define the type of one-dimensional distributed routing calculation. The

Table 5.1 Summary of Saint-Venant equations

Conservation form

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t} = 0$$

Non-conservation form

$$V\frac{\partial Q}{\partial x}+y\frac{\partial A}{\partial t}+\frac{\partial y}{\partial t} = 0$$

Momentum equation

Conservation form

$$\frac{1}{A}\frac{\partial Q}{\partial x} \quad + \quad \frac{1}{A}\frac{\partial A}{\partial t}\left(\frac{Q^2}{A}\right) \quad + \quad g\frac{\partial y}{\partial t} \quad + \quad g(S_0-S_f)= 0$$

Local acceleration term	Convective acceleration term	Pressure force term	Gravity force term	Friction force term

Non-conservation form (Unit width elements)

$$\frac{\partial V}{\partial t} \quad + \quad V\frac{\partial V}{\partial x} \quad + \quad g\frac{\partial y}{\partial x} \quad + \quad g(S_0-S_f)= 0$$

Kinematic

Diffusion

Dynamic

Note: Disregarding lateral inflow, wind shear, and eddy losses, and assuming β = 1
Source: *Chow* [1988]

equations in **Table 5.1** disregard lateral inflow, wind shear and eddy loss. The momentum equation includes the following terms: local acceleration, convective acceleration, pressure force, gravity force and friction force. Local and convective acceleration describes the changes in momentum due to velocity over time and distance, respectively. The pressure force is proportional to the change in water depth along the channel. Gravity and friction force represents the energy loss rate for the flow through the channel due to gravity and friction.

In the calculation of distributed flow routing, the full continuity equation is used, while the momentum equation eliminates some terms according to the calculation conditions. The kinematic wave scheme disregards local and convective acceleration and pressure force. This scheme assumes $S_0 = S_f$ as the uniform flow. However, the kinematic wave scheme cannot calculate distributed flow routing in condition of backwater effect, which always occurs in channels with a gentle slope. The backwater effect is incorporated in the calculation of distributed flow through local and convective acceleration and pressure force. The dynamic wave scheme includes all of the terms in the momentum equation, while the diffusion wave scheme disregards the acceleration terms but incorporates the pressure term. Both schemes are used to calculate distributed flow routing as nonuniform flow.

5.2.2 Nonuniform river flow

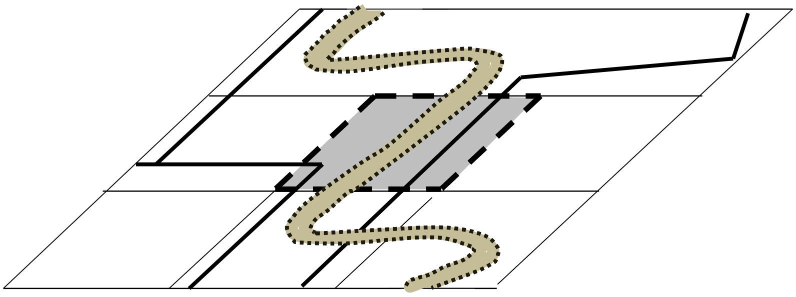
To incorporate the effects of floods in the analysis, cells along river courses and on land were considered separately. The distribution of cells along the river networks was determined based on the elevations used in the runoff analysis of the DWCM-AgWU. During periods of flooding, the flow between river cells was expressed as nonuniform flow to reflect the effect of backflow [*Minakawa* and *Masumoto*, 2014]. The continuity and momentum of flow are given by **Eqs.** (5.3) and (5.4), respectively. The momentum equation (**Eq**. (5.4)) represents the diffusion wave scheme.

$$\frac{W^{n+1}+W^{n}}{2}\frac{H^{n+1}-H^{n}}{\Delta t}=\left(\frac{\sum Q_{in}^{n+1}+\sum Q_{in}^{n}}{2}\right)-\left(\frac{\sum Q_{out}^{n+1}+\sum Q_{out}^{n}}{2}\right) \tag{5.3}$$

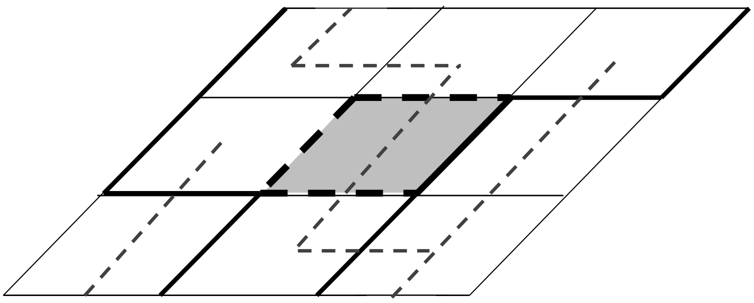
where W is the surface area of a river cell, H is the water level in a river cell, Q_{in} is the inflow to the target cell, Q_{out} is the outflow from the target cell, n is the time step, and Δt is the time step for calculation.

