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Rainfall-Runoff Simulation for the 2011 Flood in Thailand and Water Resources Prediction Research under a Changing Climate

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The Thailand's Great Flood in 2011 resulted in the great calamity causing tremendous losses impacting livelihood, social, and economics 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. By using the model, the effect of the existing dams operations is numerically evaluated. The impact of climate change on river flow in Thailand was also analyzed by feeding future climate projection data into a distributed rainfall-runoff model. The projection data used consists of daily hydrologic data downscaled by hourly precipitation for the present climate (1979-2003), the near future climate (2015-2039), and the future climate (2075-2099), which were simulated by a 20km spatial resolution general circulation model (MRI-AGCM3.1S) developed by the Meteorological Research Institute, Japan Meteorological Agency. It was found that a significant change of river flow appeared at the Pasak River basin which is a tributariy of the Chao Phraya River. Then, a detail distributed hydrologic model was applied to the Pasak River basin to analyze the water storage of the Pasak Dam to access the reservoir could satisfy the water demand under the future climate change scenario. It was suggested that water storage at the Pasak Dam will not be able to meet the current water demand under the climate change scenario.

Key Words : *Thailand, Chao Phraya River, Pasak River, water resources, climate change, river flow*

1. INTRODUCTION

Global warming will give us a serious impact on our life. Frequencies and magnitudes of floods and sedimentation disasters are predicted to increase due to the change of precipitation extremes. The IPCC, the Intergovernmental Panel on Climate Change, 4th assessment report[1),2)] describes increase of global average surface temperatures, and potential increase of frequency of heavy rainfall, and so on based on long term observations. The report also shows the projections of climate change according to several greenhouse gas emission scenarios and the impacts of climate change on water-related disasters and water resources.

To cope with water-related disasters induced by climate change, both mitigation measures and adaptation measures are essential. For adaptation measures, prediction of future water resources is a key issue. The Chao Phraya River basin was found to be one of the most affected flood prone basins in Thailand in the near future and future climate[3]. To project future river discharge using various GCM outputs, we developed a distributed routing model for the entire Chao Phraya River basin, and found that a change of flow happened at the tributaries of the Chao Phraya River and especially decrease on October discharge at the Pasak River basin[4]. Thus, we developed a water resources assessment model at the Pasak River basin, which includes a detailed distributed hydrologic model and a dam reservoir water storage prediction model. An analysis showed that water storage at the Pasak Dam will not be able to meet the current water demand under a climate change scenario. The distributed routing model is also extended to a regional distributed hydrologic model, which was confirmed to predict the Thailand's Great Flood in 2011.

2. DISTRIBUTED ROUTING MODEL

(1) Watershed model

The topography of the catchment is modeled using the eight direction method which assumes the flow direction one-dimensionally to the steepest gradient direction illustrated in Fig. 1. Each slope element determined by the flow direction is represented by a rectangle formed by the two adjacent nodes of grid cells. The watershed model is developed using the 1km resolution digital elevation model, DEM, included in HydroSHED[5], which cover the globe with about 100m spatial resolution. Figure 2 shows the delineated catchments of the Chao Phraya River basin (CPRB, 160,400km^2) and the Pasak River basin (16,291km^2) in Thailand using the channel network data in HydroSHED. The area, length, and gradient of each rectangular slope element used for runoff and channel routing are calculated according to the watershed model.

(2) Flow model

The kinematic wave model is applied to all rectangular slope and river elements to route the water to downstream according to the derived watershed model. The continuity equation for each rectangular slope element is:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q(t) \quad (1)$$

where t is time; x is distance; A is cross-sectional area; Q is discharge; and $q(t)$ is the lateral inflow per unit length of slope or channel given as runoff generation provided by MRI-AGCM3.1S. The Manning type relation of the discharge and the cross-sectional area:

$$Q = \alpha A^m, \alpha = \frac{\sqrt{i_0}}{n(1/B)^{m-1}}, m = 5/3 \quad (2)$$

is combined with the continuity equation (1) to route the water, where i_0 is slope; n is roughness coefficient; and B is width of the flow. The slope i_0 is determined according to the watershed model. The model parameters of the flow model are B and n. The value of B is determined using the regression relationship $B=aS^c$, where S is the catchment area, and a and c are constant parameters. The value of n is determined to 0.03m$^{-1/3}$s when the size of the catchment is larger than 250km^2 and 11.0m$^{-1/3}$s when smaller than 250km^2. These values were tuned to reproduce the observed data at two different catchments and applied to all basins. Hereafter, we refer to the 1km distributed flow routing model as 1K-FRM (http://hywr.kuciv.kyoto-u.ac.jp/products/1K-DHM/1K-DHM.html).

