Integrated Flood Risk Management and Evacuation Strategy in the Upper and Middle Reach of Chao Phraya River Basin, Thailand

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Abstract

Integrated Flood Risk Management and Evacuation Strategy in the Upper and Middle Reach of Chao Phraya River Basin, Thailand

The Chao Phraya River Basin (CPRB), Thailand is similar to flood disasters occurring every year. Haft of natural disasters have experienced in Thailand is flood disaster. Owing to fertile floodplain of CPRB, almost all of community areas are located along the Chao Phraya River such as Bangkok, the capital of Thailand. However, the CPRB is a flood-prone area because of its topographical characteristics and the strong influence of seasonal monsoon rainfalls. The CPRB suffered from various flood events but the remarkable flood damages occurred in 1995, 2006 and 2011 that caused huge damages and losses. In 2011, water-gates and levees in the lower CPRB broke due to very high water level of the Chao Phraya River and eventually floodwaters submerged the seven industrial parks and the western part of Bangkok. The total cost of the damage and losses amounted to US$ 46.5 billion that is highest in term of flood damages in Thailand’s recent history. Throughout the entire calendar year, more than 800 people lost their lives, millions of residents were either left homeless or displaced, and domestic and foreign investment were affected due to 2011 flooding. It remarks that the existing flood countermeasures and flood risk management in Thailand are not effective enough to control large magnitude and long duration like 2011 flood. To minimize fatalities and economic losses, integrated flood countermeasures are necessary for flood control in the CPRB. A consideration of the widest possible set of flood countermeasures is needed to develop new proper alternatives that provide the information for overcoming severe flooding.

The runoff station C.2 is very important runoff station because the data on this station is mostly used for flood management actions in CPRB. Besides, this study tries to control and keep the flood discharge of 1995, 2006, and 2011 flood events at this station lower than 3,500 m^3/s. This number is based on the analysis conducted by Royal Irrigation Department of Thailand that when the discharge at station C.2 is more than 3,500 m^3/s it results in vast inundation areas and huge economic losses in the lower CPRB. After remarkable flood

disaster in 2011, many studies have focused on lower part of CPRB due to high economic activity and single application of flood countermeasures such as dam operations and using paddy fields as flood storage; while study on the integrated flood countermeasures in the upper and middle CPRB is limited. To prevent a repeat of the severe 2011 flooding, an integrated approach that considers the possible widest set of flood countermeasures is required if flood disasters are to be managed in an efficient and sustainable way. Besides, this study focuses on the upper and middle CPRB to combine and assess all possible flood countermeasures in this basin to overcome severe flooding in 1995, 2006, and 2011. In addition, this study also provides the information of economics analysis through benefit-cost analysis to determine the feasibility of alternative flood countermeasures strategies as decision making tool for flood management.

Flood risk assessment has widely been applied to provide information of risk for implementing various types of flood mitigation measures to prevent, mitigate, and reduce damage from flooding. The assessment and mapping of flood risk are needed in the risk and disaster management. The risk map can represent in the geographical aspect of flood information and management options which is helpful to make decision on various aspects of integrated management of floods. However, there is no detailed flood risk assessment in the middle CPRB and the results of flood risk assessment in Thailand were rarely shared among citizens. This information upholds the need for CPRB to assess and develop flood risk. In this study, flood risk is fundamentally a combination of flood hazard and social vulnerability. Flood risk maps from this research could provide the data on flood risk reduction after implementing various flood countermeasures in CPRB and also present the high frequency and common flood risk areas to develop measures to lessen the vulnerability of people.

The most used strategy to reduce risk on people is evacuation. The successful evacuation management not only saves lives but also facilitates community to fast and smoothly regain their functionality. One of the factors that aggravated 2011 flood situations in the CPRB is the confusing and contradicting information from key agencies especially the evacuation information. The comprehensively planned evacuation and under-equipped evacuation shelters may cause loss of life owing to flooding. Besides, this study develops the three-step approach for the emergency flood evacuation in low-lying areas of the middle CPRB. The first step, flood evacuation zones were classified and the starting time for evacuation was specified by considering flood characteristics of 1995, 2006, and 2011 flood.

In the next step, the designed safe areas for flood shelters were determined. In the last step, this study calculates the evacuation travel time which considers a physical status of evacuees (elderly and preschool citizens), safe evacuation condition, the shortest time evacuation, and flood shelter and road capacity. Eventually, to enhance the effectiveness of evacuation, this study gives recommendation on significant structural and nonstructural measures which will facilitate the smooth and fast flood evacuation and also can increase the evacuation success rate.

Chapter 1

Introduction and motivation

1.1 The Upper and Middle Chao Phraya River Basin

The Chao Phraya River Basin (CPRB) has suffered from flooding that caused damage and losses almost every year. The CPRB covers an area of 160,000 km^2 from the northern Thailand to the Gulf of Thailand as illustrated in Fig. 1.1. The basin is normally divided into three basins: (1) the upper CPRB which is the catchment area of Bhumibol and Sirikit Dams; (2) the middle CPRB which is the floodplains with the surrounding watersheds; and (3) the lower CPRB which is the Chao Phraya Delta. The capital city, Bangkok, is the heart of Thailand which means not only the geographical location but also the cultural, educational, political, and economic center of Thailand. In the lower CPRB, Bangkok and industrial estates contribute about 43% of Thai GDP (Supratid, 2012). From this reason, Thai government has been trying to protect the lower CPRB from flooding by several flood countermeasures projects. Although various extensive flood countermeasures have been taken to control the magnitude and frequency of flood, citizens, and properties are still under threat of flood risk. Due to high discharge from upstream rivers plus very flat area of the lower CPRB, floodwater usually spills from rivers to floodplains and causes economic losses.

For the upper and middle CPRB, the catchment area covers 104,481 km^2, and accounts for about 65% of the total CPRB. In the upper CPRB, there are four major tributaries, the Ping, Wang, Yom, and Nan Rivers, which flow downstream from the northern mountainous terrains and combine to form the Chao Phraya River at the middle CPRB around the Nakhon Sawan Province as shown in Fig. 1.1. The physical characteristics of four major tributaries in the upper and middle CPRB are summarized in Table 1.1.

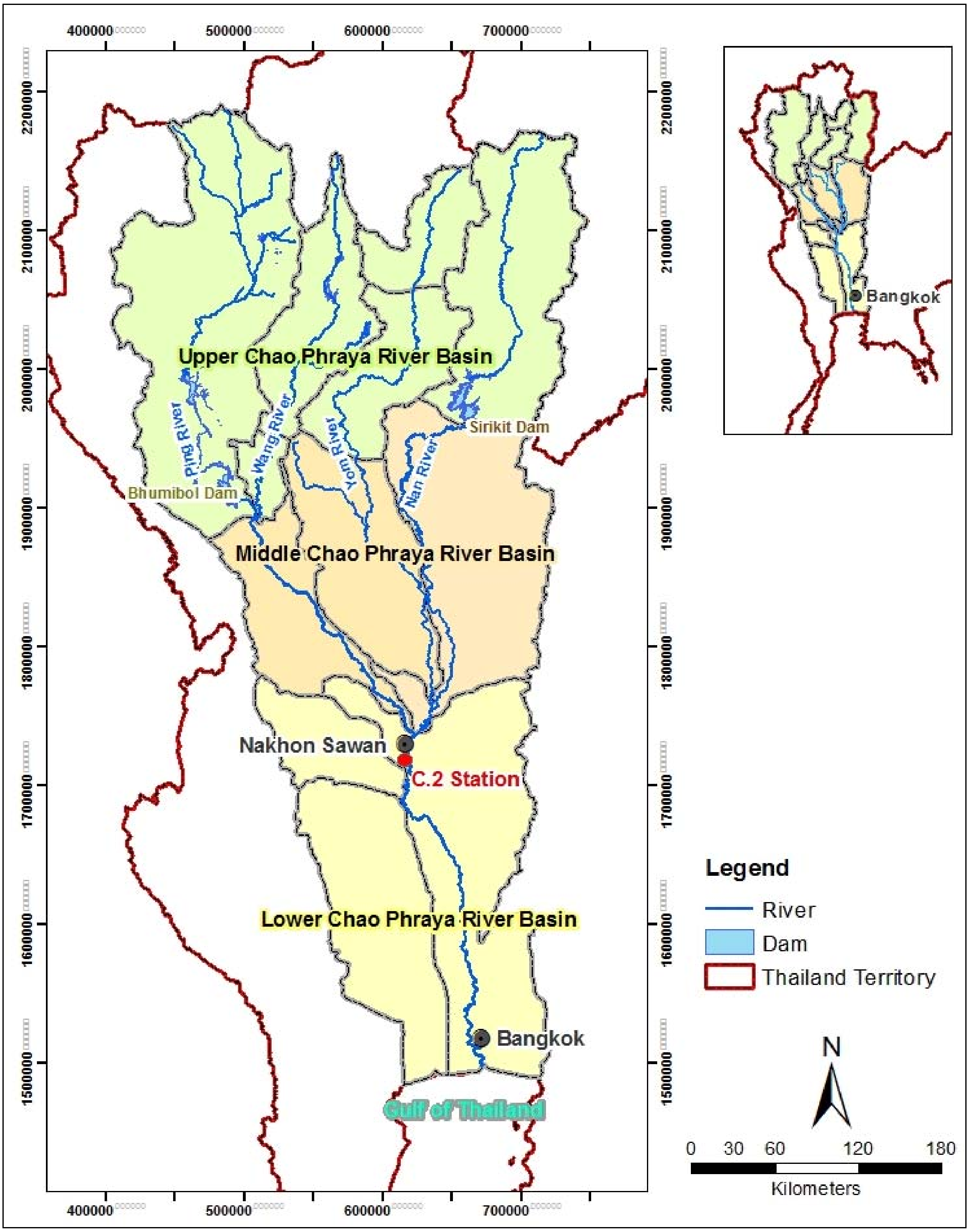


Fig. 1.1 The Chao Phraya River Basin.

Table 1.1 The physical characteristics of four tributaries in the upper and middle CPRB.

Sub Basins	Catchment Area (km^2)	Length of Main Channel (km)	Major Structures in Main Channel	
			Large Reservoir	Weir and Regulator
Ping	34,520	790	3	3
Wang	11,066	482	2	-
Yom	24,047	803	-	1
Nan	34,848	755	2	-
Summary	104,481	2,830	7	4

Source: Royal Irrigation Department (2000)

1.1.1 Land use and topographic conditions

The land use types across an area of 104,481 km^2 in the upper and middle CPRB from the land use map in year 2009 provided by the Land Development Department (LDD) can be classified into five categories as shown in Fig. 1.2. Table 1.2 shows the detail of land use types in the upper and middle CPRB. The upper reach of CPRB is mostly the mountainous ranges; while the middle basin is agricultural areas mostly paddy field, which distributes in the low-lying floodplains.

As shown in Fig. 1.3, there is exclusively different in topographic conditions varying between from 14 to 2,569 m. above mean sea level (MSL.). Because of the steep slopes and dense forest in the upper CPRB, the middle CPRB usually receives a large amount of runoff during monsoon seasons. The large runoff causes flooding in the middle CPRB almost every year. Farmland expansion and rapid urbanization have caused the forest areas to decrease by around 10% from 2002 to 2009 (Jamrussri and Toda 2017). Bradshaw et al. (2007) stated that halting deforestation or reducing the rate of natural forest loss would help alleviate the incidence and severity of flooding. Although major structures in main tributaries have been constructed such as dams, dikes, and weirs to mitigate flood damage in this basin, flooding still causes serious impacts, especially in the Yom and Nan Catchments (Tingsanchali and Karim, 2010). Water in the channel of Yom and Nan Rivers usually spills over the river bank or embankment to the floodplains due to mild channel slope and low capacity of rivers.

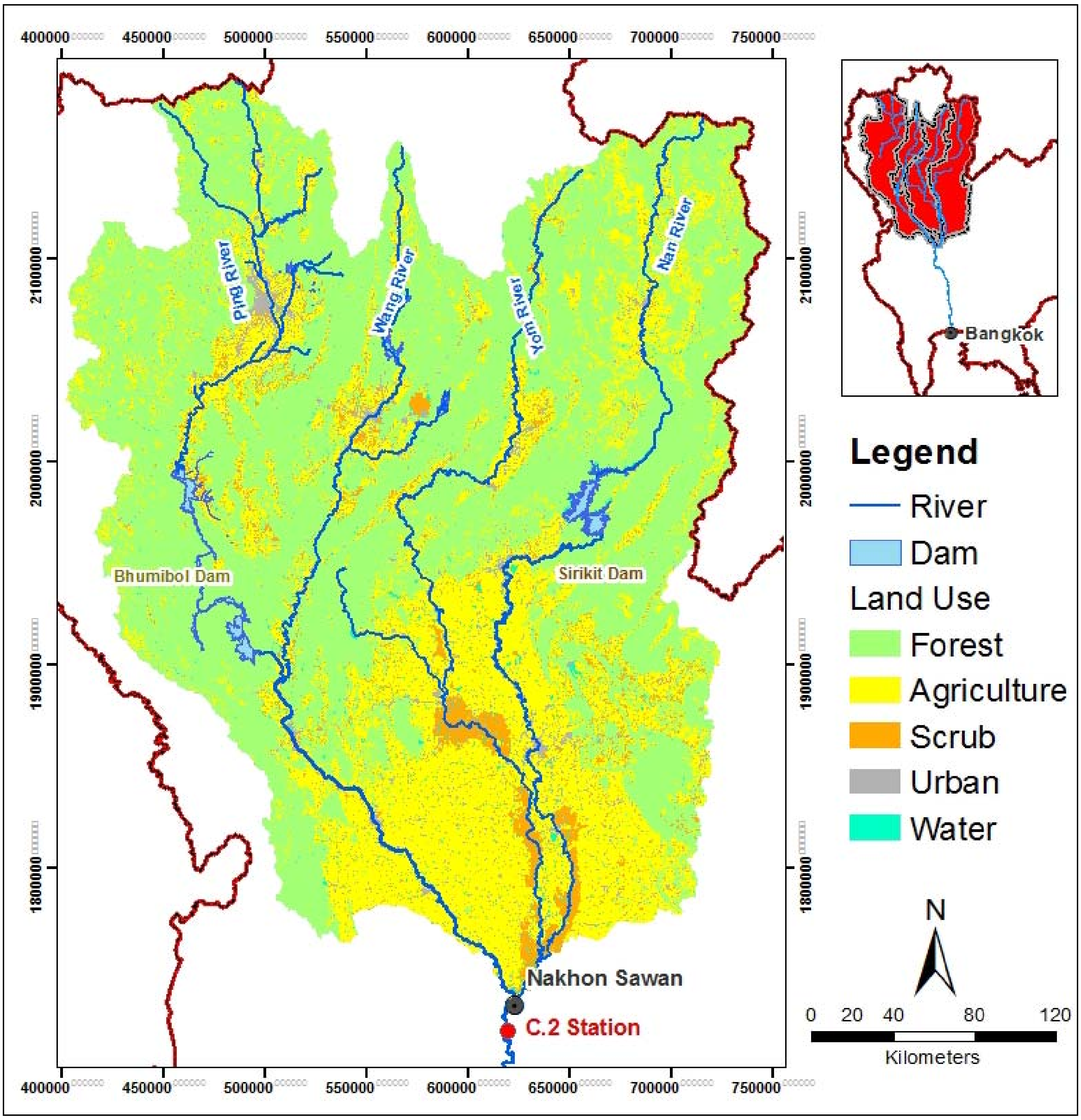


Fig. 1.2 Land use types classified in the upper and middle CPRB (Land Development Department, 2009).

Table 1.2 Land use types in the upper and middle CPRB (unit; km^2).

Sub Basins	Forest	Agriculture	Scrub	Urban	Water
Ping	8,997	22,833	695	1,238	757
Wang	8,201	1,578	350	470	467
Yom	12,104	9,077	1,583	958	325
Nan	18,713	12,605	1,481	1,235	814
Total	48,015	46,093	4,109	3,901	2,363

Source: Land Development Department (2009)

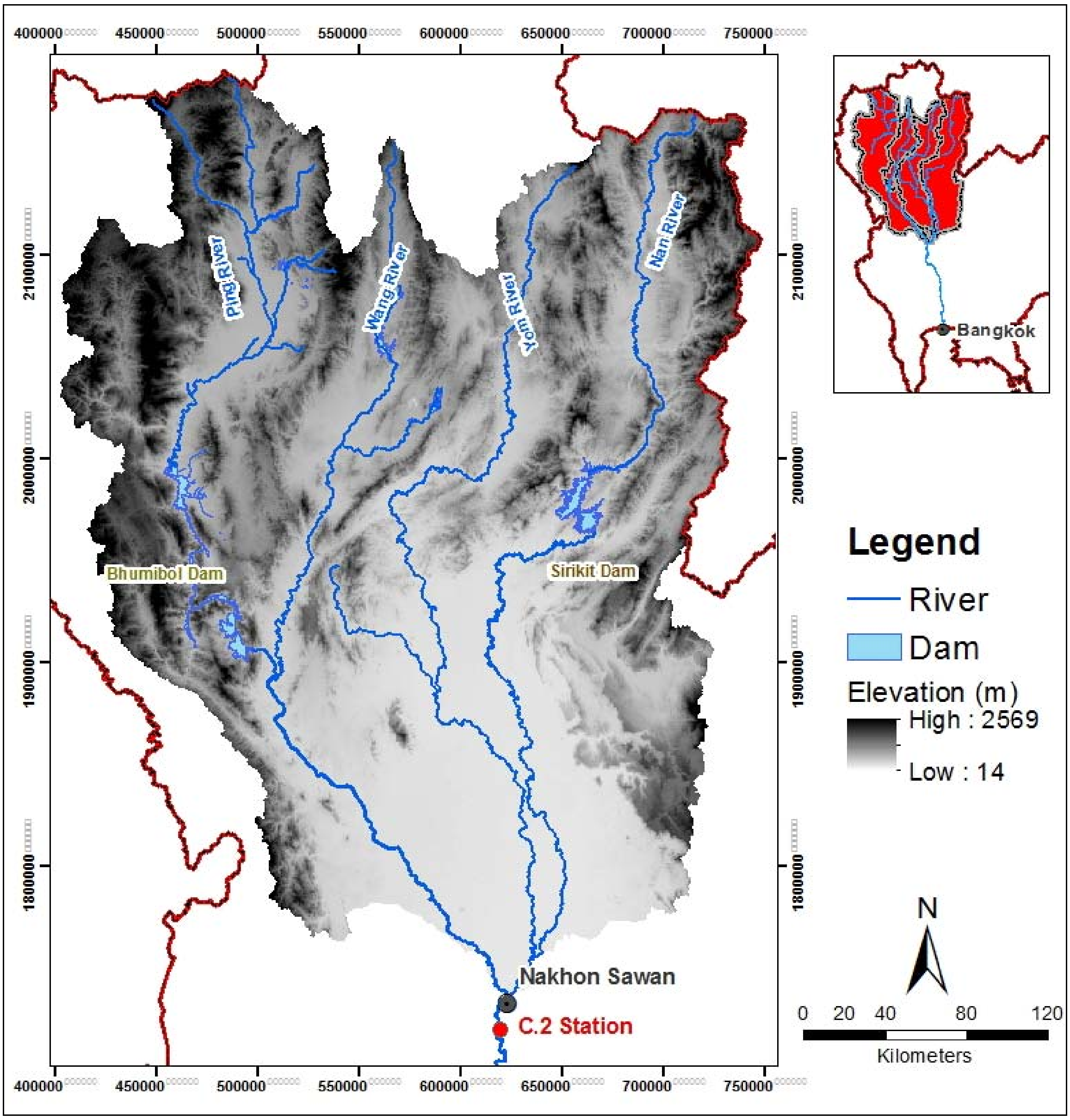


Fig. 1.3 Topographic conditions of the upper and middle CPRB (Royal Thai Survey Department).

1.1.2 Hydrology of the upper and middle Chao Phraya River Basin

Floods in the upper and middle CPRB are triggered by long-term rainfalls (May to October) and storm rainfalls (August to October) that cause frequent flooding in low-lying areas and prolonged floods cause human and economic losses. The upper and middle CPRB has a total of 262 rainfall stations (116 stations in the Ping River Basin, 27 stations in the Wang River Basin, 49 stations in the Yom River Basin, and 70 stations in the Nan River Basin). The annual rainfall in the upper and middle CPRB varies from 1,100 to 1,300 mm and average yearly rainfall is about 1,163 mm. In addition, there are a total of 215 runoff gauging stations (98 stations in the Ping River Basin, 25 stations in the Wang River Basin, 27 stations in the Yom River Basin, and 65 stations in the Nan River Basin). According to average annual discharge of 26,008 x 10^6 m^3, the major runoff derives from the Ping and Nan River Basins. The hydrology of the upper and middle CPRB is summarized in Table 1.3. In the CPRB, flooding is controlled by storing water in multipurpose reservoirs in the upper CPRB (Fig. 1.1), and excess discharge then flows downstream to the lower reach. Table 1.4 shows the characteristics of major reservoirs in the upper and middle CPRB. The total effective storage from reservoirs in the upper CPRB is around 17,986 x 10^6 m^3.

Table 1.3 Hydrology of the upper and middle CPRB.

Sub Basins	Average Annual Rainfall (mm)	Average Annual Runoff (mm)	Percentage of Total Annual Runoff (%)
Ping	1,152	8,800	33.8
Wang	1,102	1,624	6.2
Yom	1,167	3,648	14.0
Nan	1,295	11,936	46.0
Total	4,716	26,008	100

Source: Royal Irrigation Department (2000)

Table 1.4 Characteristics of major reservoirs.

Reservoir Name	Sub Basins	Effective Storage (x 10^6 m^3)
Bhumibol	Ping	9,662
Mae Ngat	Ping	253
Mae Kuang	Ping	249
Kiew Lom	Wang	102
Kiew Khoma	Wang	164
Sirikit	Nan	6,660
Khew Noi	Nan	896

Source: Royal Irrigation Department (2000)

1.1.3 Historical flood events in the Chao Phraya River Basin

The CPRB experienced many severe flood events, as identified by discharge rates, such as 1983, 1995, 1996, 2002, 2006, and 2011 flooding. However, the well-known severe flooding in CPRB occurred in 1995, 2006 and 2011. In the 1995, tropical storm, namely Lois, influenced high discharge in the upper CPRB especially in the Nan and Yom River Basins. This caused flooding in low-lying areas of middle CPRB and subsequently in Bangkok. The main reason of 1995 flooding was the limited capacity of Chao Phraya River in the lower reach. The flood extent in 1955 mostly occurred in agricultural areas around the lower CPRB for three months affected an area of 15,000 km^2 (Vongvisessomjai, 2007). After 1995 flood, Thailand formulated the first Thai Master Plan for flood protection and management. From this Master plan, the 77-km-embankment was constructed along the Chao Phraya River. The Royal Irrigation Department (RID) implemented eight retention areas in CPRB and Bangkok Metropolitan Administration (BMA) also constructed 21 temporary retention ponds within Bangkok after 1995 flood.

Since several measures introduced in 1995, Bangkok was safe from flood inundation in 2006. Vongvisessomjai (2007) mentioned the main factor of 2006 flood was a bottleneck of Chao Phraya River. Most flood extents in 2006 occurred in the middle and lower CPRB which covered an area of 19,000 km^2. For 2011, flooding stipulated by five tropical storms was the highest flood damages of Thailand. The flood extents in 2011 covered almost all CPRB from July to November which are agricultural areas, industrial estates, urban areas, and Bangkok including Don Muang International Airport. Owing to high discharge and long flood duration, RID reported the 28-control structure breach along the Chao Phraya River. DHI (2012) reported the 1995, 2006, and 2011 floods had a return period of about 50, 25, and 100 years, respectively.

1.2 Problem statement

The CPRB is similar to flood disasters occurring every year. Flood disaster, half of natural disasters from 1983 to 2012, caused the largest in terms of the amount of economic damages (AHA Centre, 2015). As flood disaster between 1995 and 2014 in Thailand, there are 72 flooding accounting for 55% of all natural disasters which results in US$ 45 billion economic damage, 3,860 people of fatality, and 55 million threatened people (Nakasu, 2017). The CPRB is a flood-prone area because of its topographical characteristics and strong influence of seasonal monsoon rainfalls. According to the spatial distribution of high rainfall intensity data (Thai Meteorological Department, 2015), it clearly shows that the low-lying area in the middle CPRB is relatively high-risk to flooding predominated by high rainfall intensity.

Flooding in the CPRB is controlled by storing water in multipurpose reservoirs in the upper CPRB, and excess discharge then flows downstream to the lower basin. In addition, flood mitigation in the CPRB is highly dependent on the operation of the Bhumibol and Sirikit Dams (Wichakul et al., 2013). If there had been no dams in the CPRB, floods in this watershed would have been much larger. Moreover, JICA (1999) reported that the river capacity of the Chao Phraya River at Bangkok (Fig. 1.1) should lead to a 1-in-3-year probability of flooding when flooding occurs in the upstream parts of the CPRB. However, flooding is infrequent at Bangkok because floodwater is stored in the floodplains of the upstream basins.

In 2011, the annual rainfall was the highest in the country's 61-year precipitation record (Thai Meteorological Department, 2011). The total rainfall in 2011 during the rainy season, estimated to be 1,439 mm, was 143% of the average rainy season rainfall from 1982 to 2002 (Komori et al., 2012). Because of the high water level of the Chao Phraya River, water-gates and levees in the lower CPRB broke and floodwaters submerged the seven industrial parks and the western part of Bangkok. The total cost of the damage and losses amounted to US$ 46.5 billion (The Ministry of Finance, 2012). In addition, the severe flood of 2011 affected domestic and foreign investment (Haraguchi and Lall, 2015). Throughout the entire calendar year, more than 800 people lost their lives and millions of residents were either left homeless or displaced. Therefore, if investment is to be maintained, it is essential to reduce flood discharge into the lower watershed of the CPRB. It has also been witnessed that existing flood countermeasures and flood risk management in Thailand are not effective enough to control large magnitude and long duration of 2011 flood. To minimize fatalities and economic losses, integrated flood countermeasures are necessary for flood control in the CPRB. A consideration of the widest possible set of flood countermeasures is needed to develop new proper alternatives that provide the information for overcoming severe flooding.

The amount of discharge at runoff station C.2, near the confluence of the Chao Phraya River (Fig. 1.1), plays an important role in determining flood management actions to reduce damages and losses in the lower CPRB. As the economic center of Thailand located in the lower CPRB, analyses of historical hydrological data have shown that the flood risk increases drastically when the discharge at station C.2 is more than 3,500 m^3/s, and results in vast inundation areas and huge economic losses in the lower CPRB. For example, the cost of the flood damage for the 1996 flood (peak discharge of 3,000 m^3/s) in the lower CPRB was

US$ 65 million; while the flood damage was US$ 248 million for the damage caused by the 1995 flood (peak discharge of 4,802 m^3/s) (Prajamwong and Suppataratarn, 2009).

As the remarkable flood disaster, many studies of the 2011 flood have concentrated on the lower CPRB (Trigg et al., 2013), and on the single application of flood protection measures such as dam operations (Chia et al., 2015; Mateo et al., 2014) and flood storage using paddy fields (Masumoto et al., 2015). Studies on the integrated flood countermeasures in the CPRB are limited. In addition, major flood defenses in the CPRB have not been developed since 1995, when a 77 km dyke was constructed along Chao Phraya River, and most of the exposed citizens are frequently impacted by flooding (Supharatid, 2012). Flooding on the same scale or more than the 2011 flood is expected to occur in the future due to climate change (Pratoomchai et al., 2014; Watanabe et al., 2014). To prevent a repeat of the severe 2011 flooding, an integrated approach that considers the possible widest set of flood countermeasures is required if flood disasters are to be managed in an efficient and sustainable way.

Flood risk assessment has widely been applied to provide information of risk for implementing various types of flood mitigation measures (Brown and Damery, 2002). The phases of the flood risk management can be seen as prevention, protection, and preparedness. Prevention can be understood as preventing flood damage by avoiding construction of infrastructure in flood-prone areas, land use regulation implementation, and modification of construction criteria standards. Protection means taking measures to reduce the characteristic and damage of floods such as via dykes strengthening and heightening. Preparedness includes forecasting and information, insurance schemes, and providing instructions and information to the public on what specific actions to undertake in the flood event.

Comparing components of risk in quantitative terms is the one of advantages of such a comprehensive risk assessment. The assessment and mapping of flood risk is needed in the risk and disaster management. The risk map can represent in the geographical aspect of flood information and management options which is helpful to make decision on various aspects of integrated management of floods (World Meteorological Organization and Global Water Partnership, 2013). A systematic process to specify data set that map was based is essential to develop flood risk map. Unfortunately, there is no detailed flood risk assessment in the middle CPRB and the results of flood risk assessment in Thailand were rarely shared among citizens (UNDP, 2012).

To lessen the vulnerability of people from flood disaster, the most used strategy is evacuation. Evacuation planning and management are included in the preparedness and response phases of disaster management activities. Successful evacuation management not only saves lives but also facilitates community to fast and smoothly regain their functionality (Perry, 1979). One of the factors that aggravated 2011 flood situations in the CPRB is the confusing and contradicting information from key agencies especially the evacuation information. The comprehensively planned evacuation and under-equipped evacuation shelters may cause loss of life owing to flooding. Due to frequent flooding in the CPRB, resident often suffer and struggle from this disaster in almost every year. It is therefore important for Thai government and emergency agencies to be prepared and develop a strategy in how people should respond to flood disaster to facilitate the effective flood evacuation.

The above information upholds the need for a consideration of the widest possible set of flood countermeasures to reduce the flood hazard by controlling flood characteristics such as flood magnitude and duration. Besides, flood risk assessment and mapping is essential for CPRB, particularly in low-lying flood prone areas, to develop flood risk reduction strategy such as an emergency flood evacuation. In addition, economic flood damages estimation is requisite and necessary to determine the feasibility of alternative flood countermeasures as decision making tool.

1.3 Research Objectives

In view of the problems mentioned in the previous section, the overall objective of this thesis which represents an original contribution to flood risk management research is to develop new set of flood countermeasures alternatives and proper and prompt flood evacuation strategies in the Chao Phraya River Basin (CPRB) that provide the information for flood risk management as adaptive measures (Fig. 1.4). More specifically, the sub-objectives are:

- To investigate the potential of various flood countermeasures types in the upper and middle CPRB.

- To assess the optimal operation of retention areas and large dams for sustainable flood management in the CPRB.

- To prevent and minimize losses and damages from severe flood events by using integrated flood countermeasures options.

- To identify the best solution from a set of flood countermeasures for each historical severe flood event (1995, 2006, and 2011).

- To assess or determine the feasibility of alternative flood countermeasures strategies in term of cost benefit approach.

- To establish the flood risk maps in 1995, 2006 and 2011 flood considered as the product of flood hazard and social vulnerability maps.

- To develop the emergency flood evacuation model to lessen the vulnerability of citizen.

- To determine the available time for safe evacuation in the middle CPRB.

- To propose recommendations to improve the efficiency of flood evacuation and reduce consequences of a catastrophic flood event.

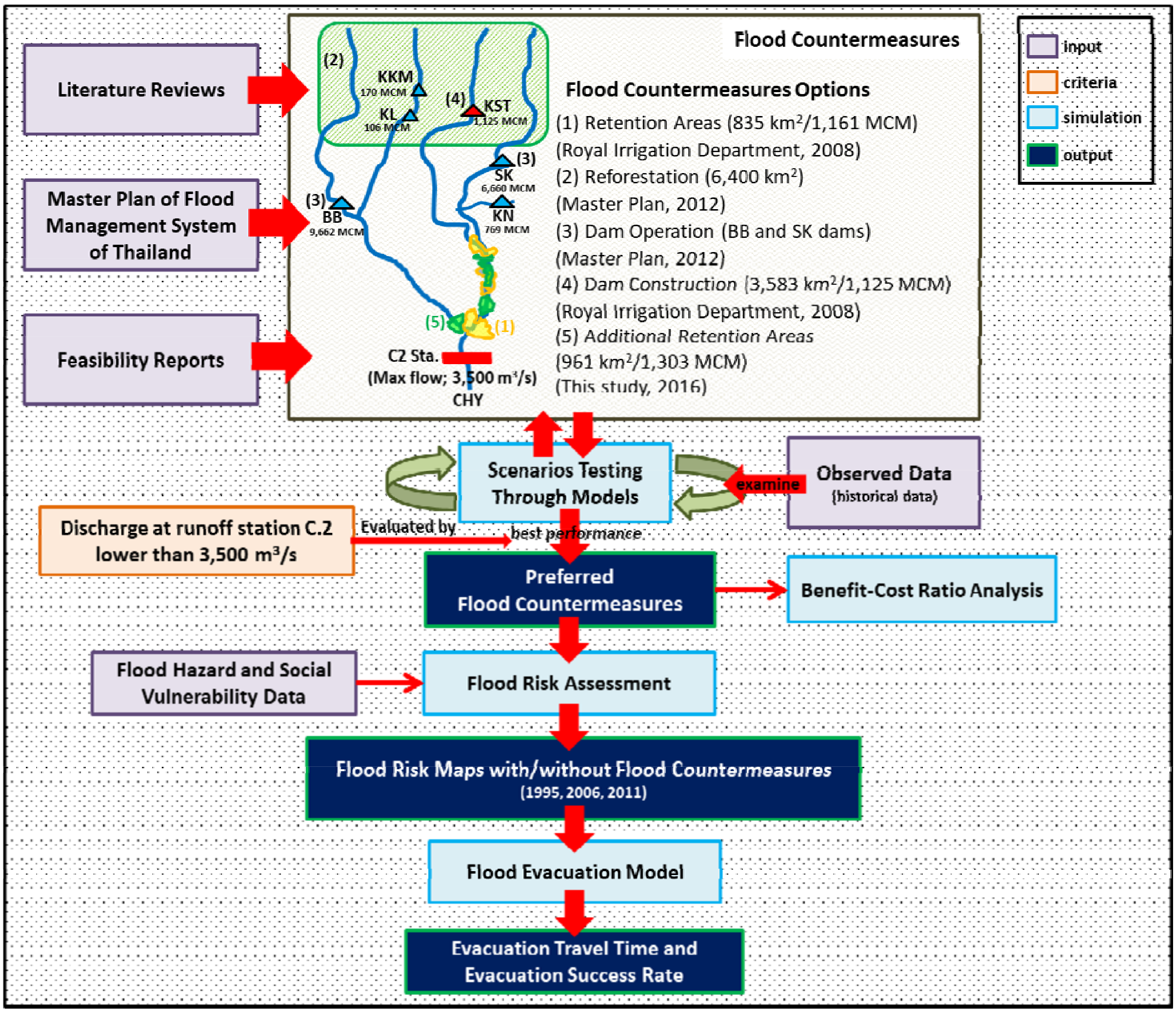


Fig. 1.4 Outline of this dissertation.

1.4 Structure of dissertation

Fig. 1.5 illustrates the flow of this thesis. The contents described in this dissertation are sequential explanations of different phases of the present research. This dissertation is composed of nine chapters in total from the introduction in Chapter 1 through the conclusion in Chapter 9, as described below:

Chapter 1 contains the introduction and motivation on this dissertation, the brief characteristics of the upper and middle Chao Phraya River Basin (CPRB), and explanation of the organization of the dissertation. Chapter 2 presents the numerical simulation models used in this research which are the hydrological model (SWAT model), reservoir operation model (HEC-ResSim model), and flood inundation model (iRIC model). Chapter 3 details the application of flood inundation model (iRIC model) for historical severe flood events which are 1955, 2006, and 2011 flood. This chapter also includes the calibration of flood inundation model. After the calibration phase, this research applies the flood inundation model to investigate and determine the potential of various flood countermeasures options in the upper and middle CPRB.

Chapter 4 includes the application of various flood countermeasures from Thai Master Plan in the upper and middle CPRB which are reforestation, retention areas, reservoirs operation improvement, and new dam construction. This chapter provides the results from the flood inundation model which present in the form of flood hydrograph at runoff station C.2. Moreover, the optimal operation of retention areas and large dams in the upper and middle CPRB are also determined in this chapter. Chapter 5 furthers the combination of flood countermeasures in Chapter 4 to overcome the historical severe flood events which are 1955, 2006, and 2011 flood by keeping peak discharge at runoff station C.2 lower than 3,500 m^3/s. In addition, in the case of flood measures from Thai Master Plan cannot overcome severe flood events, this study will provide a new alternative of flood countermeasures to cope with these flood events. Chapter 6 describes the economic feasibility of alternative flood countermeasures strategies selection proposed from this study which is the Thai Master Plan and this study suggestion. This chapter presents the results of economic flood damages estimation to household, manufacturing, and agricultural sectors. The effective flood countermeasure is determined and ranked by benefit-cost analysis. When the benefit greater than cost, it means measure is considered justified; while it will be not attractive when benefit lower than cost.

Despite flood countermeasures implementation, the flood risk assessment is essential to examine their potential in flood risk reduction. The Chapter 7 introduces the flood risk analysis to specific the high risk areas in the low-lying areas in the CPRB after and before implementation various flood countermeasures, and to lessen vulnerability of threatened people. Flood risk analysis from this research is presented in the form of flood risk map that was generated by the flood hazard and social vulnerability maps using fuzzy logic and fuzzy Analytic Hierarchy Process (AHP) approaches. After identification of high flood risk areas in the Chapter 7, Chapter 8 facilitates the emergency flood evacuation measure to reduce the loss of life due to the most frequent inundated areas in the CPRB of study area as a holistic approach. This chapter also suggests recommendations to enhance the effectiveness of evacuation. Finally, Chapter 9 summarizes main findings, scientific contributions as well as some suggestions for further study which have made through this chapter.

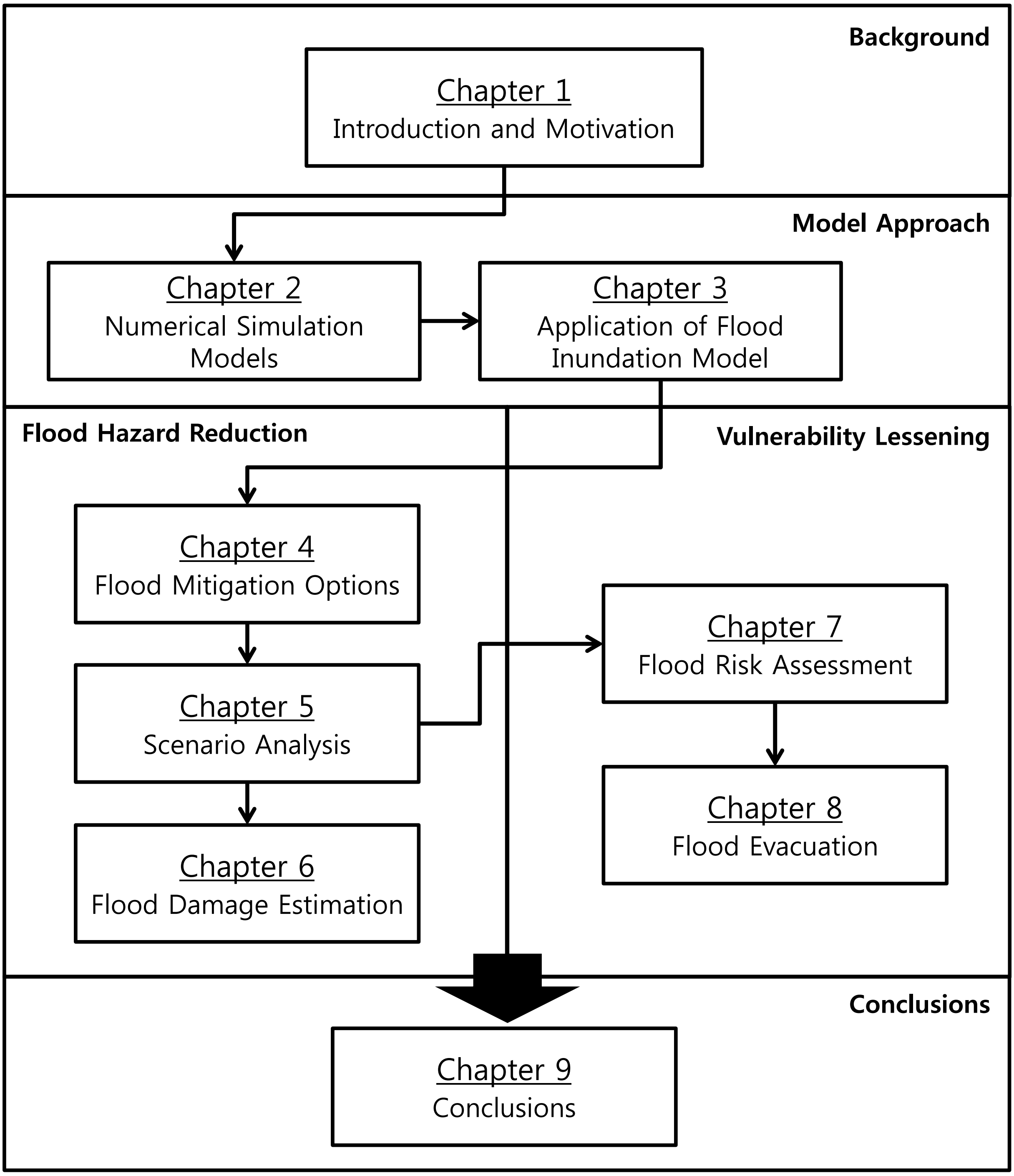


Fig. 1.5 The structure and flow of this dissertation.

Chapter 2
Numerical simulation models

2.1 Outline

In general, numerical simulation models have been taking to deal with the most important tasks in problem solving on flooding. Many discussions regarding to modelling have been revealed in various scientific literatures (Bruwier et al., 2015; Chu et al, 2015; Plate, 2009). The numerical simulation model prefers capturing a vivid way to understand some aspects of its structures or behaviors rather than reproduce all the reality of its complexity. Almost all numerical simulation models are usually applied to imitate the reality that we determine to be essential to variety of purposes to plan, develop, manage and operate various water resources schemes. Therefore, a series of mathematical equations are applied in numerical simulation model to fulfil our purpose. The numbers, forms, and interconnections of these equations ranged from very simple to highly sophisticated equations to satisfy various objectives.

Management and mitigation of flood disaster can be better facilitated through the use of models such as hydrological model, reservoir operation model, and flood inundation model. Some of models provide the well understanding in the flood extent. Some of them also assess the impact on strategies plan which is usually applied for decision-making and policy planning. According to various flood countermeasures involving in this research, there are various types of numerical simulation models. This research employs the hydrological model to consider the effect of reforestation on hydrological regimes. The reservoir operation model is also applied to examine the importance of dam construction and dam operation on flood control strategies. Nevertheless, this study also utilizes the flood inundation model to investigate and analyze flood routing and flood extent in this study area. Flowchart of the numerical simulation models used in this study is illustrated as Fig. 2.1.

