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DEVELOPING A REGIONAL DISTRIBUTED HYDROLOGICAL MODEL FOR WATER RESOURCES ASSESSMENT AND ITS APPLICATION TO THE CHAO PHRAYA RIVER BASIN

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The Thailand's Great Flood in 2011 resulted in the great calamity causing tremendous losses impacting livelihood, social and economic of the nation. A better understanding of the basin hydrological processes is necessary for studying and predicting a future flood. Consequently, this study aims to develop a regional distributed hydrological model for water resources situation prediction. The regional hydrologic model was composed of a runoff generation model with a concept of the variable infiltration capacity and a flow routing model using the kinematic wave equation. The effects of dam control were also included in the flow routing model. The model was applied to the Chao Phraya River basin to reproduce floods in 1995, 2008, 2010, and 2011. By using the model, the effect of the existing dams operations and the new dam construction on flood control is numerical evaluated.

Key Words: *Thailand, Chao Phraya River, runoff prediction, regional hydrologic modeling*

1. INTRODUCTION

Due to continuous and intense precipitation occurring in the upper part of the Chao Phraya River Basin (CPRB), the unforeseen devastating flood occurred most significantly in the lower part of the basin from July 2011 until the end of the year. There are many losses in term of human, social and economic losses. Thai Ministry of Interior revealed that 815 people were killed during the inundated period, as of January 20, 2012. The World Bank has estimated 1,425 billion baht (US$ 45.7 Bn) in economic damages and losses due to flooding, as of December 1, 2011. This is the worst recorded damage in Thailand. Thus, it is a quite important issue to develop a regional hydrologic model to evaluate the vulnerability of the existing river system for water-related disasters and water resources, and to assess a future river plan, such as a new dam construction under a changing climate.

Recently, the future of hydrological situation under climate change in the CPRB has gained more attention. For example; Hunukumbura and Tachikawa[1)] projected future river discharge to detect hotspots on rivers discharge in the CPRB. Jayawardena *et al.*[2)] applied several versions of the variable infiltration capacity (VIC) models[3)4)] to predict river flow in the Mekong and Chao Phraya basins using general circulation model output.

The main objective of this paper is to develop a regional distributed hydrological model which is up-to-date and can reproduce historical floods in the CPRB. The model is applicable to assess a river plan under a changing climate. Using this developed regional hydrologic model, we examine the effect of existing dams on reducing flood and a new dam construction on flood control.

2. STUDY AREA AND INPUT DATA

The Chao Phraya River originates in the northern region of Thailand. There are two parts of the CPRB,

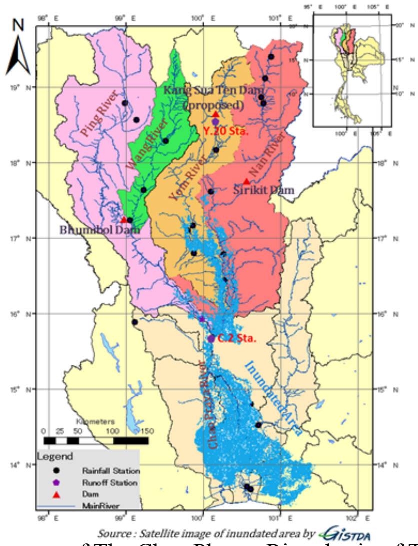

Fig. 1 Diagram of The Chao Phraya River basin of Thailand

upper and lower parts comprising of a total area of 157,925 km^2. The upper part of the basin consists of four principal sub-basins, the Ping, Wang, Yom and Nan river basins. The confluence of the Ping River and Nan River at Nakornsawan province is the beginning of the Chao Phraya River.

Rainfall data was collected from 26 stations covering the CPRB. The average of 2011 annual rainfall in those sub-basins is approximately 36% larger than the annual rainfall average over 30 years (1980-2009), whereas in the Lower CPRB the average of 2011 annual rainfall is slightly (2%) higher than the average over 30 years. Therefore, in this study we focus on the runoff generated in the upper sub-basins of the CPRB by observing mainly at the C.2 station (15°40′N and 100°06′E). **Fig. 1** illustrates a diagram of the CPRB including the satellite image of inundated area during flood 2011.