$$Q=\frac{AR^{\frac{2}{3}}}{N\sqrt{x}}\frac{H_T-H_C}{\sqrt{|H_T-H_C|}}, \tag{5.4}$$

where Q is the river flow between cells, A is the flow cross-section, R is the hydraulic radius, N is Manning's roughness coefficient, x is the river length, H is the water level,



(a) Actual river, dike and road



(b) Simplified river and road as used in the modeling

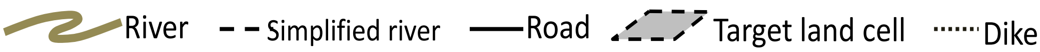


Fig. 5.1 Schematic diagram showing simplified spatial representation of rivers and roads in the modeling

and subscripts T and C indicate target and connected cells, respectively.

5.2.3 Dike overflow between river and land cells

In our simplified spatial relationship of rivers and roads (compare **Figs. 5.1 (a)** and **5.1 (b**), the main river and the river (drainage channel) in each cell are considered to flow through the river network artificially represented by the river cells (circles in **Fig. 5.2 (b)**) in the middle of land cells (represented by dotted rectangles), which are connected and/or separated from adjacent land cells by dikes of different height in reality (**Fig. 5.2 (a)**). In a target land cell, a specific river cell is always connected to one land cell as well as to several upstream and downstream river cells (**Fig. 5.2 (b)**). Overflow from a river cell to a land cell was calculated by using equations normally applied to calculate flow over weirs **(Fig. 5.2 (a))**. Two types of overflow were considered: submerged overflow (when the dike is already submerged) and complete overflow (when the dike is not submerged); the type of overflow used was determined by comparing water levels within adjacent river and land cells [*Hayase and Kadoya*, 1993].

For submerged overflow (when $h_2/h_1 \geq$ D

$$Q = C_2 B h_2 \sqrt{|H_H - H_L|} \tag{5.5}$$

and for complete overflow (when $h_2/h_1 \leq$ D

$$Q = C_1 B h_1^{\frac{3}{2}}, \tag{5.6}$$

where Q is the overflow discharge between adjacent land cells, C_1 and C_2 are overflow coefficients ($C_1 = \sqrt{2g}$ = 1.549 and C_2 = 2.598 C_1 = 4.0258), B is the width of the overflow weir determined according to the land use in a cell and its area (1 m/ha for a paddy cell, for example), H_H and H_L are the upstream and downstream water levels at river or land cells, in which the subscripts H and L represent higher and lower water levels, respectively, and h_1 ($h_1 = H_H$ -z) and h_2 ($h_2 = H_L$-z) are the difference in upstream and downstream water levels, relative to the top elevation of the weir (z), respectively.

The breached sections of dikes gradually expand as the overflow progresses. However, due to the difficulty in measuring the changing width and height of breached sections, data measured by the RID were used and it was assumed that the dikes were breached instantaneously; the resultant flows were determined by using equations normally applied to flow over weirs. Thus, the input parameters for modeling dike overflow were the greatest width and height of breached sections, as reported by the RID.

5.2.4 Volume of water within an inundated land cell and flood routing between cells

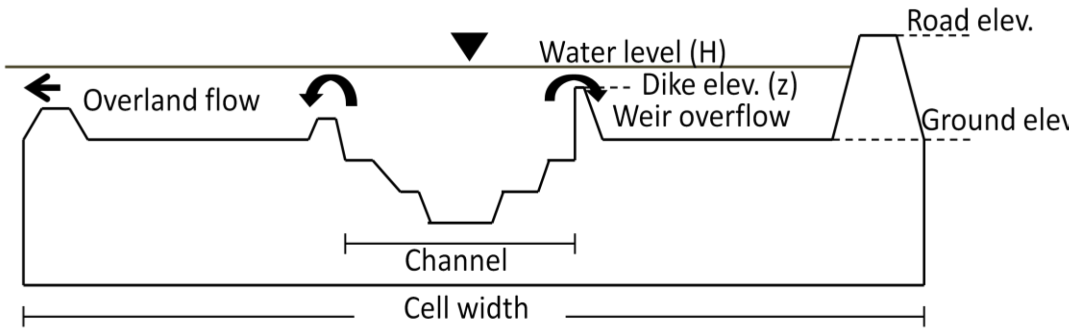
The volume of water within a land cell at a particular time was calculated from its surface area (W) and depth of inundation (H), and was determined in sequential time steps by using the following equation from *Minakawa and Masumoto* [2014]:

$$W\frac{H_i^{n+1}-H_i^n}{\Delta t} = Wr + \left(\frac{\sum Q_{in}^{n+1} + \sum Q_{in}^n}{2}\right) - \left(\frac{\sum Q_{out}^{n+1} + \sum Q_{out}^n}{2}\right) \qquad (5.7)$$