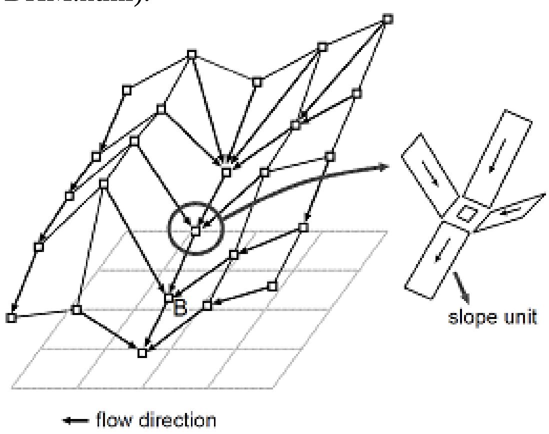

Fig. 1 Schematic drawing of a catchment modelling using DEMs.

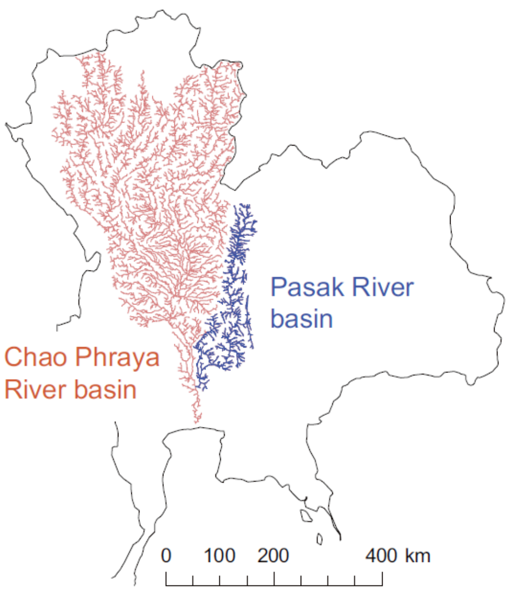

Fig. 2 Channel network data in HydroSHED for the Chao Phraya River (red) and the Pasak River (blue).

3. REGIONAL DISTRIBUTED HYDROLOGIC MODEL

The distributed routing model is extended to a regional distributed hydrologic model, which was confirmed to predict the Thailand's Great Flood in 2011. The regional distributed hydrological model consists of a hydrologic model and a flow routing model (1K-FRM). 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 was combined in the flow routing model.

(1) Hydrological Model

To develop a hydrologic model to generate surface and subsurface runoff[6),7)], we simplified the Xinanjiang (XNJ) model[8)] by reducing the number of parameters, and modifying sub-layers in the model for surface and subsurface runoff generations. Additionally, the concept of the modified XNJ model, the tension water storage variation and aquifer condition proposed by Nirupama et al.[9)] were adapted in this study.

Based on assumption that infiltration capacities over the study area vary due to variations in topography, soil, and land cover (refer to Fig. 3), the infiltration capacity i overs an area can be represented as the following equation,

$$\boldsymbol{i} = \begin{cases} \boldsymbol{0} & \boldsymbol{if\ 0 \le A \le A_i} \\ \boldsymbol{i_m}\left[\boldsymbol{1} - \left(\boldsymbol{1} - \dfrac{\boldsymbol{A} - \boldsymbol{A_i}}{\boldsymbol{1} - \boldsymbol{A_i}}\right)^{\boldsymbol{1}/\boldsymbol{b}}\right] & \boldsymbol{if\ A_i \le A \le 1} \end{cases} \tag{3}$$

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 impervious portion of the cell, and b is an empirical parameter showing a shape of the storage water capacity curve.

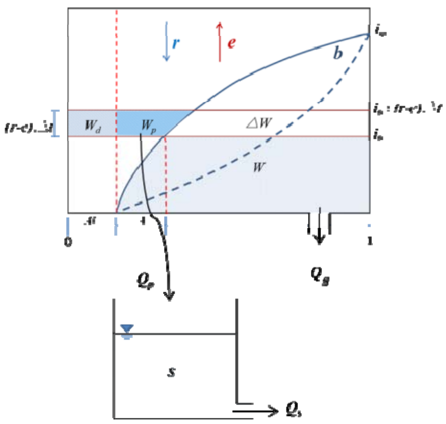

Fig.3 The distribution of runoff and infiltration as a function of grid wetness and infiltration capacity.