3. MODELING APPROACH

Principally, a distributed hydrological model consists of a hydrologic model and a flow routing model. In this study both hydrologic and flow routing models were founded as a grid-based model. In order to reproduce the realistic runoff situation in the CPRB, a dam operation model has been combined in the flow routing model.

(1) Hydrological Model

To develop the hydrologic model, we simplified the Xinanjiang (XAJ) model[5] by reducing a number of parameters and modifying sub-layers in the model for surface and subsurface runoff generations. Additionally, a concept of the modified XAJ model, tension water storage variation and aquifer condition proposed by Nirupama *et al.*[6] were adapted in this study.

Based on assumption that infiltration capacities

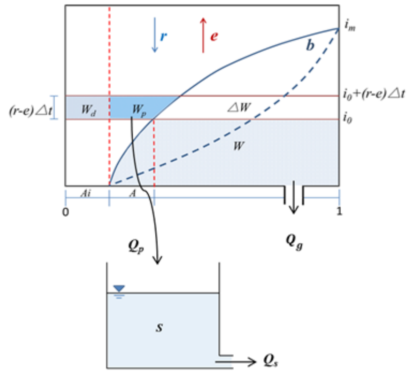

Fig.2 The distribution of runoff and infiltration as a function of grid wetness and infiltration capacity.

over the study area vary due to variations in topography, soil, and land cover (refer to **Fig. 2**), the infiltration capacity i over an area can be represented as the following equation,

$$i = \begin{cases} 0 & if\ 0 \leq A \leq A_i \\ i_m\left[1-\left(1-\dfrac{A-A_i}{1-A_i}\right)^{1/b}\right] & if\ A_i \leq A \leq 1 \end{cases} \quad (1)$$

where i_m represents the maximum infiltration capacity, A is the fraction of the cell area for the infiltration capacity and takes values between 0 and 1, A_i is the portion of direct runoff generation areas in the cell, and b is an empirical parameter showing a shape of the storage water capacity curve.

By integrating the function of the infiltration capacity i (**Eq.1**) from A_i to 1, the maximum tension water storage of the cell W_m can be expressed as

$$W_m = \frac{i_m}{1+b}(1-A_i) \quad (2)$$

Therefore, the current soil moisture W corresponding to a current infiltration capacity i_0 is obtained by the following equation.

$$W = W_m\left\{1-\left(1-\frac{i_0}{i_m}\right)^{b+1}\right\} \quad (3)$$

According to **Fig.2**, during the precipitation event, rainfall r and evapotranspiration e are taken as input to the model. From the impervious area, the direct runoff depth W_d is generated which is shown as

$$W_d = Q_d\Delta t = A_i(r-e)\Delta t \quad (4)$$

where Δt is time interval, and Q_d is the direct runoff intensity. From the pervious area, surface runoff depth W_p is calculated using the following relationships;

Case 1: If $i_m \leq i_0 + (r-e)\Delta t$
(i.e., severe rainfall occurs and/or soil is saturated)

$$W_p = Q_p\Delta t = (r-e)(1-A_i)\Delta t - W_m + W \quad (5a)$$

Case 2: If $i_m > i_0 + (r-e)\Delta t$
(i.e., normal rainfall occurs and/or soil is unsaturated)

$$W_p = Q_p \Delta t = (r-e)(1-A_i)\Delta t - W_m + W + W_m \left(1 - \frac{i_0 + (r-e)\Delta t}{i_m}\right)^{1+b} \quad (5b)$$

where Q_p is the surface runoff intensity provided by the infiltration capacity concept in pervious area.

As show in **Fig.2**, due to the shallow aquifer underneath in some part of the CPRB[7], we included the effect of the groundwater component into the upper layer of the model to separate some amount of infiltrated water for recharging to the shallow aquifer. The soil water storage contributes to the groundwater Q_g expressed as the function of a non-linear reservoir relationship. The equation presents as

$$Q_g = \left(\frac{W}{k_g}\right)^{1/p_g} \quad (6)$$

where k_g is the groundwater coefficient (hr) and p_g is the empirical parameter of aquifer storage.