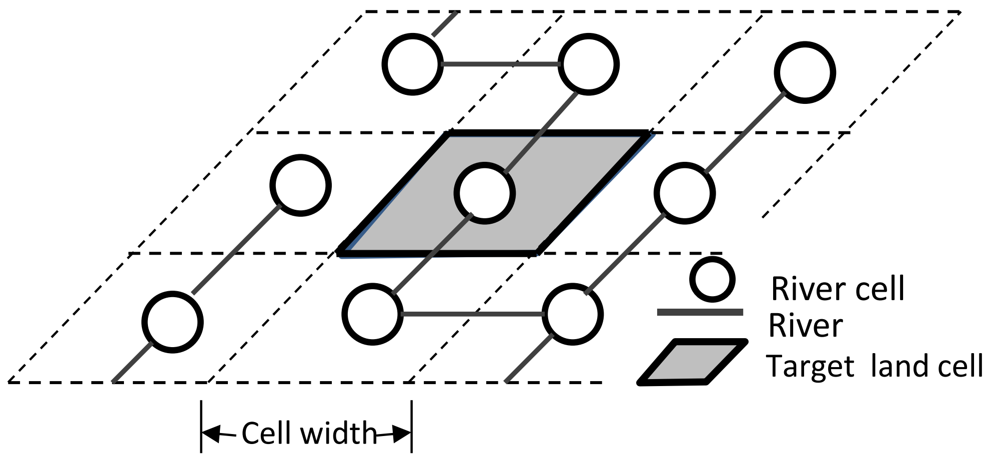
where n is the time step in that variables with the superscript n are known and those with the superscript $n+1$ are unknown, W is the surface area of a land cell, r is the amount of rainfall between time steps n and $n+1$, Q_{in} is the inflow to the target cell, and Q_{out} is the outflow from the target cell.

Each land cell was separately connected to its four surrounding cells (north, south, east and west) by weirs (**Fig. 5.1 (b)**). Flood routing between land cells was modeled by assuming weir overflow between cells, as formulated in **Eqs**. (5.5) and (5.6). The height used for the weirs separating adjoining pairs of land cells was the height of the paddy levees, railways or roads within those cells (cell edges of **Fig. 5.2 (a)**). Flow direction between land cells was defined by allocating cell numbers (increasing in the upstream direction). All river cells were considered to be downstream from adjoining land cells.

For the simplification of modeling, roads within land cells were moved to the nearest land cell edge (**Fig. 5.2**).



(a) Cross section of a river cell



(b) River cell networks with connected land cells

Fig. 5.2 Schematic of the cross section of a river cell and river-land cell connections

5.2.5 Drainage process

In the calculation of drainage after the peak of flooding, floodwaters in land cells were drained to river cells over weirs when the water levels in the river cells were lower than those in the land cells. In this process, water discharge over weirs was calculated by using **Eqs**. (5.5) and (5.6). When the depth of inundation in the land cell reached the height of the weir, the remaining water was retained in the land cell until the end of the flood simulation. The water drained into river cells was dispersed through the river network to the sea.

5.3 Prototype combined model incorporating flood processes in DWCM-AgWU

For modeling the flood processes incorporated in the DWCM-AgWU (**Fig. 5.3**), the calculation for all cells in the basin starts by applying the DWCM-AgWU, so cells defined as flooded are screened out and the basin is temporarily divided into non-flooded and flooded cells, in which the areas are categorized as *M* flooded groups. In non-flooded areas, river discharge is calculated by using the runoff sub-model (DWCM-AgWU (explicit scheme of **Fig. 5.3**)) of the Seamless-DIF model, and the calculated discharge is used as the flow boundary conditions in modeling flooded areas.

The simulation of flooding and inundation processes starts when the discharge from river cells exceeds the assumed capacity, which is judged and calculated by considering the cross-sectional area of the river under uniform flow conditions (explicit scheme part of **Fig. 5.3**). For river cells judged as flooded areas, nonuniform flow is assumed in the calculation of downstream flow from flooded river cells to the end of the river network, such as at the river mouth. Overland flow between land cells is calculated by considering the surface water in land cells (determined by using the explicit scheme part of **Fig. 5.3**) and floodwaters that are modeled to flow over the dikes bounding river cells into land cells. Flooded areas initially expand gradually to reach the maximum area of flooding, and then shrink gradually as floodwaters are drained from inundation areas. Calculation of the implicit scheme stops when the water level in a land cell recedes to 0.1 m.