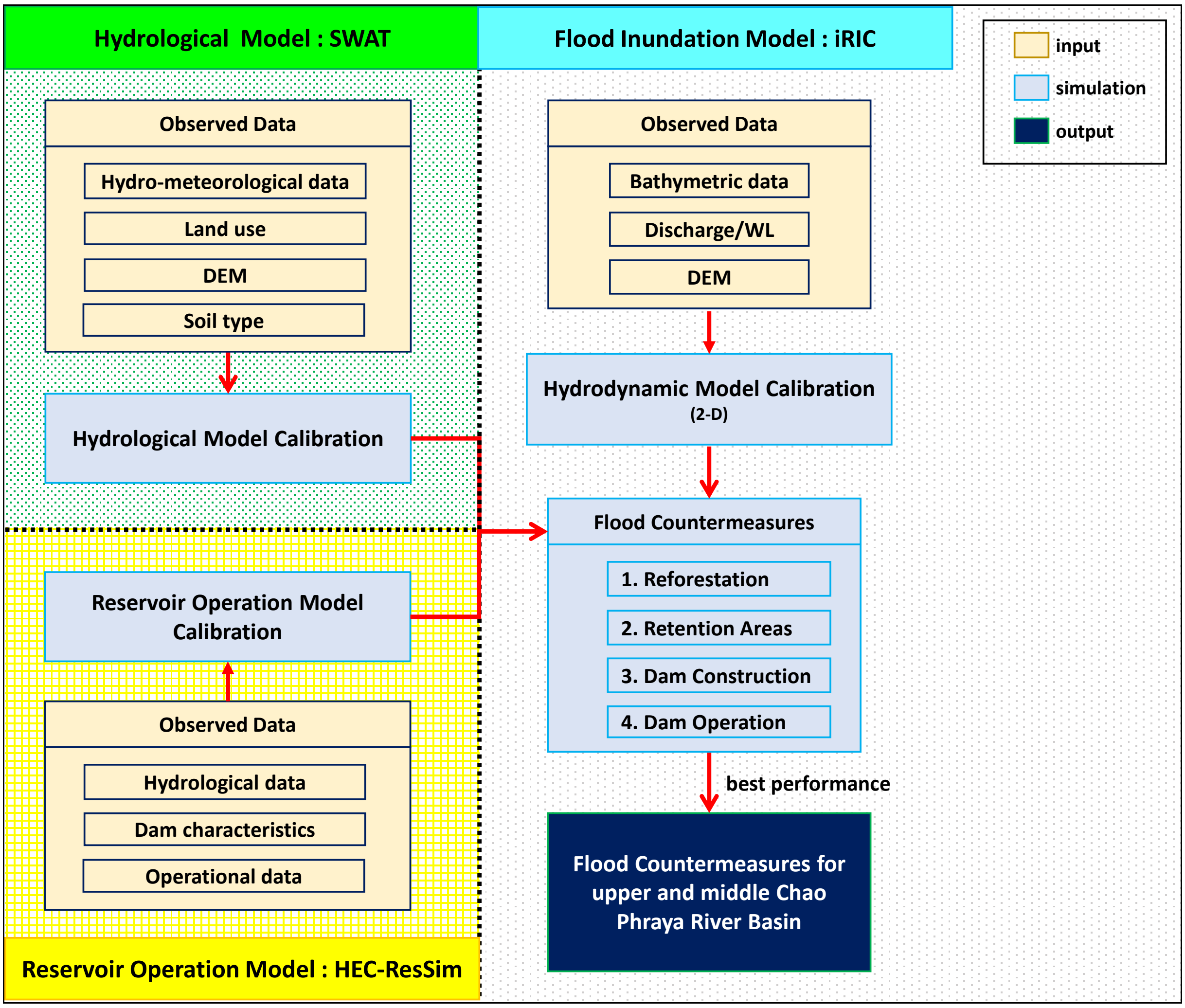


Fig. 2.1 Flowchart of the numerical simulation models.

2.2 Hydrological model

The rest of hydrologic systems are extremely complex. The abstraction is necessary and essential when we attempt to understand or control some aspects of theirs behaviors. The hydrological models have many different types and, therefore, have been developing for different purposes. In general, they are usually modelled to satisfy one of two primary purposes. The first obvious objective is to investigate and gain a better understanding on hydrologic conditions in a catchment. Another objective is to synthesize the sequences of hydrologic data in order to facilitate and use for forecasting purposes.

The watershed can be mostly considered as a hydrologic system that determines system boundary around the watershed as shown in Fig. 2.2. The rainfall is considered as the input that is distributed in space covering the hold catchment. Excess rainfall is determined by subtracting that it is intercepted by vegetation, evaporated to atmospheres, infiltrated into the soil, and percolated to the ground water. The output of the hydrological model is usually represent in the form of streamflow as hydrograph which be routed to the outlet of basin over the time. In the hydrological model, the peak flow magnitude, and time to peak can be determined through hydrograph. The information on elevation of water surface within catchment cannot be investigated through the hydrological model. Hydrological models can usually be classified as shown in Fig. 2.3.

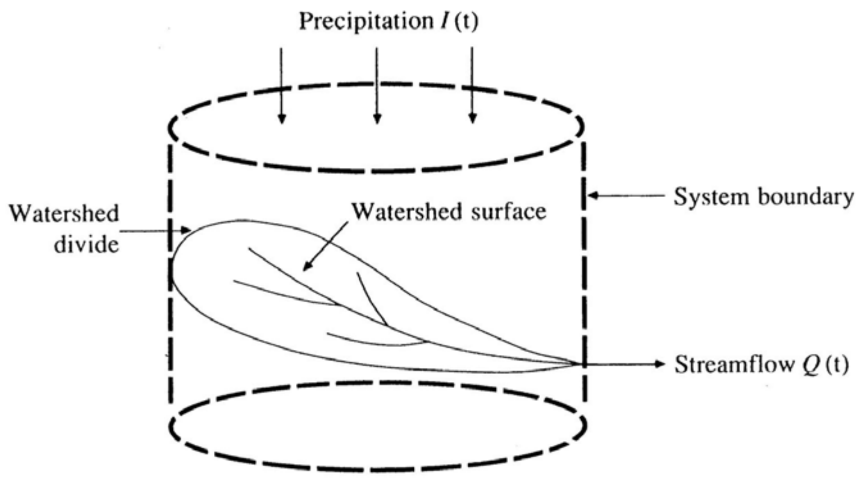


Fig. 2.2 The hydrologic system represented in catchment (Chow et al., 1988).

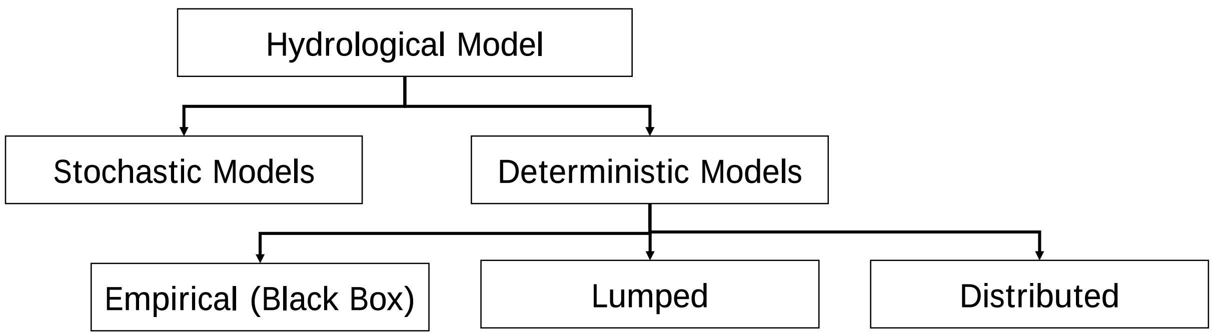


Fig. 2.3 Classification of Hydrological Models.

The stochastic model normally includes the consideration of uncertainties in both parameters and input data. Some techniques such as regression and double mass curve are usually found in the stochastic model to investigate changes in hydrologic response within catchment. However, these techniques are very difficult to determine which underlying factors have a significant effect on theirs changes. On the other hand, the deterministic model describes the behavior of hydrologic processes in a catchment using mathematical expressions related to various phases of the hydrologic cycle. The outcomes of deterministic model are precisely determined through model parameters without the random variation. Besides, the calibration and verification is the important step of this model type to affirm that the model can reproduce the reliable streamflow.

The empirical (black box) model does not attempt to model the hydrologic processes such as infiltration, evaporation, and surface runoff. This model is relatively depended on the like of mathematic between input and output variables. The parameters of this model are determined to well match between the simulated and measured outflow. The lumped hydrologic model accounts for the hydrologic processes based on hydraulic laws and empirical equations. The parameters and hydrologic variables in this model take on single lumped values over large areas of catchment without regarding to spatial variability in parameters. In order to include spatial variability to this model, subdividing the watershed into sub-basins has been applied to represent the whole hydrologic processes on catchment. This method assumes hydrologic processes occur uniformly over each sub-basin.

The distributed model provides the explanation on various aspects of model in spatial and temporal of hydrologic processes. This model can divide the watershed to uniformly grid cells rather than hydrological homogeneous sub-basins. The hydrologic processes in each cell are grouped to create the runoff which be routed to neighboring cells. The direction of runoff is determined by the slope. Besides, the data requirements are very much greater than lumped model. The distributed model is commonly found in groundwater simulation rather than the surface water modeling because of the fewer hydrologic processes and admitting of differential equations (finite difference or finite element).

This research applies the Soil and Water Assessment Tool (SWAT) as the hydrological model. The SWAT model developed by USDA-ARS is a daily time step and semi-distributed physically based model (Arnold et al., 1998). Many researches have applied SWAT model to determine variety of land management impacts on water quantity (Muttiah and Wurbs, 2002; Srinivasan and Arnold 1994), to examine environmental benefits related to various practices (Mausbach and Dedrick, 2004), and to quantify the effect of land use changes on the temporal and annual runoff (Fohrer et al., 2001, 2005; Fohrer and Frede, 2002). Similarly, the SWAT has been also successfully applied in Thailand watersheds (Bannwarth et al., 2015; Coutu and Vega, 2007; Homdee et al., 2011; Ligaray et al., 2015; Yasin and Clemente, 2014).

Recently, the SWAT 2012 model has been developed to be compatible with the

ArcGIS version 10.3 (Winchell et al., 2009). The SWAT 2012 is capable of using a geo-database approach and programming structure in the ArcGIS (Olivera et al., 2006; SWAT, 2007). The SWAT 2012 is able to classify various spatial data such as topography, land use, and soil into subdivisions. There are two main subdivisions; (1) watershed is divided into sub-watersheds by topographic discretization; and (2) each sub-watershed is further subdivided into Hydrologic Response Units (HRUs). In that state, HRUs are lumped and comprised of a unique combination of land cover, soil type, and slope.

Neitsch et al. (2005) mentioned that basically the SWAT model employs the empirical and physically-based equations that can simulate eight major components (hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management). The SWAT model also categorizes the major hydrologic processes such as infiltration, evapotranspiration, shallow and surface flow, and channel routing at different four subsystems (surface soil, intermediate zone, shallow and deep aquifers, and open channels) (Arnold and Allen, 1996). For the land phase of hydrologic cycle, the SWAT model is simulated based on the water balance equation.

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_d - Q_s - E_a - W_s - Q_g\right) \tag{2.1}$$

where SW_t is the final soil water content (mm), SW_0 is the initial soil water content (mm), t is the time (days), R_d is the amount of precipitation on day i (mm), Q_s is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), W_s is the amount of percolation and bypass flow on day i (mm), and Q_g is the amount of return flow on day i (mm).

Surface runoff is estimated by a modification of the SCS curve number (USDA-SCS, 1972). The curve number involves the moisture content of the soil that means it becomes zero when it meets the wilting point. In contrast, it turns to 100 when it is saturated. Surface runoff volume using SCS curve number expresses as given below:

$$Q_{surf} = \frac{\left(R_{day} - 0.2S\right)^2}{\left(R_{day} + 0.8S\right)} \tag{2.2}$$

where Q_{surf} is the accumulated runoff or rainfall excess (mm), R_{day} is the rainfall depth for the day (mm), and S is retention parameter (mm).

When $R_{day} > 0.2S$ the runoff will occur that is deepened on the changes in soils, land use, management, and slope. The retention parameter is defined as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \tag{2.3}$$

where *CN* is the curve number for the day.

The peak runoff in the SWAT model is calculated by the modified rational method. The rational method is calculated by the assumption that the runoff will increase from the time t = 0 until the time of concentration, $t = t_{conc}$. The runoff will flow to the outlet. The rational formula is defined as:

$$q_{peak} = \frac{C \times i \times Area}{3.6} \tag{2.4}$$

where q_{peak} is the peak runoff rate (m^3/s), *C* is the runoff coefficient, *i* is the rainfall intensity (mm/hr), *Area* is the sub-basin area (km^2), and *3.6* is a unit conversion factor.

2.3 Reservoir operation model

Reservoirs are often operated for operational goals and constraints related to environmental, economic, and public services. According to the types of systems, there are single and multi-reservoir systems. Multi-reservoir systems can be organized and operated in series or parallel. Furthermore, reservoir can be classified according to its functions such as single purpose and multipurpose reservoir. The single purpose reservoir has a clear function and amount of water delivery may be released for irrigation, power supply, and flood management. The multipurpose reservoir operates and serves various functions such as irrigation, hydropower, flood management, fisheries, and recreation. In general, reservoirs in Thailand are operated according to rule curves which are established at the planning/design stage to provide long-term operation guidelines to meet the expected water demands and constraints. Rule curves usually consist of a series of storage volumes or levels at different periods (Liu et al., 2011).

The reservoir operation model has been widely applied for flood risk management, water supply for planning studies, detailed reservoir regulation plan investigations, and real-time decision support. The HEC Reservoir System Simulate (HEC-ResSim) is one of reservoir operation models that were developed based on physical relations comprised of operational rules (US Army Corps of Engineers, 2013). The HEC-ResSim attempts to simulate as close as the reality and system characteristics under specified conditions. The HEC-ResSim model has three main modules; (1) watershed setup, (2) reservoir network, and (3) simulation. The HEC-ResSim model also provides four types of elements (junctions, routing reaches, diversions, and reservoirs) to compose the system network of reservoirs as shown in Fig. 2.4.

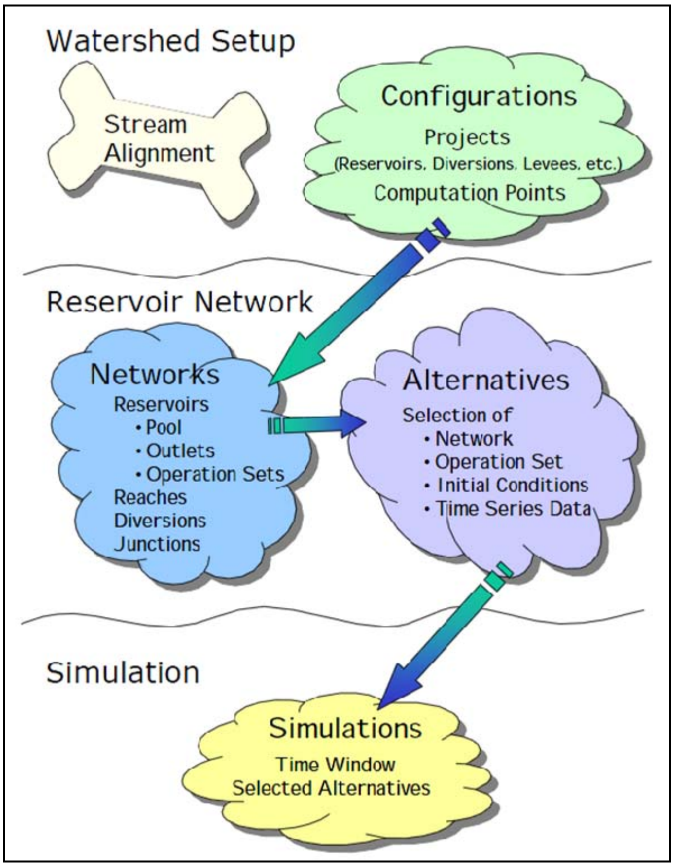


Fig. 2.4 The HEC-ResSim Module Concepts.

The HEC-ResSim model classifies dam into two main types; physical and operational components. The physical component of reservoir is composed of a pool and dam. The pool assumes as level which is no routing behavior and an elevation-storage-area table completely represents as its hydraulic behavior. The HEC-ResSim model can consider the complexity of reservoir network and also add a power plant to describe the capacity of hydropower generation. For the operational component of reservoir, the HEC-ResSim model employs the target pool elevation namely guide curve as the regulation plan. The storage of reservoir is usually divided into three components: (1) flood control; (2) conservation; and (3) dead storages. For the conservation storage, the HEC-ResSim model can allow users specific flow requirements and constraints for the reservoir operating zones and also prioritizes them in each zone. A general reservoir operation model simulates based on water balance scheme.

$$S_i = S_{i+1} + I_i - Q_i - L_i \tag{2.5}$$

where S_i is the storage of reservoir at time t, S_{i+1} is the storage of reservoir at time t+1, I_i is the inflow at time t, Q_i is the outflow at time t, and L_i is loses (evaporation and seepage) at time t.

Moreover, the HEC-ResSim model is also capable of considering the river flow routing. There are various options for hydrologic routing methods such as Muskingum, Modified Puls, and Muskingum-Cunge. Every each routing reach can specific loses during simulation.

For the Muskingum method, it was firstly introduced by McCarthy (1938) and is one of most popular method for flood routing (Chin, 2000). The Muskingum routing is a storage routing method based on the storage equation which is an expression of continuity equation.

$$\frac{dS}{dt} = I - O \tag{2.6}$$

where S is storage in the reach (m^3), I is inflow to the reach (m^3/s), O is outflow from the reach (m^3/s).

As Fig. 2.5, the routing method estimates the channel storage by the combination of prism and wedge storages. The storage relationship can be expressed as follow:

$$S = K\left[XI + (1 - X)O\right] \tag{2.7}$$

where K is a travel time of the flood wave through routing reach (s) and X is a weighting coefficient ($0 \leq X \geq 0.5$).

In natural streams, X is usually between 0 and 0.3, with a typical value near 0.2 (Chin, 2000). The total storage volume at any time instant, t can be calculating the above two storages.

$$S_t = KO + KX\left(I_t - O_t\right) \tag{2.8}$$

The Muskingum equation based on Eq. (2.6) and the water balance equation can be written as:

$$O_{(t+1)} = C_1 I_{(t+1)} + C_2 I_t + C_3 O_t \tag{2.9}$$

where

$$O_{(t+1)} = \left(\frac{\Delta t - 2KX}{2K(1-K) + \Delta t} \right) I_{(t+1)} + \left(\frac{\Delta t + 2KX}{2K(1-K) + \Delta t} \right) I_t + \left(\frac{2K(1-K) - \Delta t}{2K(1-K) + \Delta t} \right) O_t \quad (2.10)$$

therefore

$$C_1 + C_2 + C_3 = 1 \quad (2.11)$$

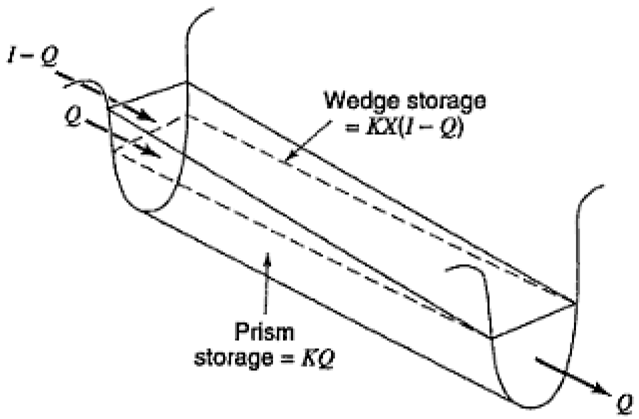


Fig. 2.5 Prism and wedge storage in a channel reach (Mays, 2009).

2.4 Flood inundation model

Flood inundation models can be used to investigate and analyze flood routing and flood inundation at different important locations. Various inundation models have also been applied to estimate and predict flood with high spatial and temporal resolutions (Looper and Vieux, 2012; Park et al., 2014; Reed et al., 2007). This information from inundation model can also be material for evacuation routes and locating suitable emergency shelters. The iRIC (international River Interface Cooperative) which has been widely used in various interests such as flood inundation and river morphology (Asahi et al., 2013; Egashira et al., 2016; Harrison et al., 2015; Nelson et al., 2015; Wongsa 2014) is employed as flood inundation model for this study. The Nays2DFlood solver one of solvers of iRIC model was developed by The Foundation of Hokkaido River Disaster Prevention Research Center. The Nays2DFlood enable users to investigate the hydraulics conditions according to river channel, floodplains and hydraulics structures in steady and unsteady states. In addition, the Nays2DFlood can analyze unsteady 2D runoff and allows users to set the inflow conditions of rivers inflow that enters at the upstream end or sides of a river. Besides, the Nays2DFlood is applied to simulate flood routing and flood inundation in the middle CPRB. The basic equations in Nays2DFlood consist of the continuity and horizontal momentum equations. These 2D equations in a Cartesian coordinate system (x,y) can be given as follows:

[Equation of continuity]

$$\frac{\partial h}{\partial t}+\frac{\partial(hu)}{\partial x}+\frac{\partial(hv)}{\partial y}=q+r \tag{2.12}$$

[Equations of motion]

$$\begin{aligned}
\frac{\partial(hu)}{\partial t}+\frac{\partial(hu^2)}{\partial x}+\frac{\partial(huv)}{\partial y}&=-hg\frac{\partial H}{\partial x}-\frac{\tau_x}{\rho}+\frac{\partial}{\partial x}\left[v_t\frac{\partial(hu)}{\partial x}\right]+\frac{\partial}{\partial y}\left[v_t\frac{\partial(hu)}{\partial y}\right]\\
\frac{\partial(hv)}{\partial t}+\frac{\partial(huv)}{\partial x}+\frac{\partial(hv^2)}{\partial y}&=-hg\frac{\partial H}{\partial x}-\frac{\tau_y}{\rho}+\frac{\partial}{\partial x}\left[v_t\frac{\partial(hv)}{\partial x}\right]+\frac{\partial}{\partial y}\left[v_t\frac{\partial(hv)}{\partial y}\right]
\end{aligned} \tag{2.13}$$

where

$$\begin{aligned}
&\frac{\tau_x}{\rho}=C_f u\sqrt{u^2+v^2}\,and\,\frac{\tau_y}{\rho}=C_f v\sqrt{u^2+v^2}\\
&v_t=\frac{\kappa}{6}u_* h
\end{aligned} \tag{2.14}$$

where h is water depth (m), t is time, u is flow velocity in the x direction (m/s), v is flow velocity in the y direction (m/s), q is inflow through a box culvert, a sluice pipe, or a pump per unit area (m/s), r is rainfall (mm), g is gravitational acceleration (m^3/s), H is water surface elevation (m), τ_x is riverbed shear stress in the x direction (N/m^2), τ_y is riverbed shear stress in the y direction (N/m^2), C_f is riverbed friction coefficient v_t is eddy viscosity coefficient, ρ is the density of water (kg/m^3), κ is Von Karman's constant (0.4), and u_* is bed shear velocity (m/s).

The finite difference method (FDM) is applied for transformation of flow equations from Cartesian coordinates (x,y) to General coordinates (ζ, η). The Cubic Interpolation Psuedoparticle (CIP) method is also applied to solve river flow equations. This method provides precise profiles of convectional variables considering value from adjacent cells.

Chapter 3
Application of flood inundation model for historical severe flood events

3.1 Area of flood inundation simulation

This study mainly focuses on the upper and middle Chao Phraya River Basin (CPRB). Because of the geographical location, the middle CPRB always receives a large amount of runoff during rainy season that causes flooding in this basin almost every year. Despite various flood countermeasures have been made to mitigate flood damage in this basin, the low-lying areas, especially Yom and Nan River Basins, are under a treat of flood risk. Chuenchooklin et al. (2007) applied the HEC-RAS model to investigate the effect of retention areas and various diversion channel sizes in Yom River Basin to reduce flood damages in this basin. For the Nan River Basin, Amnatsan et al. (2010) introduced the integration of wavelet analysis and artificial neural networks to predict water level for flood prevention.

Owing to the most sensitive to flood disaster of Yom and Nan River Basin around middle reach of CPRB, this study applies the iRIC model as flood inundation model to simulate the flood conditions in the middle CPRB, from the Ping, Yom, and Nan Rivers to Nakhon Sawan Province as shown in Fig. 3.1. The total area of computation is around 6,012 km^2.

3.2 Model calibration

A 30-m resolution digital elevation model (DEM), river geometry, and roughness coefficient are used as input data for the iRIC model. According to a 30-m resolution of DEM, this study creates the calculation grid as 50 m × 50 m grid resolution. This number is considered by the average channel width. For carrying out simulations, this study used measured daily discharge data from runoff station P.17, Y.16 and N.5A as upstream boundary conditions and used areal rainfall from eight observed rainfall station to simulate runoff between the upstream and downstream boundary as lateral boundary condition (Fig. 3.1). The observed water level at runoff station C.2 was used as downstream boundary condition. The Fig 3.2 shows the daily flood hydrograph at each upstream boundary (P.17, Y.16 and N.5A), summation of three runoff stations, and runoff station C.2. From the distribution and amount of flood hydrograph, it could be state that flooding in this basin mostly comes from the river flooding (over bank flooding) or overland flow rather than the intensity of rainfall at the computation area. In the calibration phase, flood inundations were simulated using the flow conditions from the 1st September to 31st October in 1995, 2006, and 2011. The comparison between the measured (GISTDA satellite map) and simulated (iRIC model) flood inundations are illustrated in Fig. 3.3. With the study area covers approximately 6,012 km^2, the flood inundation extent in 2006 and 2011 from satellite map provided by GISTDA was 3,270 and 4,398 km^2 respectively; while the iRIC model simulated the extent of flood area was 2,991 and 4,276 km^2 in 2006 and 2011 respectively. Therefore, it could be mentioned that the model tends to underestimate flood extent identified by GISTDA satellite map. It may be related to the coarse floodplain elevation data and roughness coefficient.

To calculate flood hydrograph at runoff station C.2, this study evaluates the discharge by multiply grid width with water depth and flow velocity that obtained by iRIC model. To reduce fluctuation of hydrograph at runoff station C.2 derived from flow velocity, the eight grid cells surrounding the grid cell that represents the location of runoff station C.2 have to be applied for calculation to smooth the flow velocity. The hydrographs in Fig. 3.4 show that the model can reproduce flood hydrographs at runoff station C.2 well for three severe flood events. Table 3.1 shows the overall model performance through the three statistic parameters; (1) the coefficient of determination (R^2), (2) Nash-Sutcliffe efficiency (NSE), and (3) Root Mean Square Error (RMSE). Equations used to evaluate statistic values are given below:

[Equation of the coefficient of determination (R^2)]

$$R^2 = \frac{\sum_{i=1}^{n}\left(Q_m - \overline{Q_m}\right)^2 - \sum_{i=1}^{n}\left(Q_m - Q_s\right)^2}{\sum_{i=1}^{n}\left(Q_m - \overline{Q_m}\right)^2} \tag{3.1}$$

[Equation of Nash-Sutcliffe efficiency (NSE)]

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_s - Q_m\right)^2}{\sum_{i=1}^{n}\left(Q_m - \overline{Q_m}\right)^2} \tag{3. 2}$$

[Equation of Root Mean Square Error (RMSE)]

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Q_s - Q_m)^2}{n}} \tag{3.3}$$

where Q_m is measured discharge at time t, Q_s is simulated discharge at time t, $\overline{Q_m}$ is mean of measured discharge, and n is the number simulation time.

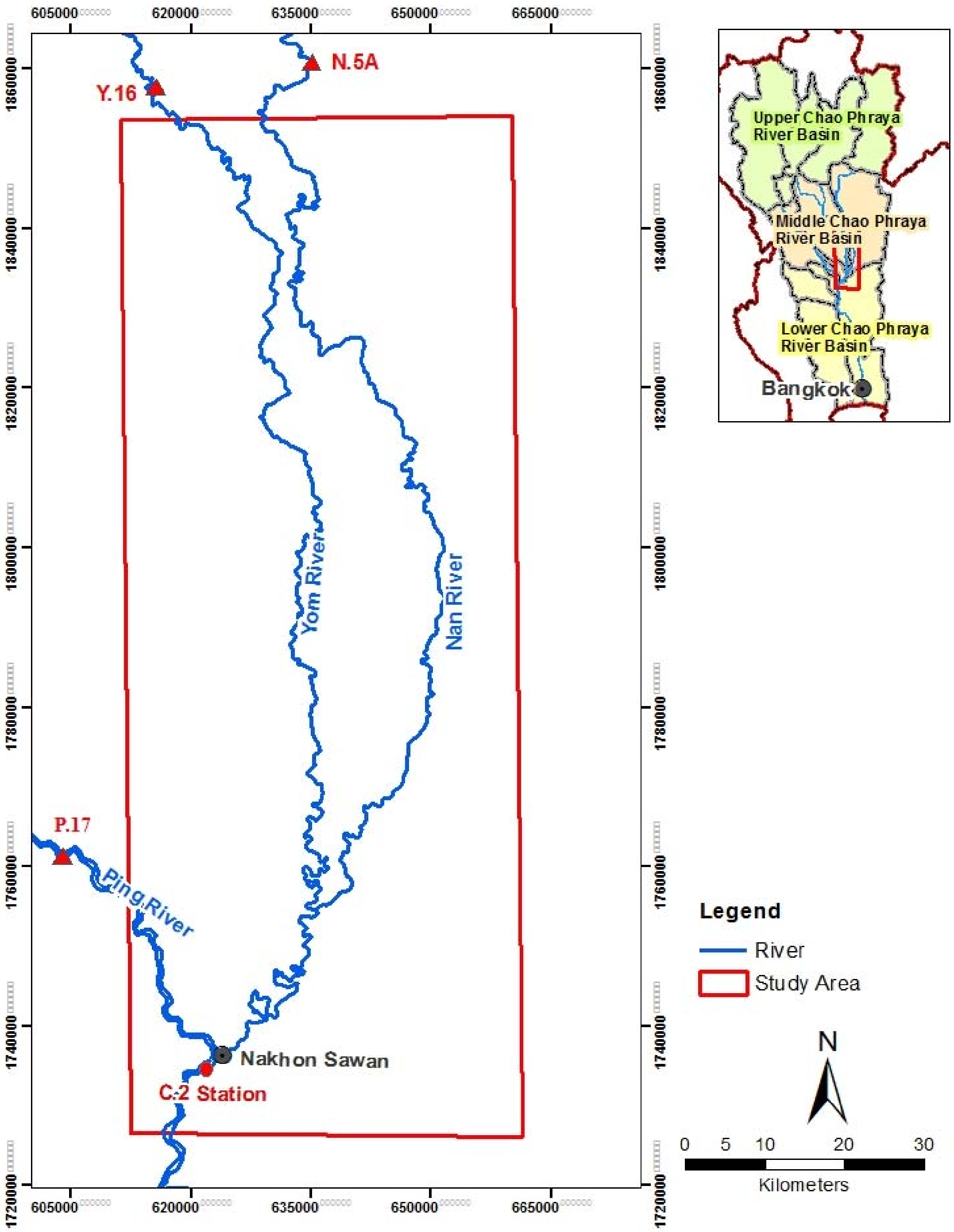
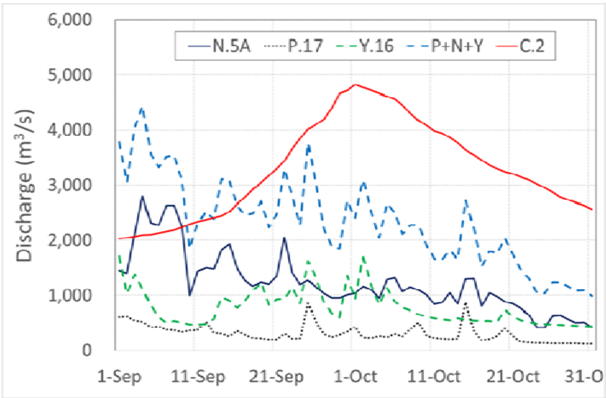
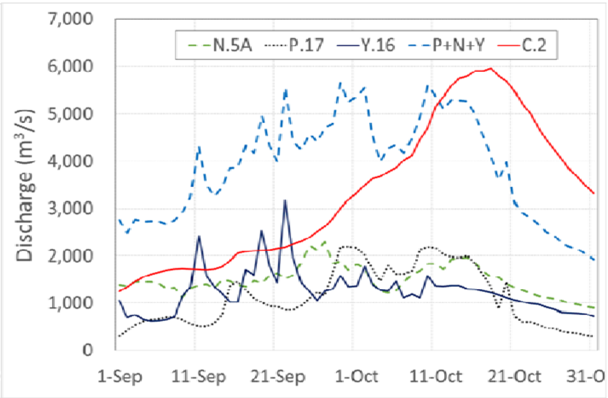


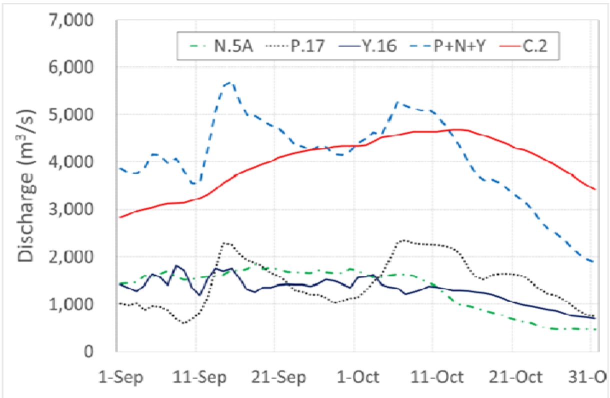
Fig. 3.1 Simulated flood inundation area.



(a)



(b)



(c)

Fig. 3.2 Flood hydrograph at each upstream boundary, summation of three runoff stations, and runoff station C.2 in (a) year 1995 (b) year 2006 and (c) year 2011.

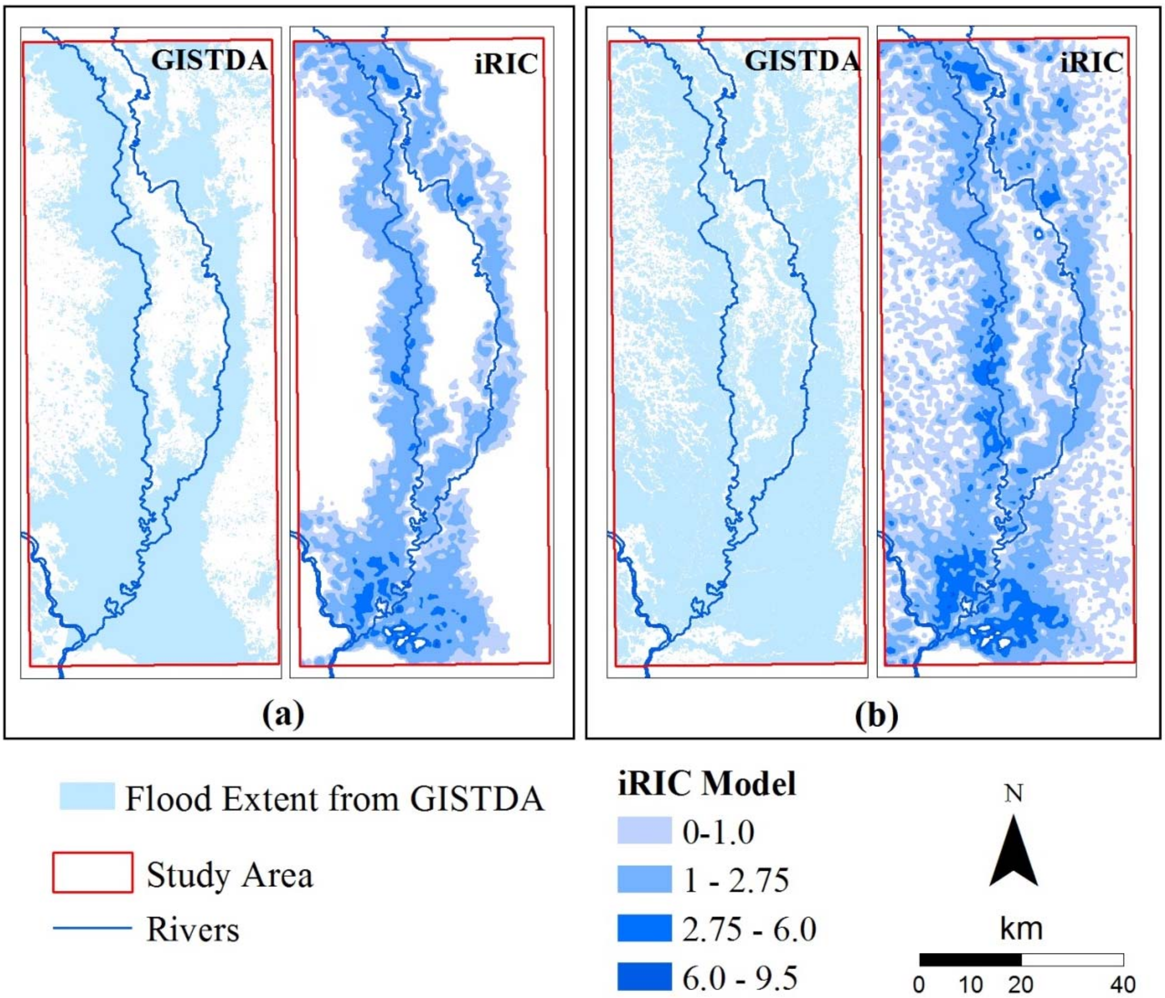


Fig. 3.3 Comparison of flood inundation between GISTDA satellite data (left) and simulated results (right) in (a) year 2006 and (b) year 2011.

Table 3.1 Model statistic values of the flood hydrograph at runoff station C.2.

Statistical index	1995	2006	2011
R^2	0.960	0.964	0.926
NSE	0.949	0.993	0.996
RMSE (m^3/s)	194.82	305.27	245.31

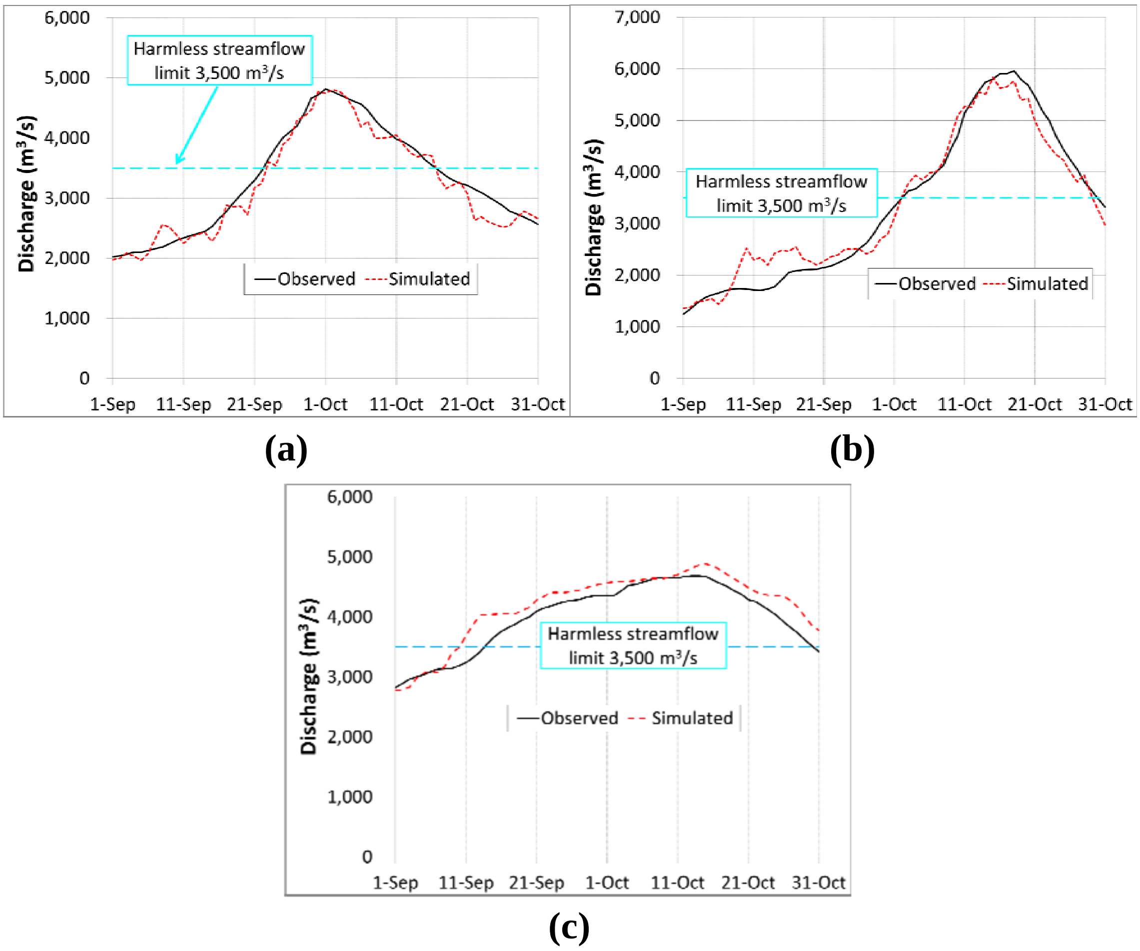


Fig. 3.4 Comparison of flood hydrograph at runoff station C.2 in
(a) year 1995 (b) year 2006 and (c) year 2011.

3.3 Effect of drainage system on severe flooding

During rainy season, drainage system plays as the one of crucial roles to reduce flood damage in the flood prone area. Drainage systems as irrigation channel or sewer system are used for flood damage alleviation. Irrigation channel is applied to carry and regulate amount of flood water to downstream and sewer system is mostly used for storm water. The capability of these measures is depend very much on the capacity of their. According to the most of study areas are the rainfed agriculture, we found that the irrigation areas and urban area cover area of 2,265 km^2 which accounts for 38% of total area. Furthermore, the biggest irrigation channel which is not locate at main tributary in this study area found at Phitsanulok Irrigation Project can convey amount of water about 177 m^3/s. When we compare the capacity of the biggest irrigation channel to severe flood event in 1995, 2006, and 2011, it found that it has a limited potential to reduce flood damage from these severe flooding. However, the capability of drainage system should be determined. Besides, this study preforms computation by iRIC to investigate the effect of drainage system on severe flooding of 2011 flood. We assume that if the flood extents due to only areal rainfall inundates some part of study area or the peak discharge at runoff station C.2 is not much reduced by using the existing drainage system, it could be stated that the contribution of drainage system in the middle CPRB to severe flooding in 1995, 2006, and 2011 is very small and negligible. In additional, this study also estimate peak discharge from rainfall data. This study roughly estimate peak discharge by the rational equation as given below:

$$Q = ciA \tag{3.4}$$

where Q is peak discharge , c is rational method runoff coefficient, i is rainfall intensity, and A is drainage area.