Thus, the updated soil moisture W is determined according to water balance in the upper layer of the model by the following equation,

$$W_{(t+\Delta t)} = W_t + (r-e)\Delta t - W_p - Q_g \Delta t \quad (7)$$

Remark that the values W vary between 0 to W_m. By referring to **Eq. 3**, the W is a function of i_0. Hence, the values i_0 can be solved as well.

The surface runoff Q_p infiltrates to be inputs of the subsurface runoff (base flow) component of the model as shown in the **Fig.2** (lower layer). The subsurface runoff component of the model is approximated by the relationship of a non-linear reservoir and continuity equation conveyed by

$$\frac{ds}{dt} = Q_p - Q_s \text{, and } s = k_s {Q_s}^{p_s} \quad (8)$$

where Q_s represents the subsurface runoff, s is the subsurface storage, k_s is the subsurface coefficient (hr), and p_s is the empirical parameter of subsurface storage. Finally, total runoff Q produced for a cell is obtained as

$$Q = Q_d + Q_s \quad (9)$$

The simplified Xinanjiang model has seven parameters in total, A_i, W_m, b, k_s, k_g, p_s, and p_g. They were identified in the process of model calibration. The model was applied for the CPRB at the 1/4 degree resolution and the model represents about 560 (20 columns and 28 rows) computational grid cells covering the basin, and 1-hr time step of the calculation. Hereafter, we would refer to the simplified Xinanjiang Model as the SXAJ model. The outputs from the SXAJ model obtained as total discharge depth (millimeter per hour) at each computational grid cell were used as inputs to a flow routing model.

(2) Flow Routing Model

Generally, excess rainfall is easily routed by lumped approaches, such as unit hydrograph, flow isochrones or linear reservoir modeling in computational of overland flow and channel flow, however it is difficult to represent land cover and topography as spatially distributed on a basin scale. Hence, the 1-km distributed flow routing model, 1K-FRM (http://hywr.kuciv.kyoto-u.ac.jp/products/1K-DHM/1K-DHM.html), was chosen for routing in this study.

A digital elevation model (DEM) was applied to define the flow direction of the catchment, assuming that the flow direction 1-dimensionally to steepest downward slope to an immediately neighboring cell. The topographic data used in the 1K-FRM were the 30 arc-second DEM and flow direction stored in HydroSHED.

The flow model is based on the one-dimensional kinematic wave model. According to the flow direction, each cell has a routing order from upstream to downstream. Then runoff generated by the SXAJ model becomes river discharge. The one-dimension kinematic wave equation for each cell is given by

$$\frac{\partial A}{\partial x} + \frac{\partial Q}{\partial x} = q(t) \quad (10)$$

where t is time, x is the distance from the top of the rectangular grid, A is cross section area on the regular grid, Q is discharge, and $q(t)$ is the lateral inflow per unit length of channel unit given as runoff generated by the SXAJ model. The Manning relation type of the discharge and cross-sectional area was joined with the continuity equation to route the water for each cell. There are two types of the cross sections used in this study, rectangular and quadratic shapes. The relationship of the discharge to the cross section area is given as follows;

$$Q = \alpha A^m \quad (11)$$

For a rectangular cross-section shape (m = 1.67), and a quadratic function shape ($y = ax^2$) (m = 1.44), respectively;

$$\alpha = \frac{\sqrt{g_0}}{n}\left(\frac{1}{B}\right)^{2/3}, \text{ and } \alpha = \frac{\sqrt{g_0}}{n}\left(\frac{a}{6}\right)^{2/9} \quad (12)$$

where g_0 is slope; n is the manning roughness coefficient; B is the width of flow; and a is cross-section parameter. The quadratic function was applied to flooded area where cross-section of the river was accordingly changed with the over bank flow. The criterion to distinguish the type of the cross section is set by the number of upstream grids. When the number is larger than 35,000 (about 35,000 km^2) the quadratic cross section is adopted for representing the inundated areas. The 1K-FRM parameters are *n, B* and *a*. In this study, we used the values of *n* and *B* same as the original model, n = 0.03 $m^{-1/3}s$ and 11.0 $m^{-1/3}s$ for channel and slope flow, respectively. The value of *B* is equal to $1.06C^{0.69}$; where *C* is catchment area at the points. These two values were determined and used in the Japanese catchment[1]. To reproduce the inundation phenomena of the flood 2011 in Thailand, we assumed the quadratic cross section shape. The cross section parameter *a* is set to 0.00012 to reproduce a flood discharge properly.