In this prototype model, the number of cells in flooded areas (defined as *M* groups in **Fig. 5.3**) is assumed to increase/decrease during flooding/drainage. In the flooding model (**Fig. 5.3**), simultaneous equations were formulated to represent the variables of water level instead of discharge in the DWCM-AgWU, in river cells (H^{m+1}_{river}) and in inundated land cells (H^{m+1}_{land}), in which superscripts $m+1$ represent unknown variables. Thus, simultaneous equations were obtained for all land and river cells for each group of areas. These equations for the *M* groups are then solved by a matrix formulation for all unknown variables in the implicit scheme for one group at a time (**Fig. 5.3**). The combined discharge of all connected river cells is determined, as expressed by **Eq.** (5.4), and is then substituted into **Eq.** (5.3) for each target river cell, so the parameters for the unknown variables can be identified for each cell. Finally, the discharge across all cell boundaries is calculated by substituting the water level (H^{m+1}_{river}, H^{m+1}_{land}) into the momentum equation (**Eq**. (5.4) for rivers, and **Eq.** (5.6) or (5.7) for land cells).

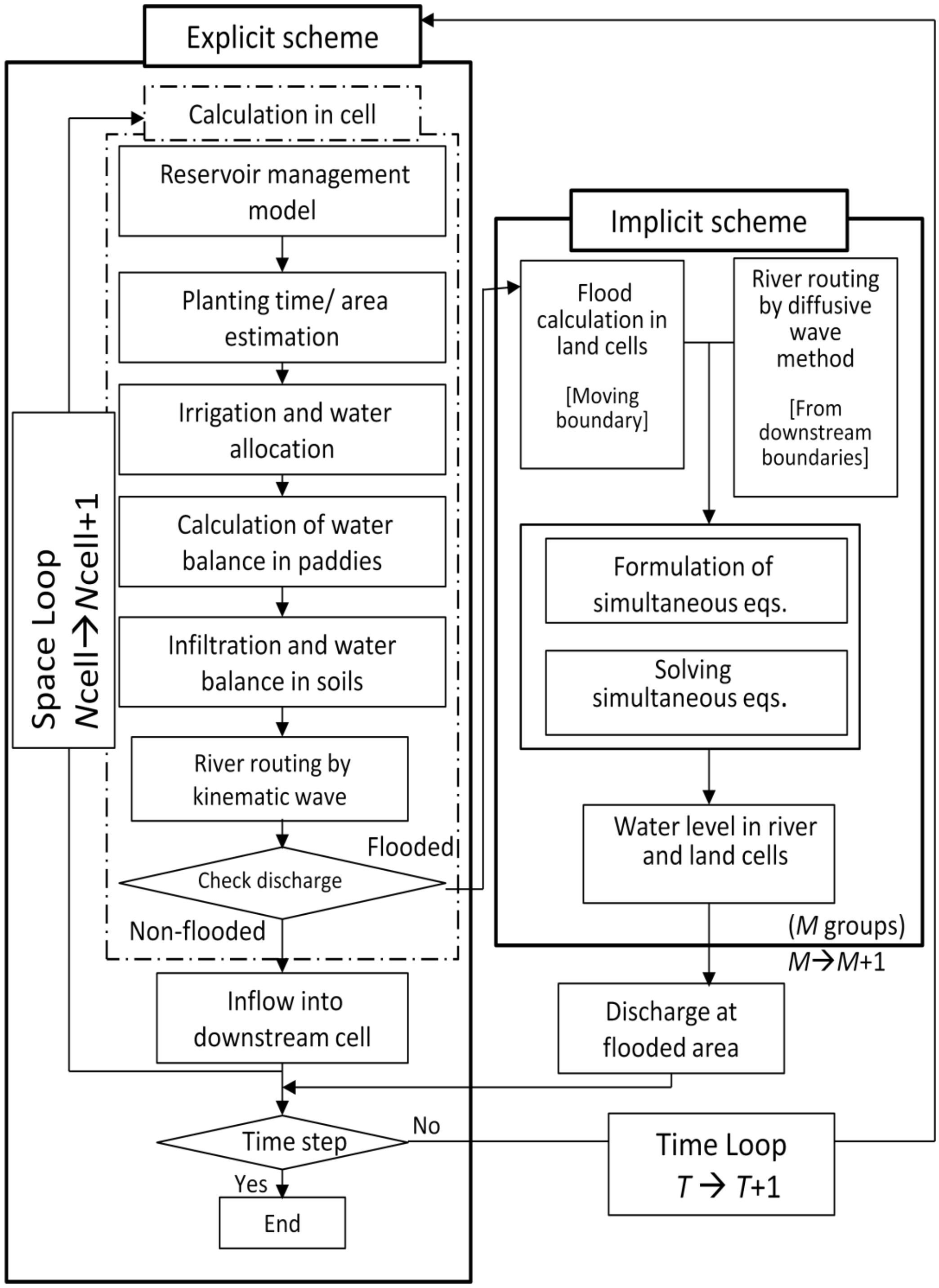


Fig. 5.3 Flow chart of processes in the Seamless-DIF model used for simulation incorporating flood processes in the DWCM-AgWU