For the calculation of peak discharge from rational equation, owing to this study area is mostly irrigation areas, we then set the rational method runoff coefficient as 0.35. Therefore, the estimated peak discharge from rational equation is 1,457 m^3/s. Fig. 3.5 shows flood hydrograph at runoff station C.2, which shows that flood hydrograph from iRIC model (simulated) is higher than peak discharge from rational equation around 60%. Due to very high difference of peak discharge between iRIC model and rational equation, it could be mentioned that the existing drainage system may provide low potential to restrain flooding from rainfall in the irrigation channels. Moreover, the flood extents due to rainfall data from iRIC model occur around 652 km^2 accounting for 11% of total area and 15% of 2011 flood inundation as shown in Fig. 3.6. It could be also stated that the drainage system provides limited capability to reduce severe flood extents from severe flooding because only rainfall data could generate flood inundation around 11% of total area. Besides, the existing drainage system in this study area can be neglected for simulating severe flood events in 1995, 2206 and 2011.

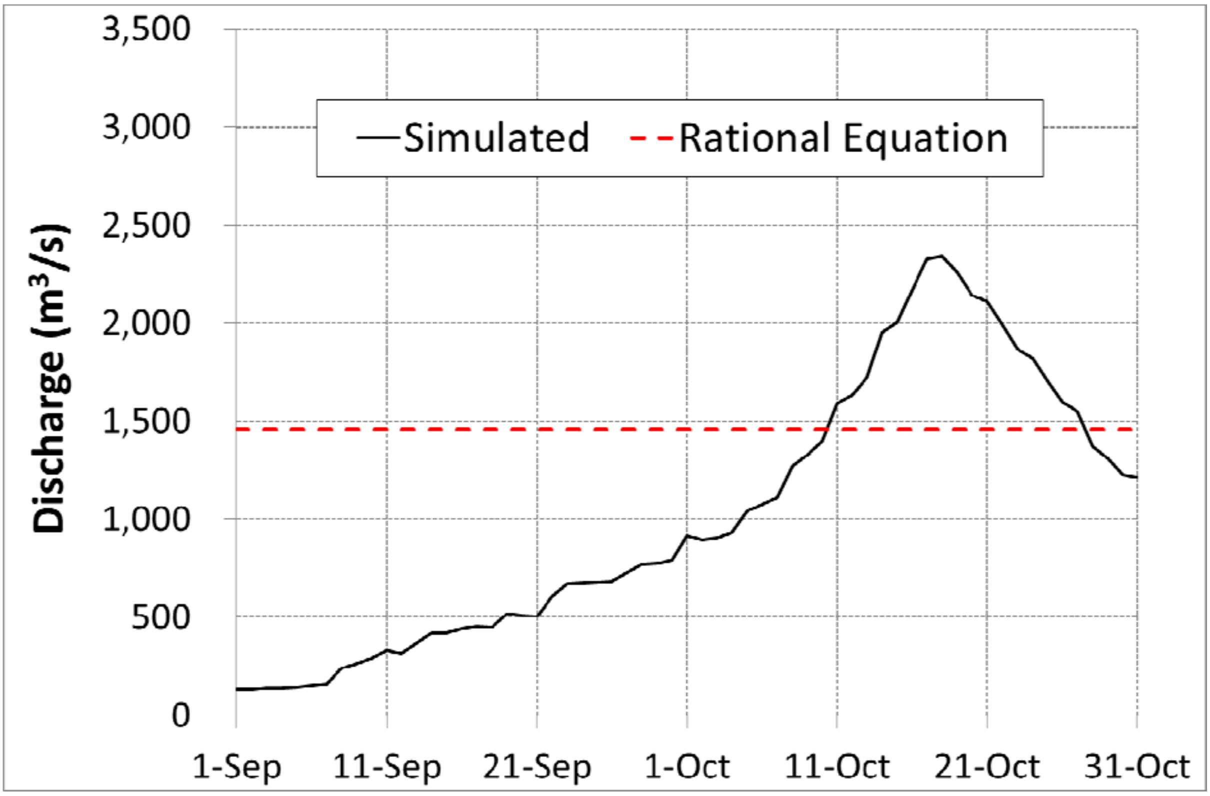


Fig. 3.5 Comparison of flood hydrograph at runoff station C.2 from iRIC model and rational equation.

3.4 Implications

Despite the iRIC model provided a little underestimation on flood extent, the statistic values from simulation show acceptable values on the coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), and root-mean-square error (RMSE) from flood hydrographs. It could be stated that the iRIC model is capable of simulating severe flood events in this study area. Besides, this study then applies the iRIC model to investigate and determine the potential of various flood countermeasures types in upper and middle CPRB which reduces peak discharge at runoff station C.2 lower than 3,500 m^3/s.

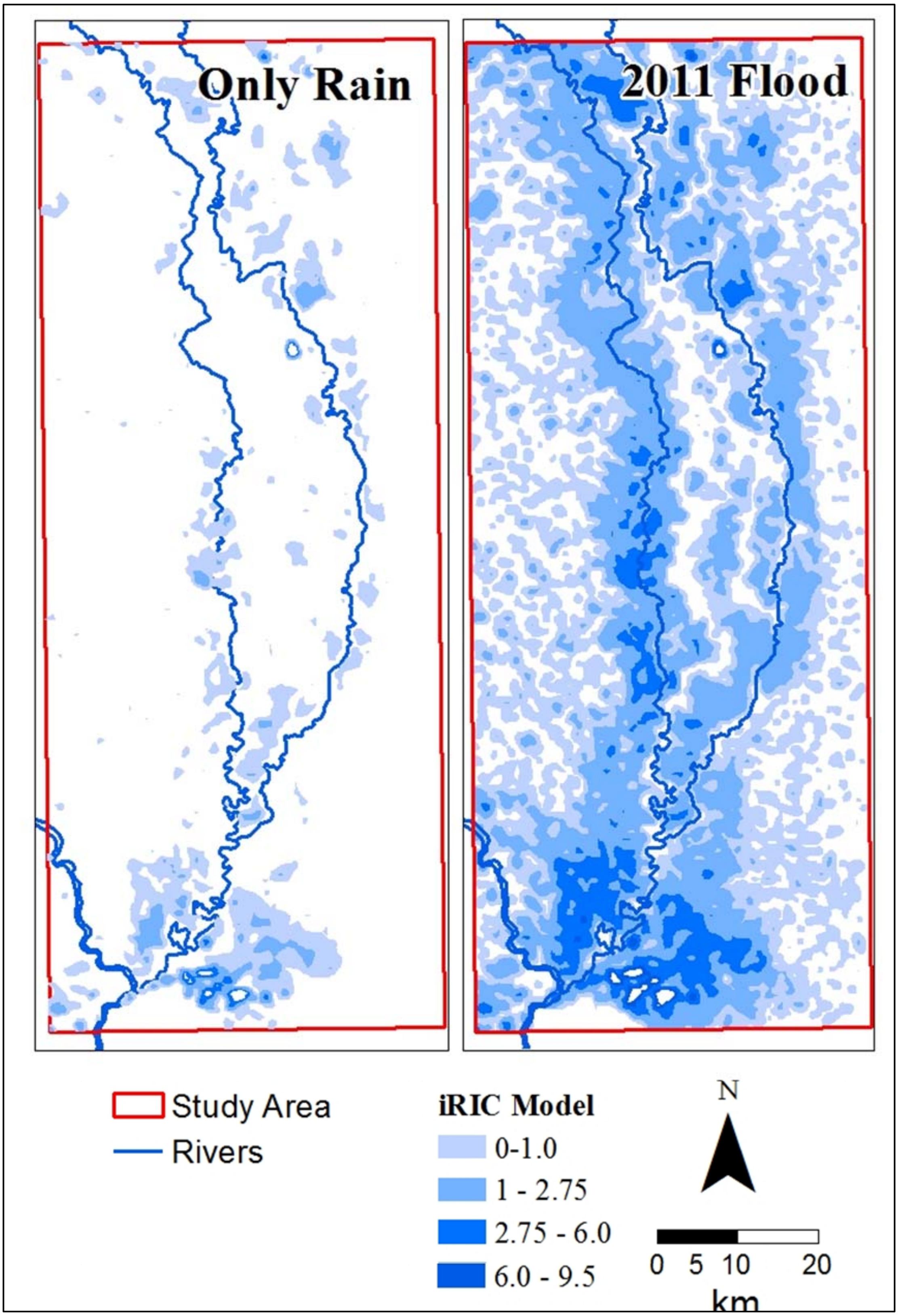


Fig. 3.6 Comparison of flood inundation between rainfall data and flood 20112.

Chapter 4

Flood mitigation options

4.1 Introduction

Flood disasters have been occurring in the Chao Phraya River Basin (CPRB) almost every year. The reservoirs in the upper CPRB were constructed to store flood water during rainy season. The first multipurpose reservoir namely the Bhumibol Dam was constructed in 1951. Almost all of the flood countermeasures in CPRB were constructed after severe flood events. For example, after 1995 flood Royal Irrigation Department (RID) constructed a 77-km dyke along Chao Phraya River to protect urban and industrial areas in the lower watershed. Historically, the preferred flood management options were structural flood countermeasures such as dams, dykes, and embankments. Nowadays, the nonstructural flood countermeasures have also been implemented such as retention areas and flood forecasting and early warning systems. Despite several types of flood countermeasures in the CPRB were constructed to alleviate flood damages, CPRB is still under the risk of flooding.

To monitor and represent the flood situation in the CPRB, the Royal Irrigation Department (RID) installed the runoff station namely C.2 as shown in Fig. 4.1. The amount of discharge at the runoff station C.2 which is the gate to lower CPRB plays a crucial role in flood management actions of CPRB. According to the analysis of historical discharge data, it found that flood damage drastically increase when the discharge at runoff station C.2 is higher than 3,500 m^3/s resulting in vast areas submerged and huge economic losses in the lower CPRB. The well-known severe flooding is 1995, 2006 and 2011 flood. The observed peak discharge of 1995, 2006 and 2011 at runoff station C.2 was 4,820 m^3/s, 5,960 m^3/s, and 4,686 m^3/s respectively. The 1995, 2006, and 2011 floods had a return period of about 50, 25, and 100 years (DHI, 2012). From the hydrological records, it is noticed that the peak discharge of 2011 flood was not the highest but the duration of flooding was the longest spanned from July to December when it was compared to others.

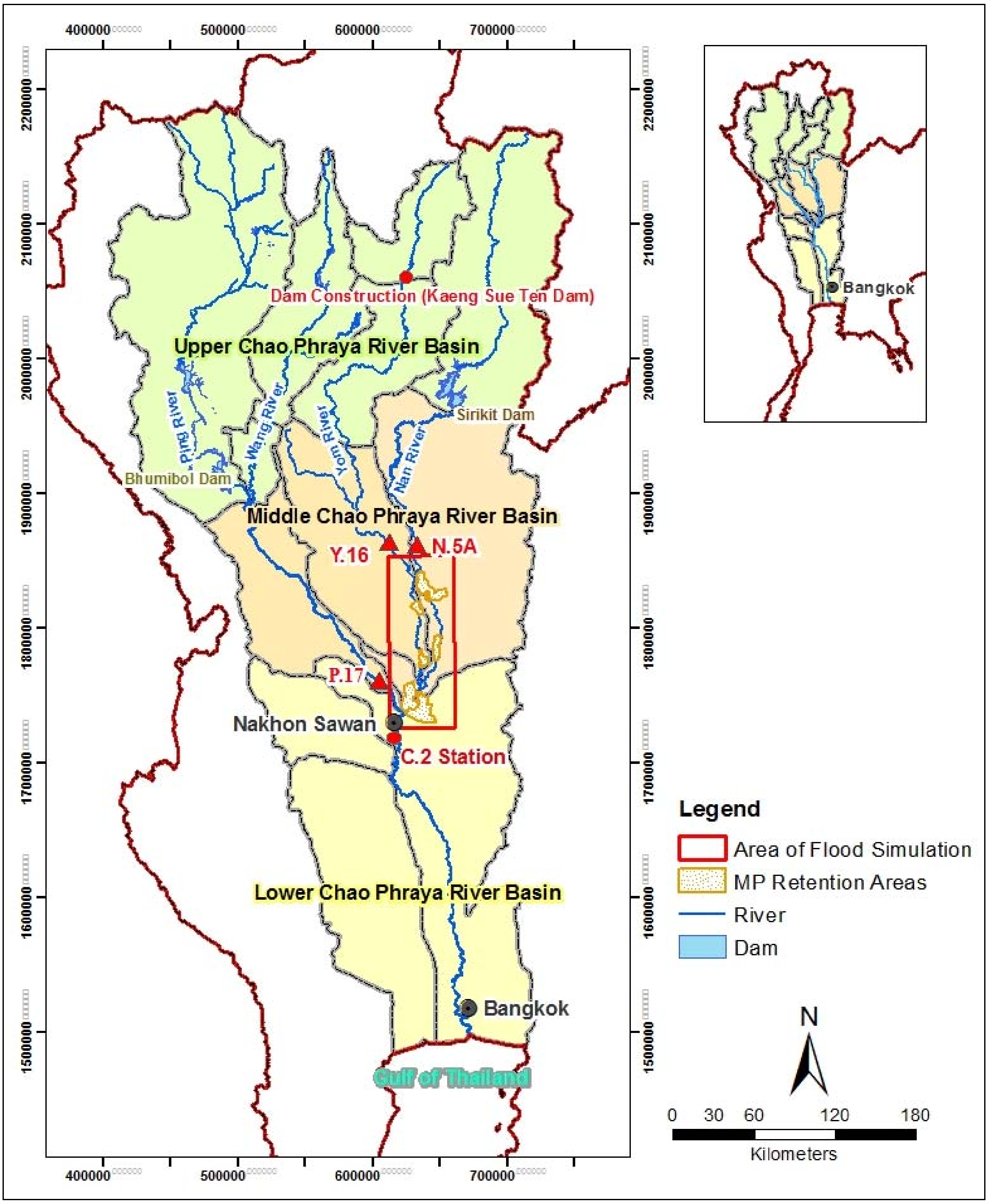


Fig. 4.1 Flood countermeasures proposed by the Thai Master Plan for the upper and middle Chao Phraya River Basin.

4.2 Flood countermeasures in the upper and middle Chao Phraya River Basin

According to the 2011 flood event in the CPRB, the economic damages and losses was 1,425 billion baht (US$ 45.7 billion) estimated by The World Bank (The Ministry of Finance, 2012). The excessive and long period of rainfall in 2011 stimulated by successive five tropical storms caused vast areas submerged more than 30,000 km^2 and also affected more than 13 million citizens in CPRB from July until December 2011 (Komori et al., 2012). The Thai Meteorological Department (TMD) reported that the annual rainfall in 2011 was the highest among country's record (TMD, 2011). The seven major industrial estates located in the lower CPRB were submerged as high as three meters during this disaster. The vast inundation areas including damages and losses from 2011 flood are the severest flood event in Thailand.

After flood in 2011, the government of Thailand established the Strategic Committee for Water Resources Management (SCWRM) to manage short and long term flood effectively. The SCWRM formulated the Master Plan on Water Resources Management; the structural and nonstructural measures are to be taken in harmony for proper flood management (SCWRM, 2012). The structural approach includes measures as "store and divert" water. The nonstructural measure is to create "room for the river" which would allow floodwaters store in flood retention areas. Master Plan on Water Resources Management consists of eight work plans which are (1) work plan for restoration and conservation of forest and ecosystem, (2) work plan for management of major water reservoirs and formulation of the national annual water management plan, (3) work pan for restoration and efficiency improvement of current and planned physical structures, (4) work plan for information warehouse as well as forecasting and disaster warning system, (5) work plan for preparedness to emergency situation in specific areas, (6) work plan for assigning water retention areas and recovery measures, (7) work plan for improving water management institutions, and (8) work plan for creating understanding, acceptance, and participation in large scale flood management from all stakeholders.

The flood management options proposed by this Master Plan were customized for each sub basin. The one clear option in the upper and middle CPRB is to construct a new dam and enlarge the reservoirs capacity. The reforestation and retention areas are also considered as the initiative to prevent rapid flooding in the upper CPRB. For various reasons, the application of the Master Plan was suspended. To date, no actions have been taken and no progress has been made towards implementing additional flood countermeasures in the CPRB, except for urgent measures such as dredging to improve drainage and structural rehabilitation. Besides, this study tries to explore the potential of flood countermeasures proposed by Thai Master Plan which are (1) reforestation, (2) retention areas, (3) dam operation improvement, and (4) dam construction as shown in Fig. 4.1.

As the important function of runoff station C.2 for flood management actions in the CPRB, if we are capable of controlling the discharge at this station in the certain degree as 3,500 m^3/s, the damages and losses from flood disaster may noticeably reduce. Besides, the hydrological, reservoir operation model, and hydrodynamic models were applied to examine the effectiveness of various flood countermeasures in the upper and middle CPRB to control the peak discharge at C.2 station lower than 3,500 m^3/s. Because this study involves several modeling and flood countermeasures, the detail of each flood countermeasure and required input data have been summarized in Table 4.1.

Table 4.1 Input data for modeling used in this study.

<table>
<tr><th>Flood Countermeasures</th><th>Hydrological model</th><th>Reservoir operation model</th><th>Inundation model</th></tr>
<tr><td>1. Reforestation</td><td>56 measured rainfall stations</td><td>-</td><td>simulated discharge by Hydrological model from each sub-basin to gauging stations (P.17, Y.16 and N.5A stations)</td></tr>
<tr><td>2. Retention areas</td><td>-</td><td>-</td><td>measured discharge (P.17, Y.16 and N.5A stations)</td></tr>
<tr><td>3. Dam construction</td><td>-</td><td>measured discharge (Y.20 station)</td><td rowspan="2">simulated discharge by Muskingum method through reservoir operation model from dams (Bhumibol, Sirikit, and Kaeng Sue Ten Dams) to gauging stations (P.17, Y.16 and N.5A stations)</td></tr>
<tr><td>4. Dams operation</td><td>-</td><td>measured inflow (Bhumibol and Sirikit Dams)</td></tr>
</table>

4.3 Reforestation

Due to urbanization and agricultural purposes, most of forest areas in the upper and middle CPRB have been deteriorated around 10% from 2002-2009 (Jamrussri and Toda, 2017). Many researchers have revealed that deforestation influences on the increasing of runoff coefficient that increases the amount of runoff (Andréassian, 2004; Bosch and Hewlett, 1982; Bradshaw et al., 2007). Therefore, it is necessary to examine the inextricable link between reforestation and hydrological regime in the CPRB because it may provide a significant effect on reducing severe flood events. Thus, reforestation in the upper and middle

CPRB is considered to be one of flood countermeasures options to reduce and control flood discharge of Chao Phraya River lower at runoff station C.2 than 3,500 m^3/s.

To examine the effect of reforestation on severe flood events, this study applies The Soil and Water Assessment Tool (SWAT) as the hydrological model. The required data for SWAT model are hydro-meteorological, land use, digital elevation model (DEM), and soil type data as shown in Fig. 4.2 and Table 4.2. The land use and soil type maps are obtained from the Land Development Department (LDD). This study employed two land use maps. The 2009 land use map was used for model calibration and contrastingly 2002 land use map was applied to analyze the land use change from year 2002 to 2009 to develop the reforestation scenarios. The DEM data, a 30-meter resolution obtained from the Royal Thai Survey Department (RTSD), was applied to calculate drainage basins and delineate sub watersheds.

The 1993-2011 weather data which are daily climate data, precipitation, temperature, solar radiation, wind speed, and humidity data were provided by the Thai Meteorological Department (MED). This study applied 56 gauging stations to represent the upper and middle CPRB areal rainfall. On the other hand, 19 major weather stations which include daily temperature, solar radiation, wind speed, and humidity data were adopted to represent the weather condition in the upper and middle CPRB. Moreover, the six runoff stations (P.7A, W.3A, Y.20, Y.6, N.7A and C.2) from the Royal Irrigation Department (RID) and two inflow data of Bhumibol and Sirikit Dam from Electricity Generating Authority of Thailand (EGAT) were used for model calibration and validation phase.

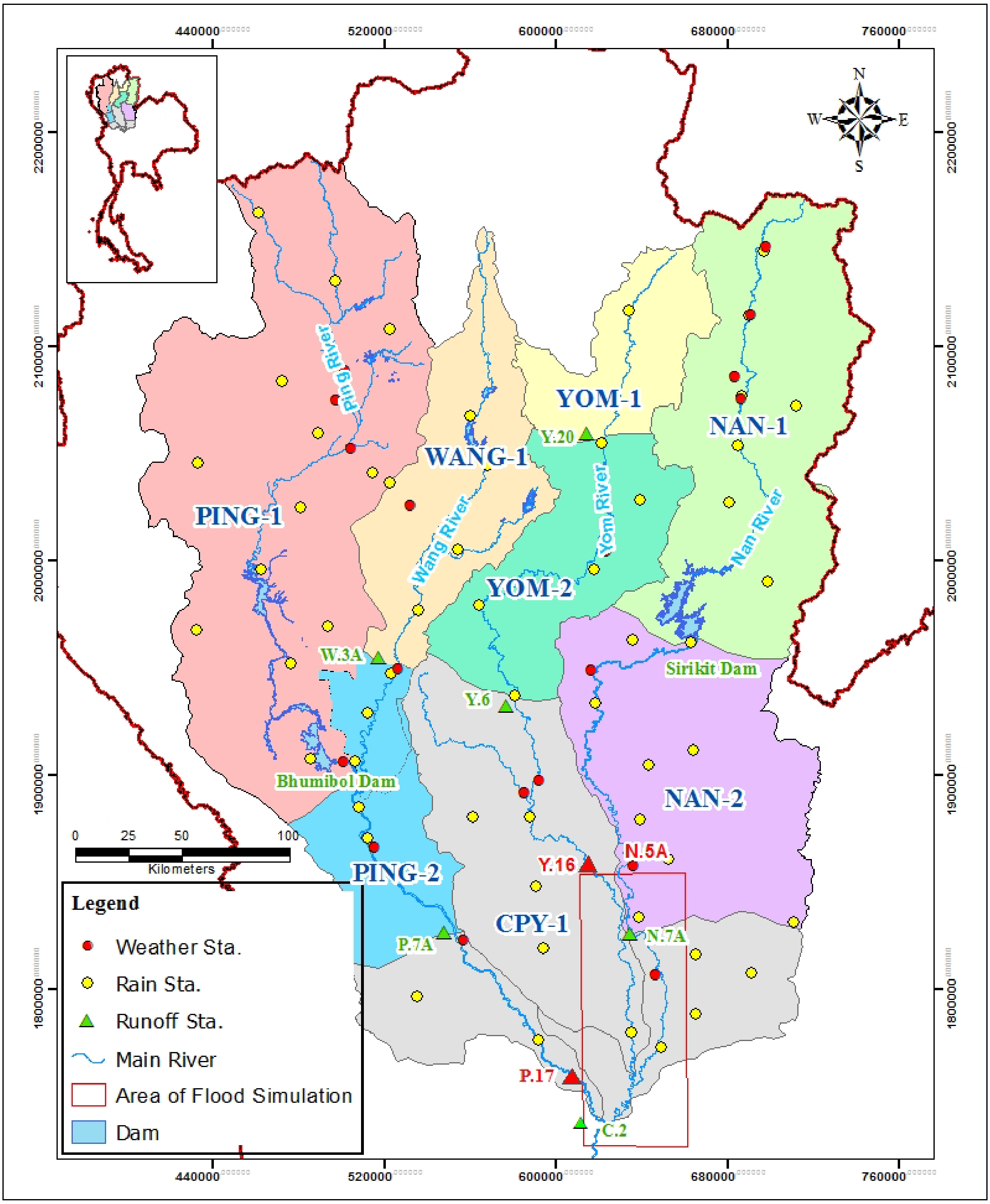


Fig. 4.2 The eight sub basins and gauging stations for SWAT model in the upper and middle Chao Phraya River Basin.

Table 4.2 Data collection for SWAT model.

Series No.	Data	Period	Type	Source
A. Hydro-meteorological data				
1	Rainfall	1993-2011	Daily	MET
2	Discharge	1993-2011	Daily	RID and EGAT
3	Temperature	1993-2011	Daily	MET
4	Relative Humidity	1993-2011	Daily	MET
5	Wind Speed	1993-2011	Daily	MET
6	Solar Radiation	1993-2011	Daily	MET
B. Spatial data				
1	DEM	30 m x 30 m	Raster	RTSD
2	Land Use	2002, 2009	Vector	LDD
3	Soil Type	2015	Vector	LDD

4.3.1 Hydrological model calibration

There are various parameters influence and involve in runoff generation according to the SWAT model, the semi-distributed physically based model (van Griensven et al., 2006). Determining the most sensitive parameters for study area is recommended and requisite before model calibration and validation process (Arnold et al., 2012a,b). Generally, the sensitivity analysis has been widely used to examine the rate of change in model output corresponding to the change in model inputs (parameters). This study applies the SWAT-CUP to determine the most sensitivity parameter for the upper and middle CPRB. This program can provide the relative sensitivity of parameters in SWAT model (Abbaspour et al., 2007). A multiple regression analysis is applied to evaluate the sensitivity of each parameter represented by two parameters; (1) T-test and (2) P-factor. The relative significance of each parameter is expressed through T-test. The greater sensitivity of parameter will provide the larger value. The P-value indicates the level of significance of the sensitivities. The smaller value means a higher level of statistical significance.

The SWAT-CUP also provides the SUFI-2 algorithm to map the uncertainties which are parameter, conceptual model, and input expressed as uniform distributions. The SUFI-2 algorithm tries to capture the most of the measured data that range within the 95% prediction uncertainty of the model in an iterative process, namely 95PPU. The uncertainty in SWAT-CUP is quantified by two statistics: P-factor and R-factor (Abbaspour et al., 2004).

Based on sensitivity and uncertainty analysis, 11 parameters were retained for model calibration as shown in Table 4.3.

Table 4.3 Sensitivity ranking and category of the most sensitive parameters for the upper and middle Chao Phraya River Basin.

Rank	Name	Definition	Category
1	CN2	Soil conversion service (SCS) runoff curve number for moisture condition 2	Very High
2	SURLAG	Surface runoff lag coefficient	Very High
3	SOL_AWC	Available water capacity of the soil layer (mm/mm soil)	High
4	ALPHA_BF	Baseflow alpha factor (days)	High
5	REVAPMN	Threshold depth of water in the shallow aquifer for percolation to the deep aquifer (mmH2O)	High
6	CH_K2	Effective hydraulic conductivity in main channel alluvium (mm/h)	High
7	GW_REVAP	Groundwater “revap” coefficient	High
8	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	High
9	ESCO	Soil evaporation compensation factor	High
10	SOL_Z	Maximum canopy index Soil depth	High
11	RCHRG_DP	Deep aquifer percolation fraction	High

For the model calibration and verification phases, this study simulated the 19-year discharge from 1993 to 2011 in eight sub basins as shown in Fig. 4.2. Owing to runoff data for each gauging station spanned in different years, the around 2/3 of data is count for calibration and the rest is for verification process. The first two years is applied to establish the initial conditions of each basin as warm-up period that excludes from model analysis. The two statistical indicators which are coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NSE) were used to evaluate the overall model performance. The Fig. 4.3 shows the best fit between the observed and calculated daily runoff at eight gauging stations through SWAT model. As the results, it could be stated that the basins which have a good distribution of rain stations (PING-1, WANG-1, and NAN-1sub-watersheds) provide the acceptable values of statistical indicators as shown in Table 4.4. On the other hand, the basin which has a limited rainfall station that cannot well represent the whole catchment rainfall results in the lower values of statistical indicators (YOM-1 1sub-watershed). Moreover, the runoff stations located in the flood plain also provides a small statistical value (PING-2, NAN-2, and CPY-1 sub- watersheds).

However, the overall statistical result shows that SWAT model performs well in generating daily runoff. Due to the objective of this study to alleviate flood damages from severe flood events, the ability of capturing the peak flow is necessary and required. The Fig. 4.4 shows the ability of SWAT model in capturing the peak flow. As statistical values for daily runoff and peak flow in every year, it could be mentioned that SWAT model is able to capture the hydrological characteristics of study area and also to generate the acceptable daily runoff.

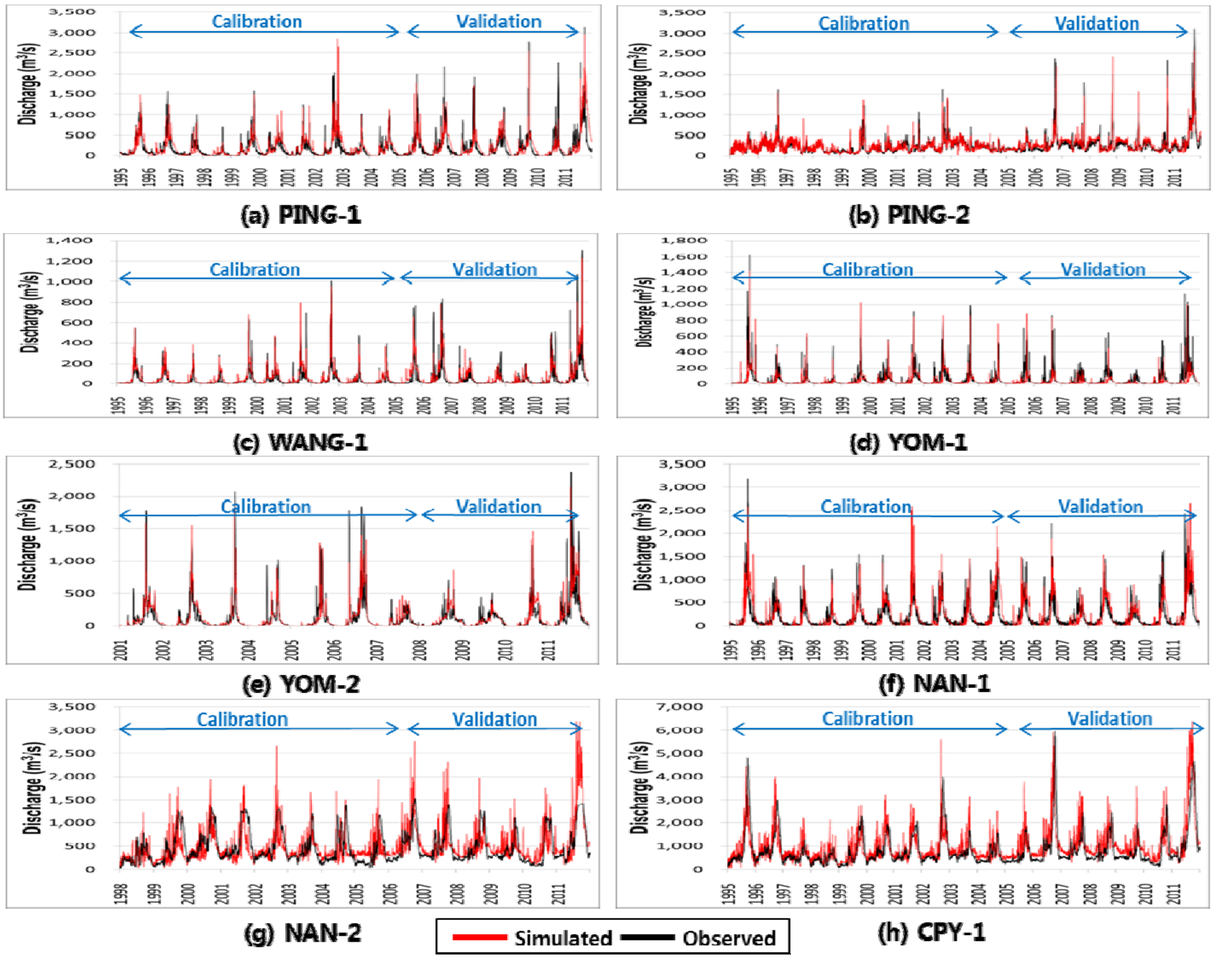


Fig. 4.3 Comparison of simulated runoff by SWAT model and observed data.

Table 4.4 Model statistic values of daily runoff stations.

Statistical index	PING-1		PING-2		WANG-1	
	Calibration	Verification	Calibration	Verification	Calibration	Verification
R^2	0.617	0.589	0.411	0.429	0.673	0.639
NSE	0.598	0.555	0.376	0.410	0.595	0.586

Statistical index	YOM-1		YOM-2		NAN-1	
	Calibration	Verification	Calibration	Verification	Calibration	Verification
R^2	0.384	0.272	0.506	0.429	0.592	0.562
NSE	0.355	0.164	0.496	0.383	0.523	0.510

Statistical index	NAN-2		CPY-1	
	Calibration	Verification	Calibration	Verification
R^2	0.262	0.521	0.45	0.511
NSE	0.199	0.302	0.395	0.377

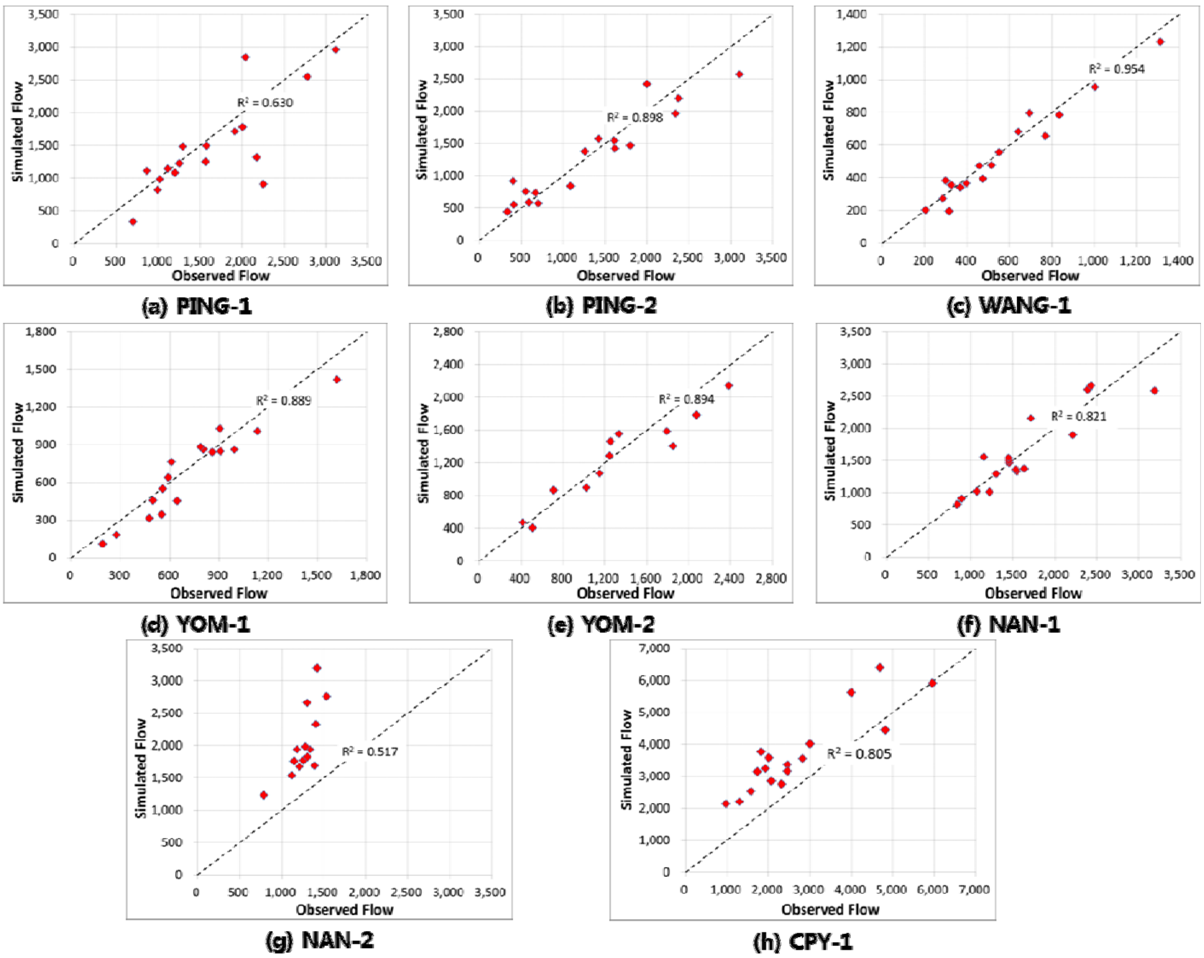


Fig. 4.4 Curves fitted between simulated and observed peak flows.

4.3.2 Effect of reforestation on hydrological regime

The land use types across an area of 104,481 km^2 in the upper and middle CPRB from the 2009 land use map can be classified into seven categories; forest (46%), range-brush (15%), paddy field (15%), agricultural area (12%), orchard (6%), water resources (2%), and urban (4%). To investigate the effect of reforestation and also affirm that reforestation is an effective way for flood management option in the CPRB, this research then applies the SWAT model to determine the effect of reforestation. Firstly, this study establishes forestation scenarios considering two main aspects to ensure that these scenarios were realistically formulated. According to the Master Plan, the reforestation was planned around 6,400 km^2. Thus, the maximum area of reforestation is specified as large as 6,400 km^2. The second aspect is the area which was to be transformed to forest area was developed based on the land use change from the 2002 and 2009 land use map as shown in Table 4.5.

As the SWAT model has been widely developed to examine the impact of land management (Jha et al., 2004), there is option to convert the percentage of one land cover to another one (Arnold et al., 2012a,b). Based on two main assumptions on reformations and competency of SWAT model, this study then formulated three reforestation scenarios; 1) conversion of range brush to forest, called 100% of reforestation from the Master Plan, 2) conversion of orchard to forest, called 30% of reforestation from the Master Plan, and 3) conversion of agricultural land to forest, called 10% of reforestation from the Master Plan. The forestation scenarios in the upper and middle CPRB were tested through the SWAT model during 1995–2011 (17-year runoff). Table 4.6 shows the changes in daily runoff under different land use scenarios. In every scenario shows that the runoff in rainy season and peak discharge decrease; in the contrast, in the dry season the runoff increases.

Table 4.5 Land use change from 2002 to 2009.

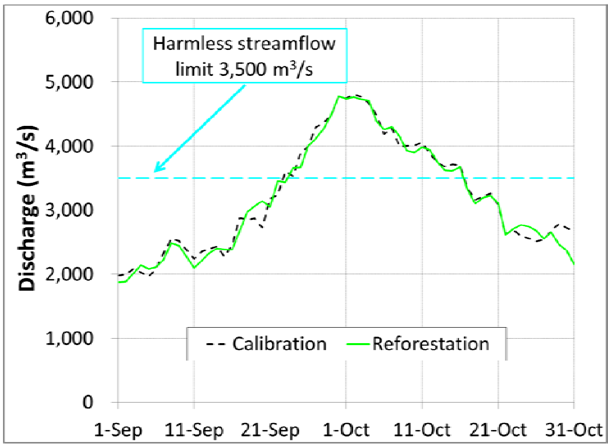
Land use	Land use in 2002		Land use in 2009		Land use change (2002-2009)
	Area (km^2)	(%)	Area (km^2)	(%)	
Agricultural land	12,380	11.85	12,967	12.41	+587
Forest	57,622	55.15	48,015	45.96	-9,607
Orchard	4,190	4.01	5,858	5.61	+1,668
Paddy field	18,348	17.56	15,616	14.95	-2,732
Range brush	7,032	6.73	15,761	15.09	+8,729
Urban area	3,017	2.89	3,901	3.73	+884
Wet land	1,892	1.81	2,363	2.26	+471
Sum.	104,481	100	104,481	100	0

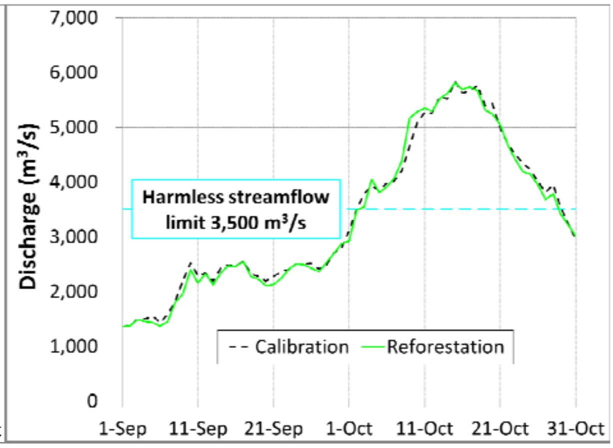
Table 4.6 Change in average annual runoff for the whole basin under different land use scenarios.

Land use change scenarios	Annual runoff; (m^3/s) (%change)	Seasonal runoff; (m^3/s) (%change)		Yearly peak flow; (m^3/s) (%change)
		Wet season	Dry season	
Current land use	1,331.85	1,900.74	783.16	4,705.75
Scenario 1. conversion of range brush to forest 100% of the master plan proposal (6,400 km^2)	1,324.70 (-0.54%)	1,887.13 (-0.69%)	783.50 (+0.04%)	4,540.86 (-3.50%)
Scenario 2. conversion of orchard to forest 30% of the master plan proposal (1,920 km^2)	1,325.74 (-0.46%)	1,890.16 (-0.53%)	784.17 (+0.13%)	4,680.35 (-0.54%)
Scenario 3. conversion of agricultural land to forest 10% of the master plan proposal (640 km^2)	1,331.77 (-0.01%)	1,900.48 (+0.01%)	785.87 (+0.35%)	4,687.05 (-0.40%)

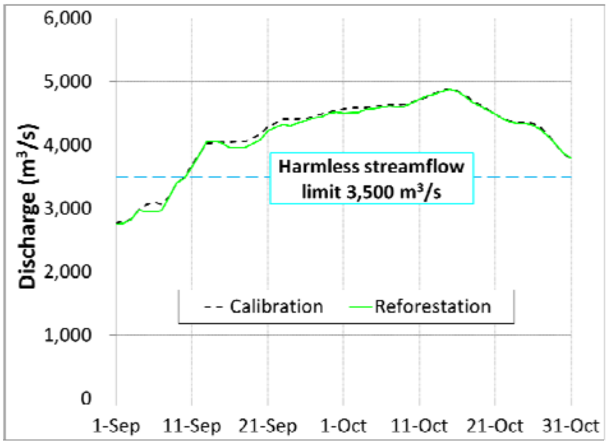
4.3.3 Flood inundation simulation

According to results from reforestation scenarios, this research considered the case of 100% of the master plan proposal (6,400 km^2) to be a representative reforestation measure. The effect of reforestation on flood hydrograph and flood inundation of severe flood events (1995, 2006 and 2011 floods) was evaluated by iRIC model. For iRIC model, this study used the simulated runoff from SWAT model to be the input data of iRIC model as upstream boundary. The simulated runoff was routed from each sub basin to gauging stations which are runoff station P.17, Y.16, and N.5A as shown in Fig. 4.2. The flood hydrograph at runoff station C.2 in each flood event was shown in Fig. 4.5. The results show that reforestation measure in the upper and middle CPRB is not significant to reduce flood peak and volume of severe flood events. In spite of reforestation provides the low capability of reducing peak discharge of severe flood events, the reforestation contribute to the social aspect of Thai government and people. There are some believes that forest areas could reduce damage from flood disaster. Considering reforestation as one of measures to overcome severe flood events is essential and necessary to confirm and demonstrate the ability of reforestation to provide further discussion in scientific approach.