(3) Dam Operation Model

As mentioned in the study area, flow in the Chao Phraya River is significantly influenced by the dams operation. Therefore, dam operation models for the Bhumibol dam and Sirikit dam were embedded into some particular grids of 1K-FRM where the dams locate. An algorithm to develop a general reservoir operating rule is a flexible function that can be adjusted for different dam features.

The kinds of information, which are required for input to the dam operation model, are spillway capacity, downstream requirement, active storage, min/max storage, and upper/lower rule curves. The monthly operation basis of the dam model is to store water in wet season (May-December) and to release water in dry season (January-April).

Finally, an overall framework of the distributed hydrological model to achieve the simulated discharge in the river at each focused point can be schematized as in **Fig. 3**.

3. PARAMETERS IDENTIFICATION

The SXAJ model have seven parameters, i.e., the shape parameter of the soil water storage curve *b*, the groundwater parameter k_g, the baseflow parameter k_s, the parameter of groundwater storage p_g, the parameter of sub-surface storage p_s, the maximum soil moisture storage W_m, and the fraction of direct runoff generation areas A_i, to be calibrated for each computational grid in the basin.

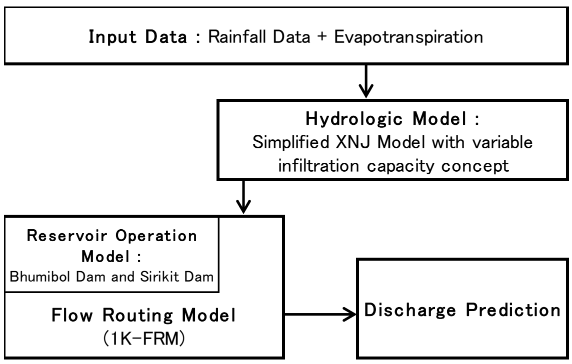

Fig. 3 Framework of the distributed hydrological model.

According to the CPRB size (large), its non-homogenous geological, and its topographic characteristics, the best combination of the model parameter was estimated using the observed discharge data of the year 2011 at the C.2 station, Bhumibol dam and Sirikit dam. Also the observed data of year 1995, 2008 and 2010 at those points was compared with the simulated discharge to verify the model parameters. We, therefore, separated the set of parameters to three sets depending on the topographic and geologic conditions. The first set of parameters was applied to the lower part of the Yom and Nan River, the second set was proposed to the Ping River basin, and the last set was used for remaining areas over the CPRB.

To identify the parameters, the trial-and-error method and the following procedures were conducted for the model calibration in this paper: (a) setting initial values of the parameters, (b) comparing simulated and observed discharge, (c) adopting a coarse step-size and then a finer step-size to identify the range of probable parameters and refine values, respectively.

The optimized SXAJ model parameters are given in **Table 1**. In the SXAJ model, a relationship between the k_g value and the effect of groundwater was not in direct proportion (**Eq. 6**). Consequently, the high values of k_g were obtained in the general grids and Ping River basin resulted from a lesser effect of shallow groundwater in those areas. With these sets of parameters, the SXAJ model generated runoff as an input for the routing model, and initial condition of the routing model was set accordingly to the observed discharge. The comparisons of simulated and observed discharge at the Bhumibol dam, Sirikit dam, and C.2 Station are respectively illustrated in **Fig.4** for the model calibration and **Fig.5** for the model verification. The model was calibrated by maximizing the Nash-Sutcliffe efficiency (NSE) of the daily discharge, and some error indicators, coefficient of determination R^2, and root mean square error RMSE, were used to justify the model performance. The summary of the model performance indicators of the calibration and verification stages are given in the **Table 2**.