5.4 Application of a prototype model

5.4.1 Area modeled

The author applied our prototype Seamless-DIF model to the delta plain of the lower Chao Phraya River Basin (**Table 5.2**), namely the area from the south point of the confluence of the main tributaries of the Chao Phraya River to the sea. The simulation was carried out with a one-day time step during 2011. Although several discrete areas for flooding should be modeled, that is, each flooded area changes in size as the floodwaters spread and recede, the observed maximum extension area of flooding was used as the boundary for the modeling. The explicit scheme of the combined model (**Fig. 5.3**) was applied to the upper river basin north of Nakhon Sawan and the implicit scheme was applied to the area from the south of Nakhon Sawan. Flooding in the

Table 5.2 Key data and data sources for modeling

DWCM-AgWU	
1. Rainfall	43 stations
2. Meteorological data	43 stations
3. Land elevation	1 m in 1 km^2
4. River cross section	124 sections
5. Number of cells	2063 cells (100 km^2/cell)
Maximum area for application of a Seamless-DIF modeling	
1. Number of land cells	721
2. Number of river cells	721
3. Time step of simulation	One day
4. Road elevation	175 boundaries
5. Daily seawater level data	2 points
6. Breaching point data	28 points
7. Width of weirs (land cells)	1 m/ha
8. Height of weirs (land cells)	(0.1 m)
9. Seawater levels	2 points

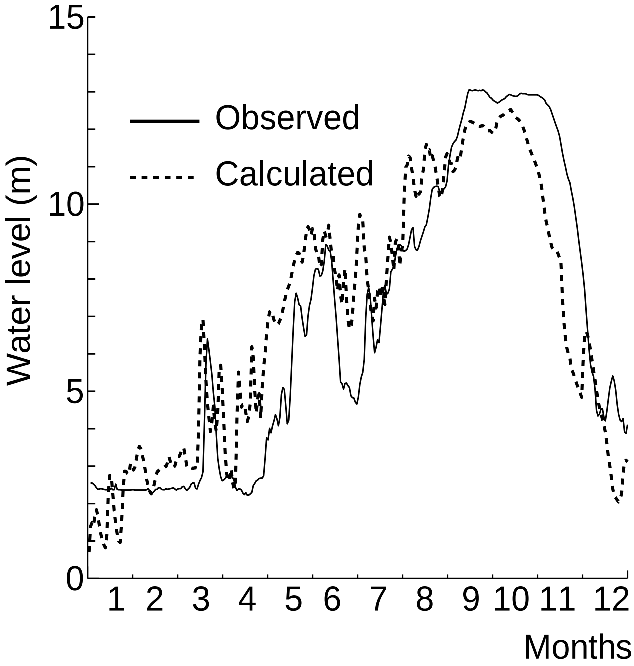
middle reaches of the basin (the area between the Bhumibol and Sirikit dams and Nakhon Sawan) was simply modeled by considering the capacity of the rivers in that area at specific points (mentioned in **4.2.2 (2)**). We used simplified river cross sections along the main channel of the Chao Phraya, which were defined based on the channel width, height and gradient, and Manning's roughness coefficient on both sides of the channel was applied (**Fig. 5.2 (a)**). Moreover, observed seawater level at two measurement points (mentioned in **Section 2.4 (Figs. 2.7 (a)** and **(b))**) were input to consider the influence of the backwater effect of tides.

5.4.2 Assessment of performance of combined model

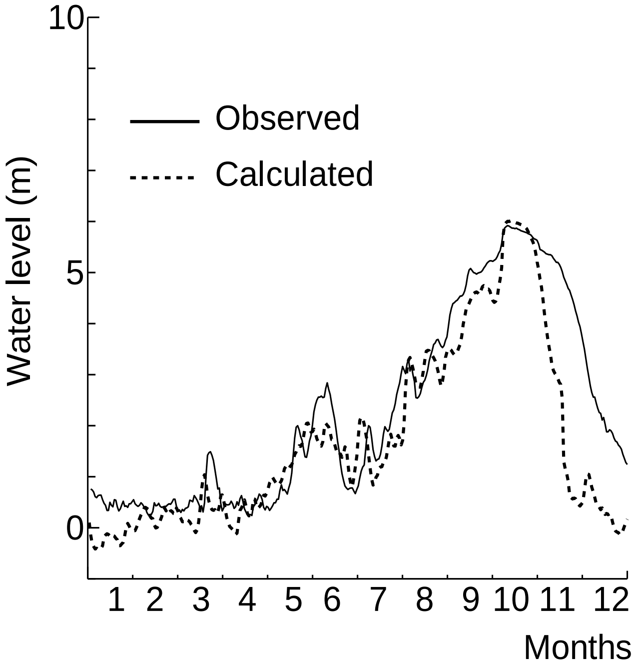
Observed water levels at the Sing Buri and Ayutthaya hydrological stations (locations shown in **Fig. 5.1**) were used to assess the performance of the combined model (**Figs. 5.4 (a)** and **5.4 (b)**).