Based on the function of the infiltration capacity, surface runoff, subsurface runoff and groundwater runoff are calculated for each grid cell and total runoff for each grid cell is given to the flow routing model 1K-FRM. 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.

(2) Flow Routing Model

The distributed routing model 1K-FRM is used for river routing. 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. These two values were determined and used in the Japanese catchment[4)]. To reproduce the inundation phenomena of the flood 2011 in Thailand, we assumed the quadratic cross section shape 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 rules 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-Dec.) and to release water in dry season (Jan-Apr.). Finally, the 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.4.

(4) Simulation Result

Figure 5 shows a spatially distributed river flow discharge at CPRB on Oct. 14, 2011 using the calibrated regional distributed model. Figure 6 shows a simulated discharge at C.2 station. The model well reproduces time and space distribution of river discharge.

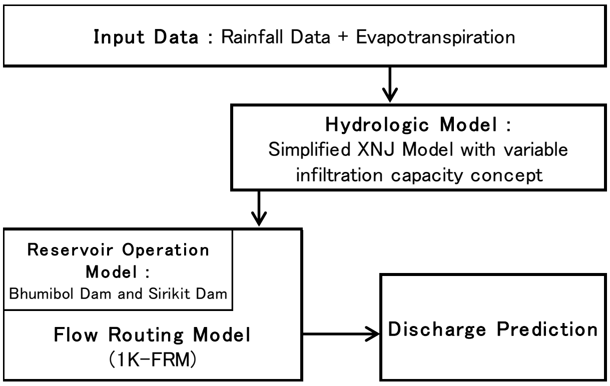

Fig. 4 Framework of the distributed hydrological model.

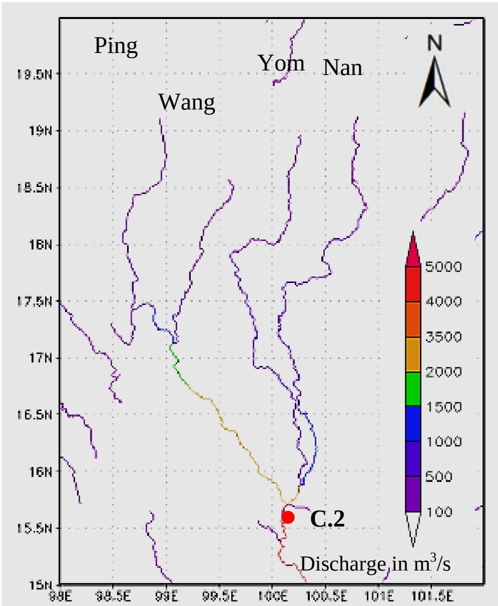

Fig.5 A spatial distribution of estimated discharge on Oct 14, 2011.

4. IMPACT OF CLIMATE CHANGE ON RIVER FLOW REGIME

(1) GCM DATA USED FOR RIVER FLOW PROJECTION

The flow model was applied to all catchments and 75 years runoff simulations were conducted. The simulated river discharge data of daily maximum and daily mean were stored for each day with about 1km spatial resolution. The projection data used here is simulated by the general circulation model (MRI-AGCM3.1S) developed by the Meteorological Research Institute in Japan. MRI-AGCM3.1S realizes 1920×960 of grid cells of about 20 km spatial resolutions[10),11)]. The products of MRI-AGCM3.1S consists of various atmospheric and hydrologic variables of the present climate experiment (1979-2003), the near future climate experiment (2015-2039), and the future climate experiment (2075-2099), which were simulated under the SRES A1B scenario.

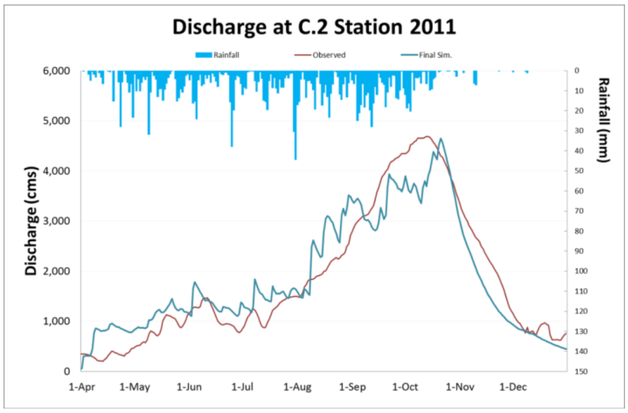

Fig.6 Comparison of Simulated and Observed Daily Discharge at C.2 Station.