(a) **(b)**



(c)

Fig. 4.5 Comparison of flood hydrograph of reforestation case at runoff station C.2 in (a) year 1995 (b) year 2006 and (c) year 2011.

4.4 Retention areas

The low-lying areas in the middle CPRB are generally exploited for agriculture purposes especially for paddy field. As the natural floodplains, most of low-lying areas are submerged throughout the rainy season. According to frequent flooding in the middle CPRB, the geomorphological units were corresponded with flood condition that it provides 4.5-5 meters of inundation depth around higher natural levees and the silty soil is mostly found in this basin (Haruyama, 1993). Many studies mentioned that retention areas are capable of reducing flood risk in the downstream (Förster et al., 2008; Huang et al., 2007). Camnasio and Becciu (2011) applied retention areas to be the water storage for agriculture purpose in dry season. Moreover, the surface water in the retention areas creates the floodplain's functions such as floodplain habitat heterogeneity (Tockner et al., 2000) and natural disturbance and succession (Junk et al., 1989). Yoshikawa et al. (2010) applied the use of paddy fields for flood mitigation in Japan. In addition, the mitigation for heavy floods using paddy fields introduced in various studies (Abler, 2004; Groenfeldt, 2006; Kim et al., 2006; Matsuno et al., 2006). Thus, the use of paddy fields for flood mitigation may be the effective measure for the CPRB.

4.4.1 Retention areas from Thai Master Plan

High discharge rates and flood volume from 2011 flooding in the CPRB led to a significant shift in managing river flood safety. Nowadays, the conventional flood measures such as raising and strengthening embankments along the rivers were substituted to retention areas which make more room for flood water (Scholz and Sadowski, 2009; Scholz and Yang, 2010; Yeh and Labadie, 1997). The agricultural lands in floodplains were usually selected to be flood protection measures so called retention areas.

Due to mild slope and low capacity of Yom and Nan Rivers, the water usually spills over river bank to floodplains. Besides, the five lowland areas in the middle CPRB along the Yom and Nan Rivers were proposed to be used as retention areas as shown in Fig. 4.1. The retention areas were selected by the considering that all areas are mostly paddy fields and natural floodplains which usually be submerged during rainy season. The five retention areas proposed by Thai Master Plan can accommodate flood volume around 1,161 $x10^6$ m^3. The detail of five retention areas is shown as shown in Table 4.7.

Due to the irreconcilability between government agencies and civil society groups, the Master Plan retention areas have not been yet implemented. From this reason, this study attempts to assess the potential of these five retention areas to hold flood water from historical severe flood events (1995, 2006 and 2011 flood). According to designed water lever from the Master Plan (Table 4.7), it is not neither possible nor practical to divert all flood events to retention areas by using only one diversion level because the middle CPRB has various flood sizes according to peak flow and amount of runoff. In addition, Sujono (2010) stated that flood reduction using paddy fields is depended very much on the water management technique used.

Table 4.7 Design storage volume and water level of five retention areas.

No.	Retention areas		Storage Volume ($x10^6$ m^3)	Designed Water Level (m MSL)
N1	Northern part of Nakhon Sawan Province	Tha Bau District (East Side)	233	25.0
N2		Tha Bau District (West Side)	238	25.5
N3		Dong Set Thi District (South Side)	240	30.5
N4		Dong Set Thi District (North Side)	147	37.0
N5		Phai Chum Phon District	303	38.0

Therefore, this research tries to propose various levels of diversion level to investigate and indicate that which level is suitable to each size of flood event and which range of diversion level is appropriate for the middle CPRB. According to the high flood risk and damage when discharge at runoff station C.2 higher than 2,000 m^3/s, nine flood events were selected as shown in Fig. 4.6. The selected flood events was then classified into three flood sizes; small-, medium- and big- flood event. The peak discharge between 2,000-3,000 m^3/s which are 1999, 2007, 2008 and 2010 flood events was set as small-flood event. The 1996 flood event which has peak discharge between 3,000-4,000 m^3/s was categorized as medium-flood event. When the peak discharge is higher than 4,000 m^3/s, it was classified as big-flood event as 1995, 2002, 2006 and 2011 flood events.

According to geographic location of study area, a diversion level of retention area was set as three levels, 1.00, 1.50 and 1.75 meter above river bank. Fig. 4.7 shows the concept of diversion level of retention area. In the case of 1.00 meter, it found that this level is as similarly high as the designed water level of the Master Plan (Table 4.7). Besides, this case represents the potential of the Master Plan's retention areas. Moreover, this study assumed that there is no flooded water in retention areas as the initial of simulation. During simulation, floodwater in retention areas was stored until it reached a storage capacity and then the excess of floodwater spilled over the crest of road embankment in downstream.

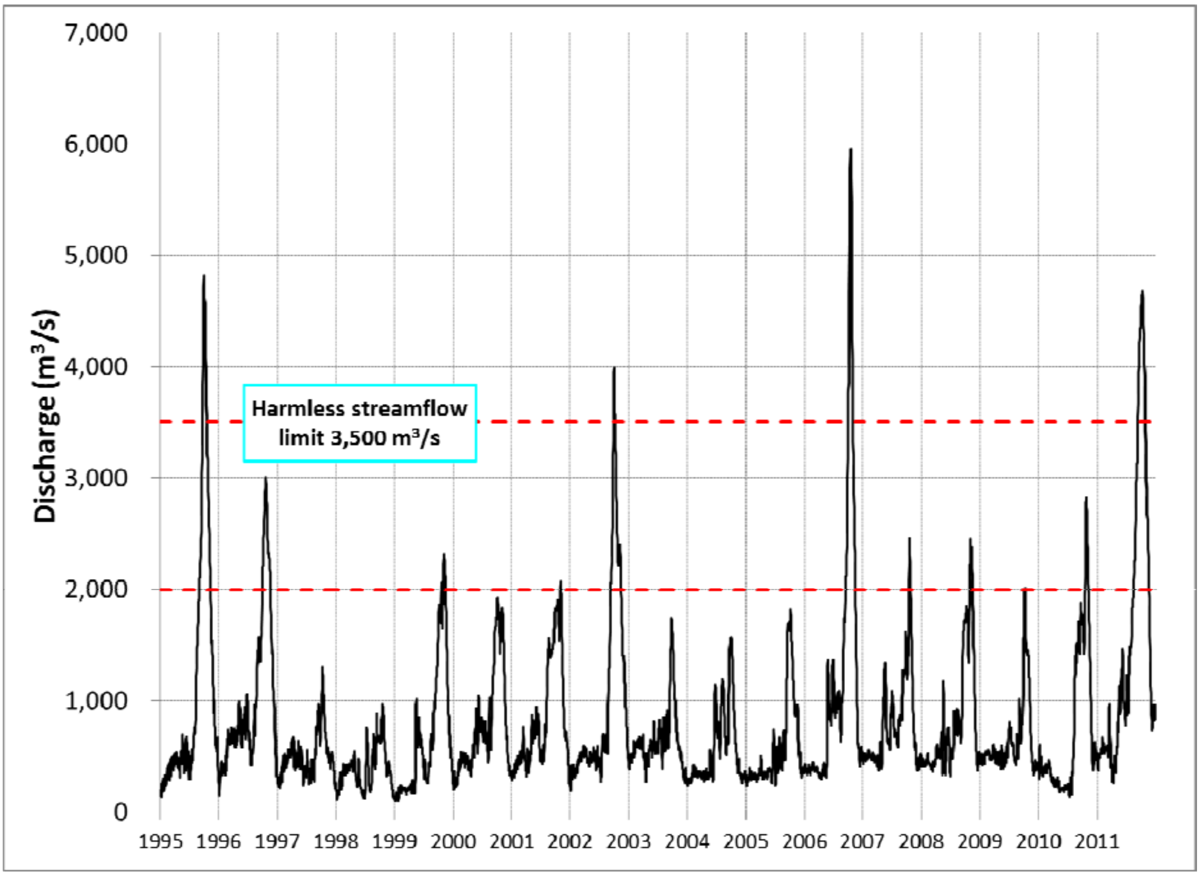


Fig. 4.6 Flood series at runoff station C.2.

4.4.2 Assessing the effects of operational diversion level on flood propagation

Due to peak discharge of these nine selected flood events occurred in different time, the simulation time of each flood event is then different but the total computation time is equal to all flood events which is a 61-day simulation. The effect of diversion level on various sizes of floods has been tested on the middle CPRB. From the numerical simulation results, this study found that the diversion level has a significant effect on flood volume and flood peak reduction as shown in Table 4.8 and Fig. 4.8. By considering flood volume reduction as shown in Table 4.8, this study found that diversion level of 1.00, 1.50 and 1.75 meter is appropriate for the small, medium and large flood respectively. Therefore, it could be mentioned that the retention areas of the Master Plan (the case of 1.00 meter) can alleviate only the small- to medium- flood. Moreover, by considering the amount of flood peak reduction in Fig. 4.8, it found that the 1.00 meter diversion level case provides inverse proportion to flood volume. The cases of 1.50 and 1.75 meter diversion levels can reduce the peak discharge most in the 2010 and 2002 flood respectively.

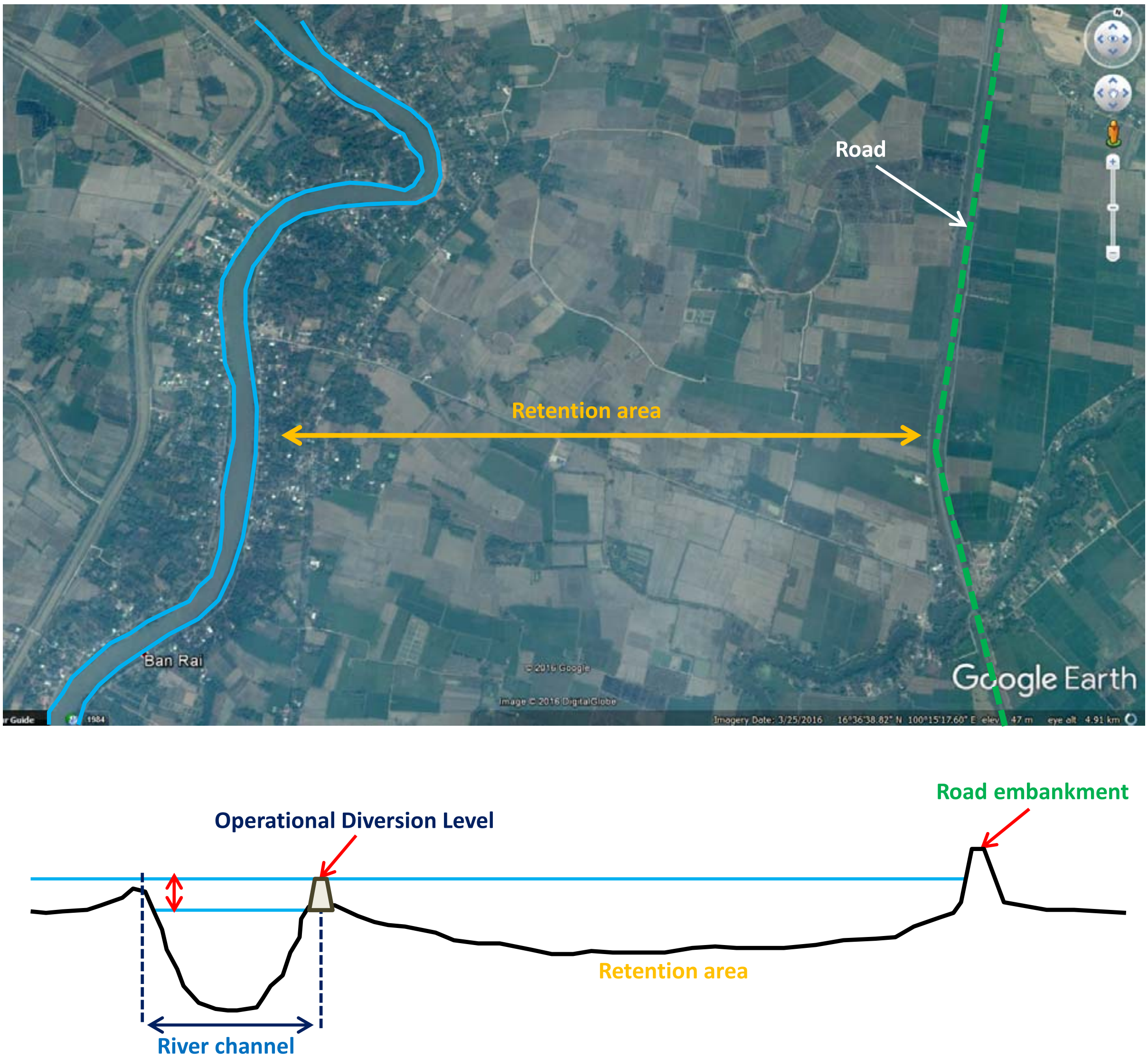


Fig. 4.7 Concept of diversion level to divert flood water from river into the retention areas.

Moreover, the diversion level influences the flood propagation providing negative and positive effects. For example, the 1.75 meter diversion level provided the most potential to alleviate big flood (1995, 2002, 2006 and 2011 flood) because if we set the diversion level lower than 1.75 meter, the retention areas will reach full capacity too early that cannot reduce the peak flow. However, this diversion level resulted consequently in enlarging of flood volume to all small flood events (Table 4.8) and also increasing of the peak discharge of 2007 flood (Fig. 4.8).The results of this study suggest the designed water level of retention areas should be adjustable varied from 1.00 to 1.75 meter in order to divert peak flow of various types of flooding. Based on simulation results, it could be mentioned that the five retention areas in the middle CPRB show the potential to retain floodwater whether how height of diversion level was set.

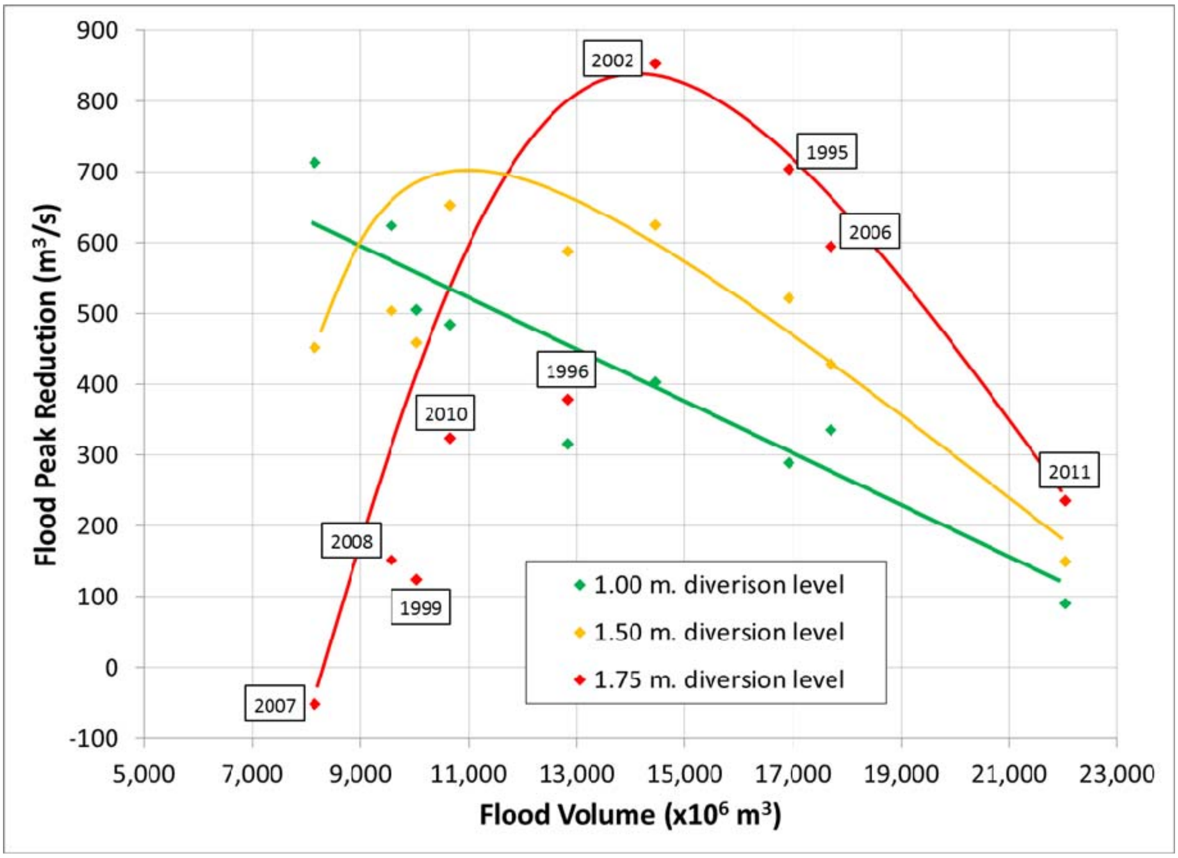


Fig. 4.8 Flood peak reduction of runoff station C.2 by changing operational diversion level of 5 retention areas during critical time.

4.3.3 Flood inundation simulation

To reduce catastrophic inundation, the diversion level in this study was set as 1.75 meter above river bank. The effect of retention areas on flood hydrograph and flood inundation of severe flood events (1995, 2006 and 2011 floods) was evaluated by iRIC model. The flood hydrograph at runoff station C.2 in each flood event was shown in Fig. 4.9. The results show that even though diversion level was implemented and heightened up to 1.75 m, the peak discharge of severe flood events (1995, 2006, and 2011) is still higher than 3,500 m^3/s.

Table 4.8 Flood volume reduction at runoff station C.2 by changing operational diversion level.

Flood size	Year	Peak discharge (m^3/s)	Flood volume ($x10^6$ m^3)	Flood volume reduction ($x10^6$ m^3)		
				1.00 meter above river bank (MP* case)	1.50 meter above river bank	1.75 meter above river bank
Small	1999	2,409	10,048	1,434 (14.27%)	640 (6.37%)	-161 (-1.61%)
	2007	2,426	8,161	784 (9.60%)	136 (1.66%)	-348 (-4.26%)
	2008	2,586	9,576	1,450 (15.14%)	615 (6.42%)	-29 (-0.30%)
	2010	2,899	10,659	1,362 (12.78%)	972 (9.12%)	322 (3.02%)
Medium	1996	3,066	12,839	1,387 (10.80%)	1,836 (14.30%)	848 (6.61%)
Big	1995	4,803	16,928	1,339 (7.91%)	1,443 (8.52%)	1,758 (10.38%)
	2002	4,019	14,455	1,367 (9.46%)	1,423 (9.85%)	1,557 (10.77%)
	2006	5,840	17,713	1,160 (6.55%)	1,189 (6.71%)	1,297 (7.32%)
	2011	4,885	22,041	556 (2.52%)	787 (3.57%)	1,262 (5.72%)

Note; MP* = Master Plan

-161* × 10^6 m^3= a flood volume increase

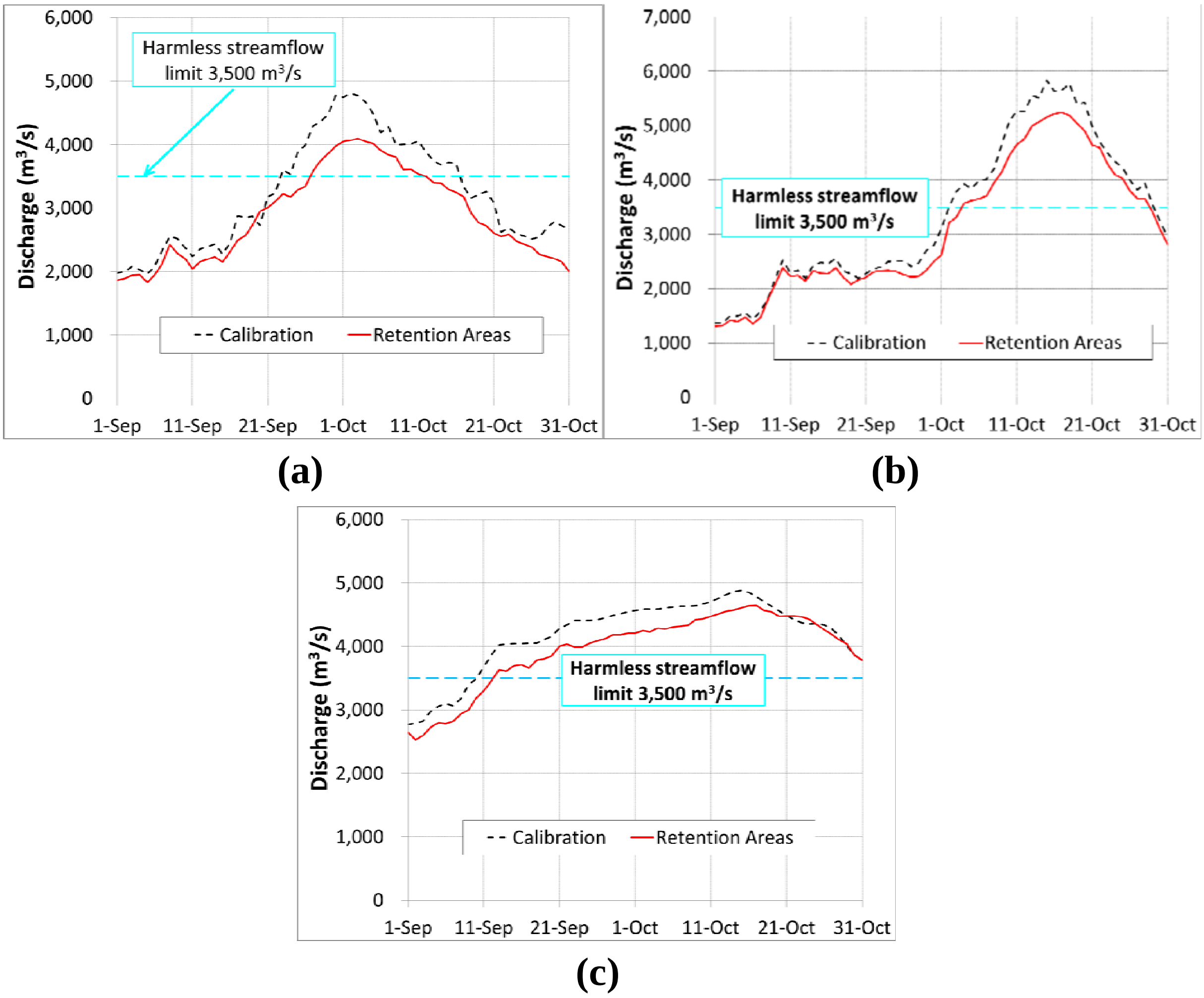


Fig. 4.9 Comparison of flood hydrograph of retention areas case at runoff station C.2 in (a) year 1995 (b) year 2006 and (c) year 2011.

4.5 Reservoirs operation improvement

There are big two multipurpose dams in upper CPRB; (1) the Bhumibol Dam constructed on the Ping River has an effective storage 9.66x10^{9} m^{3}, and (2) the Sirikit Dam was constructed on the Nan with a reservoir capacity of 6.66x10^{9} m^{3} as shown in Fig. 4.1. One of the main objectives of dams is to properly operate for emergency situation (Hasebe and Nagayama, 2002; Needham et al., 2000; White et al., 2005). If dam operate poorly, it will provide an unexpected negative result. Several studies stated that upstream dams in the CPRB affect the downstream hydrologic regime (Sayama et al., 2015). Komori et al. (2013) also mentioned that the Bhumibol and Sirikit Dams could reduce flood period from the August-November to September-October; however they could not reduce peak discharge at runoff station C.2.

According to highest amount of rainfall in the country's 61-year precipitation record occurred in 2011, flooding started submerging downstream areas of the Bhumibol and Sirikit Dam since July. Besides, these big two dam had to reduce amount of release to downstream from that time. However, the rainfall still was running from July to December that caused there are more enough capacity of flood mitigation and opened the spillway in the early October. From this reason, various sources stated that these two dams released much water while flooding is already submerged downstream areas (Bangkok Post, 2011). However, Bangkok Pundit of Asian Correspondent (2011) reported that one main reason of not reducing dam storage for flood mitigation is the lack of long term forecasting (3-6 months) and the fear of running out of water used for the next year because the CPRB faced the drought period many successive years before the 2011 flood.

Dam management in Thailand is generally operated by the rule curves. The rule curve provides two lines of operation which are upper and lower rule curves. Since big dams in Thailand are multipurpose reservoir, amount of water is released towards various functions such as irrigation, hydropower, fisheries, environmental condition, and recreation. It is essential and requisite to establish the operation curve for long term operation. After 20-year simulation by modeling, the upper and lower rule curves were obtained to guarantee if we operate dam by controlling water level between these two lines, we will satisfy the expected water demands and constraints and also reduce drought and flood problems.

After catastrophic and devastating 2011 flood the dam operation curves was reconsidered to improve their efficiency by relevant agencies. The main objective on this revision is to increase the efficiency of all existing dams for coping with 2011 flood (Royal Irrigation Department, 2012). Due to increasing flood mitigation in 2012, Thailand has been facing with water-supply problems during droughts in many of the successive years. Thus, this study introduces the new rule curve of these two dams that line between former (2005) and latest (2012) rule curve as shown in Fig. 4.10.

As the storage capacity of the Bhumibol and Sirikit Dams, approximately 90% of total storage of all dams in the CPRB, this study then examines and explores only the effect of these two dam operation. In the Thailand, the upper rule curve is applied to operate dam during rainy season. The concept of the upper rule curve in this study is described as followed:

(1) When the water level in reservoir is higher than the upper rule curve, the water will

be released through controlled outlets. The amount of released runoff must not larger than the maximum capacity of controlled outlets (excluding spillway).

(2) When the water level jumps up higher than the flood control level, the water will be released through all controlled outlets (including spillway) until the water level go down as high as flood control level.

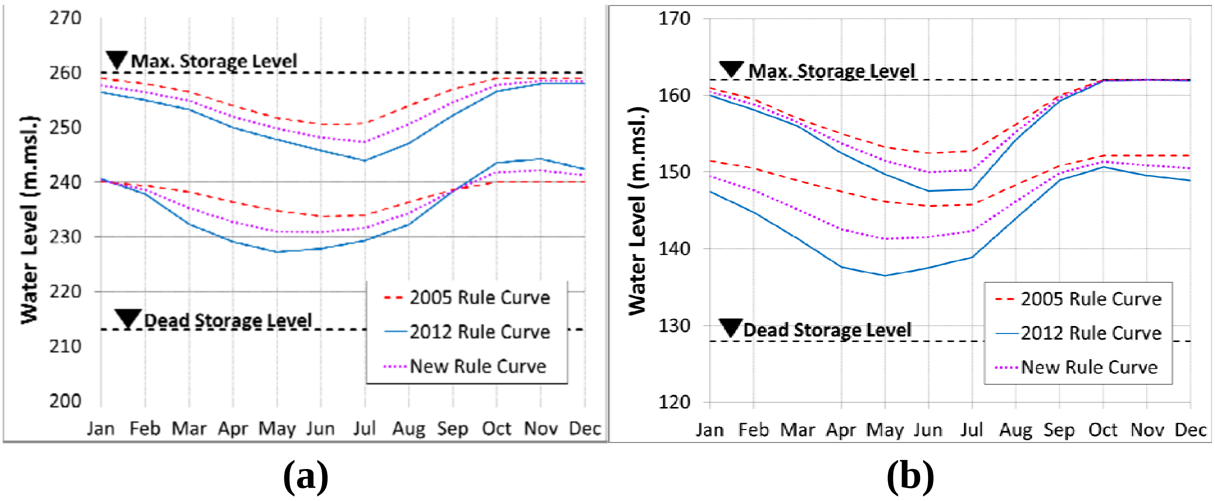


Fig. 4.10 Rule curve of (a) Bhumibol Dam and (b) Sirikit Dam.

4.5.1 Reservoir operation model calibration

Reservoir operation model has been widely used for water resources management and optimization. This study applies the HEC Reservoir System Simulate model (HEC-ResSim) as reservoir operation model. The model configuration for HEC-ResSim model is shown in Fig. 4.11. The 30-year historical daily hydrology record (1985-2014) and physical components of Bhumibol and Sirikit Dams (elevation-area-capacity curve, controlled outlet and spillway capacity, and operating rules) were applied as input to the HEC-ResSim model for model calibration. In the model calibration, model performance was evaluated by a comparison between the simulated and observed water level using three statistic indicators which are the correlation coefficient (R^2), efficiency index (EI), and root mean square error (RMSE). Table 4.9 shows the statistic values in calibration period that are mostly well matched to the observed data. The simulated water level against observed data is shown in Fig. 4.12. With these good statistical fits, it could be stated that the HEC-ResSim model has a good potential to be applied for investigating the effect of dam operation in severe flood events.

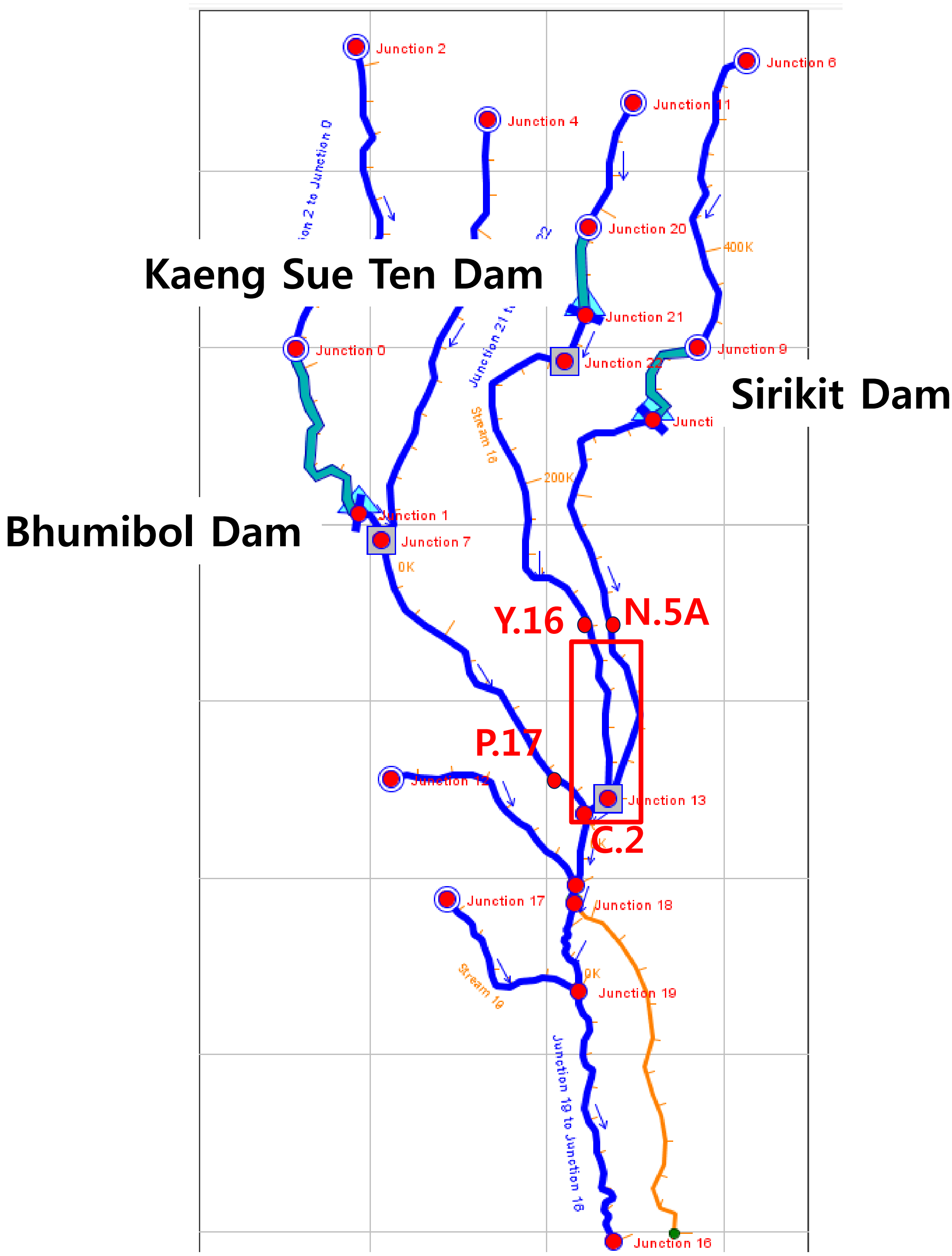
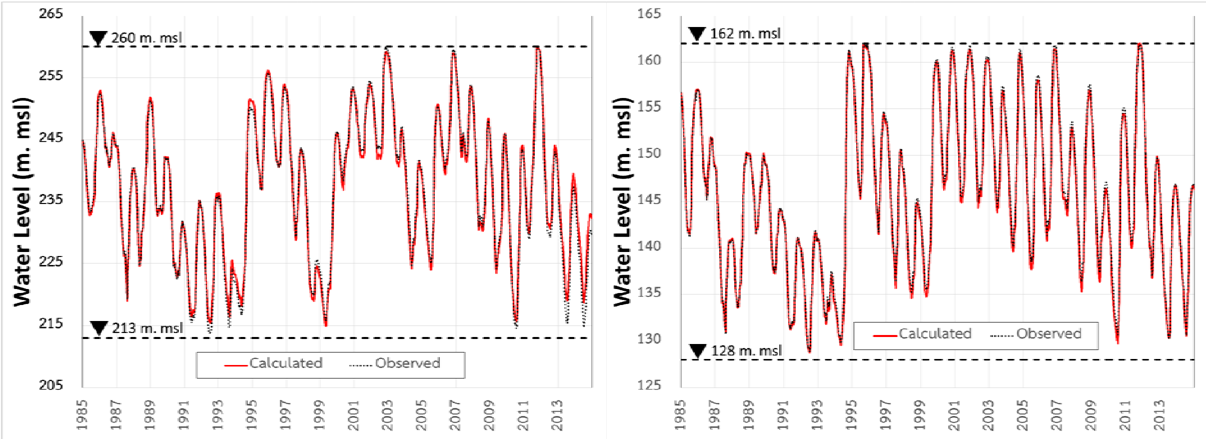


Fig. 4.11 Model configuration for reservoirs operation improvement.

Table 4.9 Model statistic values of Bhumibol and Sirikit Dams.

Statistic Indicators	Water Level	
	Bhumibol Dam	Sirikit Dam
correlation coefficient (R^2)	0.984	0.996
efficiency index (EI)	99.14%	99.73%
root mean square error (RMSE)	1.05	0.44



(a) **(b)**

Fig. 4.12 Water level of (a) Bhumibol dam and (b) Sirikit dam for model calibration.

4.5.2 Effect of reservoirs operation on flood mitigation

Table 4.10 shows the simulated water release from the Bhumibol and Sirikit Dams through various upper rule curves which are 2005, 2012, and new rule curve comparing to the historical water release (human adjustment). During the rainy season (Jul.-Dec.) in 1995 and 2006 flood event, the historical water release shows the best result in average water and peak flow release among other rule curves. Due to the real operation, the operators did not comply with the guideline of upper rule curve because they believed the existing capacity in that time was enough for the next flood volume. The good example is the case of the 1995 flood event. It shows the average water release and peak discharge from Sirikit Dam in every rule curve is more than the historical dam operation. However, the practical of allowing water level higher than upper rule curve could not deal with the 2011 flood. Owing to the long duration and huge inflow stimulated by five tropical cyclones in 2011, the Bhumibol Dam had to release extensive runoff of 1,217 m^3/s through spillway that worsened flood situation. From this simulation, it could be stated that the timely and accurate rainfall forecasting system plays a crucial role in dam operation and management in CPRB. If we could forecast the distribution as long as 3 months with high accuracy, it would drastically reduced flood damage in CPRB. However, as the overall results, the new rule curve proposed by this study shows the best outcome in the average water release and peak flow. Most importantly, this rule curve shows a significant potential to mitigate flood damage in 2011 that it is capable of reducing peak flow from the Bhumibol and Sirikit Dams around 43% and 19% when it compare to the historical data.

Table 4.10 Water release from the Bhumibol and Sirikit Dams during the rainy season (July–December).

Year	Rule Curve Type	Average water release (m^3/s)		Peak flow of water release (m^3/s)	
		Bhumibol Dam	Sirikit Dam	Bhumibol Dam	Sirikit Dam
1995	Historical dam operation (human adjustment)	67	247	320	569
	Rule curve 2005	67	331	320	2,400
	Rule curve 2012	70	344	320	660
	New rule curve	67	335	320	854
2006	Historical dam operation (human adjustment)	196	141	683	404
	Rule curve 2005	212	156	696	636
	Rule curve 2012	294	164	683	619
	New rule curve	254	160	691	608
2011	Historical dam operation (human adjustment)	333	388	1,217	815
	Rule curve 2005	341	401	1,370	718
	Rule curve 2012	411	429	691	654
	New rule curve	367	409	696	660

4.5.3 Flood inundation simulation

To reduce catastrophic inundation, the operational curve for Bhumibol and Sirikit Dams in this study was set as the new rule curve (Fig. 4.10). The effect of dam operation on flood hydrograph and flood inundation of severe flood events (1995, 2006 and 2011 floods) was evaluated by iRIC model. For iRIC model, this study used the simulated runoff from HEC-ResSim model to be the input data of iRIC model. The simulated runoff was routed by Muskingum method from the Bhumibol and Sirikit Dams to gauging stations P.17 and N.5A; while runoff at runoff station Y.16 is the same as calibration phase as shown in Fig. 4.11. The flood hydrograph at runoff station C.2 in each flood event was shown in Fig. 4.13. The results show that the new rule curve is only able to reduce peak discharge of 2011 flood. However, the new rule curve cannot reduce peak discharge lower than 3,500 m^3/s. In contrast, the new rule curve increase peak discharge at runoff station C.2 in 1995 and 2006 flood events owing to the greater amount of water release compared to historical data.

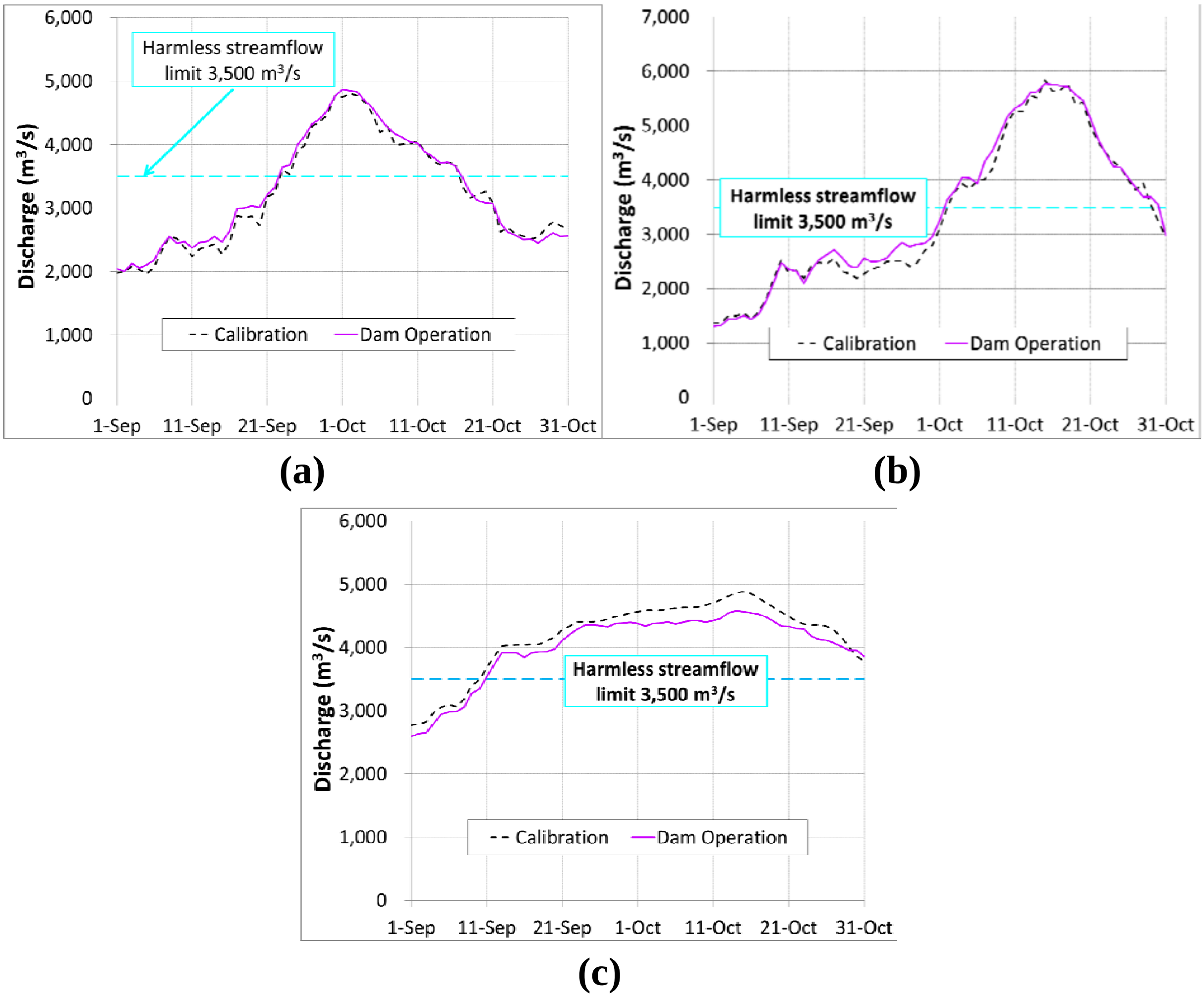


Fig. 4.13 Comparison of flood hydrograph of reservoirs operation improvement case at runoff station C.2 in (a) year 1995 (b) year 2006 and (c) year 2011.