Errors in daily simulated and observed water levels at Sing Buri and Ayutthaya were 21% and 32%, respectively. The peak of flooding and changes in water level were well reproduced at both stations. The simulated discharge estimated from the water levels in **Fig. 5.4** during the dry season and at the beginning of the rainy season was overestimated due to the release of irrigation water from the Chao Phraya Diversion Dam for use in areas on the eastern and western sides of the lower river basin around mid-June through to the end of May, and the operation of the control gates of the Chao Phraya Diversion Dam (**Fig. 4.7**). Underestimation of the water level in the high flow period (November–December) (**Fig. 5.4**) was subjected to large errors, and thus the result for this period needs to be improved. The simulated area of flooding in low-lying areas of the basin was 15,048 km^2, whereas that determined from satellite data was 20,692 km^2 (**Fig. 5.5**). About 12,172 km^2 of simulated flooded land was within the observed extent of flooding, which represents about 41% of the total observed area of flooding. Inundated areas between the Chainat-Pasak Irrigation Canal, Chao Phraya River and Pasak River were used to compare the simulated and observed volumes of floodwater (**Fig. 5.5**). At the peak of flooding, the observed floodwater volume was about 3750×10^6 m^3 (**Fig. 3.10** in **Section 3.6.3**), whereas our simulation indicated a volume of $2,795\times10^6$ m^3.

Moreover, as the first trial, the maximum sea levels of the two observed stations were input as the tidal data, and from that calculation, the calculated water levels at Ayutthaya, which is located approximately 100 km from the river mouth of the Chao Phraya River, were higher than the observed levels. Then, the observed water levels mentioned above were replaced by those of the averaged value between the maximum and minimum height in each day. The result was improved as shown in **Fig. 5.4 (b)**. On the other hand, the Sing Buri Station was not influenced by this change. Therefore, tidal water level fluctuation must be taken into consideration when applying the Seamless-DIF model.



(a) Sing Buri



(b) Ayutthaya

Fig. 5.4 Comparison of observed and simulated water levels at Sing Buri and Ayutthya hydrological stations during 2011

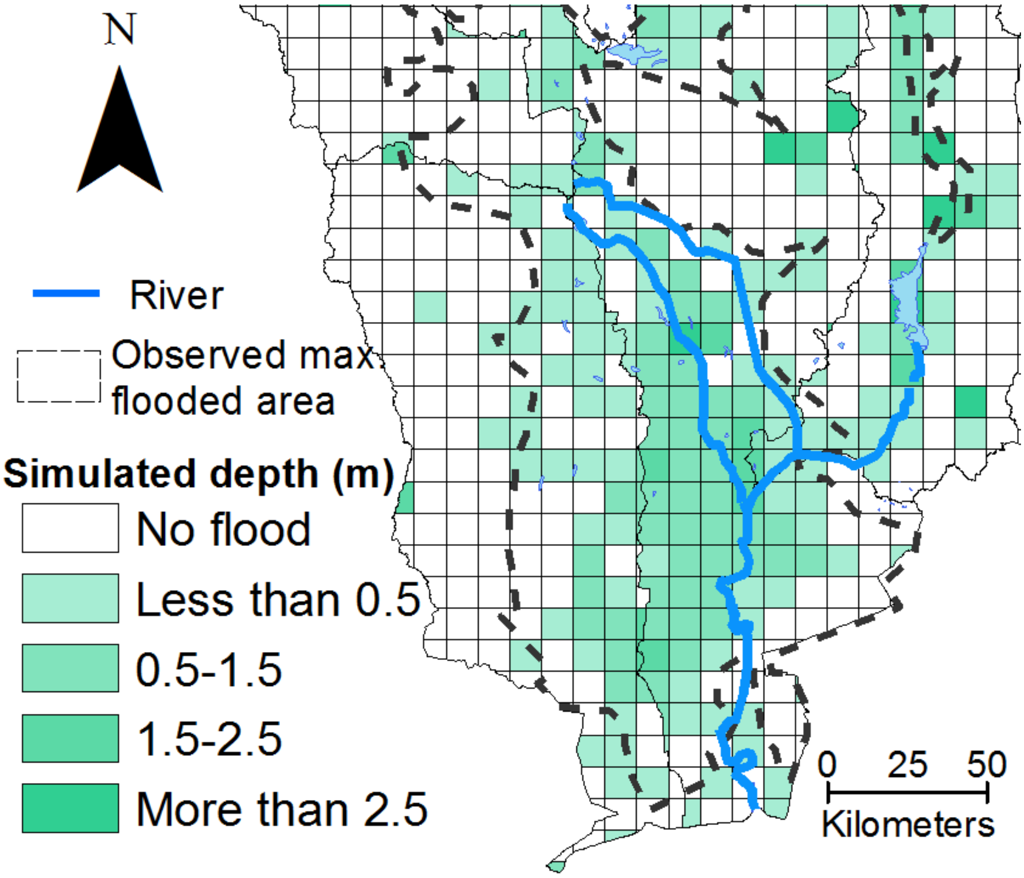


Fig. 5.5 Comparison of the maximum extension of inundated areas between satellite observations and the simulation in 2011