The river discharge for the Chao Phraya River basins is predicted by feeding the future climate projection data into the 1K-FRM. The hydrologic projection variables related to river discharge is shown in Figure 7. The inputted data to the distributed hydrologic model is daily surface runoff generation and daily sub-surface runoff generation data, which are simulated by the land-surface process model embedded in the MRI-AGCM3.1S.

The time-scale of daily runoff generation data is insufficient to reproduce the hourly flood peak discharge, thus it was downscaled using the time-series of hourly precipitation data of MRI-AGCM3.1S to add the same hourly distribution pattern into the daily surface runoff generation data. We confirmed that river discharge simulation with the timely downscaled surface runoff generation and daily subsurface runoff generation data successfully reproduced almost similar river discharge simulated by using hourly precipitation, daily snowmelt, daily evaporation and daily transpiraion[12)]. Thus, the timely downscaled surface runoff generation data and daily subsurface runoff generation data were used as inputted data to the distributed hydrologic model.

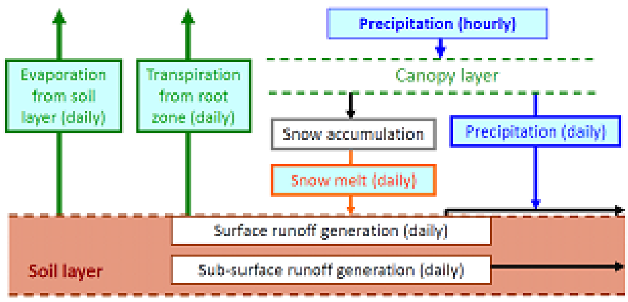

Fig. 7 Hydrologic projection data provided by MRI-AM20km used for river discharge simulation.

(2) IMPACT OF CLIMATE CHANGE ON RIVER FLOW REGIME

Runoff simulations of 75 years for the present climate experiment, the near future climate experiment, and the future climate experimen were conducted for the area covering the entire Chao Phraya River basin. Runoff simulation data of hourly maximum and daily mean are stored for each day with about 1km spatial resolution. The simulated discharge data were analyzed to discuss the change of the flood risk and water resources.

It was found that generally, the annual maximum discharge of the main stream of the Chao Phraya River does not change; however the one of the tributaries changes location to location[4]. Especially, we found that the monthly discharge on October decreases at the Pasak River basin.

Figure 8 shows the last 10% daily flow duration curve for each 25 years climate experiment at the lower reach of the Pasak River shown in Figure 1. The figure shows the decrease tendency of the low discharge at the area. Figure 9 shows the projected monthly discharge at the lower reach of the Pasak River. The figure shows the clear pattern of the decrease of the October discharge.

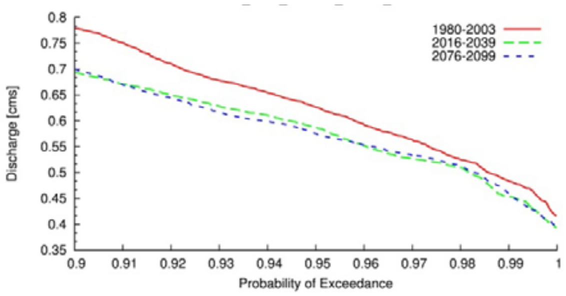

Fig. 8 Change of the ratio of the mean October river discharge in the future climate experiment with respect to the present climate experiment.

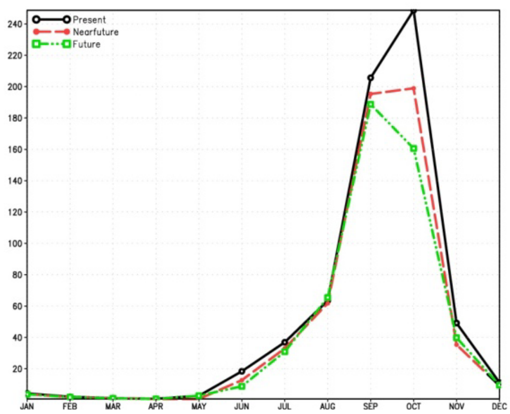

Fig. 9 Change of the monthly discharge at the lower reach of the Pasak River.