Table 1 The SXAJ model parameters.

Parameters	General grids	Lower Yom&Nan River Basin	Ping River Basin
Ai	0.35	0	0.30
W_m	350	1500	400
b	1.5	0.2	1.5
k_s	150	400	200
k_g	1500	40	1500
p_s	0.6	0.6	0.5
p_g	0.6	0.6	0.6

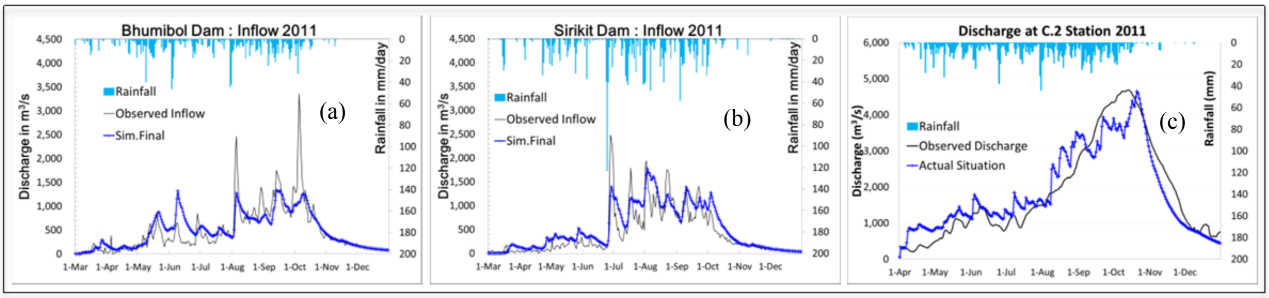

Fig. 4 Comparisons of discharge at the Bhumibol dam, Sirikit dam and C.2 station for the model calibration, 2011.

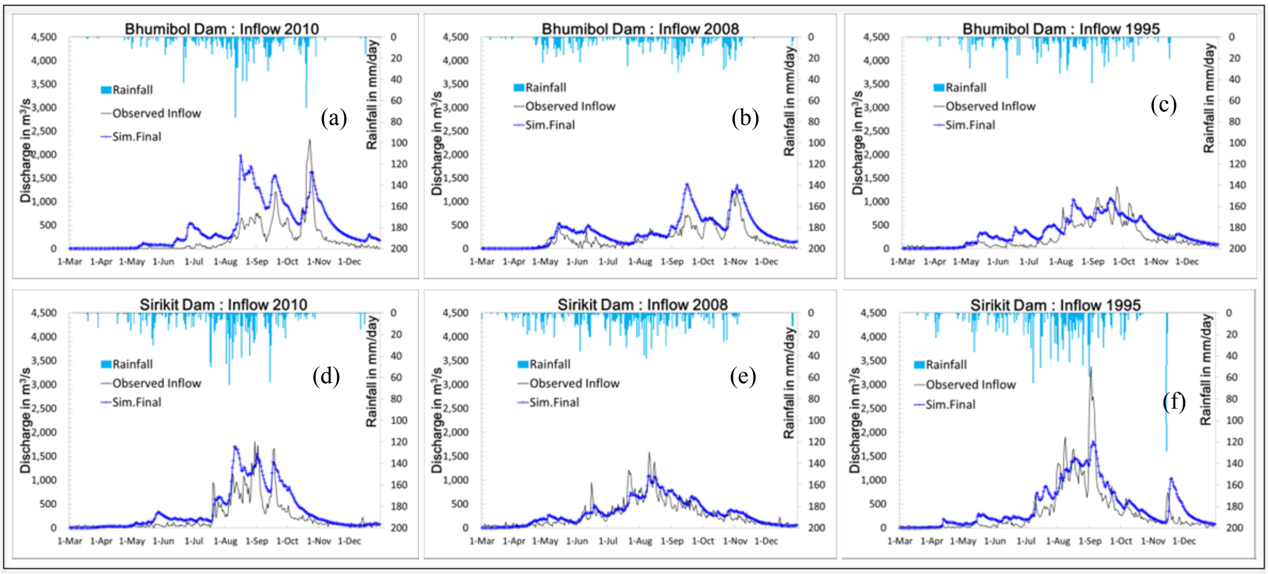

Fig. 5 Comparisons of discharge at the Bhumibol dam and Sirikit dam for the model verification, 2010 2008 and 1995.