5.5 Summary

The author developed a prototype distributed water circulation model that combines the DWCM-AgWU with the modeling of flood processes (a Seamless-DIF model) and applied it to the Chao Phraya River Basin to simulate the water circulation during a year of massive flooding. The proposed model was able to count out the interaction among the operation of dams, the management of irrigation facilities, and the flood processes in the Chao Phraya River Basin, so it is concluded that the model can be used to dynamically and simultaneously simulate water circulation, including water used for irrigation, as well as both flood and drought phenomena, in the Chao Phraya River Basin.

However, the Seamless-DIF model requires further refinement to better simulate progressive changes in inundation areas during flooding and to incorporate the use of flood control gates at the Chao Phraya Diversion Dam. These further improvements of the model will allow it to be used to predict and mitigate the effects of future floods and droughts.

Chapter 6

Conclusion and Recommendations

6.1 Conclusion

Climate change is predicted to result in an increased frequency of extreme weather events such as floods and droughts. To prevent or at least mitigate potential damage, countermeasures and/or adaptation to such extreme events must be proposed and evaluated. As an essential tool for evaluating the proposed measures, this thesis presents the development of a seamless model that effectively takes into account the interaction between floods and agricultural water use. The target study area is the Chao Phraya River Basin, Thailand, which was affected by extreme flooding in 2011.

A prototype seamless method was developed for the simulation of distributed water circulation that integrates the modeling of flood and inundation processes with the Distributed Water Circulation Model Incorporating Agriculture Water Use (DWCM-AgWU). This model simultaneously simulates the water circulation in the basin and extreme events such as floods and droughts. Moreover, agricultural water use and water management, including floodwaters, through irrigation facilities are among the components considered in this model. From the results of this study, the following conclusions can be drawn.

Chapter 2 describes the characteristics of the Chao Phraya River Basin. Meteorological data from the observed stations was interpolated and used to generate rainfall and estimate evaporation within individual cells in the DWCM-AgWU. Information on land use, particularly for agricultural areas, was used to calculate water circulation in the basin by considering agricultural water use. Moreover, irrigation facilities and their management in irrigation areas were introduced for modification of the DWCM-AgWU. Water in the middle and lower parts of the Chao Phraya River Basin is used mainly for agricultural purposes in which the flow is controlled by irrigation facilities such as dams and irrigation systems. Two large dams, the Bhumibol and the Sirikit, are the main sources of irrigation water for the middle and lower irrigation areas in the dry season, and they are also used for flood control in the downstream part of the basin in the rainy season.

Chapter 3 evaluates the cause and effect of the 2011 flood in the Chao Phraya River Basin. The operation of irrigation facilities to manage the flood was introduced in the model. Evaluation of the storage function of paddies, particularly in the eastern irrigation area that is surrounded by the Chao Phraya River, Chainat-Pasak Irrigation Canal and Pasak River showed that water storage in this area significantly reduced the flood volume at Ayutthaya and Bangkok.

In Chapter 4, the DWCM-AgWU was modified according to the information in Chapter 2 on agricultural water management incorporating the irrigation facilities. As a result, it was shown, taking the Bhumibol and Sirikit Dams as examples, that dams and irrigation systems play useful roles for agricultural water resource management, especially in the middle and lower parts of the Chao Phraya River Basin, which were affected by floods in 2011. However, the modified model was unable to fully simulate the inundation and flood processes.

Chapter 5 explains the development of a Seamless-DIF model to solve the problems described in Chapter 4. The model uses a two-dimensional analysis to formulate the flow of floodwaters in low-lying areas. Nonuniform flow analysis was utilized to introduce the effect of backwater flow in rivers. Floodwater management through irrigation facilities was integrated into the DWCM-AgWU model as the interaction of the processes between agricultural water use and floods/inundation. The model also takes into account the effects of elevated roads and railways on inundation during flooding and it estimates overflow by simulating such roads and railways as weirs. As the result of analyses for inundation and flood processes, comparison between simulated and observed water levels at Ayutthaya revealed simulation errors of 28%. The total extent of flooded areas simulated by our model was fortunately just 41% of that calculated from satellite data.