5. WATER RESOURSES ASSESSMENT MODEL AT THE PASAK RIVER BASIN

Through the river discharge projection of the entire Chao Phraya River, it was revealed that the Pasak River basin (Fig. 10) would be one of the hotspot basins for the river discharge change. Thus, we focus the catchment and developed a water resources assessment model to analyze the storage of the Pasak Dam reservoir could satisfy the water demand under the future climate change scenario[13].

Figures 11 and 12 show the change of annual precipitation and evapotranspiration simulated by MRI-AGCM3.1S. Precipitation change is not significant but evapotranspiration clearly shows an increase trend because of temperature increase. Figures 13 to 15 show 25 years river flow simulation results of the inflow to the Pasak Dam reservoir for the current, near future and future climate experiment by our detailed distributed hydrologic model.

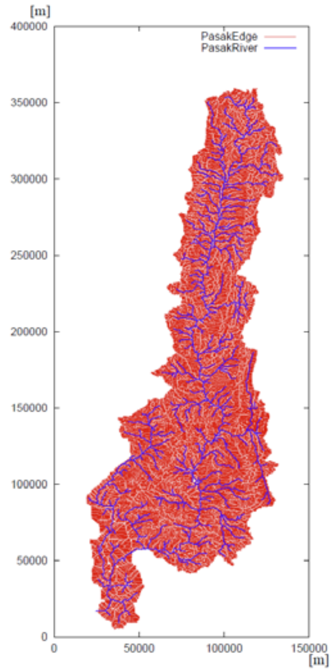

Fig. 10 Detail topographic modeling using HydroSHED for a distributed hydrologic model at the Pasak River basin.

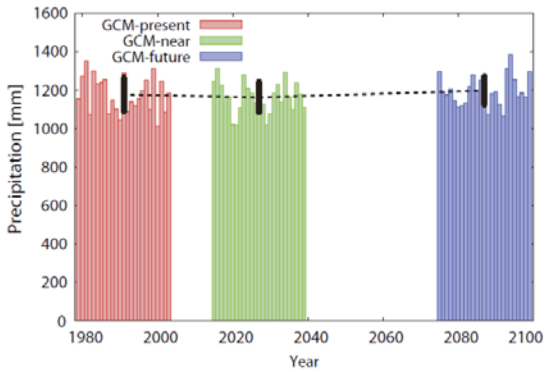

Fig. 11 Annual precipitation simulate by MRI-AGCM3.1S.

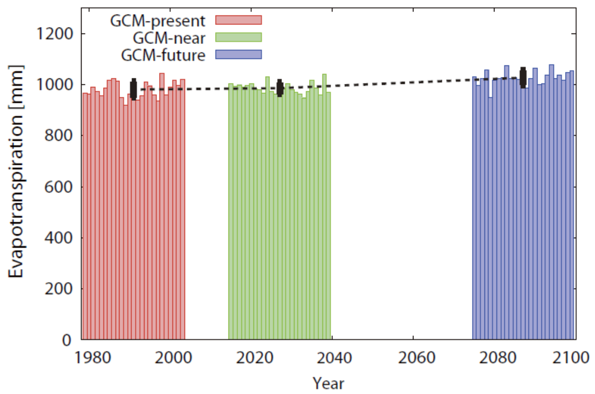

Fig.12 Annual evapotranspiration simulate by MRI-AGCM3.1S.

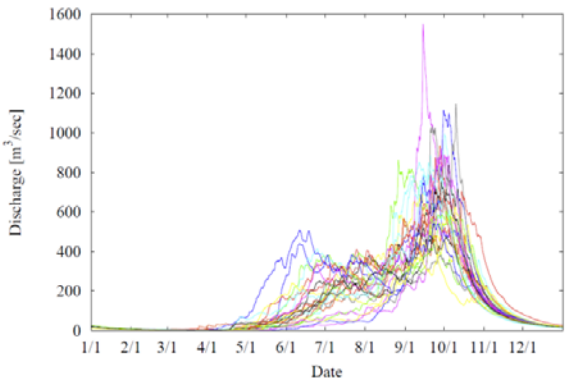

Fig. 13 25 years river flow simulation of the inflow to the Pasak Dam reservoir for the current climate experiment (1979-2003).