Table 2 Summary of model performance indicators.

Period		Statistical criterion	Location		
			Bhumibol Dam	**Sirikit Dam**	**C.2**
Calibration	2011	NSE	0.62	0.71	0.87
		RMSE (m^3/s)	310.61	265.16	498.53
		R^2	0.63	0.75	0.87
Verification	2010	NSE	-0.28	0.47	0.49
		RMSE (m^3/s)	397.42	247.75	562.9
		R^2	0.56	0.77	0.85
	2008	NSE	0.2	0.75	0.55
		RMSE (m^3/s)	217.34	138.07	396.64
		R^2	0.75	0.77	0.6
	1995	NSE	0.53	0.68	0.7
		RMSE (m^3/s)	192.46	295.41	663.97
		R^2	0.67	0.71	0.77

4. ASSESSMENT OF DAM FLOOD CONTROL

(1) The effect of the Bhumibol and Sirikit dam

The Bhumibol (BB) dam was built in 1964 with the capacity 13,420 billion m^3 and the spillway capacity 6,000 m^3/s at the Ping River basin. Afterwards, in 1974 the Sirikit (SK) dam was built with the capacity of 9,510 billion m^3 and the spillway capacity of 3,250 m^3/s at the Nan River basin. The catchment areas of the BB and SK dams are 26,400 km^2 and 13,130 km^2, respectively. In the simulation shown in **Fig. 4c**, the dam operation of two dams was embedded according to the actual operation data to the 1K-FRM with the condition of releasing water 200 m^3/s and 250 m^3/s during January-April and 15% and 30% of natural inflow during May-December for BB Dam and SK Dam, respectively. The comparisons between simulated and observed reservoir storage of these two dams are shown in **Fig.6**. To assess the effect of dams on the flood 2011, we have done a simulation of the year 2011 using the runoff input generated by the SXAJ model to the 1K-FRM without considering the dam operation model, as illustrated in **Fig.7**. The result shows the volume of simulated hydrograph without two dams was 54,812 million m^3, which was as much as a 23% increase when compared to the actual situation, focusing at the C.2 station during April-December 2011. Moreover, the dams facilitate water storage during the early stage of the flooding period by decreasing 15% of the peak discharge compared to the value obtained with no dams.

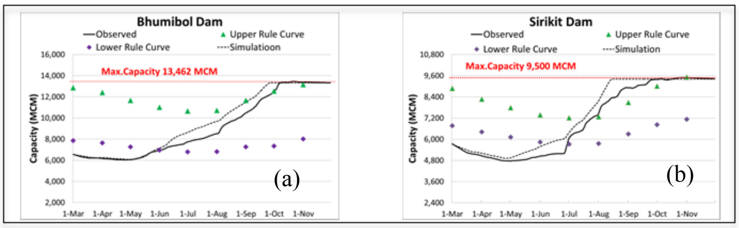

Fig.6 Reservoir Storage of the BB Dam SK Dam, Mar-Nov 2011.

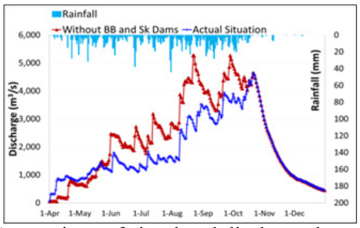

Fig.7 Comparison of simulated discharge between actual situation, and without the BB and SK dams at C.2 station.

(2) The effect of proposed dam construction on the Yom River

Tentatively, the government of Thailand has proposed to develop one more dam named Kang Sue Ten (KST) in the Yom River basin to relieve water resources problems. The catchment area of the KST dam is 3,538 km^2. The active storage is 1,125 million m^3, and the spillway capacity is 5,355 m^3/s.