4.6 New dam construction

The Kaeng Sue Ten (KST) Dam was firstly planned to be constructed at Yom River in 1980 as shown in Fig. 4.1 (Mekong River Commission, 2016). The main purpose of KST Dam is to deliver water supply for irrigation in the dry season and to relieve flood disaster in the rainy season. Due to the KST Dam located in the forest areas of Yom River, there is a controversy from various stakeholders such as the inhabitants, scholars, Non-Governmental Organization (NGO). According to the various demonstrations, there are several times to restudy the feasibility of KST Dam to minimize and solve problems. As the final study on KST Dam, the catchment area was planned 3,538 km^2 that can accommodate water supply around 1,125x10^6 m^3. The spillway capacity was designed around 5,355 m^3/s. Anyway, the KST Dam has not been yet constructed that makes the Yom River is the only main tributaries which has no large control structure.

Owing to enormous flood damage on 2011 flood, the Master Plan proposed the KST Dam as one of flood countermeasures. Despite the negative impact of dam construction on various aspects such as flow regimes (Graf 2006; Magilligan and Nislow 2005; Nislow et al. 2002; Räsänen et al. 2012; Yang et al. 2008) and displacement problem (Jackson and Sleigh 2000; Kirchherr et al. 2016; Tilt et al. 2009), dam is capable of reducing flood discharge and increasing the river flow in dry season (Dai et al. 2012). Therefore, it is very necessary to determine the potential of KST Dam on flood mitigation in the CPRB.

4.6.1 Effect of Kaeng Sua Ten Dam on flood mitigation

In this study, KST Dam was constructed nearby the runoff station Y.20 (Fig. 4.1) and the main purpose of this dam is to mitigate flood disaster of severe flood events (1995, 2006 and 2011 flood) through the HEC-ResSim Model. Besides, the measured historical runoff data at runoff station Y.20 is applied as reservoir inflow. Accordance with unclear required flow during the dry season, the concepts of KST Dam operation in this study is set as follows:

(1) At beginning of the rainy season (1st July), 80% of effective storage of KST Dam (940×10^6 m^3) has to be assured for flood storage.

(2) During the rainy season (July–December), water release is set as 80% of the inflow but it should not exceed 220 m^3/s estimated from the capacity of the Yom River.

The configuration of KST Dam and area-volume-level curve of KST Dam are shown in Fig. 4.11 and Fig. 4.14 respectively. After the KST Dam configuration, simulation results show that the KST Dam is capable of reducing peak discharge of Yom River at gauging station Y.20 and the designed flood storage (931×10^6 m^3) of KST Dam in this study can mitigate flood volume as shown in Table 4.11 and Fig. 4.15.

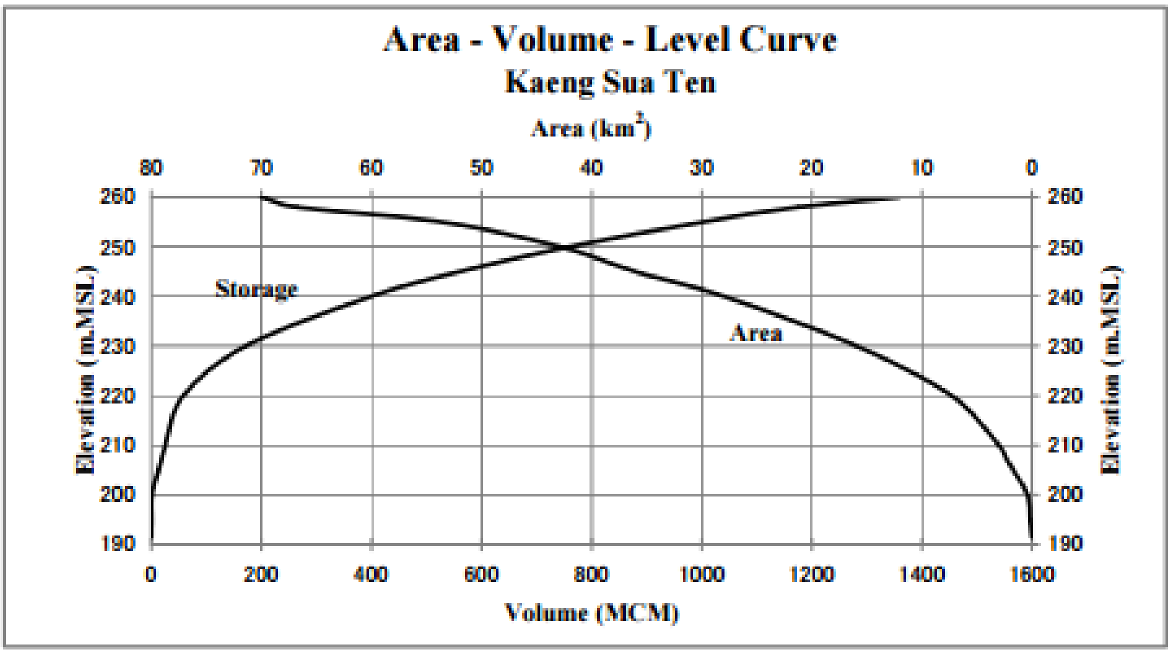


Fig. 4.14 Area-Volume-Level Curve of KST Dam.

Table 4.11 Peak flow and flood volume reduction during rainy season (July–December) at runoff station Y.20.

Year	KST Dam construction Option	Peak Flow (m^3/s)	Flood Volume ($x10^6$ m^3)
1995	Before-KST Dam construction	1,620	2,627
	After-KST Dam construction	220 (86%)	1,696 (35%)
2006	Before-KST Dam construction	861.5	1,451
	After-KST Dam construction	220 (74%)	931 (36%)
2011	Before-KST Dam construction	1,035.2	2,484
	After-KST Dam construction	220 (79%)	1,653 (33%)

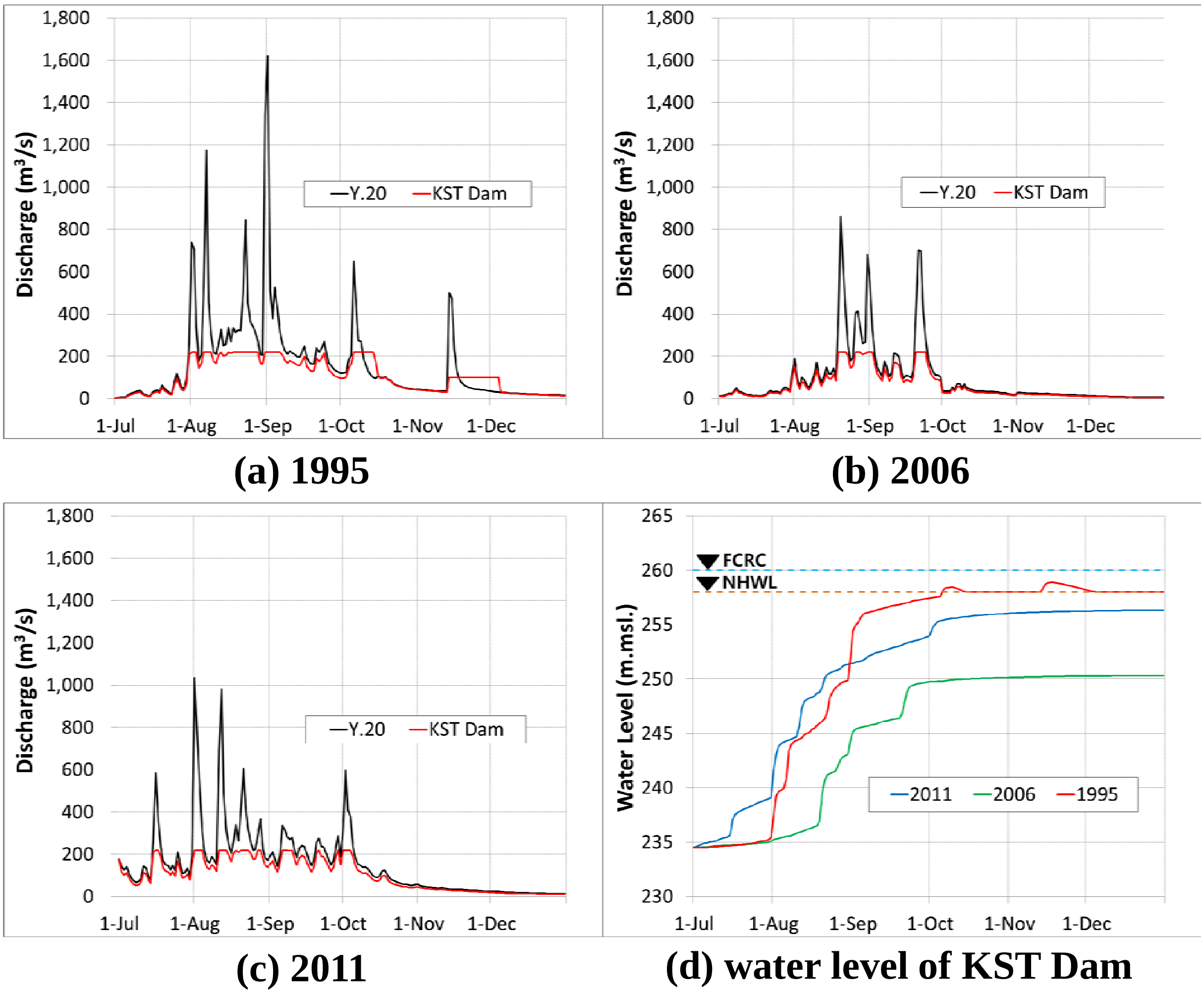


Fig. 4.15 Flood hydrographs at runoff station Y.20 and water level of KST Dam in each year.

4.6.2 Flood inundation simulation

The KST Dam is considered as one of flood countermeasures to reduce peak discharge of severe flood events (1995, 2006 and 2011 floods) at runoff station C.2 lower than 3,500 m^3/s. The effect of KST Dam on flood regimes in the CPRB was evaluated by iRIC model. For iRIC model, this study used the simulated runoff from HEC-ResSim model to be the input data of iRIC model. The simulated runoff was routed by Muskingum method from KST Dam and tributaries to gauging stations Y.16; while runoff at runoff station P.17 and N.5A is the same as calibration phase as shown in Fig. 4.11. The flood hydrograph at runoff station C.2 in each flood event was shown in Fig. 4.16. Despite the KST Dam has a significant effect on reduction flood volume in the Yom River (Table 4.11 and Fig. 4.15), the results from iRIC model show that the KST Dam cannot reduce peak discharge of all severe flood events less than 3,500 m^3/s. It may come from the huge amount of runoff from others tributaries (the Ping and Nan Rivers).

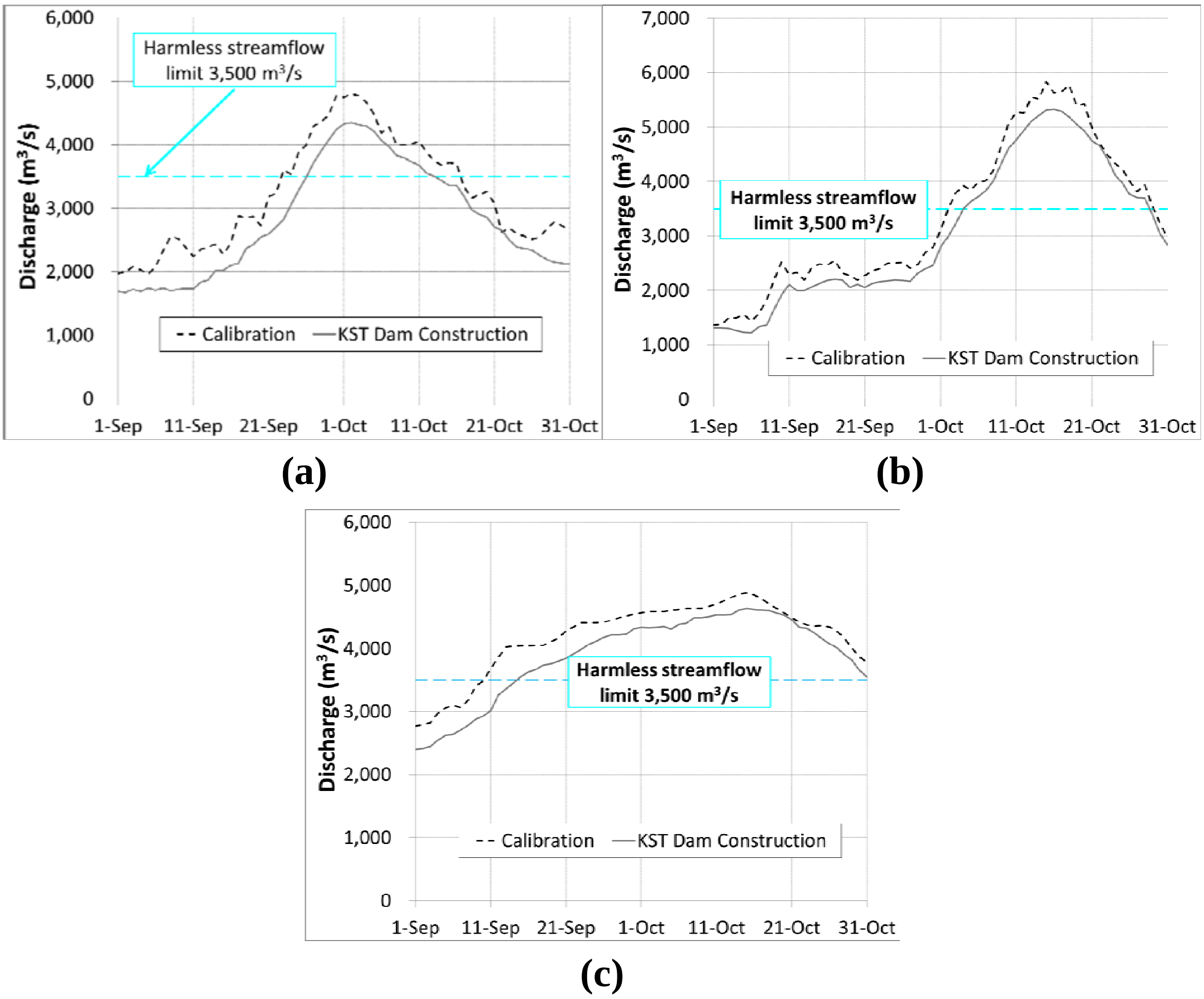


Fig. 4.16 Comparison of flood hydrograph of construction Kaeng Sua Ten Dam case at runoff station C.2 in (a) year 1995 (b) year 2006 and (c) year 2011.

Chapter 5

Scenario analysis

5.1 Introduction

Accordance with the single application of flood countermeasures proposed from Thai Master Plan could not reduce and control the peak discharge at runoff station C.2 lower than 3,500 m^3/s, scenarios were created by the combination of flood countermeasures which are (1) reforestation, (2) retention areas, (3) dam operation improvement, and (4) new dam construction. Combined nonstructural and structural flood countermeasures in harmony may be the most appropriate approach for flood damages relief in the CPRB. Integrated flood management embraces principles embedded in integrated water resource management and risk management in a river basin to reduce the loss of life due to flooding. Base on literature review (Chia et al., 2015; Mateo et al., 2014; Masumoto et al., 2015), the study on the integrated flood countermeasures in the upper and middle CPRB proposed by the 2012 Thai Mater Plan to overcome severe flood events (1995, 2006 and 2011 flood) is the first attempt.

In addition, this study also develops flood countermeasure scenarios to address the best mix of them for 1995, 2006 and 2011 flood event. Supposing these flood countermeasures cannot reduce the peak flow at runoff station C.2 lower than 3,500 m^3/s, the new flood countermeasure was then introduced. This study applies the iRIC model to determine the suitable alternative flood countermeasures.

5.2 Hydraulic examination on combination of flood countermeasures

The set of combination of flood countermeasures was created based on the four flood countermeasures proposed by the Thai Master Plan for the upper and middle CPRB. The objective of integrated flood countermeasures is to keep and reduce the peak discharge of historical severe flood events (1995, 2006 and 2011 flood) at runoff station C.2 lower than 3,500 m^3/s. The eight scenarios cases were established to evaluate their potential through the iRIC model as shown in Table 5.1.

Table 5.1 Scenarios cases analysis in the upper and middle reach of CPRB.

No.	Scenarios	Flood Countermeasure Option
1	Cali	No Additional Flood Countermeasures (Calibration)
2	Sce.1	Reforestation
3	Sce.2	Retention Areas
4	Sce.3	Reforestation + Retention
5	Sce.4	Dam Construction
6	Sce.5	Reforestation + Retention + KST Dam Construction
7	Sce.6	Dam Operation
8	Sce.7	Reforestation + Retention + KST Dam Construction + Dam Operation

5.2.1 Simulation Results

According to simulation results as shown in Table 5.2, the combination of all flood countermeasures from the Thai Master Plan for the upper and middle CPRB are not sufficient to reduce the peak discharge at runoff station C.2 to lower than 3,500 m^3/s. However, these combinations show significant potential to reduce flood damage. For example, the scenario 6 which is the combination among reforestation, retention areas, and KST Dam construction was almost able to control the peak discharge of the 1995 flood to lower than 3,500 m^3/s.

According to dam operation of Bhumibol and Sirikit Dams, it can alone reduce the flood volume and peak flow of the 2011 flood. However, this flood countermeasure option increases the flood volume of the 1995 (250 $x10^6$ m^3) and 2006 (441 $x10^6$ m^3) floods. Besides, the best scenario for the 1995 and 2006 floods is the combination of reforestation, retention areas, and KST Dam construction; while the best scenario for the 2011 flood is a combination of all the flood measures proposed by the Thai Master Plan. The flood hydrograph at runoff station C.2 of the best scenario in each flood event was shown in Fig. 5.1.

Table 5.2 The results of combination of flood countermeasures from Master Plan analysis at runoff station C.2.

Year	Scenario	Flood Countermeasure	Peak Flow (m^3/s)	Flood Volume Reduction ($x10^6$ m^3)
1995	Cali	No additional flood countermeasures (Calibration)	4,803	0
	Sce.1	Reforestation	4,780	140
	Sce.2	Retention areas	4,098	1,758
	Sce.3	Reforestation + Retention	4,052	1,852
	Sce.4	KST Dam construction	4,358	2,092
	Sce.5	Reforestation + Retention + KST Dam construction	3,576	3,924
	Sce.6	Dam operation	4,870	-250
	Sce.7	Reforestation + Retention + KST Dam construction + Dam operation	3,626	3,549
2006	Cali	No additional flood countermeasures (Calibration)	5,840	0
	Sce.1	Reforestation	5,816	161
	Sce.2	Retention areas	5,245	1,297
	Sce.3	Reforestation + Retention	5,132	1,743
	Sce.4	KST Dam construction	5,330	1,524
	Sce.5	Reforestation + Retention + KST Dam construction	4,353	3,251
	Sce.6	Dam operation	5,779	-441
	Sce.7	Reforestation + Retention + KST Dam construction + Dam operation	4,655	2,782
2011	Cali	No additional flood countermeasures (Calibration)	4,885	0
	Sce.1	Reforestation	4,874	176
	Sce.2	Retention areas	4,649	1,262
	Sce.3	Reforestation + Retention	4,645	1,429
	Sce.4	KST Dam construction	4,632	1,574
	Sce.5	Reforestation + Retention + KST Dam construction	4,307	3,382
	Sce.6	Dam operation	4,579	863
	Sce.7	Reforestation + Retention + KST Dam construction + Dam operation	4,032	4,261

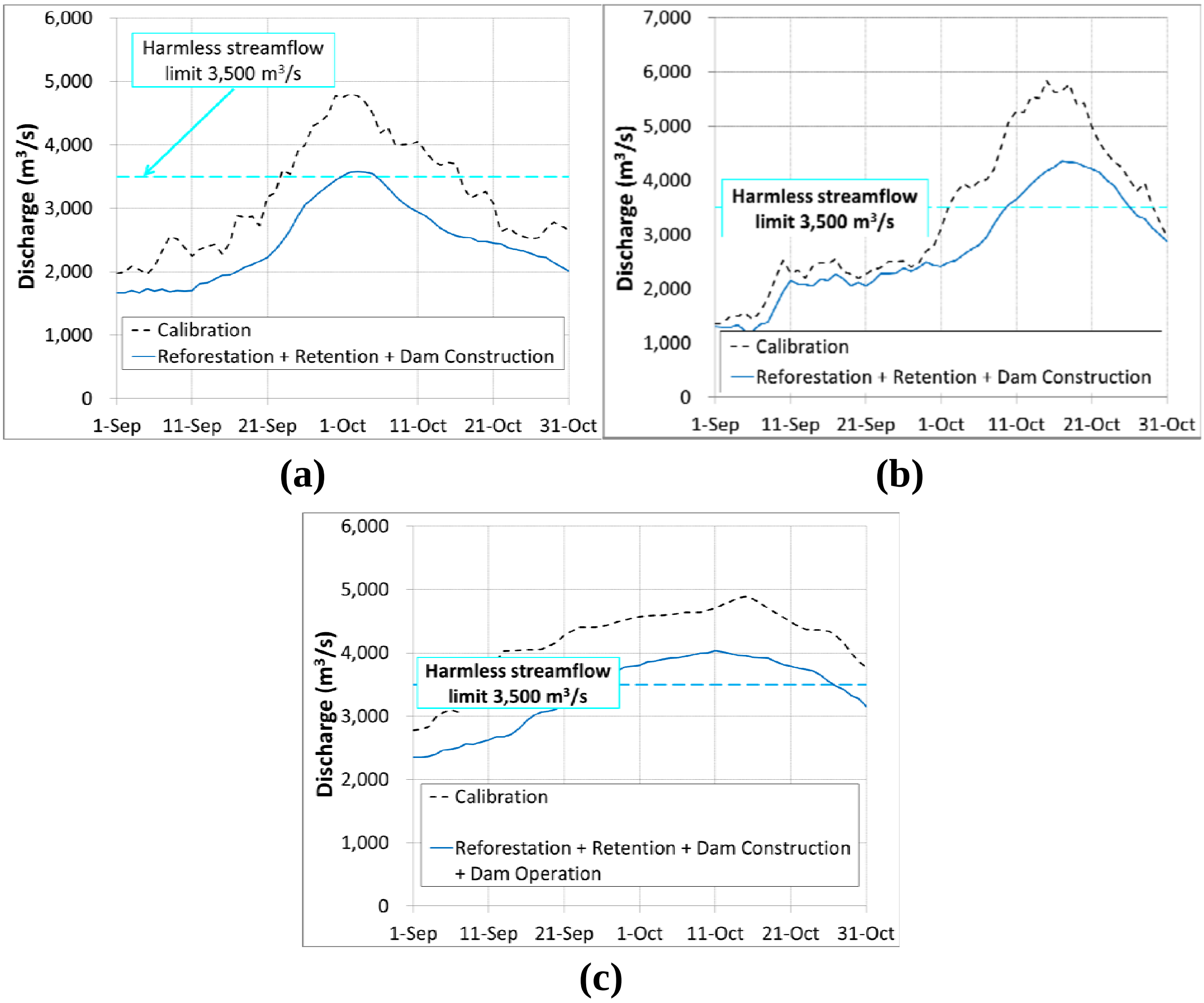


Fig. 5.1 Comparison of flood hydrograph of the best Thai Master Plan's flood options combination at runoff station C.2 in (a) year 1995 (b) year 2006 and (c) year 2011.

5.3 New retention areas scenario

The combination of all flood countermeasures from 2012 Thai Master Plan cannot overcome severe flood events by keeping the peak discharge at runoff station C.2 lower than 3,500 m^3/s. It therefore confirms that Thailand needs the additional flood measures to control the peak discharge to lower than 3,500 m^3/s. Owing to frequent flooding in the middle CPRB along Yom and Nan Rivers, resident have learned to live with flooding. When compared the crop damage which classified as US$ 0.32 billion for rice and US$ 0.22 billion for field crops (JICA, 2013) from 2011 flood to the total damages as US$ 46.5 billion (The Ministry of Finance, 2012), it seems small. This study therefore proposed the new approach to overcome severe flood events.

The retention areas from the Master Plan showed significant potential to retard and retain flood water according to simulation results through iRIC model. Moreover, particularly in the middle CPRB, almost areas are low-lying areas that are generally used for agriculture purpose and mostly submerged during the rainy season. Therefore, we proposed the additional retention areas adjacent to the Yom and Nan Tributaries as shown in Fig. 5.2. The new retention areas can accommodate flood volume around 1,303 $x10^6$ m^3 surrounded with area of 961 km^2. The detail of new retention areas is shown as shown in Table 5.3.

The approach used in selecting of the new retention areas is based on the criteria of the Thai Master Plan that focuses on the large low-lying areas. Most importantly, these areas which are generally used for agriculture cannot be cultivated in the rainy season owing to insufficient drainage system and limited water management. To control and reduce the peak discharge at runoff station C.2 lower than 3,500 m^3/s, the present study assessed and evaluated the new retention areas as engineering aspect to protect the communities and industrial estates in the lower CPRB that caused huge damages and losses to Thailand. The social, economic, and environmental aspects will be considered in the further study. In addition, based on results from the operational diversion level from Master Plan retention areas case, this study then applied the 1.75 meter diversion level to be diversion level.

To overcome all severe flood events, the new retention areas approach was combined with the best simulation results of the Master Plan scenarios analysis in each year (year 1995, 2006 and 2011). The simulation results were also achieved by the inundation model as shown in Table 5.4. The flood hydrograph at runoff station C.2 of combination between the best scenario of Master Plan and new retention areas in each flood event was shown in Fig. 5.3. Fig. 5.4 summarizes flood peak at runoff station C.2 from nine scenarios. The results show that the integrated approach considering the reforestation, retention areas, KST Dam construction, and new retention areas is the best measure for alleviating 1995 and 2006 floods. This approach is capable of controlling and reducing the peak discharge at runoff station C.2 less than 3,500 m^3/s. For 2011 flood, in spite of combination all possible flood protection options in the upper and middle CPRB, the peak discharge was still higher than 3,500 m^3/s and flood water volume was also large. The comprehensive integrated basin management in the whole basin might be the most suitable approach for overcoming and mitigating flood damage in 2011.

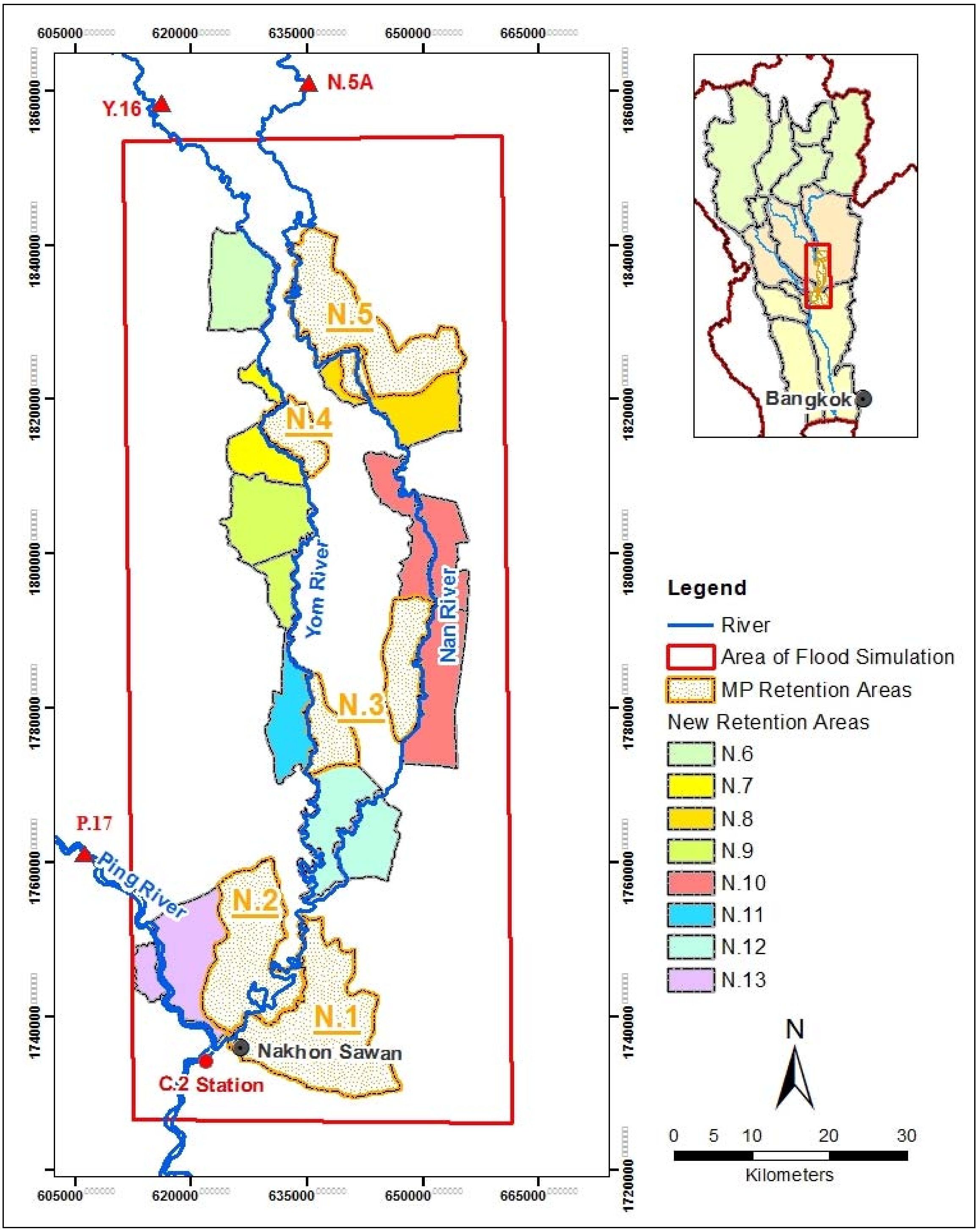


Fig. 5.2 The Master Plan’s and additional retention areas in the middle CPRB.

Table 5.3 Design storage volume and water level of new retention areas.

No.	Retention areas	Storage Volume ($x10^6$ m^3)	Designed Water Level (m MSL)
N6	Bang Rakam District (South Side)	131	39.5
N7	Sam Ngam District (West Side)	124	37.0
N8	Pichit District (North Side)	152	36.5
N9	Pha Pratap Chang District	217	36.0
N10	Taphan Hin District	243	33.0
N11	Pho Thale District	124	32.0
N12	Chum Saeng District (North Side)	189	30.0
N13	Kao Liao District (West Side)	123	26.5

Table 5.4 The results of the combination of flood countermeasures from Master Plan and new retention areas at runoff station C.2.

Year	Scenario	Flood Countermeasure	Peak Flow (m^3/s)	Flood Volume Reduction ($x10^6$ m^3)
1995	Cali	No additional flood countermeasures (Calibration)	4,803	0
	Sce.5	Reforestation + Retention + KST Dam construction	3,576	3,924
	Sce.8	Reforestation + Retention + KST Dam construction + New retention Areas	3,009	4,886
2006	Cali	No additional flood countermeasures (Calibration)	5,840	0
	Sce.5	Reforestation + Retention + KST Dam construction	4,353	3,251
	Sce.8	Reforestation + Retention + KST Dam construction + New retention Areas	3,420	4,528
2011	Cali	No additional flood countermeasures (Calibration)	4,885	0
	Sce.7	Reforestation + Retention + KST Dam construction + Dam operation	4,032	4,261
	Sce.9	Reforestation + Retention + Dam construction + KST Dam operation + New retention Areas	3,662	5,411

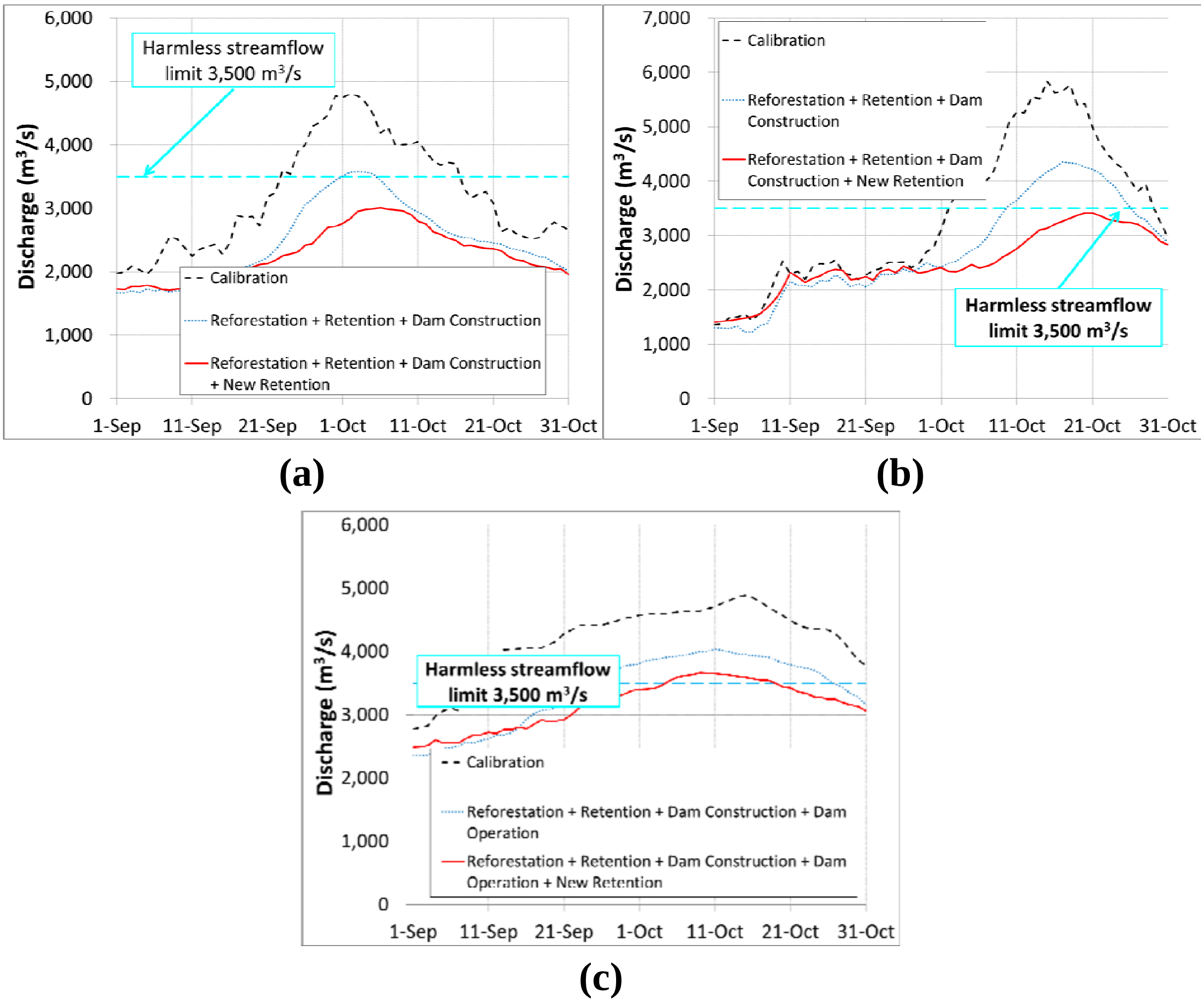


Fig. 5.3 Comparison of flood hydrograph between the best scenario of Master Plan and new retention areas at runoff station C.2 in (a) year 1995 (b) year 2006 and (c) year 2011.

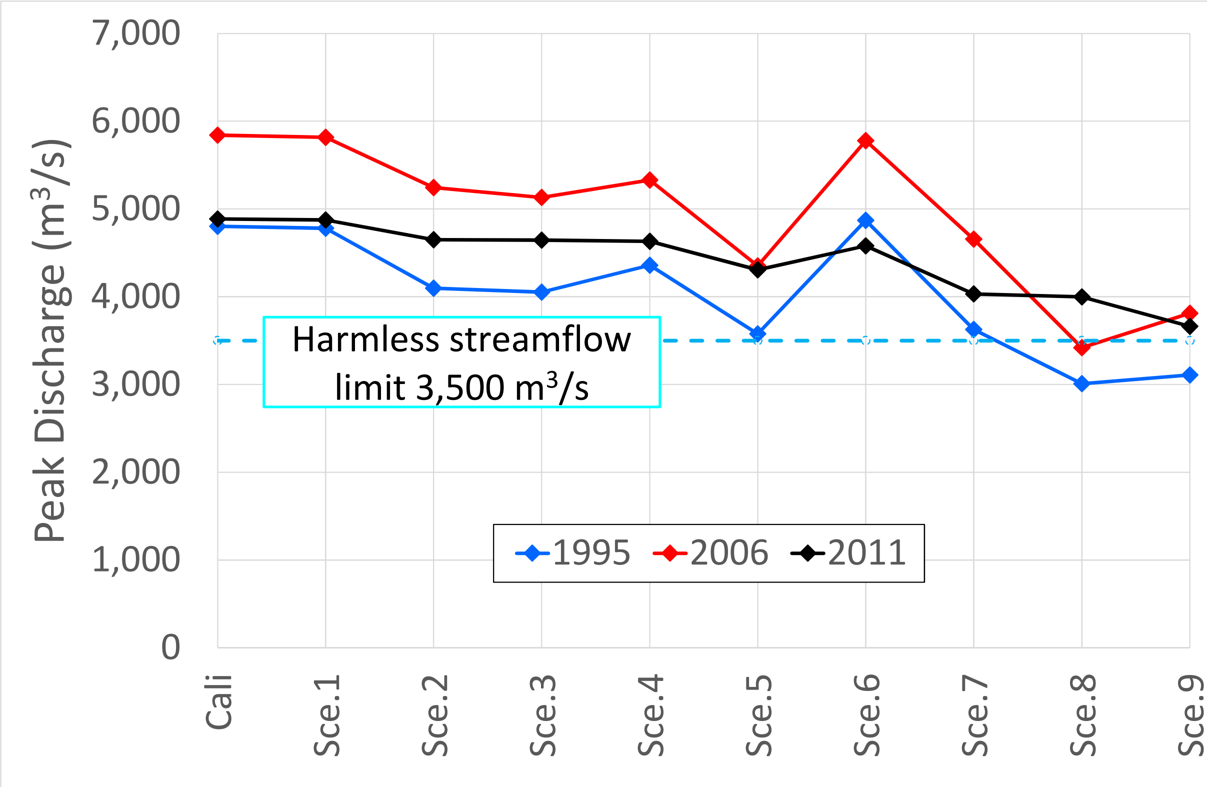


Fig. 5.4 Flood peak at runoff station C.2 from nine scenarios.

5.4 Conclusions

To our knowledge, evaluating the performance of integrated flood countermeasures from the 2012 Thai Master Plan in the upper and middle CPRB is the first study and novel. This study provides insights and new direction for Thailand to better develop and manage flood disaster in CPRB. The findings emphasize that even though all flood countermeasures from Thai Master Plan were implemented in this basin, the peak discharge of all severe flood events was still higher than 3,500 m^3/s. However, integrating all these flood countermeasures can greatly accommodate floodwater.

To obviate all divesting flooding, this study suggested the additional retention areas along Yom and Nan Rivers. Combination the new retention areas with the Master Plan was able to control and reduce peak discharge of 1995 and 2006 flood events at runoff station C.2 lower than 3,500 m^3/s. Unfortunately, this approach was insufficient to overcome the 2011 flood, even though it could reduce 5,411 $\times 10^6$ m^3 of flood volume and control peak discharge to 3,662 m^3/s. From this reason, it could be mentioned that the flood countermeasures from Master Plan plus the additional retention areas provide the appropriate alternative in the upper and middle CPRB to alleviate flood damage and minimize economic losses and fatalities. To cope with the severest flooding in 2011, integrated basin management regarding the existing flood countermeasures in the lower CPRB might be the most appropriate approach. Another method to assess the feasibility of implementing the Master Plan flood countermeasures plus the new retention areas in the upper and middle CPRB is flood damages reduction analysis. For such a frequent flooding in this basin, it is necessary and essential to determine flood risk in the upper and middle CPRB to develop measures to reduce the risk profile. In addition, one of the important and required measures to reduce loss of lives of residents is the emergency flood evacuation. From these reasons, the analysis of flood damages estimation, flood risk assessment, and emergency flood evacuation strategies are considered and applied in this study that mention in the Chapter 6, Chapter 7, and Chapter 8 respectively.

Chapter 6

Flood damage assessment

6.1 Introduction

The catastrophic flood inundated in 2011 from July through December 2011 was more than 30,000 km^2 of land in 66 of the country's 77 provinces and affected more than 13 million people. The submerged farmland areas approximately 17,500 km^2 was mostly located in the low-lying areas in delta of CPRB and Yom and Nan River Basins in the middle CPRB (Haraguchi, 2013). The World Bank (2012) estimated agricultural damages and losses around US$ 1,009 million and 70% of total agricultural damages were paddy fields. Another damages and losses in 2011 is the industrial estate sector. In the Chao Phraya Delta, seven industrial parks, namely Bang Pa-in, Bankadi, Factory Land (Wangnoi), Hi-tech, Nava Nakorn, Rojana, and Saha Ratta Nanakorn, affected about 2–4 m inundation depth and overall damage due to 2011 flooding in the industrial sectors was approximately US$ 7.4 billion (The World Bank, 2012).

Moreover, 1.5 million houses and four million structures were also impacted throughout five-month flooding in 2011 flood (Aon Benefield, 2012). World Bank (2012) estimated an economic loss of about US$ 2.7 billion for these sectors. The International Airport located in central Bangkok, namely the Don Mueang Airport, was also affected by flooding from October through November. After 2011 flood, various terminal building and runways had to be renovated and reopened in March 2012. The transportation infrastructures such as rural roads, highways, and bridges were heavily impacted due to catastrophic 2011 flooding. The economic cost of these infrastructures was around US$ 4.5 billion (Aon Benefield, 2012). In addition, multiple railway lines in the lower CPRB were also submerged. As countless calamities in 2011 of CPRB, it is essential and necessary to implement some flood countermeasures to reduce tremendous losses on livelihood, social, and economic of the Thai nation.

To assess or determine the feasibility of alternative flood countermeasures strategies not only structural measures but also nonstructural approaches, flood damage assessments have been gaining more importance as decision making tool for flood disaster management. In general, flood damages can generally be classified into the tangible and intangible damages.

The tangible damages (quantitative damages) can be easily expressed in monetary values; while intangible damages (qualitative damages) is difficult to be estimated or traded in monetary terms. In addition, tangible and intangible damages are further classified into direct and indirect damages. Direct damages can be evaluated by the physical contact of floodwaters to residents, property, or objects. Indirect damages are normally considered outside the flooding in space and time. These damages are influenced by direct damages and may have an impact in time scale of months or years such as business and public services. The examples for different types of flood damages are shown in Fig. 6.1 (Meyer and Messner, 2005; Parker et al. 1987; Penning-Rowsell et al. 2003; Smith and Ward 1998).