A Seamless-DIF model is one tool for developing and/or evaluating adaptation or countermeasures for extreme events. This model can continuously simulate water circulation over a long period that includes many extreme events such as floods and drought. The model has many functions for water management including irrigation facilities and agricultural water use. Although this model is effective for the entire river basin in that it is mainly used for agricultural areas, it can be modified to take into consideration other characteristics in river basins, such as urban areas and/or transportation networks.

6.2 Recommendations

6.2.1 Further model development in future

Given that the Seamless-DIF model is a combination of the DWCM-AgWU and the modeling of flood and inundation processes, further development should be carried out using a separate approach for each part.

1) Further development for the DWCM-AgWU

Introducing the operation of rule curves for the Bhumibol and Sirikit dams

Although the Bhumibol and Sirikit dams supply the water for remote irrigation areas in the middle and lower of the basin, particularly in the dry season, these two dams also have important roles to supply water for domestic use and ecology preservation, and flood control during rainy season as multi-purpose reservoirs. From those objectives, these dams are operated by visualizing rule curves, namely upper and lower ones. They are used for flood protection and water shortage preventions. In the simulation, however, those operational rules are not introduced, so that the dams release water without any safety consideration to the downstream. So, the upper and lower rule curves should be instituted to the dam and reservoir management model.

Eventually, EGAT did not operate the dams by following their operational rules, such as water release below lower rule curve and water storage above the upper one. Those operations depend on political decision as well as the situation of water requirements of many sectors. In addition, RID regulates the amount of diverted water for irrigation areas and release through the Chao Phraya Diversion Dam, based on governmental political decisions in water delivery. It is difficult to simulate in the model. So, the model needs the development of new decision rules and/or criteria some for those decisions.

Introduction of water user

In the water allocation model, irrigation water is supplied only to paddies. In the Chao Phraya River Basin, however, there are other types of field crops, such as sugar cane and cassava, for which water is supplied through irrigation canals. That is, other agricultural lands except for paddies count for approximately 24% of the whole irrigation areas in the basin. Thus, for model development in the future, upland and/or perennial crops and fisheries should be considered in irrigation water use. Water requirements for each agricultural activity would be calculated by using a database on monthly crop coefficients. Moreover, urban areas are also an important water user. However, domestic use from main streams is not considered even though the dam operation sub-model has a release function for domestic use. This type of component would be calculated based on the size of the area or the area population.

Introducing hydraulic scheme for irrigation canals and hydraulic structures

In the proposed model, irrigation water is allocated to paddies as rainfall input; the water distribution in the irrigation canals and the influence of hydraulic structures in the irrigation systems are not considered. Especially in the Chao Phraya River Basin, the areas are quite large and complex, and so water is frequently supplied by irrigation canals. Hence, the introduction of hydraulic schemes for irrigation canals incorporating hydraulic structures would be effective for water management in irrigation projects.

Introducing estimated damage for rice cultivation

In the sub-model for cropping time and area, the transition of cropping areas is estimated by considering the availability of irrigation water and the advancement of cultivation under normal conditions. However, there is no process for estimating the reduction in cropping area due to flooding. This type of process would be introduced by considering both flood duration and advancement of rice cultivation technologies.

2) Further improvement of flood processes

Introducing flooded groups

At this stage, the Seamless-DIF model was applied to the lower areas of the Chao Phraya River Basin as areas of flooding, while flat plain areas in the middle part of Yom and Nan sub-basins were modeled using simple flood treatment in the DWCM-AgWU. However, there are several separate intermontane plain areas in the Ping, Wang and upper Yom sub-basins that are affected by floods. Those in upper and middle reaches would be considered within the fully flooding and inundation processes as the lower areas; the maximum area of each flooded areas groups would be specified as an area of high flood risk. Therefore, a Seamless-DIF model must be simultaneously carried out flood and inundation processes for each group individually.

Introducing movement of flood boundary

As for the reducing valuables in implicit schemes, the number of cells in flooded areas is assumed to increase/decrease during the flood/drainage process. Although several discrete areas of flooding were modeled, the boundary would change as the floodwaters expand and recede. The observed maximum area of flooding was used as the boundary for our modeling. The boundary should be moved by considering the flooding and drainage situation, as mentioned above.

6.2.2 Adaptation measure development

Although the development of a Seamless-DIF model was the main objective of this study, the model also facilitates the development of adaptation and countermeasures to extreme events such as the 2011 flood. In addition, it is used as an example of assessing model performance. In the verification of model performance, the results showed that paddy areas in the lower Chao Phraya River Basin, especially the paddies in the eastern irrigation area surrounded by the Chao Phraya River, Chainat-Pasak Irrigation Canal and Pasak River, have large storage potential during flooding. However, the floods in this area were caused by dike breaches along the Chao Phraya River. For the development of adaptation and countermeasures by considering the importance of flood storage by paddies, the intake facilities used to divert water to this area should be increased, otherwise floodwaters cannot be effectively diverted and controlled.

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