In this paper, we considered the dam for flood protection purpose only. The operation condition of this dam was made by optimizing the historical discharge data of 19 years (1992-2010) at the Y.20 station to figure out the suitable downstream release flow. Dam operation conditions of the KST dam are releasing water 40 m^3/s during Jan-Apr and 40% of natural inflow during May-December. We assumed that was what would happen to the flood 2011 if the KST dam had already been built.

The results of this simulation show that there was an insignificant effect on the overall water resources situation in the CPRB. The volume of the hydrograph at the C.2 station was only a 1.5 % decrease as shown in **Fig.8a**. However, the KST has significant effect on a water resources situation of the Yom River basin by increasing in dry season flow and also reducing about 50% of peak discharge during the wet season as presented **Fig. 8b**.

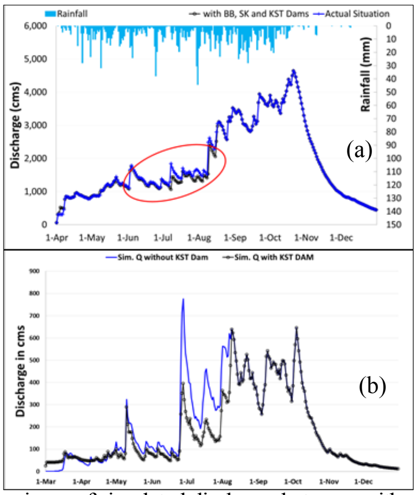

Fig.8 Comparisons of simulated discharge between with and without KST dam at the C.2 Station (a) and downstream of the dam (b).

5. CONCLUSION

In this study, we have successfully developed the regional distributed hydrological model embedding the dam operation model to reproduce the flood 2011 in the CPRB and to investigate effects of dams on a water resources situation of the CPRB. The hydrological model was developed based on a concept of the variable infiltration capacity including the effect of shallow groundwater. Overall, the agreement between observed discharge and simulated discharge, and the water balance of simulated and observed hydrographs were satisfied by the NSE ranges from 0.62 to 0.87 and the R^2 ranges from 0.63 to 0.87 for the calibration period. As expected the NSE for the model validation is smaller than the model calibration. But the R^2 for the model validation, which ranges from 0.56 to 0.85, is almost the same range with the model calibration. The dams in the upper part of the CPRB were proved that they are useful for the flood protection in the basin. Our future work tasks are to predict a future water resources situation under a changing climate and to propose an adaptive measure to cope with water related disasters.

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REFERENCES

1) Hunukumbura, P. B. and Tachikawa, Y., River Discherge Projection under Climate Change in the Chao Phraya River Basin, *J. of the Meteorological Society of Japan*, 90(A), 137-150, 2012.
2) Jayawadena, A. W., ASCE, M., and Mahanama, S. P. P., Meso-Scale Hdrological Modeling: Application to Mekong and Chao Phraya Basins, *J. of Hydrologic Engineering*, 7(1), 12-26, 2002.
3) Wood, E. F., Lettenmaier, D. P., and Zartarian, V. G., A Land-Surface Hydrology Parameterization With Subgrid Variability for GCM, *J. of Geophys. Res.,* 97(D3), 2717-2728, 1992.
4) Liang, X., Lettenmaier D. P., Wood, E., and Burges, S. J., A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *J. Geophys. Res.*, 99 (D7), 14415–14428, 1994.
5) Zhao, R. J., Zhuang, Y. L., Fang, L. R., Liu, X. R. and Zhang, Q. S., The Xinanjiang model, Hydrological Forecasting Proc., Oxford Symp., Int. Assoc. of Hydrological Sciences, 129, 351-356, 1980.
6) Nirupama, Tachikawa, Y., Shiiba, M., and Takasao, T., A Simple Water Balance Model for a Mesoscale Catchment Based on Heterogeneous Soil Water Storage Capacity, *Bull. Disas.Prev. Res. Inst., Kyoto Univ.*, 45(391), 61-83, 1996.
7) DGR of Thailand, Pilot Study and Experiment on Managed Aquifer Recharge Using Ponding System in the Lower North Region River Basin, Executive Summary Report, 2012.

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