Flood damages estimation is normally evaluated by damage functions (Apel et al., 2006, Dawson et al., 2008; Moel and Aerts, 2011). Damages functions usually describe the relation between the damage level and flood characteristics such as water depth and velocity, flood duration, and sediment loads. There are various approaches apply flood model to estimate flood losses. In Japan, they applied both physically based distributed hydrologic model to calculate a distributed flood loss by considering different flooding parameters and land use features (Dutta et al., 2003). In 2008, Jonkman et.al (2008) presented an integrated flood damage model which combined several data on land use and economic data to calculate direct damages and indirect damages. Examples of non-Thai studies which estimate and analyze flood damage and losses to residential properties are found in various studies (Appelbaum, 1985; Beck et al., 2002; Black, 1975; CH2M Hill, 1974; Child of ANUFLOOD, 1998; Smith, 1991; Davis and Skaggs, 1992; DeGagne, 1999; Green and Parker, 1994; Hubert et al., 1996; Islam, 1997; Risk Frontiers, 2002; Sangrey et al., 1975; Smith and Greenaway, 1980; Smith et al., 1981; Torterotot et al., 1992; US Army Corps of Engineers, 1993;2000).

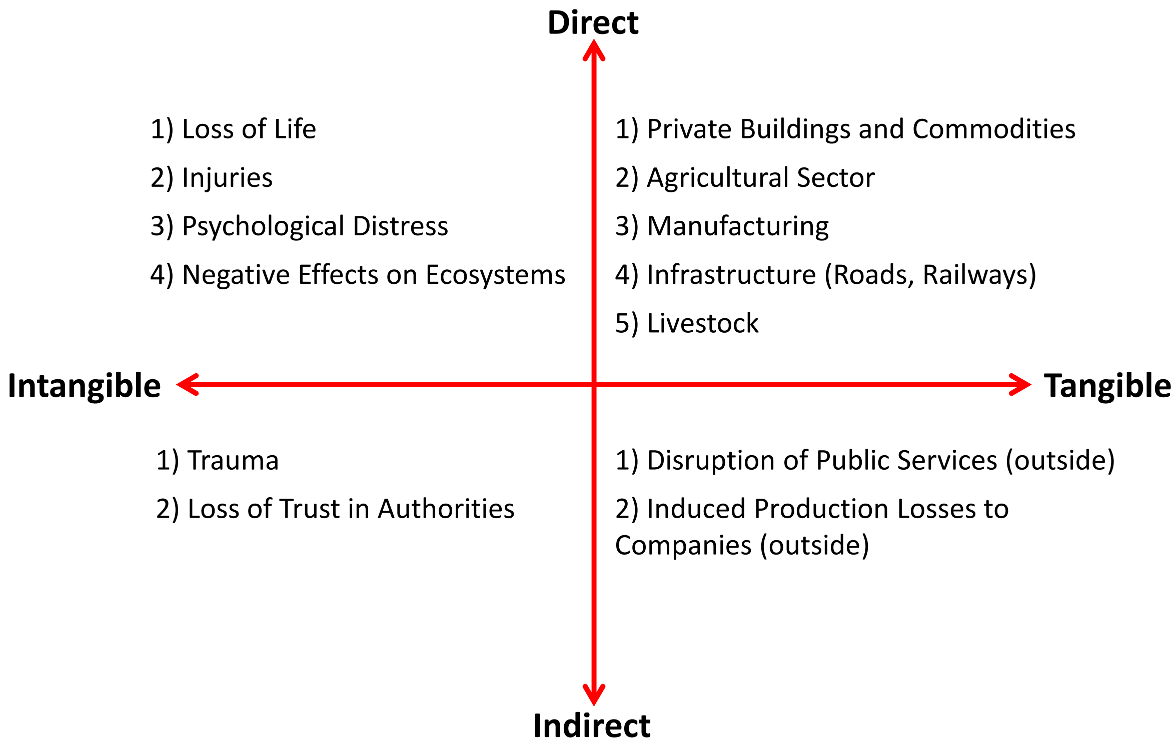


Fig. 6.1 Types of flood damages.

6.2 Direct tangible damages

Ideally, flood damage assessment should comprise all flood damage dimensions. However, most of methods for flood damage estimation are generally focuses on the direct tangible damages on public and private properties such as buildings, cars, and roads (Buchele et al., 2006; Merz,et al., 2004; Meyer and Messner, 2006; Nascimento et al., 2006; Penning-Rowsell et al., 2003). Damage to direct tangible damages on roads, buildings, industrial facilities, electricity, energy supply system, and private property are the most immediate evident impact of flooding. The direct tangible damage is evaluated in the concept of loss functions in monetary terms that are related to the type of assets and flood inundation depth or duration at those assets. There are various methodologies in several countries have tried to synthesize and generalize the relationship between flood damages to residential and commercial property, and flood characteristics such as England (Penning-Rowsell and Chatterton, 1977), Netherlands (Jonkman et al., 2008), Canada (Boyle et al., 1998), and Japan (Dutta et al., 2003). The most comprehensive approach commonly used in these studies to estimate flood damages is the stage-damage functions.

The stage-damage functions provide information by plotting between flood levels and percent damage in a variety of building types and occupancies. Functions are applicable to single buildings as well as groups of buildings of a given type. Moreover, these functions are more reliable as predictors of damage for large groups of buildings rather than small ones. The survey after flood event is necessary for establishing these stage-damage functions, namely empirical approaches. When data available is limited, it is recommended to use synthetic stage–damage functions which are created from previous flood damage studies via what-if-scenarios. The synthetic stage–damage functions are synthesized for standardized property rather than actual properties. Besides, the standard buildings types are classified by the construction types and purposes of building to evaluate its vulnerability on flood disaster. White (1964) is the pioneer to introduce the synthetic stage–damage functions.

Additionally, the stage-damage functions can be found in relative or absolute functions. The relative damage functions are simplicity because various data sources on the value of properties are available. Using values of all object assets might bring in uncertainty. In contrast, the absolute damage functions do not need asset values and estimated monetary damage is directly related to flood scenarios. However, this function regularly needs re-calibration. Chosen either relative or absolute functions depend very much on the available data.

The chosen scale of flood damage estimation depends not only on the size of the study area but also on the availability of necessary data. Direct tangible damages contribute mostly to an important proportion of total damages in monetary values. Besides, this present study focuses on direct tangible damages. To evaluate the total direct tangible damage, information on flood characteristics and property types should combine with the stage-damage functions. The direct tangible damage can be estimated by the following formula:

[Direct Tangible Damages in Inundation Areas (Bath)] = [Area of Inundation (km^2)] × [Damageable Values (Bath/km^2)] × [Damage Rate by Stage-Damage Functions (%)]

This study exclusively estimates the flood damages to household, manufacturing, and agricultural sectors. For the flood characteristic data, this study used results (flood depth and duration) from flood inundation model (iRIC model) described in Chapter 5 to calculate direct tangible damages of the 1995, 2006 and 2011 flood events. Due to limited data available and very big size of study area, the assets data (household, manufacturing, and agricultural sectors) used in this study is the secondary data obtained from various agencies in Thailand. The depth-damage functions from previous study (JICA, 2013) were applied and synthesized to suite with characteristics of study area. In addition, floor levels are estimated from building approval records and previous study (JICA, 2013).

6.2.1 Household sector

Most flood damages models mostly focus on the residential sector. There are many examples on types of flood damages models. Penning-Rowsell et al. (2005) presented the model for UK using synthetic damage data with absolute damage functions. In contrast, B¨uchele et al. (2006) and Thieken et al. (2008) applied data on empirical damage with relative damage functions to estimate building and contents damages. Moreover, ICPR (2001) introduced a combination of both empirical and synthetic damage data which exclusively considers the flood depth into consideration to evaluate the damages to immobile and equipment of building. Based on three examples on flood damage model estimation, models differ greatly in parameter used to estimate flood damages. Penning-Rowsell et al. (2005) consider various parameters to evaluate damage of building fabric items and household inventory such as water depth, flood duration, and building type and age.

The direct tangible damage to household sector in this present study is estimated by multiplying the damageable values by the damage rate that varies to flood depth. The flood simulation by the iRIC model provides the inundation depth of each 50 m × 50 m grid resolution with the study area of 6,012 km^2. From this reason, the flood damages are then estimated on the same grid cell size. This study also applied the secondary data from the Department of Provincial Administration (2016) to represent the number of houses in study area as shown in Fig. 6.2. In addition, this data also provides the type of house and their commodities.

Flood damages to household sector in this research are comprised of houses values and house commodities. The values of each house type are calculated by multiplying the type of house to perennial estimated unit cost of construction. The data on types and numbers of house obtained from the Department of Provincial Administration (2016) are single-family detached house, townhouse, condominium, apartment, and commercial buildings. The perennial estimated unit cost of construction was obtained from the Treasury Department (2016).

For the house commodities, the damages are the product of multiplying the number of house commodities to standard price of commodities. This study applied the data on ownership rates of household assets obtained from the Department of Provincial Administration (2016) to represent the number of commodities which are TV, DVD, mobile phone, computer, refrigerator, microwave, washing machine, air condition, car, motorcycle, tractor, and wheel plough. The standard price of commodities obtained from the Treasury Department (2016).

To estimate flood damages to household sector, the floor level and stage-damage functions is essential to be determined. The floor level mostly defines as the level free from property inundation. When the level of flood depth is higher than the floor level, the damage will be occurred. Floor level is normally set by the building approval records or field survey. Since study area is familiar to flooding, it assumed that house owners are well-prepared and houses are generally adjusted to flooding. Thus, this study specified 1.20 meter above ground level to be the floor level in the low-lying areas in the middle CPRB. This level is as high as 5-yaer return period. Regarding to stage-damage functions, this study applied the previous study from JICA (2013) due to limited data on stage-damage functions in this study area. The floor level and stage-damage functions for flood damages to household sector are summarized in Table 6.1. The direct tangible damage to household sector can be estimated by the following formula:

[Direct Tangible Damages to Household Sector (Bath)] = [House Value + House Commodities (Bath)] × [Damage Rate by Stage-Damage Functions (%)]

where

[House Value (Bath)] = [Number of Houses] × [House Types] × [Unit Cost of Construction (Bath)]

[House Commodities (Bath)] = [Ownership Rates of Household Assets] × [Standard Price of Commodities (Bath)]

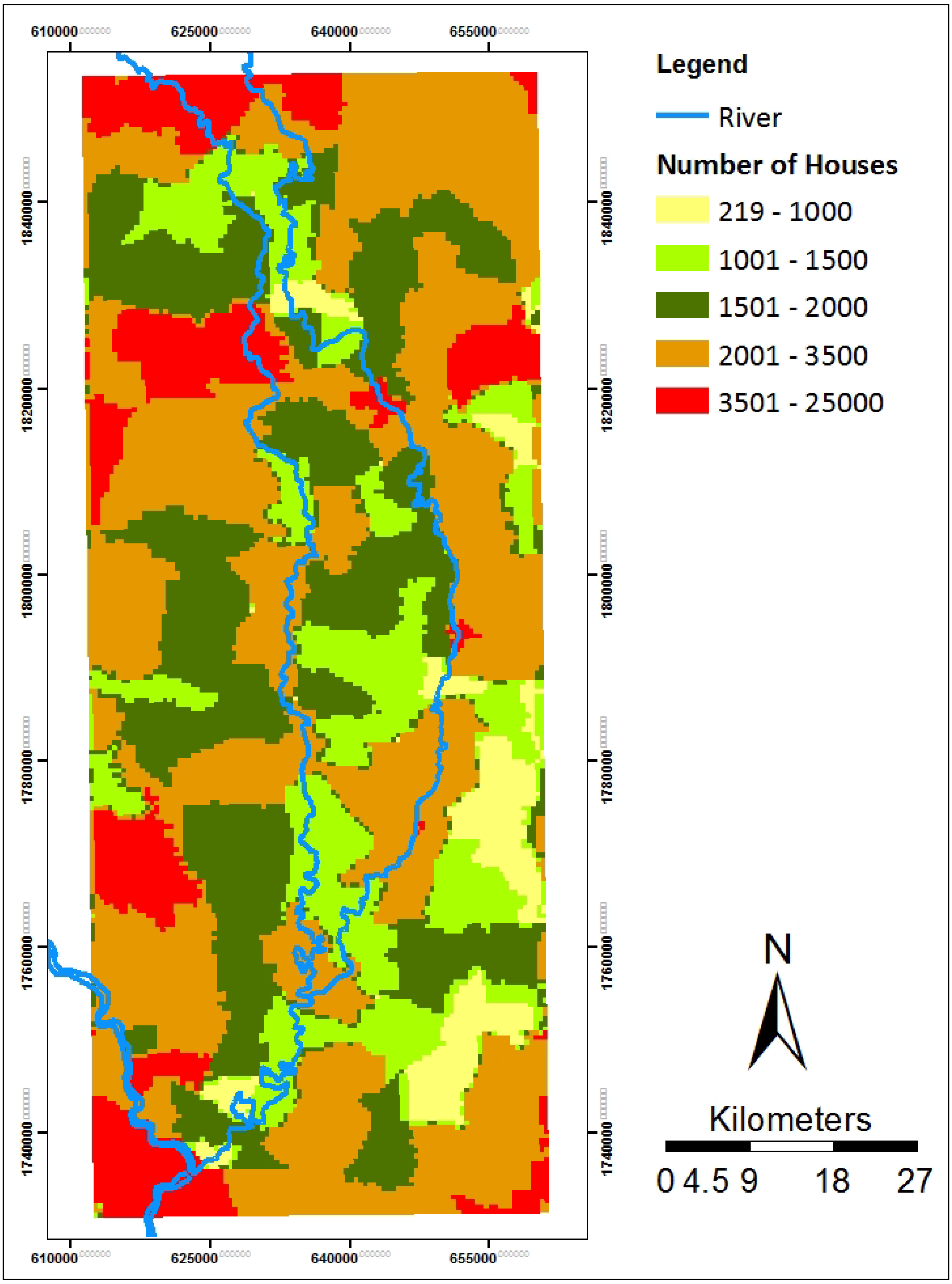


Fig 6.2 The number of houses in study area (Department of Provincial Administration, 2016).

Table 6.1 Floor level and stage-damage functions for flood damages to household sector.

Floor level	Stage-damage functions					
	Damageable Value	Flood Depth over Floor Level				
		0-0.5 m	0.5-1 m	1-2 m	2-3 m	Greater than 3m
1.20 meter above ground level (5-yaer return period)	House building	0.092	0.119	0.266	0.580	0.834
	House commodities	0.145	0.326	0.508	0.928	0.991

Source: "Project for the Comprehensive Flood Management Plan for the Chao Phraya River Basin in the Kingdom of Thailand" (JICA, 2013)

6.2.2 Manufacturing sector

Models for estimation of direct damage to manufacturing sector are different based on interests, parameters, and functions. Most of models are based on synthetic or empirical damage and absolute or relative damage functions. However, some aspects such as resistance parameter are specified damage model of manufacturing sector. The resistance parameter varies to the size and location of industry (Scawthorn et al., 2006; NR&M, 2002). The damage to manufacturing sector is mostly classified into various types (FEMA, 2003). Scawthorn et al. (2006) specified manufacturing damages into buildings, inventory, and equipment; while Kreibich et al (2010) separately damages to buildings, equipment and goods, products, and stock.

As the Department of Industrial Work (2017) provides only the number of factories and assets values in each sub-district as shown in Fig. 6.3, therefore, this study cannot distinguish the different types of manufacturing sector. Thus, this study assumed all industrial assets as fixed assets. The estimation of manufacturing damages is similar to the household sector that multiplies the industrial assets by damage function varying to flood depth.

For the floor level, this study assumed that the factory buildings are constructed with a certain margin to flooding. This study assumed 0.70 meter (2-yaer return period) above ground level as floor level. This assumed level is lower than the household level floor because the factory buildings are located in protection area and the owners are not similar to flooding and may not much careful than those of house owners. Moreover, this study also applied the stage-damage functions from the study of JICA (2013) to estimate flood damages. The floor level and stage-damage functions for flood damages to manufacturing sector are summarized in Table 6.2. The direct tangible damage to manufacturing sector can be estimated by the following formula:

[Direct Tangible Damages to Manufacturing Sector (Bath)] = [Number of Factories] × [Assets Values (Bath)] × [Damage Rate by Stage-Damage Functions (%)]

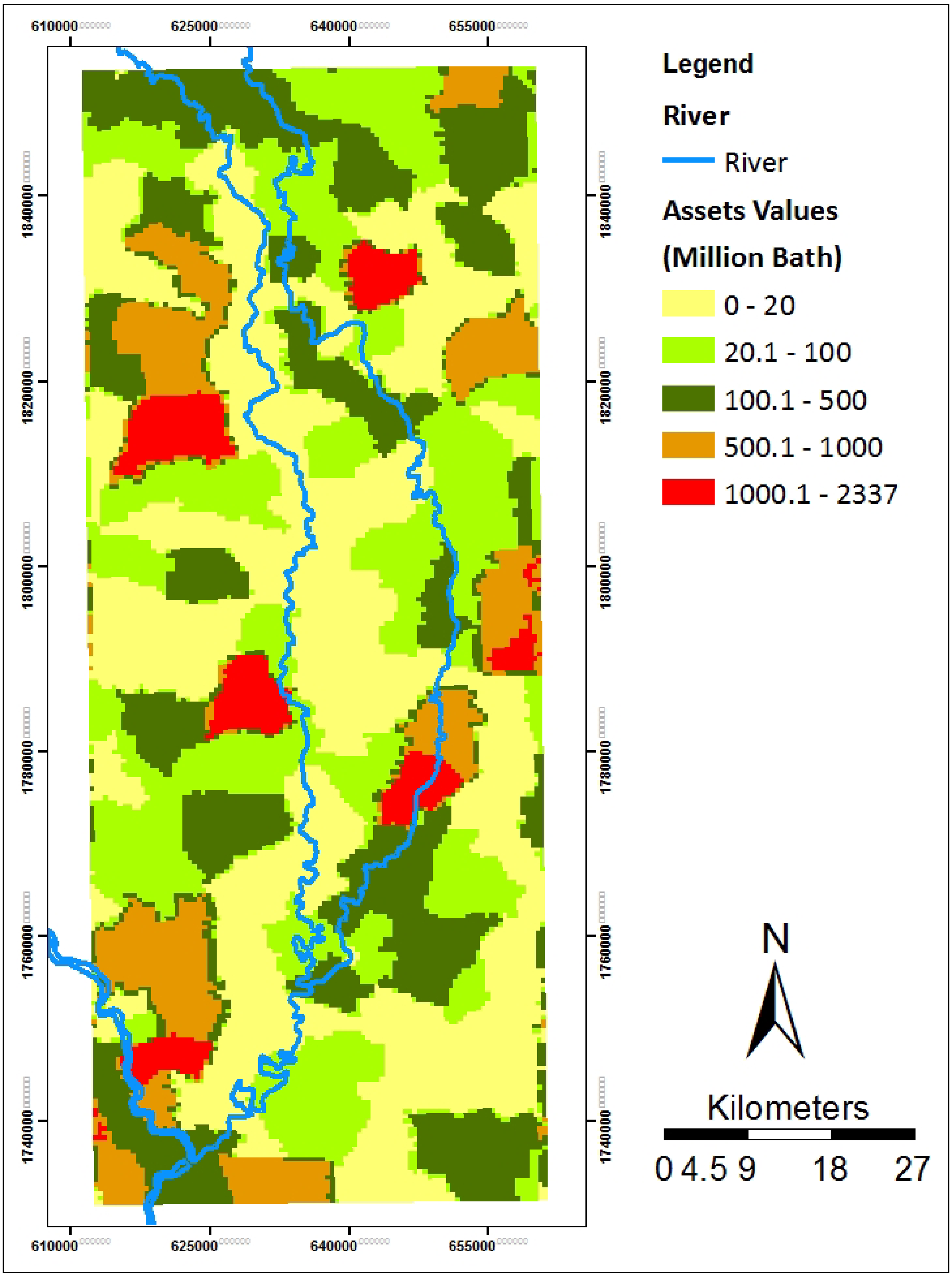


Fig 6.3 The asset value of manufacturing in study area (Department of Industrial Work, 2017).

Table 6.2 Floor level and stage-damage functions for flood damages to manufacturing sector.

Floor level	Stage-damage functions					
	Damageable Value	Flood Depth over Floor Level				
		0-0.5 m	0.5-1 m	1-2 m	2-3 m	Greater than 3m
0.70 meter above ground level (2-yaer return period)	Factory building	0.232	0.453	0.789	0.966	0.995

Source: "Project for the Comprehensive Flood Management Plan for the Chao Phraya River Basin in the Kingdom of Thailand" (JICA, 2013).

6.2.3 Agricultural sector

The assessment of agricultural losses is important to estimate the compensation for farmers after flood disaster. Flood damages model for agricultural sector includes losses of crops and farm equipment (Dutta et al., 2003). The yield of production and farm price may additionally require for damage estimation. Additionally, Pivot et al. (2002) presented the model to calculate soil damages that expresses in the soil quality. Generally, the total damages to agricultural sector are much less than household and manufacturing sectors. The important parameter to estimate production losses is duration of flooding. Besides, the flood variables on flood depth and velocity are rarely taken into account to estimate flood damage to agricultural sector. Some production losses models consider the occurrence of flood event corresponding to the stages of crop growth to estimate flood damages (Penning-Rowsell et al., 2003).

The estimation of damages to agricultural sector in this study mainly focuses on the loss of agriculture production. For the damage rate for agricultural sector, this study applied the duration of flood inundation instated of flood depth. The duration-damage functions obtained from Ministry of Agriculture and Cooperative (2015) are exclusively represented for all kinds of farming as summarized in Table 6.3.

Based on land use types from the Land Development Department (2009), agricultural types can be further classified into seven main categories; paddy field (94%), cassava (0.1%), corn (0.1%), sugarcane (3.2%), mixed field crop (0.5%), mixed orchard (2.0%), and mixed truck crop (0.1%) as shown in Fig. 6.4. The direct tangible damages to agricultural sector are estimated by multiplying the production of farming by damage rate that vary to flood duration. The production of farming is comprised of the average yield of production and farm price. The average yield of production and farm price were obtained from the Office of Agricultural Economics (2014). The direct tangible damage to agricultural sector can be estimated by the following formula:

[Direct Tangible Damages to Agricultural Sector (Bath)] = [Average Yield of Production (kg)] × [Farm Price (Bath/kg)] × [Damage Rate by Inundation-Damage Functions (%)]

Table 6.3 The duration-damage functions for flood damages to agricultural sector.

Damageable Value	Inundation Duration (days)			
	0-15	15-20	20-30	30-60
Agriculture sector	0.12	0.27	0.58	0.83

Source: Ministry of Agriculture and Cooperative (2015)

6.3 Flood damages estimation

This section presents the results of economic flood damage estimation. For this present study, flood damages estimation of direct tangible damages involves two related steps. This first is the estimation of damages to household, manufacturing, and agricultural sectors. Monetizing of these damages to monetary values is the second step. Using damageable values in household, manufacturing, and agricultural sectors, floor levels, and damage functions (depth/duration), flood damages can be estimated according to flood characteristics obtained from iRIC model simulation. The direct tangible flood damages from severe flood events (1995, 2006 and 2011 floods) are summarized in Table 6.4.

According to JICA report (2013), the total estimated flood damages to household and manufacturing sectors from 2011 flood around study areas were THB 8,169 and 3,650 million. This flood damage estimation from JICA report covered an area of 32,918 km^2 (five provinces in study area). While the damage to agricultural sector estimated in the whole CPRB (160,000 km^2) was THB 12,870 million. The different damages estimation from this study and JICA report might involve in the scale of flood extent area, flood characteristic used, and data analysis on household, manufacturing, and agricultural sectors.

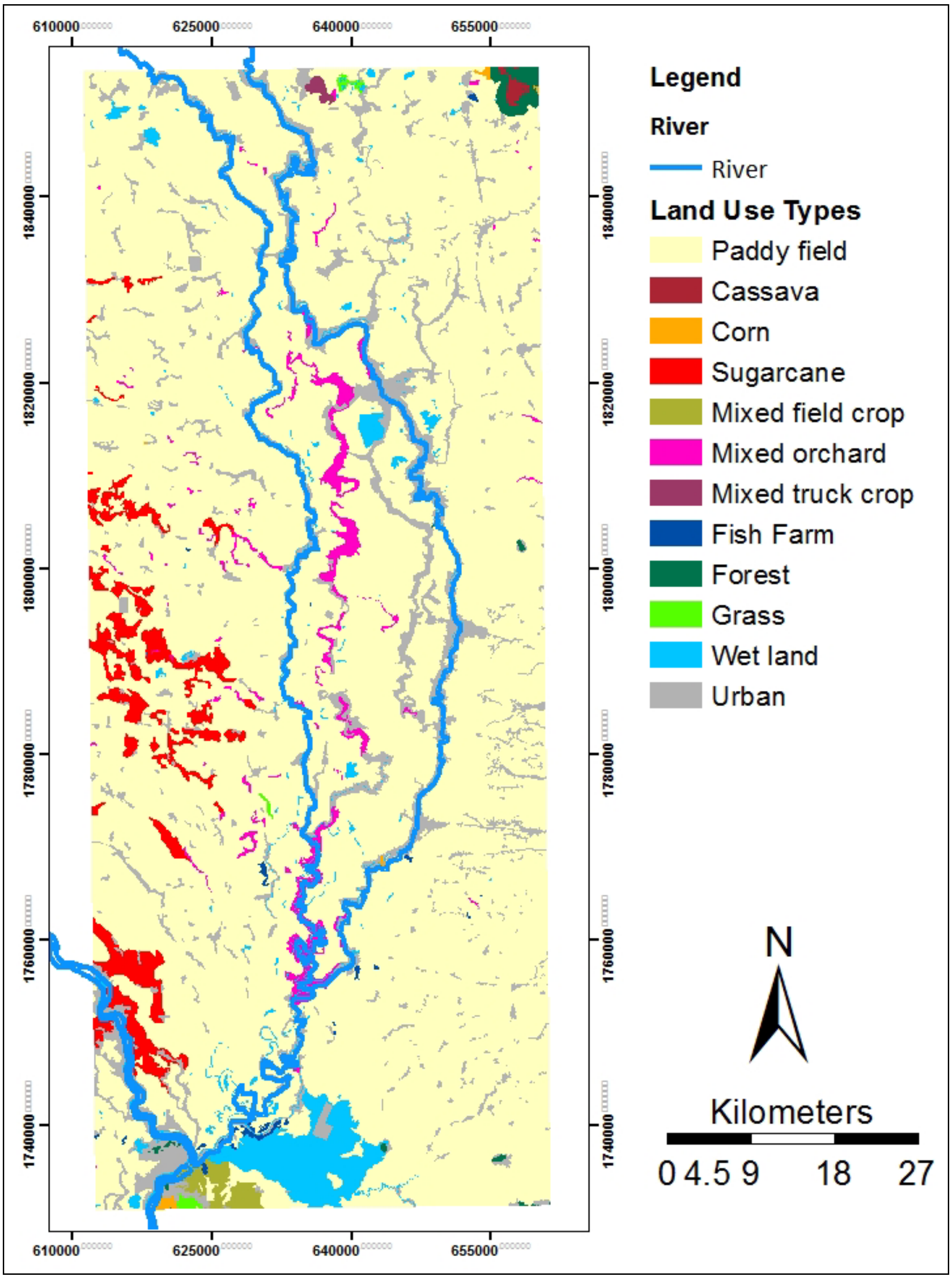


Fig 6.4 Land use types in study area (Land Development Department, 2009).

Table 6.4 The direct tangible flood damages from severe flood events.

Flood Events	Estimated Direct Tangible Damages (million THB)			
	Household Sector	Manufacturing Sector	Agricultural Sector	Sum.
1995	7,105	3,524	1,628	12,258
2006	7,664	4,209	1,628	13,501
2011	9,979	4,709	1,628	16,316

6.4 Flood countermeasures options evaluation

The flood damages assessment is mostly applied to assess or determine the feasibility of alternative flood countermeasures strategies as decision making tool for flood management. Economic feasibility of implementation plays crucial role in the estimating of flood countermeasures options selection. Decision alternatives can be ranked based on their expected benefit. Most of studies focus on within the scope of benefit-cost analysis because it can be carried out to assess the profitability of a project as assisting tool for decision making and project evaluation (Ganoulis, 2003; Olsen et al., 1998; Penning-Rowsell et al., 2005; Rose et al., 2007). Generally, benefit-cost analysis is evaluated by comparing benefit of measure against cost of activity. When the benefit greater than cost, it means measure is considered justified; while it will be not attractive when benefit lower than cost. In the context of flood management, cost of flood option to increase flood safety is normally compared to the expected flood damages reduction. Cost of flood measures is usually divided into (1) capital cost (costs of facilities and equipment construction, and consulting services) and (2) maintenance and management cost. The benefit is evaluated by observing the difference of damages values between the before and after implementation of the flood mitigation measures. The benefit includes the direct and indirect tangible damages. In benefit-cost of projects in practice, the analysis is usually specified to the consideration of tangible monetary effects.

This study conducts the benefit-cost ratio approach to evaluate the effectiveness of flood countermeasures options in the upper and middle CPRB. The project evaluation is 40 years. The estimated cost in this study which is collected from various sources such as Department of Provincial Administration (2016), Department of Industrial Work (2017), and JICA (2013) mainly focuses on the construction cost of facilities and equipment as shown in Table 6.5. In addition, the maintenance cost was set as 10% of construction cost per year. The benefit is estimated from the direct tangible damages reduction from after construction various measures. The direct tangible damages in each scenario are summarized in Fig. 6.5 and Table 6.6. According to 40-year project evaluation, the future benefit must be evaluated. The estimated average 40-year benefit from the project was calculated by following equation;

$$B_{\overline{40}} = \left(\frac{1}{2} \times B_{Tr_2}\right) + \left(\frac{1}{5} \times B_{Tr_5}\right) + \left(\frac{1}{10} \times B_{Tr_{10}}\right) + \left(\frac{1}{25} \times B_{Tr_{25}}\right) + \left(\frac{1}{50} \times B_{Tr_{50}}\right) + \left(\frac{1}{100} \times B_{Tr_{100}}\right) \quad (6.1)$$

where $B_{\overline{40}}$ is the estimated average 40-year benefit (million THB), and B_{tr} is estimated direct tangible damages reduction from each return period (million THB).

As DHI (2012) estimated the 1995, 2006, and 2011 floods had a return period of about 50, 25, and 100 years, respectively, this study applied the direct tangible damages reduction results from nine scenarios to formulate the linear equation for calculation of benefit in each return period. Besides, the benefit-cost analysis is evaluated by following equation;

$$\mathrm{B-C\ ratio} = \frac{40 \times B_{\overline{40}}}{\left(\mathrm{construction\ cost} + (40 \times \mathrm{maintenance\ cost})\right)} \tag{6.2}$$

where *B-C ration* is benefit cost ratio, $B_{\overline{40}}$ is the estimated average 40-year benefit (million THB).

The linear equation, benefit in each return period, project cost, and benefit-cost ratio in the middle of CPRB is summarized as Table 6.7. According to the results, it found that the retention areas plus reforestation (scenario 3) provides the highest value of benefit-cost ratio. Actually, the implementing all types of flood countermeasures can mostly reduce the flood damages in downstream areas such as seven industrial parks, urban areas, the biggest irrigated areas, and Bangkok. Besides, this study tries to evaluate flood damages reduction in the downstream areas towards different flood countermeasures options. Unfortunately, the simulation data from this research has only in the low-lying areas in the middle CPRB. Therefore, this study applies data from Prajamwong and Suppataratarn (2009) and JICA (2013) which provides the flood damages in the lower CPRB. As flood damage is relied not only peak discharge but also size of flooding, this study establishes the relationship between flood damages in the lower reach of the CPRB as summarized in Table 6.8. Fig. 6.6 shows the relationship between flood damages at lower reach of CPRB and both flood volume and flood peak discharge. It could be stated that it is difficult to specify or apply these relationship to estimate flood damages reduction in the lower CPRB because this damage from 2011 flood is dominant the relationship due to remarkable flood damages. It may come from the structure-breaches in the lower CPRB broken and inundated around the seven industrial parks and the western part of Bangkok that it has not been experienced in Thailand.

Table 6.5 The flood countermeasures and construction cost.

Case	Description	Construction cost (million THB)	Maintenance cost (million THB/year)
Calibration	No Additional Flood Countermeasures	0	0
Scenario 1	Reforestation	0	0
Scenario 2	Retention	6,536	654
Scenario 3	Reforestation + Retention	6,536	654
Scenario 4	Dam Construction	12,994	1,299
Scenario 5	Reforestation + Retention + Dam Construction	19,530	1,953
Scenario 6	Dam Operation	0	0
Scenario 7	Reforestation + Retention + Dam Construction + Dam Operation	19,530	1,953
Scenario 8	Reforestation + Retention + Dam Construction + Expanded Retention	27,051	2,705
Scenario 9	Reforestation + Retention + Dam Construction + Dam Operation + Expanded Retention	27,051	2,705

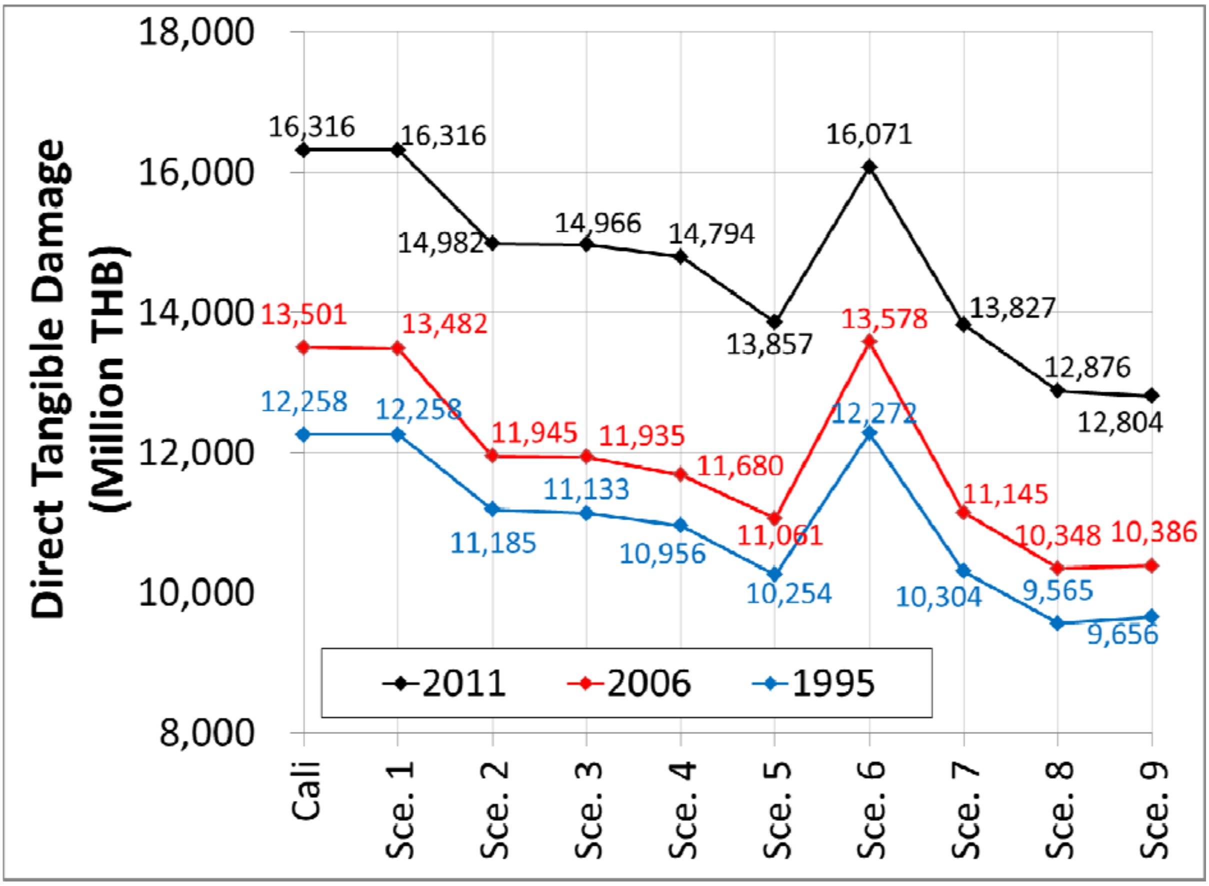


Fig 6.5 The direct tangible flood damages from each scenario.

Table 6.6 The direct tangible flood damages from each scenario in severe flood events.

1995 Flood				
Case	Estimated Direct Tangible Damages (million THB)			
	Household Sector	Manufacturing Sector	Agricultural Sector	Sum.
Calibration	7,105	3,524	1,628	12,258
Scenario 1	7,105	3,524	1,628	12,258
Scenario 2	6,395	3,287	1,503	11,185
Scenario 3	6,366	3,264	1,503	11,133
Scenario 4	6,234	3,219	1,503	10,956
Scenario 5	5,834	3,025	1,396	10,254
Scenario 6	7,115	3,530	1,628	12,272
Scenario 7	5,875	3,033	1,396	10,304
Scenario 8	5,450	2,812	1,303	9,565
Scenario 9	5,492	2,861	1,303	9,656
2006 Flood				
Case	Estimated Direct Tangible Damages (million THB)			
	Household Sector	Manufacturing Sector	Agricultural Sector	Sum.
Calibration	7,664	4,209	1,628	13,501
Scenario 1	7,684	4,170	1,628	13,482
Scenario 2	6,830	3,613	1,503	11,945
Scenario 3	6,820	3,613	1,503	11,935
Scenario 4	6,634	3,543	1,503	11,680
Scenario 5	6,313	3,352	1,396	11,061
Scenario 6	7,734	4,216	1,628	13,578
Scenario 7	6,351	3,398	1,396	11,145
Scenario 8	5,882	3,163	1,303	10,348
Scenario 9	5,921	3,162	1,303	10,386
2011 Flood				
Case	Estimated Direct Tangible Damages (million THB)			
	Household Sector	Manufacturing Sector	Agricultural Sector	Sum.
Calibration	9,979	4,709	1,628	16,316
Scenario 1	9,979	4,709	1,628	16,316
Scenario 2	9,089	4,390	1,503	14,982
Scenario 3	9,073	4,390	1,503	14,966
Scenario 4	8,901	4,390	1,503	14,794
Scenario 5	8,438	4,024	1,396	13,857
Scenario 6	9,796	4,647	1,628	16,071
Scenario 7	8,408	4,023	1,396	13,827
Scenario 8	7,841	3,733	1,303	12,876
Scenario 9	7,811	3,690	1,303	12,804

Table 6.7 The equations, benefit in each return period, and benefit-cost analysis in the middle of CPRB.

Case	Equations	Benefit in each return period (million THB)						40-year benefit	Construction cost (million THB)	Maintenance cost (million THB/year)	Benefit-Cost ratio
		2	5	10	25	50	100				
Scenario 1	y = -0.0543x + 9.5	9	9	9	8	7	4	8	0	0	∞
Scenario 2	y = 2.355x + 1183.4	1,188	1,195	1,207	1,242	1,301	1,419	1,044	6536	654	1.28
Scenario 3	y = 1.956x + 1232.6	1,237	1,242	1,252	1,282	1,330	1,428	1,084	6536	654	1.33
Scenario 4	y = 1.6583x + 1451.2	1,455	1,459	1,468	1,493	1,534	1,617	1,272	12994	1299	0.78
Scenario 5	y = 5.2561x + 1994.2	2,005	2,020	2,047	2,126	2,257	2,520	1,766	19530	1953	0.72
Scenario 6	y = 3.8922x - 175.74	184	195	215	273	370	565	176	0	0	∞
Scenario 7	y = 6.495x + 1887.6	1,901	1,920	1,953	2,050	2,212	2,537	1,681	19530	1953	0.69
Scenario 8	y = 9.3513x + 2549.9	2,569	2,597	2,643	2,784	3,017	3,485	2,275	27051	2705	0.67
Scenario 9	y = 11.534x + 2403.4	2,426	2,461	2,519	2,692	2,980	3,557	2,160	27051	2705	0.64

Table 6.8 Flood damages in the lower CPRB, flood peak discharge, and flood volume.

Flood event	Flood damages (Billion THB)	Peak discharge (m^3/s)	Flood volume ($x10^6$ m^3)
1995	8	4,803	16,928
1996	2	3,066	11,326
2002	2	4,019	14,028
2006	4	5,840	17,713
2011	569	4,885	22,041

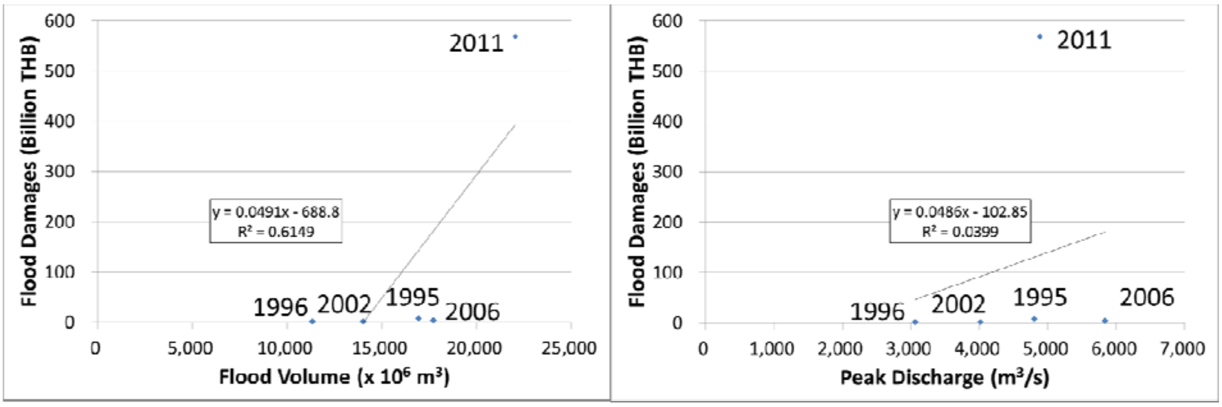


Fig 6.6 The relationship between flood damages in the lower reach of the CPRB with flood volume and flood peak discharge.

6.5 Conclusions

Such frequent flooding in the CPRB, it is important to assess the feasibility of flood countermeasures in the term of cost benefit approach which is necessary for rational decision-making. The cost effectiveness of a measure mostly depends on the ratio between investments and risk reduction. According to results of benefit-cost ratio in this study, the highest value (1.33) on benefit-cost ratio is the retention areas plus reforestation (scenario 3). There are three main explanations. First one is the area of estimation might be small (5.75%) when comparing to the whole CPRB. Unfortunately, only data on runoff station C.2 (peak discharge and flood volume) could not establish relationship on flood damages to the lower CPRB. Another explanation is that data limitation can pose a substantial challenge because this study adopts all data from various previous studies that might provide the significant levels of uncertainty. The last one is focusing on monetary values of benefit-cost analysis. In fact, not all costs and benefit can be estimated in term of monetary terms such as human lives saved and trust from resident.

However, it should be noted that the most favorable alternative in economic aspects may change when other values such as ecological, social, and political considerations take in to consideration. Estimation of flood damage involves in several uncertainty sources such as flood inundation models and availability of data used. It brings various questions and different opinions when decision making occurs. To identify the best strategies, it is important to assess the risk in the areas affected by flooding. Thus, despite estimation of flood damages, the flood risk assessment and reduction are essential. In the Chapter 7, this study introduces the flood risk analysis to specific the high risk areas in the low-lying areas around Yom and Nan Rivers. As flood risk management, Chapter 8 will facilitate a measure to reduce the loss of life due to the most frequent inundated areas in the CPRB.

Chapter 7
Flood risk assessment

7.1 Introduction

Natural hazard such as flooding, rain, tsunami, wind, tornadoes, mudslide, and earthquakes refers to a phenomenon from the natural environment that causes damage to society, especially residences. This dissertation focuses on flood disaster. IRFC (2002) reports people and property are dramatically exposed to the potential for natural disaster even though fatalities have been decreased. Natural disasters according to annual direct economic losses increased from US$ 75.5 billion in 1960 to US$ 659.9 billion in 1990 (Munich Re., 2002). UNDP (2004) also reports that about 75% of world's population lived in the threatened areas of earthquakes, tornado and flood. Human worldwide is vulnerable to flood disaster. Berz (2000) stated that Asian countries are more susceptible to the occurrence of flooding due to theirs climatology and geographical location that took around 42% of flood occurrence in the world. The flood impact in this region, accounting to 53% of worldwide economic losses, is also higher than even the America or European countries due to the denser population and limited capacity of flood protection. In addition, death toll from flood disaster ranged 91% of all fatalities.

In recent years, the flood impact has gained importance because of the increased socio-economic and land use development. According to natural disaster records (1983-2012) in Thailand, damages from flood disaster in economic was highest (AHA Centre, 2015). In 2011, flood in the CPRB caused damages and losses around US$ 46.5 billion and casualties ranged more than 1,000 people (The Ministry of Finance, 2012). Since various flood countermeasures have been implemented, flood risk in the CPRB is still high due to its topographical characteristics. Thai people around 27.5 million people (41% of total population) live in an agriculture sector (National Statistical Office, 2014). Most of agriculture areas are rainfed areas that are not planned for flood protection (Department of Water Resources, 2007; Royal Irrigation Department, 2010). To date, many studies and models have been developed and conduced to assess the extent of past floods in CPRB (Chia et al., 2015; Mateo et al., 2014). However, there are only few studies which assess flood hazard, flood vulnerability, and flood risk in the CPRB.

Flood risk assessment has been evaluated to prevent, mitigate, and reduce damage from flooding. Without a clear and detailed flood risk, it is difficult to allocate a reasonable budget. To determine the risk area, it is deepened not only on the frequency and intensity of flooding but also on the vulnerability to residents and properties. Since flood risk assessment has drawn addition to researchers, there are various studies. Sayers et al. (2002) defined risk is a combination of the chance of a particular event, with the impact that the event would cause if it occurred. World Health Organisation (2003) suggested that assessment of hazard and vulnerability should be carried out together in order to can compare and combine results. For example, two urban areas may have the same vulnerability value but they might have different flood hazard due to their ground elevation and flood protections.

These studies indicate that risk is fundamentally a combination of hazard and vulnerability. The social vulnerability can characterize the predisposition of society to get hurt by flood hazard. An overview on the extent of social vulnerability to river flooding in Thailand is clearly missing. Besides, flood risk assessment in this study is evaluated as a product of flood hazard and social vulnerability. It is essential to define the definition of flood risk, flood hazard, and social vulnerability to scope the research interest and objective. According to the definition from the UNISDR Terminology on Disaster Risk Reduction (UNISDR, 2015), this study defines "flood risk" as "the potential flood disaster which losses in lives and property (assets) and also affects the socio-economic development.", "flood hazard" as "a potentially damaging flood event (flood characteristics) that may cause the loss of life or injury, property damage, social and economic disruption.", and "social vulnerability" as "people and property (assets) exposed to the flood hazard.".

7.2 Methodology

The mapping is a powerful tool for decision-making for flood management options selection because it can present the information in the geographical context that is easy to understand and provides a stronger impression. Besides, the flood risk assessment in low-lying areas of the middle CPRB is evaluated and mapped as the product of flood hazard and social vulnerability assessments. To understand flood risk, it is necessary to set appropriate conditions of flood events and socio-economic situations to assess the conditions of floodplains. Profoundly understanding floodplains conditions provides the basic information for considering the methods to reduce and avoid risks and eventually for developing adaptation measures (Büchele et al., 2006; Kaplan and Garrick, 1981; Moel et al., 2009). The identification of flood risk factors is the most important step at the flood risk assessment. The inclusion of flood risk factors should be performed within a framework to ensure that the whole problem is enclosed.

Owing to huge economic losses and vast inundation areas, severe flood events in 1995, 2006, and 2011 were selected to establish flood hazard map for this study area. As flood depth, flow velocity, and flood duration play a crucial role in loss of life and economic damages, this study carried out the simulation results in these three parameters from iRIC model (Chapter 5) to generate flood hazard map. These data are represented in as grid with 50 m × 50 m resolution at different time.

To define the concept of vulnerability, there have been many attempts to capture the meaning of this term. McEntire (2010) and Hufschmidt (2011) stated that the vulnerability is defined according to the hazard to which people are exposed to. Flood vulnerability is defined as the degree of loss of a given element resulting from a flood disaster such as household, manufacturing, agricultural land, public utilities, and transportation that is normally expressed on scale 0-1. In addition, van der Veen and Logtmeijer (2005) broadened the concept of flood vulnerability related to an economic point of view.

The flood vulnerability comprised of three main factors; resilience, susceptibility, and exposure. An example of flood vulnerability is house. A house has resilience in its ability to prevent structural collapse due to external water pressure. A house also has susceptibility and exposure due to its value and location. Based on available data and extensive literature review (Kandilioti and Makropoulos, 2012; Meyer et al., 2009; Siddayao et al., 2014), this study collected and employed seven indicators in socio-economic to generate the social vulnerability map to flooding as shown in Table 7.1. Through standardized processing, all seven data layers in social vulnerability were converted into grid data as large as flood hazard data.

Base on geographic and statistical data used for this study, it is very distinct that there is multiplicity, complexity, and uncertainty (Liu et al., 2014). The fuzzy logic method has been introduced to cope with these problems (Guo et al., 2014). Flood risk assessment normally applies fuzzy logic because it is simple to describe fuzzy character and can represent the actual situation on objectiveness (Ahmad and Simonovic, 2011; Guleda et al., 2004; Jiang et al., 2009; Jun et al., 2013). Moreover, to estimate the weight values to each parameter, this study also applies the fuzzy analytic hierarchy process (AHP). The flowchart for flood risk assessment in low-lying areas of the middle CPRB is shown in Fig. 7.1.

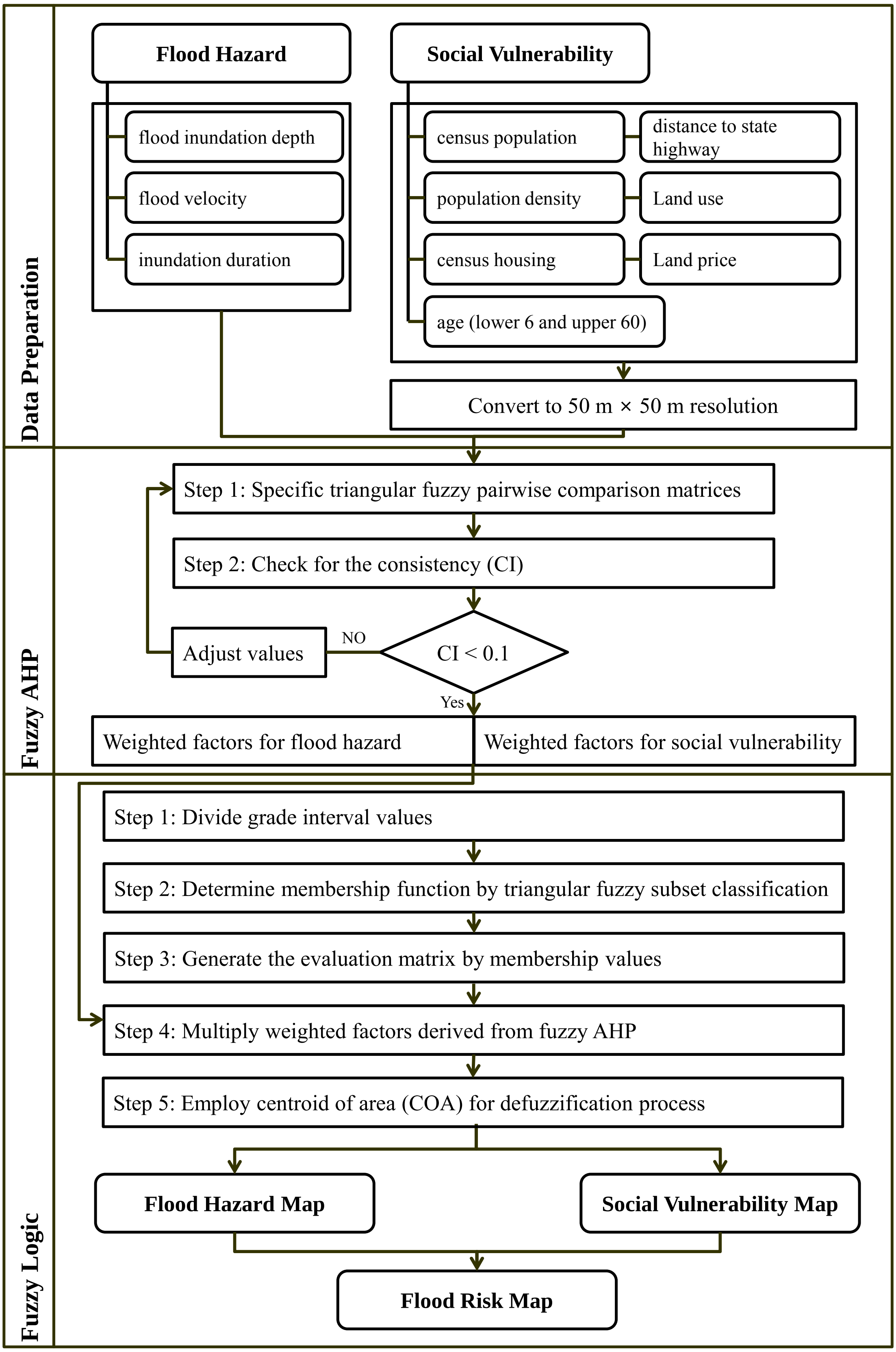


Fig 7.1 Flowchart for the flood risk assessment in low-lying areas of the middle CPRB.

Table 7.1 Factors for flood hazard map and social vulnerability map.

Indicators	Description	Source
Flood Hazard Map		
F1	Flood Inundation Depth	Flood Inundation Model (Chapter 5)
F2	Flood Velocity	Flood Inundation Model (Chapter 5)
F3	Inundation Duration	Flood Inundation Model (Chapter 5)
Social Vulnerability Map		
S1	Census Population	Department of Provincial Administration (2016)
S2	Population Density	Department of Provincial Administration (2016)
S3	Age (lower 6 and upper 60)	Department of Provincial Administration (2016)
S4	Census Housing	Department of Provincial Administration (2016)
S5	Distance to State Roads	Department of Highways (2016)
S6	Land Use	Land Development Department (2009)
S7	Land Price	The Treasury Department (2015)

7.3 Model approach

Before this study carries out the comprehensive flood risk assessment in the low-lying areas in the CPRB, it is firstly to introduce the fuzzy Analytic Hierarchy Process (AHP) method for weights calculation and the fuzzy logic method for value generating.

7.3.1 Fuzzy AHP

The Analytic Hierarchy Process (AHP) has been widely used for estimating weight factors in several areas of human interests (Dura´n and Aguilo, 2008; Pourghasemi et al., 2013; Subramanian and Ramanathan, 2012). In the AHP, the weights of criteria are not obviously distinguished, as in the direct assessment multiple-criteria decision-making (MCDM) methods. The weights are generated from judgement matrices of pairwise comparisons considered by the importance of the criteria proposed by Saaty (1980). As the traditional AHP, the pairwise comparisons are represented as crisp values. However, uncertainties, ambiguities and vagueness in the real situation cannot be handled by a crisp value. As a result, fuzzy AHP was developed to solve these problems. This study then applied the extent study on fuzzy AHP developed by Chang (1996). In addition, using triangular fuzzy numbers in fuzzy AHP has proven that it is effective for problem statement where the limited data is subjective and ambiguous (Mosadeghi et al., 2015; Papaioannou et al., 2015; Zimmerman, 1996). Therefore, the fuzzy AHP model with triangular fuzzy numbers in a pairwise comparison process was employed to generate weights factor for flood hazard and social vulnerability map in this study.

To check the discordances between the pairwise comparisons and the reliability of the weighted value, the consistency ratio (CR) has to be evaluated. In AHP, the consistency applied to establish a matrix is expressed by a consistency ratio, which must be less than 0.1; otherwise, it is necessary to review the subjective judgments (Saaty, 1980). For computing the consistency ratio (CR), the following formula was applied:

$$CR = \frac{CI}{RI} \tag{7.1}$$

where *CI* is the consistency index, and *RI* is the random index representing the consistency of a randomly generated pairwise comparison matrix. The *CI* was calculated using the following formula:

$$CI = \frac{\lambda - n}{n - 1} \tag{7.2}$$

where *n* is number of indicators (three for flood hazard map and seven for social vulnerability map) and λ is average value of the consistency vector.

7.3.2 Fuzzy logic

Fuzzy set is firstly introduced by Professor Zadeh in 1965 as a mathematical approach to represent and deal with vagueness as we often deal with in our daily life (Zadeh, 1965). Over the last three decades, the enormous success of commercial applications has been developed with fuzzy technologies by various Japanese companies to gain more conventional technologies in many scientific and engineering applications, especially in control systems and pattern recognition (Newsweek, 1990). With the advancement of fuzzy logic, some mathematical models have been developed based on fuzzy theories to achieve a greater accuracy.

According to Fig. 7.2, fuzzy logic systems are rule-based systems. The input is fuzzified that converts a crisp variable to a fuzzy set by rule base processes. Consequentially, this rule base performs the defuzzifier operation to convert fuzzy to crisp number in final step. The centroid of area defuzzification is the most popular method for defuzzifier illustrated in Fig. 7.3. The crisp number output (y_d) is expressed in the x-coordinate of the set's center of gravity as following equation:

$$y_d = \frac{\int_S y\mu_y(y)d_y}{\int_S \mu_y(y)d_y} \tag{7.3}$$

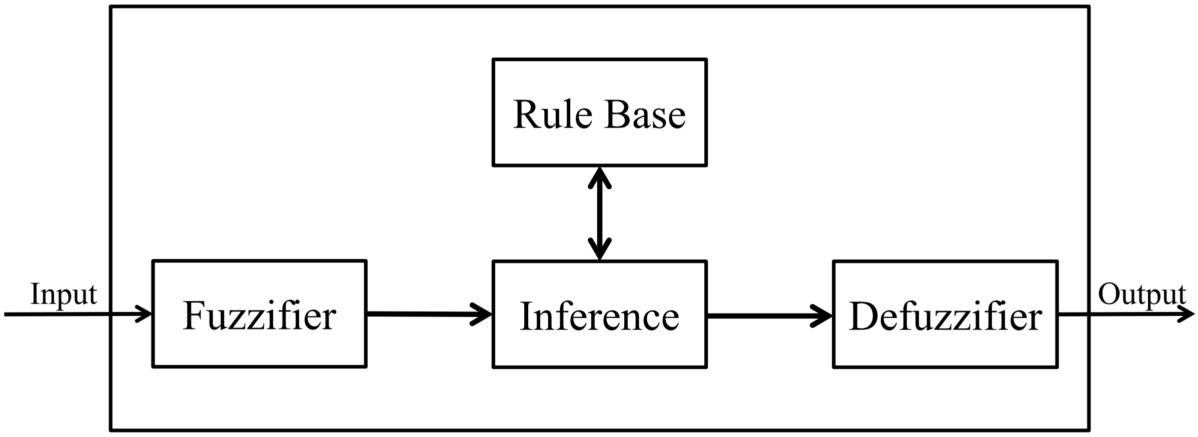


Fig. 7.2 Structure of a fuzzy logic system.

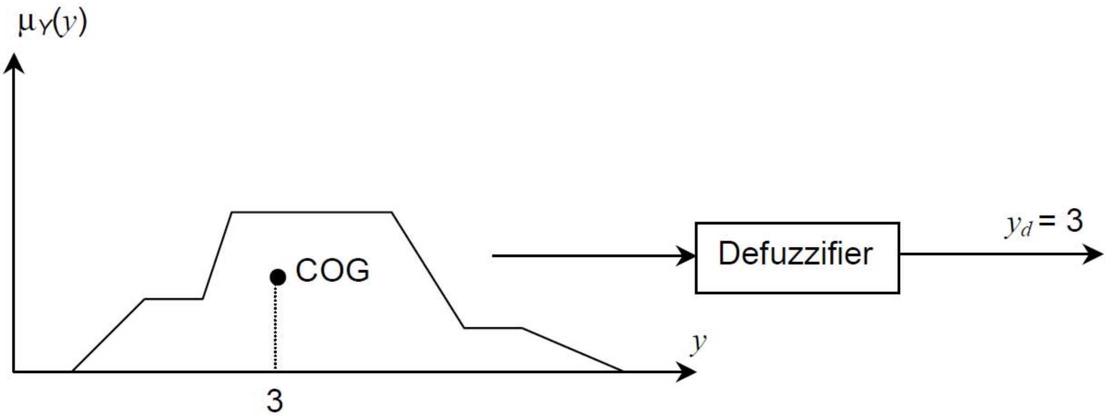


Fig. 7.3 Example of centroid of area defuzzification.

As mentioned previous, this study involves many indices and it is difficult to specify an exact value (crisp value) to them; however fuzzy model provide a possibility to identify their values between 0 and 1. When value belongs in full membership, it represents 1. In contrast, it will become 0 when that value is a non-membership. Using different type of fuzzy numbers is deepened on data and problem (Chang, 2001). The fuzzy synthetic evaluation (FSE) categorizes data in several groups and calculates each individual value considering the whole situation (Lu et al., 1999). This study then applied FSE to generate the flood risk map. The triangular fuzzy numbers were also utilized to express their relative membership. Fig. 7.4 represents the triangular fuzzy numbers and it can be described as:

$$\mu_{\tilde{N}}(x) = \begin{cases} \frac{x-l}{m-l}, & l \leq x \leq m \\ \frac{u-x}{u-m}, & m \leq x \leq u \\ 0, & otherwise \end{cases} \tag{7.3}$$

where the parameters, *l*, *m*, and *u* is the smallest possible value, the most promising value, and the largest possible value respectively. The triangular fuzzy number is generally represented as (*l*, *m*, *u*).

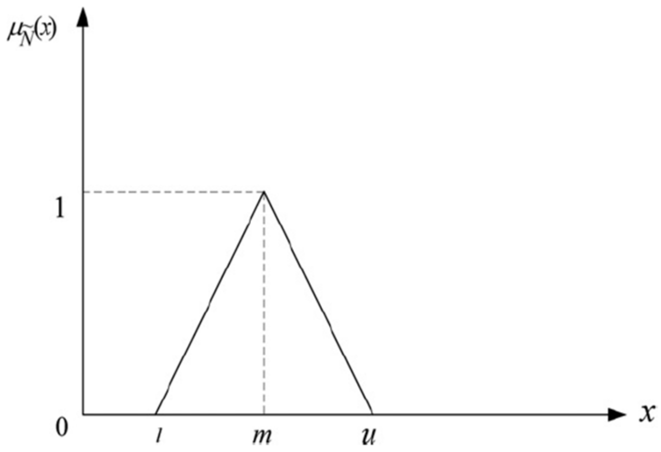


Fig. 7.4 Triangular fuzzy member.

7.4 Flood risk map

This study defines risk as relating to mathematical expectation. Therefore, quantitative descriptions of hazard and vulnerability are essential to estimate risk as mathematical values. Flood risk maps in low-lying areas of the middle CPRB were developed using flood hazard and social vulnerability maps through fuzzy AHP and fuzzy logic. The flood risk assessment model (Fig. 7.1) was set up to generate flood risk maps. The specific technique of this model describes as follows:

(1) According to the basic assessment units, this study counted out three flood hazard indicators, flood inundation depth, flood velocity, and inundation duration as Table 7.1. On the other hand, social vulnerability assessment, there is a corresponding seven-indicator as Table 7.1, consisting of census population, population density, age (lower 6 and upper 60 years old), census housing, distance to state roads, land use, and land price.

(2) This study collected and converted the socio-economic data from various agencies

to grid data with a resolution of 50 m × 50 m resolution corresponding to flood inundation model simulation results.

(3) For fuzzy AHP model, this study specified triangular fuzzy pairwise comparison matrices. Pairwise comparison matrices were formed by the characteristics of the middle CPRB and literature review (Kienberger et al., 2009; Malczewski, 2006). The local weights of flood hazard and social vulnerability map that passed the consistency test are presented in Table 7.2. For the consistency ratio (CR) of flood hazard and social vulnerability maps were 0.046 and 0.052 respectively.

(4) According to basin characteristics, historical information, literature review, and so on (Scheuer et al., 2010; Stefanidis and Stathis, 2013; Zou et al., 2013), this study divided the grade interval value for flood risk map, flood hazard map and social vulnerability maps into five grades, noted as low zone, low-medium zone, medium zone, medium-high zone, and high zone as shown in Table 7.3.

(5) Through the piecewise linear function (triangle) in fuzzy logic, the membership function of each grade was calculated and eventually the assessment factors will be obtained by the fuzzy subset classification (Fig. 7.4). The parameters, l, m, and u in this study are the lowest value, the middle value, and the highest value of each grade interval value respectively (Table 7.3).

(6) The evaluation matrices were generated by the membership values and were then multiplied by weighted factors derived from fuzzy AHP. The defuzzification is the last step in the fuzzy logic process. This study applied centroid of area for defuzzification process and eventually the flood hazard and social vulnerability assessment results can be obtained through fuzzy logic. The flood hazard and social vulnerability maps are shown in Fig. 7.5.

(7) With the flood hazard and social vulnerability results, eventually it is able to generate the flood risk maps for low-lying areas in the middle CPRB through fuzzy logic.

(8) According to this research provides the best set of flood countermeasures options to each severe flood event (in Chapter 5), flood risk maps of with and without flood countermeasures are shown in Fig. 7.6 and are summarized in Table 7.4.

Table 7.2 Local weights and pairwise comparison matrix of the flood hazard map and social vulnerability map indicators.

Flood Hazard Map			
Indicators	F1	F2	F3
F1	(1,1,1)	(1/3,1/2,1)	(1/2,1,1)
F2	(1,2,3)	(1,1,1)	(1/2,1,2)
F3	(1,1,2)	(1/2,1,2)	(1,1,1)
	*	*	*
Weights	0.429	0.206	0.364

Social Vulnerability Map							
Indicators	S1	S2	S3	S4	S5	S6	S7
S1	(1,1,1)	(1,3,5)	(1,2,3)	(1/2,1,1)	(1/2,1,1)	(1/2,1,1)	(1,3,5)
S2	(1/5,/1/3,1)	(1,1,1)	(1/3,1/2,1)	(1/3,1/2,1)	(1/3,1/2,1)	(2,1,1/2)	(1/2,1,1)
S3	(1/3,/1/2,1)	(1,2,3)	(1,1,1)	(1/2,1,1)	(1/2,1,1)	(1/3,1/2,1)	(1,2,3)
S4	(1,1,2)	(1,2,3)	(1,1,2)	(1,1,1)	(1/2,1,1)	(1/2,1,1)	(1,2,3)
S5	(1,1,2)	(1,2,3)	(1,1,2)	(1,1,2)	(1,1,1)	(1/2,1,1)	(1/3,/1/2,1)
S6	(1,1,2)	(2,1,1/2)	(1,2,3)	(1,1,2)	(1,1,2)	(1,1,1)	(1,2,3)
S7	(1/5,/1/3,1)	(1,1,2)	(1/3,1/2,1)	(1/3,/1/2,1)	(1,2,3)	(1/3,/1/2,1)	(1,1,1)
	*	*	*	*	*	*	*
Weights	0.109	0.204	0.136	0.111	0.116	0.113	0.212

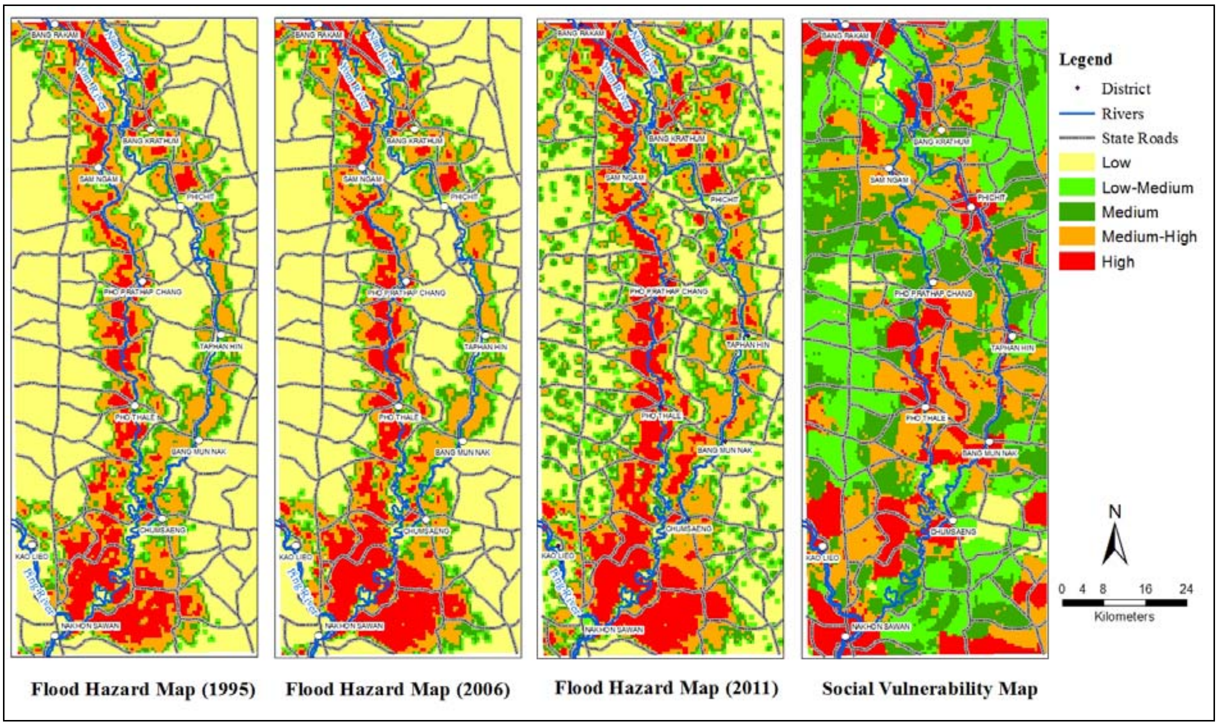


Fig. 7.5 Flood hazard and social vulnerability maps for low-lying areas in the middle CPRB.

Table 7.3 The factors classification of flood hazard map, social vulnerability map and flood risk map including the triangular fuzzy member (l, m, and u in Fig. 7.4).

Flood Hazard Map		Grade Interval Value				
Factor type	Weight factor	Low hazard zone (l-u)	Low-medium hazard zone (l-u)	Medium hazard zone (l-u)	Medium-high hazard zone (l-u)	High hazard zone (l-u)
F1: Flood Inundation Depth (m)	0.429	0-0.52	0.30-1.12	0.52-1.75	1.12-2.25	1.75-18.50
F2: Flood Velocity (m/s)	0.206	0-0.30	0.10-0.75	0.30-1.25	0.75-2.00	1.25-7.80
F3: Inundation Duration (days)	0.364	0-4	1-11	4-22	11-45	22-61
Social Vulnerability Map		Grade Interval Value				
Factor type	Weight factor	Low hazard zone (l-u)	Low-medium hazard zone (l-u)	Medium hazard zone (l-u)	Medium-high hazard zone (l-u)	High hazard zone (l-u)
S1: Census Population (population)	0.109	0-15	10-25	20-40	30-100	75-850
S2: Population Density (population/km^2)	0.204	0-63	40-113	63-225	113-1,000	225-3,500
S3: Age (lower 6 and upper 60) (population)	0.136	0-2	1-5	3-10	8-15	12-150
S4: Census Housing (housing)	0.111	0-5	2-10	7-20	15-40	30-350
S5: Distance to State Roads (km)	0.116	0-5	2.0-9.5	5.0-14.5	9.5-18.5	14.5-21
S6: Land Use (type)	0.113	0-1.5	1-2.5	1.5-3.5	2.5-4.5	3.5-5
S7: Land Price (Baht/1,600 m^2)	0.212	0-35,000	18,000-75,000	35,000-550,000	75,000-3,750,000	550,000-7,000,000
Flood Hazard Map		Grade Interval Value				
Factor type	Weight factor	Low hazard zone (l-u)	Low-medium hazard zone (l-u)	Medium hazard zone (l-u)	Medium-high hazard zone (l-u)	High hazard zone (l-u)
Flood Risk Map	0.50	0-1.5	1.0-2.5	2.5-3.5	3.0-4.5	4-5
Social Vulnerability Map	0.50	0-1.5	1.0-2.5	2.5-3.5	3.0-4.5	4-5

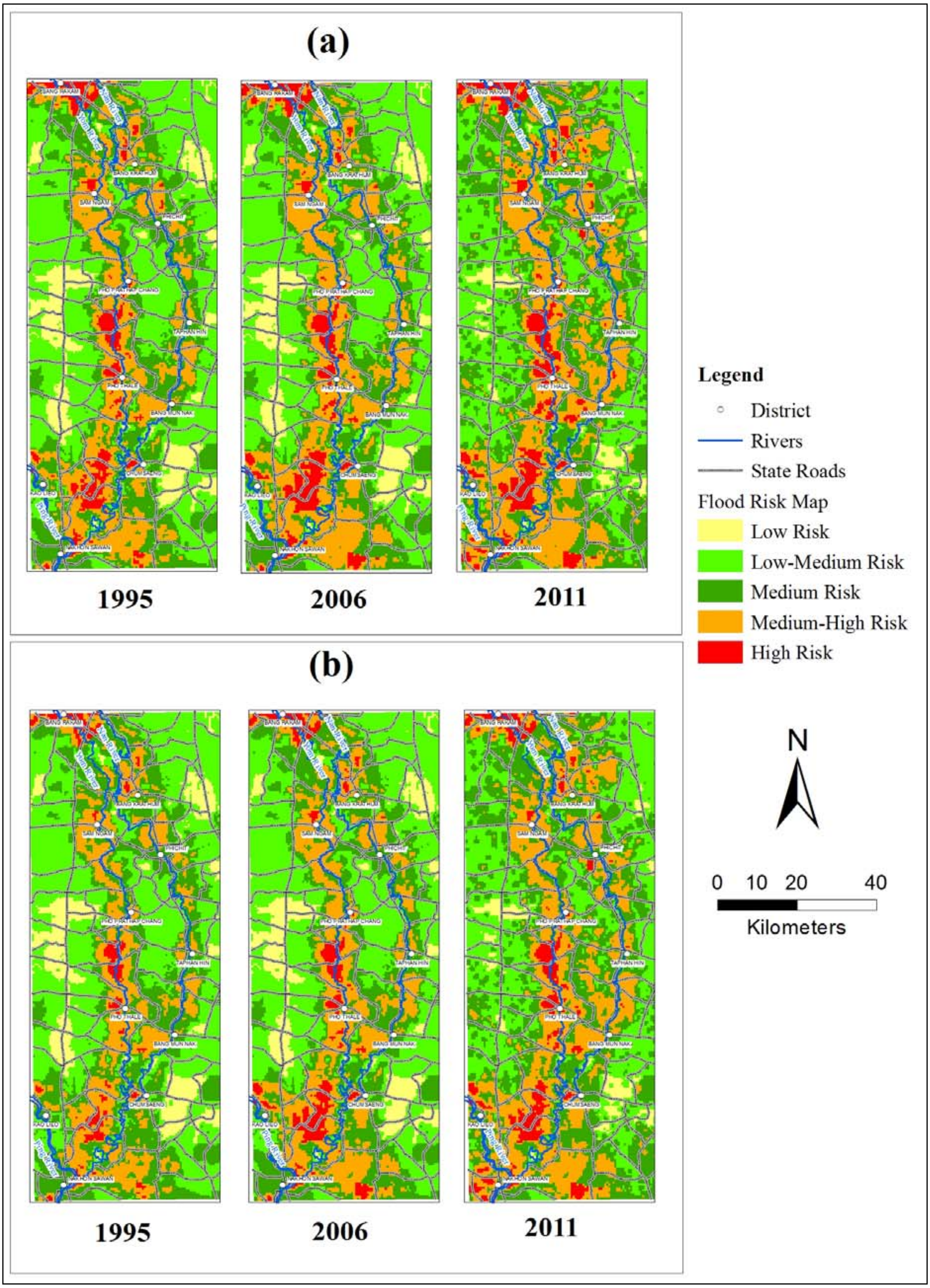


Fig. 7.6 Flood risk maps for low-lying areas in the middle CPRB in 1995, 2006 and 2011 (a) without flood countermeasures and (b) with flood countermeasures.

Table 7.4 Percentage of risk zones of with and without flood countermeasures for 1995, 2006 and 2011 floods in low-lying areas of middle CPRB.

Flood Events	Low risk zone	Low-medium risk zone	Medium risk zone	Medium-high risk zone	High risk zone
1995 without	8.25%	41.02%	27.53%	19.06%	4.14%
1995 with	8.46%	43.38%	29.04%	16.73%	2.39%
2006 without	8.05%	39.66%	26.31%	20.84%	5.14%
2006 with	8.16%	40.87%	27.76%	19.26%	3.95%
2011 without	2.87%	30.62%	33.87%	26.25%	6.39%
2011 with	2.89%	31.26%	36.31%	24.93%	4.61%

7.5 Discussion

Flood risk maps enable decision makers to clearly identify risk areas. Comparing components of risk in quantitative terms is the one of advantages of such a comprehensive risk assessment. This study examines the flood risk as a result from flood hazard and social vulnerability maps. For flood hazard maps (Fig. 7.5), most of the high flood hazard areas lie along the Yom River and span around the confluence of the Chao Phraya River owing to the mild slope. On the other hand, the social vulnerability map shows that the high social vulnerability areas are located in urban areas because of a well-being of communities and dense population (Fig. 7.5). With the results of flood hazard and social vulnerability maps, the relative flood risk maps for each 50 m × 50 m grid resolution in this study show almost all low and low-medium risk zones lie in the agricultural areas especially a paddy field. On the other hand, it could obviously be seen that the medium-high and high flood risk areas spanned along the rivers, especially at the Yom River and some areas are located in the urban areas. The large spread of high flood risk areas are located in the Bang Rakam, Pho Thale, Chum Saeng and Nakhon Sawan District (Fig. 7.6), which corresponds to the report from the Royal Irrigation Department (RID) indicating these areas are ubiquitous and severest in this basin owing to flooding (RID, 2011). Moreover, after implementation flood countermeasures on low-lying areas in the middle CPRB, the high risk areas gradually reduce only about 1.75%, 1.19% and 1.78% in 1955, 2006 and 2011 flood respectively. It may come from the characteristics of this basin that has a gentle slope and low capacity of rives.

According to Fig. 7.6 in the case of without flood countermeasures, the common high flood risk area which appears in all three severe flood events is around 96 percent compared to the 1995 flood, the smallest flood event in this study. It could be stated that these areas are frequent to high-risk and there are more than 42,000 citizens who live and spend daily life in these high-risk areas. It is very important and necessary for relevant agencies to prepare and facilitate the effective disaster planning and management. According to concept of flood risk assessment in this study, there are two main methods to reduce the flood risk to people. One is reducing the hazard and danger from flooding by using several types of flood countermeasures introduced in Chapter 5. Another one is reducing vulnerability of people.

The work described in this chapter tackles the quantitative flood risk assessment and formulates disaster management strategies and recommendations on the management of those risks. As the results of flood 2011, it was notable that relying only on structural measures is not a proper way for the CPRB. As the community areas, adjacent rivers, in low-lying areas of the middle CPRB, it is not possible to avoid high material damage when an extreme flood arrives but it is possible to save lives of residents. Many countries use the lessons learned post disaster to revise their disaster management legislation and plans. In conclusion, this study intend to develop the emergency flood evacuation model for devastating flood events to lessen the risk of people especially those living in high flood risk areas and explore the safety evacuation with a different starting time of evacuation.

Chapter 8

Flood evacuation

8.1 Introduction

Accordance with 2011 flood, low-lying areas in the middle CPRB suffered and struggled from this catastrophic flooding from the late of July to November and at least 100 persons died due to this severe flooding (HAII, 2012). One of the factors that aggravated 2011 flood situations in the CPRB is the confusing and contradicting information from key agencies especially the evacuation information. Once floods reached a large extent, many stakeholders and the public complained that they often received conflicting flood information which worsened situations. The limited flood evacuation information together with the lack of proactive evacuation planning may increase flood damages and losses. It could be mentioned that there is no provisions in the act or plan for large scale disaster as flood 2011 in CPRB (UNDP, 2011).

Based on the flood risk assessment in the low-lying flood prone areas (Chapter 7), there are citizen at least 42,000 persons living in the high-risk areas. The above information upholds the need for a realistic, hands-on evacuation preparation for the middle CPRB, particularly in low-lying areas. Thus, the emergency flood evacuation model were performed and tested in the low-lying area of the middle CPRB.

8.2 Flood evacuation model

According to numerous studies on natural disasters, researches primarily highlight on the functions of infrastructures and responses of residents during extreme event (Cutter, 2003). Evacuation, one of emergency responses, has received significant attention to be utilized to lessen vulnerability of threatened people (Shaw, 2011). Evacuation is mostly defined as the movement of people from the exposed areas to safe areas before they contact with physical effects of a disaster resulting in loss of life. Many studies identified a number of influential factors considering a complexity of social and engineering sciences. However, investigation of these factors is depended very much on the available data, and results on these effects vary from notable to unnotable across types of disaster (Murray-Tuite and Wolshon, 2013). Many researches on evacuation tried to develop a model to estimate the travel time of evacuation and determine the appropriate evacuation routes. However, the most of these models focus on hurricanes in developed countries (Baker, 1991; Dow and Cutter, 2002; Hasan et al. 2011; Hasan et al., 2012; Lindell et al, 2005). Despite this acknowledgement, the understanding and developing flood evacuation model is appropriate and necessary (Fischer et al., 1995). Moreover, evacuation scheme is depended on the area size and magnitude and spatial of the distribution of population age. In addition, evacuation rate also involves the capacity of escape routes and time of the day. Bellamy (1986) stated that the number of evacuee provides the increasing of evacuation time. Hans and Sell (1974) also mentioned that the evacuation time is closely related to the population density.

In Thailand, many field investigations often reported that many people have lost the chance to evacuate because of their late decision and limited information (UNDP, 2011). Due to the vast flood inundation and general well-being of communities in the middle CPRB, this study then identify the high-risk areas in this basin to be the pilot study for flood evacuation. Thus, present research developed a mathematical model, namely the emergency flood evacuation model, to evacuate citizens in this area to flood shelters in order to facilitate an evacuation plan and determine the available time for evacuation as a protective action strategy.

The three-step approach proposed in this study was adopted for the emergency flood evacuation in low-lying areas of the middle CPRB. For the first step, it is necessary to investigate flood characteristics of 1995, 2006, and 2011 flood and then classify flood evacuation zones to specify evacuees and the starting time for evacuation. In the next step, the designed safe areas for flood shelters were determined in geographical information systems (GIS) using topographic maps at a scale of 1:50,000. In the last step, the coordinates of high-risk grid cells, state roads, and flood shelters as well as the distance among these three layers were extracted from GIS to be used as input data to calculate the evacuation travel time. The evacuation travel time in this model is calculated based on a physical status of evacuees (elderly and preschool citizens), safe evacuation condition, the shortest time evacuation, and flood shelter and road capacity.

8.2.1 Flood evacuation zones classification

With wide-area evacuation in this study (6,012 km^2), firstly it has to define the flood evacuation zones. Evacuation zone is very important because if it is not conducted and planned effectively, the mass evacuation can cause traffic congestion and also leave evacuees in dangerous consequences resulting in unexpected losses. Understanding an area which be affected by flooding enables relevant agencies to design and carry out appropriate development frameworks. Wilmot and Meduri (2005) stated that evacuation zones should be conducted based on an expected event with traffic analysis and the number of zones should be minimized for easy and fast communication.

Basically, most of flood evacuations are planned and considered based on a static factor of flood event, but flood is a dynamic process. Besides, flood evacuation plan need to consider various flood events. To obtain the optimal emergency flood evacuation, this study considered various devastating and catastrophic flood events in the CPRB which are 1995, 2006 and 2011 flood events. Thus, flood evacuation zones were determined by various flood characteristics. An understanding in flood mechanism and timing is very crucial step to develop flood emergency plan effectively because it avoids problems that move residents to subsequently inundated areas. Besides, this research combined flood inundation results in spatial and temporal of catastrophic flood events in 1995, 2006 and 2011 from hydrodynamic model together with flood risk maps to classify and specify flood evacuation zones as shown in Fig. 8.1. Identifying evacuation zones in this study gives a priority on resident similarities, such as residential district or neighbor association because it is effective to facilitate mutual cooperation among residents during evacuation.

After analysis, it was found that although there is a slightly difference in arrival time of flood water owing to different shape and amount of flood hydrograph, there is still a significant common pattern of flood inundation in study area which may come from a low-lying area and very large scale of flood event that causes water instantly and easily spills over the river bank into floodplains. According to the classification results considered an overall similarity, this study could account for five flood evacuation zones and specify a starting evacuation time for each zone considered by the arrival time of flood water coming into each zone. The flood evacuation zones map for the middle CPRB is presented in Fig. 8.2 and the detail of each flood evacuation zone against flood events is summarized in Table 8.1.

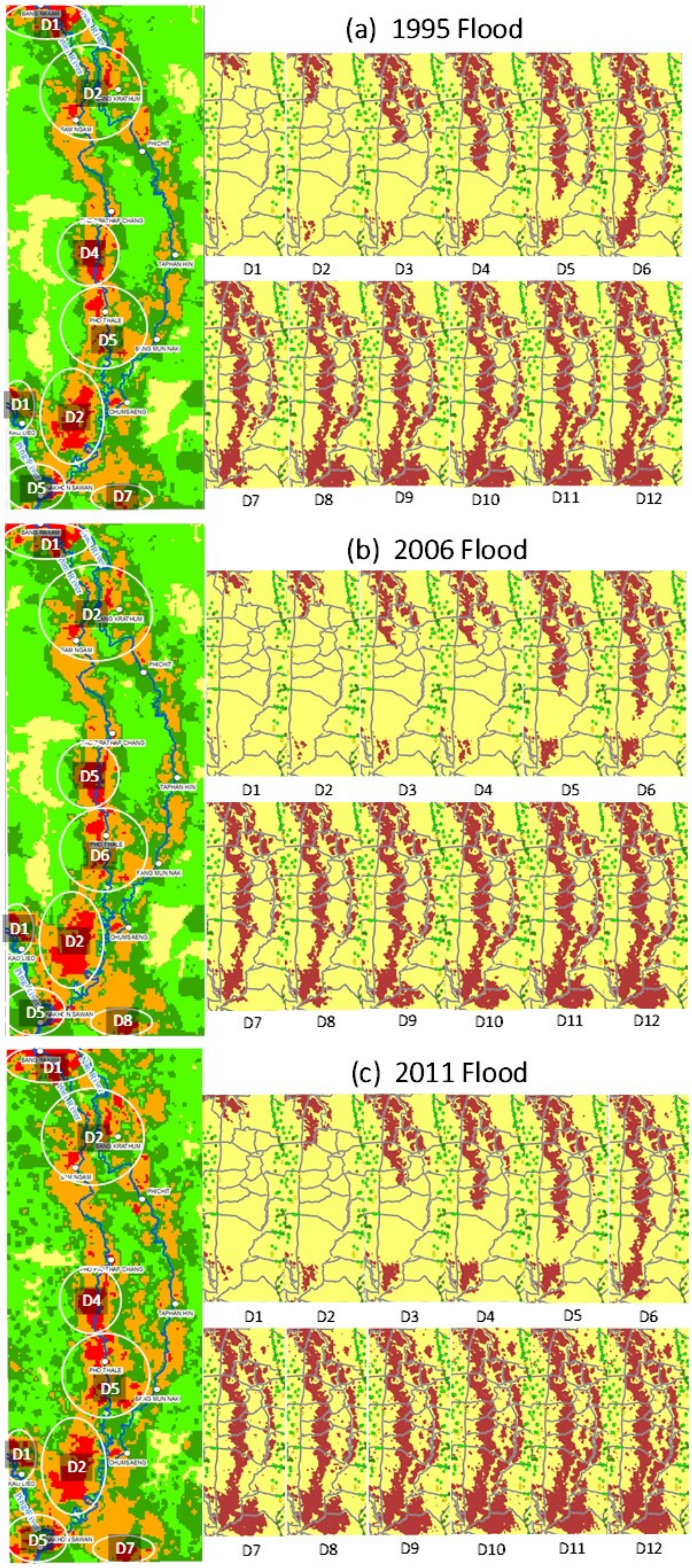


Fig 8.1 The spatial and temporal flood extent of low-lying areas in the middle CPRB.

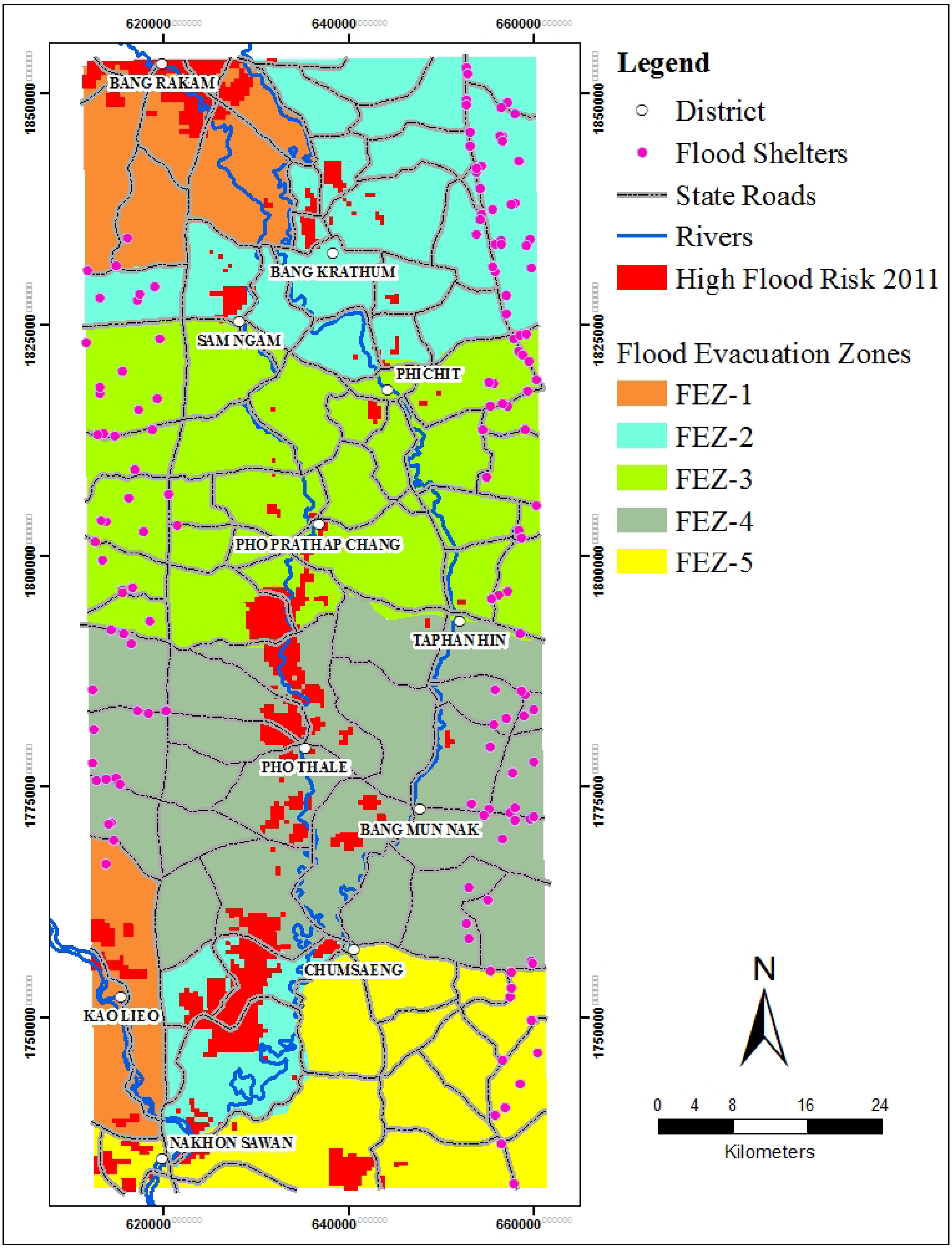


Fig. 8.2 Flood evacuation zones for the middle CPRB.

Table 8.1 The detail of each flood evacuation zone in the middle reach of CPRB.

Flood evacuation zone (FEZ)	FEZ 1	FEZ 2	FEZ 3	FEZ 4	FEZ 5	Sum.
1995 Flood						
No. of high flood risk (grid)	247	316	160	220	47	990
Evacuees	14,397	9,192	6,802	8,938	4,395	43,724
Elderly and preschool (%)	10.20	13.79	15.57	15.52	13.04	13.39
Vehicle in use (private cars)	3,600	2,298	1,701	2,235	1,099	10,933
Starting evacuation time (day)	1	2	4	5	7	-
2006 Flood						
No. of high flood risk (grid)	312	393	170	263	90	1,228
Evacuees	17,129	10,305	7,138	10,097	5,500	50,169
Elderly and Preschool (%)	10.47	16.23	15.11	16.96	16.98	14.33
Vehicle in use (private cars)	4,283	2,577	1,785	2,525	1,375	12,545
Starting evacuation time (day)	1	2	4	5	7	-
2011 Flood						
No. of high flood risk (grid)	349	418	221	400	140	1,528
Evacuees	18,826	12,963	10,283	14,383	19,958	76,413
Elderly and Preschool (%)	10.17	14.41	12.36	19.93	6.22	11.99
Vehicle in use (private cars)	4,707	3,241	2,571	3,596	4,990	19,105
Starting evacuation time (day)	1	2	4	5	7	-

8.2.2 Flood shelters selection

The shelters should have adequate space, basic living requirements and not be located in hazardous area (Saadatseresht et al., 2009). GIS have widely been applied to identify and select flood shelters (Cova and Church, 1997; Iannoni et al., 2009; Mansourian et al., 2006; Vakalis et al., 2004). In this study, this study aims to find appropriate locations of flood shelters. Firstly, this study sought for the candidate shelter locations by considering existing public buildings in this study area such as school, temple and community center that have the adequate area and necessary utilities for number of evacuees to stay and store relief packages. The candidate flood shelters are considered by GIS through topographic maps at a scale of 1:50,000. Accordance with 2011 flood event, many flood shelters provided by agencies were located in inundated area and some of them had to be closed owing to shelters submerged that caused trouble to citizens. Thus, flood shelters in this study are set to be free from flood inundation records. This research then applied the vastest flood inundation area (flood 2011) to screen flood shelters.

After overlaying flood 2011 inundation with topographic maps, it obtained 142 buildings located in the safe area from flooding as shown in Fig. 8.2. Due to the unknown capacity of each flood shelter, this study assigned its capacity as 500 persons whose average flood shelters capacity reported by DDPM (2012). Besides, the total capacity of flood shelters in this study is 71,000 vacancies.

8.2.3 Evacuation travel time calculation

Accordance with 2011 flood, many transportation infrastructures, 1,700 roads, highways and bridges, were damaged and the economic cost of these infrastructures was around US$ 4.5 billion (Aon Benfield, 2012). Besides, this study assumed that only state roads are not inundated and available for a transportation network during flood evacuation. Another assumption is that all evacuees in each grid cell evacuate together and comply with the orders of evacuation. In this study, the evacuation travel time calculation is classified into three stages; 1) the travel time from high flood risk to state roads (walking travel time), 2) the travel time along roads network (vehicle travel time), and 3) the travel time from state roads network to flood shelter (walking travel time).

8.2.4 Travel time of walking

The walking time, an important parameter used in evacuation models, is the primary stage of access to flood shelter when there is no access road. This study divided the travel time of walking into two phases; 1) from high flood risk grid cell to a state road, and 2) from a state road network to flood shelters. Walking speed usually varies with many factors, such as walking types, walking conditions, occupant types, and place types (Chen et al., 2003; Fang et al., 2004; Lee et al., 2003; Yeo and He, 2009). A high proportion of elderly and preschool people in the residents also influences evacuate responses (Heller et al., 2005; Lindell and Whitney, 2000; Schiff, 1997). Elderly and preschool evacuees walk slower than adults due to their weak physical status and level of prompting. According to the study on walking speeds (Shi et al., 2009), this study assumed the walking speed for a normal evacuee (adult group) as 1.4 m/s. Owing to this study assumed that all evacuees in each grid cell evacuate together, the average walking speed in each grid cell was calculated by the percentage of elderly and preschool evacuees belonging to each grid cell. It could be stated that the greater proportion of elderly and preschool evacuees, the more walking travel time will be taken.

Due to considering severe flood events in this study, it is extremely dangerous for evacuees to walk cross inundated areas. Therefore, it is necessary to assess the certain degree of safety for evacuees walking through floodwaters (Xia et al., 2011). Estimating loss of life in flood disaster are widely examined (Jonkman and Vrijling, 2008; Penning-Rowsell et al., 2005) but life-threatening conditions in flood evacuation have rarely been investigated (Ishigaki et al., 2005; Ishigaki et al., 2008; Jonkman and Penning-Rowsell, 2008). Ishigaki et al. (2008) proposed a safety condition of specific force per unit width along the evacuation route expressed as:

$$\frac{u^2 h}{g} + \frac{h^2}{2} \langle 0.125 \tag{8.1}$$

where h (m) is water depth, u (m/s) is flow velocity, g (m/s^2) is the acceleration due to gravity, 0.125 (m^3/m) is the threshold value for safe evacuation by walk during flood.

Besides, this research then adopted this parameter, safe evacuation condition, along with the results from hydrodynamic model to determine in which grid cell is safe for evacuation. This study assumed that during evacuation evacuees cannot walk across to another grid cell beyond the threshold value for safe evacuation condition, 0.125 m^3/m. It could be stated that if the eight points surrounding considered grid cell have a safety condition value greater than 0.125 m^3/m evacuees in that grid cell cannot evacuate to flood shelters because they have a chance to lose their lives. To reduce complexity of modeling, we calculate the safe evacuation condition on an hourly basis. After set up assumptions and constraints, the next task is to exact the coordinates among high flood risk grid cell, state roads network, and flood shelters to calculate the distance among them. Additionally, the coordinates of the centroid of high flood risk grid cells are considered as their location. Eventually, the optimum travel time of walking is determined by choosing the shortest path satisfying with safe evacuation constraint and also by the proportion of elderly and preschool evacuees in grid cell.

8.2.5 Travel time of vehicle

Macroscopic and microscopic models are usually represented as evacuation models. A macroscopic model represents traffic as a flow. This model generally focuses on the evacuate travel time and used for wide-area evacuation. For a microscopic model, it examines traffic and vehicles at more circumstantial levels. Due to wide-area evacuation and considering only the state roads networks, this research then formulated the emergency flood evacuation model as macroscopic based on a static traffic model. The static traffic model is normally used to evaluate current and future use of road networks. Traffic flow in static traffic model is assumed to be constant from the origin to final destination. The free-flow (base) speed represents the average speed of vehicles that are not constrained by any disruption such as traffic control and roundabout. According to the study on free-flow speed during the hurricane evacuations from Dixit and Wolshon (2014), this study then modified these values considering the roads capacity in the study area. Eventually a free-speed for state road was carried out as 40 km/hour. Moreover, HCM (2010) defines road capacity as the maximum hourly flow rate of expected vehicles passing a point during a specified time period. Department of Highways (2015) reported that average state roads capacity around study area is 1,897 vehicles per hour. This study then brought this value into consideration as one of constraints that limits outbound flow rate during evacuation through roads network in our emergency flood evacuation model.

With the study area covers approximately 6,012 km^2 and state roads network includes over 1,545 km of roads (Fig. 8.2), the paths between high flood risk areas and flood shelters using state roads as a transportation network were determined by a GIS network analysis tool. A road network database on state roads in the study area was obtained from the Department of Highways. Furthermore, this study assumed a private car is the primary vehicle to bring evacuees to flood shelters and vehicle occupancy is set as four evacuees per vehicle due to considering the background of Thai people that prefer to travel by their own car. Consequently, the travel time of vehicle is then calculated, where each vehicle is routed to the nearest flood shelter under the shortest path. According to the 500-evacuee flood shelter, it is impossible to accommodate all evacuees who come from the same grid cell in the same flood shelter. Therefore, the emergency flood evacuation model will take the residual evacuees to another shelter which is the second shortest flood shelter.

8.3 Computational results

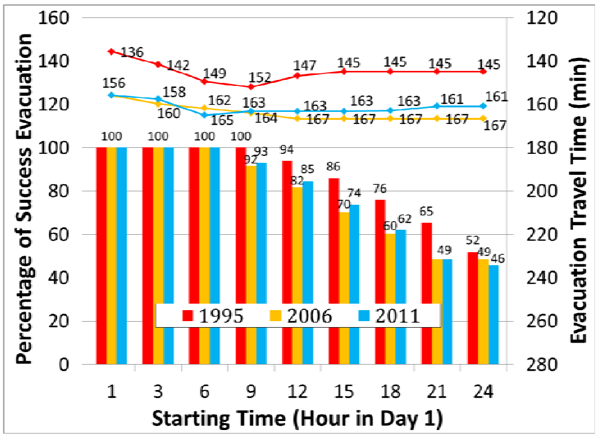
The emergency flood evacuation model is tested and explored the evacuation trip for the middle reach of CPRB as shown in Fig. 8.3. The experimental results are presented in two indicators. The first, the evacuation travel time, as line in Fig. 8.3, describes the time that evacuees can move from their grid cells to flood shelters with safe determined by the safe evacuation condition proposed by Ishigaki et al. (2008). The second indicator is the percentage of success evacuation, as bar chart in Fig. 8.3, describes the percentage of evacuees can move to flood shelters safely. Once time is limited, the percentage of success evacuation is applied to indicate the loss of life during flood evacuation. Furthermore, both indicators were examined at different staring time choices for evacuation as horizontal axis in Fig. 8.3. The evacuation travel time and percentage of success evacuation are calculated based on a physical status of evacuees (elderly and preschool citizens), safe evacuation condition, the shortest evacuation path, and shelters and road capacity. The staring time for evacuation in each flood evacuation zone has a different starting time considered by the arrival time of flood water coming into each zone. Depending on the characteristics of each zone, such as flood conditions during evacuation, the number of residents, a road network density, and existing flood shelters, the need for complete evacuation can be examined. Moreover, in this study the different time choices for evacuation related to the evacuation warning dissemination in particular are investigated using this model to determine the late evacuation for each zone to execute a suitable evacuation strategy or to develop the leading time of flood forecasting and warning program. In the severest case, flood 2011 event, the 76,413 evacuee-agents and 19,105 vehicle-agents are treated in the area of 6,012 km^2.

Based on simulation results, it shows that we could evacuate all residents to flood shelters safely in flood evacuation zone 1, 2, 3 and 4. Unfortunately, in the zone 5 we are not able to move all evacuees to flood shelters because the capacity of flood shelters (71,000 vacancies) is insufficient for all evacuees in 2011 flood event (76,413 evacuees). Evacuation is a possible risk management measure for flood disaster. When an evacuation begins late, not all evacuees can leave their home to flood shelter safely. Different starting time choices for flood evacuation can be performed to select the suitable strategy under actual circumstances. In zone 1, 2, 3 and 4, it found that the residents have a chance to evacuate safely within 6 hours, 6 hours, 9 hours and 6 hours of the evacuation time announcement respectively. If we neglect the insufficient flood shelters for evacuees in the case of 2011 flood, it has time around 12 hours for the safe evacuation. From simulation results, except the insufficient flood shelter provision, it could be mentioned that all residents in the middle CPRB can evacuate to flood shelters safely if they have enough time. More importantly, the available time for safe evacuation shows the need of required time to make a decision for evacuation in the middle CPRB. Therefore, main government agency can adopt these values to execute an evacuation strategy and required time (Barendregt et al., 2005; Jonkman, 2007; van Zuilekom et al., 2005). Furthermore, the required time for evacuation can help relevant authorities to create the proper condition for evacuation such as the contra flow.

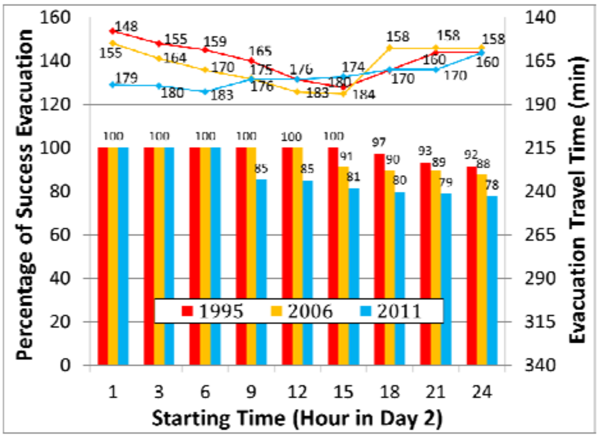
Moreover, the results also show that the evacuation travel time for 1995 and 2006 flood event in the zone 5 was dominated by flood shelters since the nearest flood shelters were occupied by the previous flood zones. Besides, the location and coverage of flood shelters are one of important factors for flood evacuation. Due to evacuation during catastrophic flood event, the safety condition then plays a crucial role in flood evacuation that made evacuees to walk further to escape the unsafe grid cells. For the safe evacuation of all flood events, it also found that the evacuation travel time in the middle CPRB on average took around 170 minutes to evacuate all residents to a safe place. Moreover, when study compared the walking time to vehicle time in first hour of evacuation to minimize the effect of safe evacuation condition, it found that the walking time takes place around 70 percent of traveling time. It could be stated that the density of road network also plays a crucial role in flood evacuation.

8.4 Recommendations

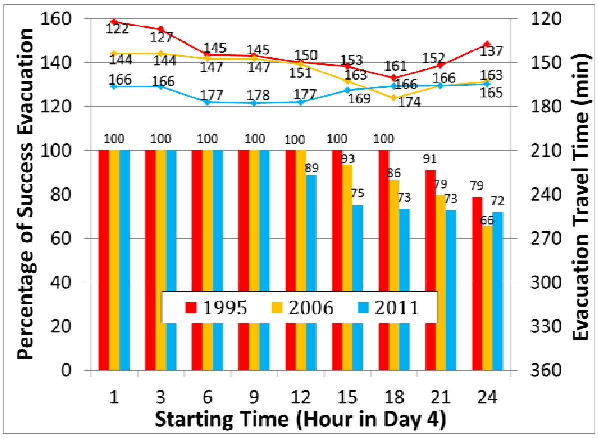
To more effectively protect residents and communities, the comprehensive flood risk assessment is urgent and critical to strengthen their resilience. Since structural measures alone cannot deal with all disasters, non-structural measures especially flood evacuation plan is particularly important to reduce such damages. Based on results from this study, the important finding is that the government agency should prepare infrastructures, organize evacuation, and make a decision for flood evacuation in the middle CPRB within 6 hours as the minimum time when flood water arrives at each zone. To enhance the effectiveness of evacuation, this study gives recommendation on significant structural and nonstructural measures which will facilitate the smooth and fast flood evacuation and also can increase the evacuation success rate. These six recommendations address issues which are pivotal to eradicate the most obvious flood management problem revealed in 2011 flood. They are as follows:



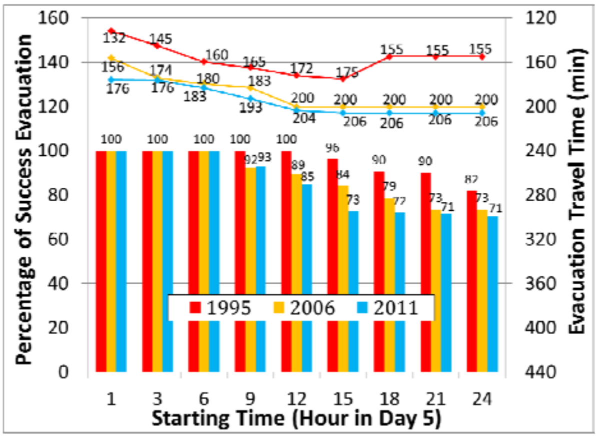
(a) Flood Evacuation Zone 1



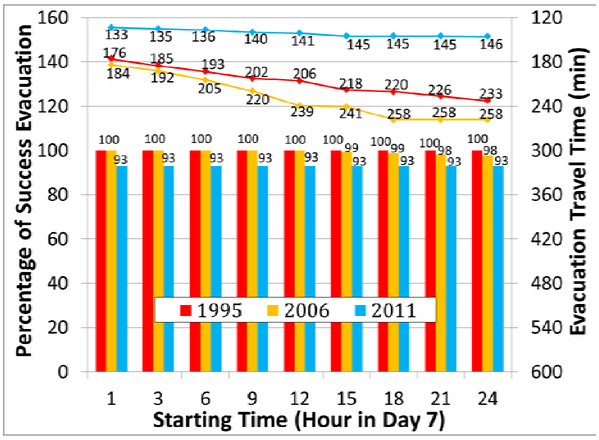
(b) Flood Evacuation Zone 2



(c) Flood Evacuation Zone 3



(d) Flood Evacuation Zone 4



(e) Flood Evacuation Zone 5

Fig. 8.3 Computational results of emergency flood evacuation simulations.

8.4.1 Structural measures

(a) Road network rehabilitation and traffic management

According to flood 2011, road networks are severely affected by long duration of submergence. During 2011 flood, many local government offices reported that materials support from the District and Provincial offices was difficult to deliver due to transportation interruption by flooding (UNDP, 2011). Therefore, the road network should be improved and be more susceptible to damage from flood events. Increasing susceptibility of roads to flood damage not only reduces weakened road structures but also improves traffic loadings. The road improvement works should be considered a more comprehensive and consistent hydraulic designs.

Generally, residents will act spontaneously when there is no information and these responses can bring an overload of road system that may affect the evacuation travel time, resulting in less effective use of infrastructures. Besides, traffic management during flood evacuation should be implemented to make road networks more robust. Traffic management can create the optimal circumstances for evacuees and substantial capacity of evacuation such as the contraflow system (Gruntfest and Carsell, 2000). In addition, using public transportation provided by government as public bus may reduce traffic congestion during evacuation.

(b) Flood shelters provision

Based on assumptions from this study, the flood shelters were only 142 buildings with an area of 6,012 km^2. It has been found that these are not sufficient for the number of victims in 2011 flood. As the flood shelter has effect on evacuation as mentioned in Section 8.3, existing flood shelters should be modified and improved their capacity. High resolution of topographic maps should be applied to identify and prepare other appropriate buildings to accommodate mass evacuees as the case of the flood 2011. Furthermore, new public facilities should be constructed at appropriate locations. Different types of shelters can be distinguished two types; (1) single use shelters are constructed with the sole purpose and (2) multi-use shelters have a certain regular function during normal condition. Many guidelines on flood shelters against different types of natural disasters are available (ARC, 2002; FEMA, 1988, 2006, 2008).

8.4.2 Non-structural measures

(a) Timely and effective flood forecasting and warning system

As shown in Fig. 8.3, the percentage of success evacuation is depended very much on the starting time of evacuation. To increase rate of success evacuation and reduce evacuation travel time, the available time window plays an important factor for flood evacuation. The available time for evacuation can be improved through flood forecasting and warning system that provide a longer available time and decrease the possibility that residents cannot evacuate to flood shelters related to flood circumstances. Flood forecasting and early warning system is very powerful tool to mitigate flood hazard. The early warning is an important precondition and allows implementation of more emergency measures. One of reasons why private households and businesses did not comply emergency measures was a lack of time (Kreibich et al., 2011). Many study stated that the precise and timely dissemination of information provides the better preparedness and reduces loss of live due to flooding (Dow and Cutter, 2000; Gruntfest and Carsell, 2000; Gruntfest and Ripps, 2000; Haque, 1997; Parker et al., 2007; Paton, 2003; Tobin and Whiteford, 2002). Despite early warning can prevent serious consequences, it can result in unnecessary evacuation with the associated costs if the event does not happen.

(b) Land use regulation

Risk awareness remains low among government agencies and people in Thailand (DDPM, 2010). In spite of many safety campaigns have been utilized, most Thai people still believe that their country is safe, and pay less attention to the impact of disaster and the way to mitigate it. Moreover, the policies development especially in land use planning and urbanization were not comprehensively enough to recognize the potential risks. It may in turn cause more vulnerability and increase a chance for man-made disasters. The government agencies should enforce a land use planning policy to detect new urban areas and industrial estates in high flood risk areas of floodplains (Bo¨hm et al., 2004; Rucinska, 2015; Stevens et al., 2008; Su et al., 2015). The new development should be also implemented with adaptive measures in risk reduction (Pardoe et al., 2011). It found that local governments are usually hesitant to follow the land use regulation but it can lubricate by-law (Stevens and Hanschka, 2014). Furthermore, living with floods through land use planning is also believed to increase public awareness resilience.

(c) Community participation and education

Evacuation is one of integral parts of emergency responses. While guidance on evacuation orders and plans in place, there is a pivotal problem that people do not evacuate when they can but they want to evacuate when situation becomes severe. Many Thai people believed that relief and assistance will be delivered to their doorsteps. Such belief comes from their experiences of doorstep delivery in the past flood events (DDPM, 2010). Many studies pointed out citizens will act in their own manner, will take measures when they feel uncomfortable, and will evacuate to a place they feel safe (Helsloot and Ruitenberg, 2004; Quarantelli, 1998; Perry and Lindell, 2003). Round community support by community consultation is very notable for mitigation options. Providing education on flood evacuation to community can increase the collaboration, support and acceptance from communities. The effectiveness of flood evacuation needs increased cooperation and collaboration across sectors and public participation. Participation at local and national levels of government agencies, technical specialists and local residents is critical in carrying out risk assessment of the area (World Meteorological Organization & Global Water Partnership, 2006).

(d) Communication and information

Most importantly, the clear and effective evacuation orders are very sensitive. The content of evacuation, dissemination source, and distribution channel can significantly influence not only the number of evacuees, but also the urgency during evacuation (Lindell and Perry, 2004; 2012). Nowadays, people gather information through various sources, especially social media. Even though there is a potential negative uses in social media, the benefit using social media for disaster responses and risk reduction could be seen (Bird et al., 2012; Boulos et al., 2011). Thus, employment other than those from the government should be taken in consideration and supports it with extra information. Mileti et al. (1975) mentioned that people can react in a more appropriate manner when more information available.

8.5 Conclusions

In Thailand, the results of flood risk assessment were rarely shared among citizens (UNDP, 2012). The findings from this study emphasize that low-lying plains are frequent to high flood risk and more than 42,000 citizens struggle with flooding. It is very important and necessary for relevant agencies to prepare and facilitate the effective disaster planning and management; however, unfortunately there is no study on flood evacuation in the middle CPRB. Thus, this research attempts to develop the emergency flood evacuation model for devastating flood events to lessen the risk of people. Based on assumptions in this study, the response to catastrophic flood events in 1995, 2006 and 2011 demonstrated that citizens are capable of evacuating to flood shelters safely.

One role of the model is to foresee the consequences of action before implementing it. However, evacuation process is dynamic and rapidly changes due to various uncertainties (Saadatseresht et al., 2009; Zeigler et al., 1981). For example, when road accident occurs they may provide traffic congestion and previously safe routes may become unsafe. Developing contingency plans in flood evacuation may manage and reduce a fraught and messy evacuation process. Moreover, the behavior of residents in wide-area evacuation is crucial for the success of the evacuation because it influences the development of evacuation. It is essential for government and emergency agencies to consider these factors to facilitate the best evacuation possible. However, with an available time window from this study, it may be beneficial and provide an opportunity for relevant authorities to implement several measures to improve the effectiveness of evacuation. This study believe that results from this study can provide direction or open further discussion to draw attention, improve and create the most effective flood risk management and flood evacuation plan based on the characteristics of the middle CPRB.

Chapter 9

Conclusions

9.1 Achievements of this dissertation

As section 1.3 defined the overall objective, the work demonstrated the merits and feasibility for carrying out an integrated flood risk management and evacuation in the upper and middle Chao Phraya River Basin (CPRB), Thailand. This dissertation marks a comprehensive step towards understanding the potential of various flood countermeasure types in the upper and middle CPRB. The single application of flood countermeasures proposed from Thai Master Plan, namely (1) reforestation, (2) retention areas, (3) dam operation improvement, and (4) new dam construction, shows insufficient capacity to cope with all severe historical flood events in CPRB (1995, 2006, and 2011 flooding). However, some measures provided the remarkable capability of reducing and controlling flood discharge at runoff station C.2. The most flood volume reduction in 1995, 2006 and 2011 comes from the new dam construction namely Kaeng Sue Ten (KST) Dam; in contrast, the most flood peak reduction found in the case of retention areas located along the Nan and Yom Rivers.

For the diversion level of retention areas, this dissertation suggested the suitable level of retention areas diversion to deal with severe flood events (peak discharge higher than 4,000 m^3/s) should be set as 1.50 meter above river bank. In addition, the designed diversion level of retention areas proposed by Thai Master Plan which is as similarly high as 1.00 meter above river bank showed the best performance in reducing and controlling floodwater for the small- to medium- flood scale. It is important for relevant agencies in Thailand to concern that if they would like to overcome severe flood events the designed diversion level should be heightened. Moreover, the reservoirs operation rule curve for severe flood event proposed from this thesis which lines between the former (2005) and latest (2012) rule curve showed the significant potential to mitigate flood damage in 2011. It is capable of reducing peak flow from the Bhumibol and Sirikit Dams around 43% and 19% when it compare to the historical data. However, this new rule curve increases peak discharge in 1995 and 2006 flood events.

To prevent and minimize losses and damages from severe flood events, this dissertation attempted to integrate and develop a set of combination of flood countermeasures proposed by the Thai Master Plan for the upper and middle CPRB. The eight scenarios were established to cope with severe flood event. According to simulation results through flood inundation model, the combination of all flood countermeasures from Thai Master Plan are not sufficient to reduce the peak discharge at runoff station C.2 to lower than 3,500 m^3/s. It therefore confirmed that Thailand needs the additional flood measures. Besides, this thesis proposed the additional retention areas adjacent to the Yom and Nan Rivers which are low-lying areas and generally used for agriculture purpose and mostly submerged during the rainy season.

This study suggested to utilize these retention areas because the damage to agriculture is around 1.16% of total damages and residents who live in these areas have learned to live with flooding due to frequent flooding. The new additional retention areas can accommodate flood volume around 1,303 $x10^6$ m^3 surrounded with area of 961 km^2. As simulation results, the integrated approach considering the reforestation, retention areas, KST Dam construction, and new additional retention areas which is the best measure for alleviating 1995 and 2006 floods is capable of controlling and reducing the peak discharge at runoff station C.2 to less than 3,500 m^3/s. After implementing all possible flood protection options in the upper and middle CPRB (reforestation, retention areas, KST Dam construction, dam operation improvement, and new additional retention areas), the peak discharge of 2011 flood event is found around 3,662 m^3/s; however, this measure provide significant potential to accommodate flood volume of 5,411 $x10^6$ m^3. To cope with the severest flooding in 2011, integrated whole basin management regarding the existing flood countermeasures in the lower CPRB might be the most appropriate approach.

To our knowledge, this dissertation provides insight and novel to integrated flood countermeasures in the upper and middle CPRB. The results from this study may facilitate the new direction and approach for Thailand to better develop and manage flood disaster in CPRB. Moreover, this thesis also concerns the economic feasibility of implementing these measures according to 10 scenarios developed. This study applies the benefit-cost analysis to examine the most economical measure. This study mainly focuses on the construction cost of facilities and equipment and yearly maintenance cost. The benefit from construction of each flood countermeasure is calculated from the direct tangible damage reduction to household, manufacturing, and agricultural sectors. The results show that the retention areas plus reforestation provide the highest value (1.33) on benefit-cost analysis.

Due to limited studies which assess flood hazard, flood vulnerability, and flood risk in the CPRB, this study therefore intended to provide the flood risk assessment in this middle CPRB along Yom and Nan Rivers because this area is the most frequent flooding in CPRB. The flood risk analysis was established in the form of flood risk map generated by flood hazard and social vulnerability maps. The flood hazard map considers the characteristic of flooding which is flood inundation depth, flood velocity, and flood inundation duration; while the social vulnerability map involves the data on socio-economic which are census population, population density, age (lower 6 and upper 60), census housing, distance to state roads, land use, and land price. Base on geographic and statistical data used for this study, the fuzzy logic was applied to cope with multiplicity, complexity, and uncertainty problems and fuzzy analytic hierarchy process (AHP) to estimate the weight values to each parameter.

According to 1995, 2006, and 2011 flood risk map, high risk areas spanned along the rivers, especially at the Yom River and some areas are located in the urban areas which are Bang Rakam, Pho Thale, Chum Saeng and Nakhon Sawan District because of a well-being of communities and dense population. This study also compared the flood risk areas between with and without flood countermeasures that suggested the best set of measures in 1995, 2006, and 2011 flood events. The results found that the high risk areas gradually reduce about 1.75%, 1.19% and 1.78% in 1955, 2006 and 2011 flood respectively according to a gentle slope and low capacity of rivers. Moreover, there are 42,000 citizens who live and spend daily life in the common flood risk areas of all flood events. Thus, this thesis attempted to prepare and facilitate the effective disaster planning and management such as emergency flood evacuation strategy.

This dissertation provides novel knowledge and techniques which contribute to flood evacuation in the CPRB that is rarely found among the studies on flood disaster in this basin. This study developed flood evacuation model to be performed and tested in the low-lying area of 6,012 km^2. The model was developed based on the three-step approach. The first one is defining and classifying flood evacuation zones considering the characteristics of 1995, 2006 and 2011 flood events. The next one is determining the flood shelters which are free flood area of 2011 flooding. As five flood evacuation zones and 142 flood shelters, the last step is evaluating evacuation travel time which is calculated from a physical status of evacuees (elderly and preschool citizens), safe evacuation condition, the shortest time evacuation, and flood shelter and road capacity.

The analyzed results are presented in two indicators. The first, the evacuation travel time describes the time that evacuees can move from their locations to flood shelters with safe. The second indicator is the percentage of success evacuation describes the percentage of evacuees can move to flood shelters safely. All results in evacuation travel time and percentage of success evacuation were determined by different time choices for evacuation related to the evacuation warning dissemination to evaluate the late evacuation time and to develop the leading time of flood forecasting and warning program. Based on results from this study, the important finding is that the government agency should prepare infrastructures, organize evacuation, and make a decision for flood evacuation in the middle CPRB within 6 hours as the minimum time when flood water arrives at each zone. To enhance the effectiveness of evacuation, this dissertation gives recommendation such as road network rehabilitation and traffic management, more flood shelters provision, timely and effective flood forecasting and warning system, land use regulation, and providing community participation and education in order to facilitate the smooth and fast flood evacuation and increase the evacuation success rate.

As the work summarized here, the author believes that results from this study can provide direction or open further discussion to draw attention, improve, and create the most effective flood mitigation measures, structural and nonstructural approaches, flood risk management, and flood evacuation plan or strategy based on the characteristics of the middle CPRB.

9.2 Recommendations for further study

9.2.1 Flood simulation model

In spite of contributions of this dissertation, many knowledge gaps and insight approaches remain in the overcoming severe flood events such 2011 flood in the CPRB. One major work would be to refine the coarse DEM resolution to fine resolution topographic data, such 5 m × 5 m resolution or LIDAR (light detection and ranging) data, for floodplain analyses in order to enhance understanding of floodplain processes. Increasing the resolution should be considered together with profoundly care because the relative uncertainty from predicting the interactions between flood characteristics and floodplain elevation data. However, high-resolution topographic data facilitates the development of more appropriate management strategies for CPRB and gains insights related to flood profile of study area. Furthermore, consideration of timing of discharge from main tributaries is very necessary for better understating flood disaster in CPRB. Delay the timing of inflow as regulated water flow may provide more insight on overcoming 2011 flood. Another important issue is flood management in Thailand is closely related to a political decision according to single committee for flood disaster management. To bridge this gap, the model needs to be developed for such this constraint.

According to integrated all possible flood countermeasures in the upper and middle CPRB could not control and keep the peak discharge of runoff station C.2 in 2011 lower than 3,500 m^3/s, one approach for solving this problem would be to consider the full range of flood countermeasures in the whole CPRB. The comprehensive linkages of flood situation information among upstream, middle, and lower basins should be set in the unit. Moreover, enhancing the national flood forecasting and warning system that in a timely manner can facilitates measures and would be valuable for decision making on evacuation. In addition, future research should focus on bridging the gap between the engineering, social, and environmental aspects of flood countermeasures options.

9.2.2 Flood damages estimation and benefit-cost analysis

The research clarified flood damages reduction by various flood countermeasures scenarios. As an economic perspective, the synthetic stage–damage functions from a previous study in Japan were applied for the flood reduction computations in this study due to limited data available in Thailand. For next step, effort should be spent to enhance and develop the stage–damage functions for especially Chao Phraya River Basin (CPRB). Improved and expanded a wide range of parameters of this thesis (household, manufacturing, and agricultural sectors) to others variables such as ecological and environmental parameters for calculation should be adopted for further study. In addition, direct intangible (loss of life, injuries, and psychological distress), indirect tangible (disruption of public services and induced production losses to companies), and indirect intangible (trauma and loss of trust in authority) should be calculated and evaluated for damage estimation.

Moreover, consideration of benefit-cost analysis on lower reach of CPRB is very essential and required. As the case of remarkable flood damages in 2011, it calls for the profoundly estimation on another aspects such as the flood depth in flood plain or the size of flood extent. Since the data on runoff station C.2 could not provide the realistic and reliable relationship from its data, the further study should apply the variety of significant data such as structure-breaches and other runoff stations in the lower CPRB. In addition, as the important of runoff station C.2 for flood management in CPRB, it is necessary to identify the threshold or critical level or amount of discharge comparing with various runoff stations in lower reach of CPRB.

9.2.3 Flood risk analysis and flood evaluation model

To considering a wider set of the flood hazard and social vulnerability parameters amongst residence components should be considered and explored to refine the flood risk. The flood risk transfers throughout the residence such as ethnicity, family contexts, and education would need to be analyzed. Generally, flood risk maps are used for emergency planning, raising awareness, and spatial planning. The full potential of regulating land use by flood risk map in CPRB is seldom reached because of low risk awareness to government agencies and people in Thailand. Besides, enforcement a land use planning policy in high flood risk areas of floodplains should be stipulated.

This dissertation also covered the flood risk reduction to residents using flood evacuation model. Further development of the flood evacuation strategy in the CPRB would also consider the evacuee behavior analysis to properly model the evacuation time. It is necessary to examine the evacuee responses because each human being has their way of thinking regarding flood disaster. Participation of individual evacuee is depended very much on his or her prior experiences and confidence on relevant agency to develop an evacuation plan. Moreover, evacuation involves various uncertainties due to unpredictability of time, place, and human behavior. Besides, employing robust optimization, scenario-based, or reliability programming has been applied to minimize these uncertainties.

9.2.4 Future climate change

Finally, this research is limited to the current climate. The information of past climate alone is no longer an appropriate baseline to plan strategies and develop measures. Flood management should incorporate future climate scenarios from global or regional climate models. This information is an integral tool and assists planners to develop adaptive measures. Furthermore, the further flood risk map should take effect of climate change into account.

Considering the effect of climate change may provide an important driver for spatial planners and investors to gain more sustainable and adaptive measures in flood-prone areas. However, climate change amplifies complexities of flood management owing to increased uncertainties.

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