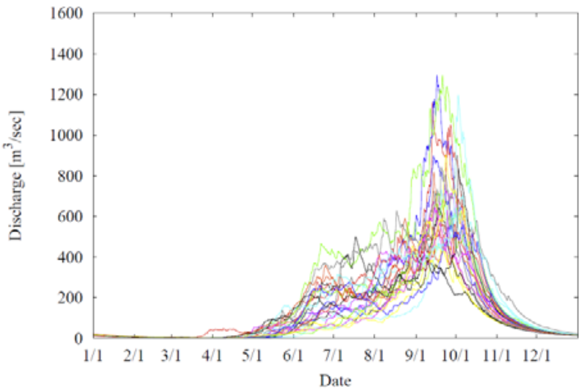

Fig. 14 25 years river flow simulation of the inflow to the Pasak Dam reservoir for the near future experiment (2015-2039).

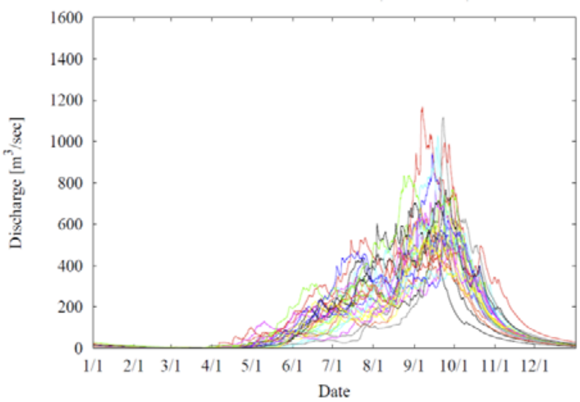

Fig. 15 25 years river flow simulation of the inflow to the Pasak Dam reservoir for the future climate experiment(2075-2099).

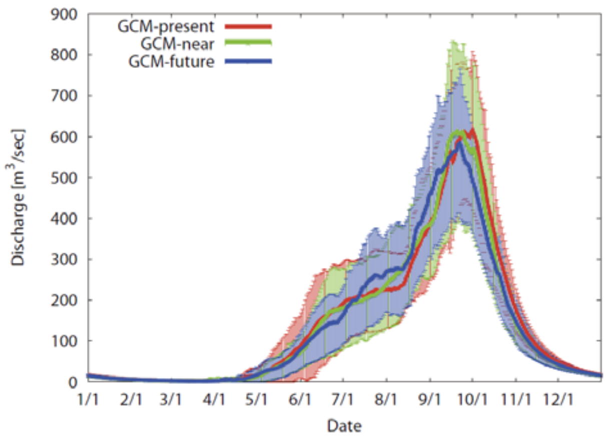

Fig. 16 25 years river flow simulation results of the inflow to the Pasak Dam reservoir for the current climate experiment.

Figure 16 shows the mean and standard deviation of simulated discharge for each climate experiment. It is found that the inflow from June to mid-July of the future experiment decreases about 20%, while the inflow from the mid-July to August increases and the one in October decreases much.

Using the simulated inflow, we investigated the change of the Pasak dam reservoir storage. To consider the bias of the GCM data, two methods were adopted. The first method is to obtain the ratio of the monthly inflow of the current climate experiment and the future climate experiment for each month as:

$$r_{n,i} = \overline{I_{n,\iota}}/\overline{I_{c,\iota}}, i = 1, 12$$
$$r_{f,i} = \overline{I_{f,\iota}}/\overline{I_{c,\iota}}, i = 1, 12$$

where $\overline{I_{c,\iota}}$, $\overline{I_{n,\iota}}$, and $\overline{I_{f,\iota}}$ are mean monthly inflow of each 25 years climate experiment. Then, the ratios are multiplied to each month of the observed monthly inflow as:

$$I_{n,i} = r_{n,i} \times I_{o,i}, i = 1, 12$$
$$I_{f,i} = r_{f,i} \times I_{o,i}, i = 1, 12$$

where $I_{n,i}$ and $I_{f,i}$ are modified monthly inflow data for the near future and future climate experiment. These inflow, mean monthly observed outflow and mean monthly evapotranspiration loss estimated by the observed inflow and outflow were used to estimate the change of the dam storage. The simulation was conducted for about 10 years data after the Pasak dam completion of construction in 1999.

Figure 17 shows the change of the simulated storage. The current climate experiment satisfies the rule curve determined at the Pasak dam reservoir. However, the simulated storage using the near and future climate experiments decreases year to year and after 2 years and 7 months, the storage becomes zero if the outflow pattern is the same.

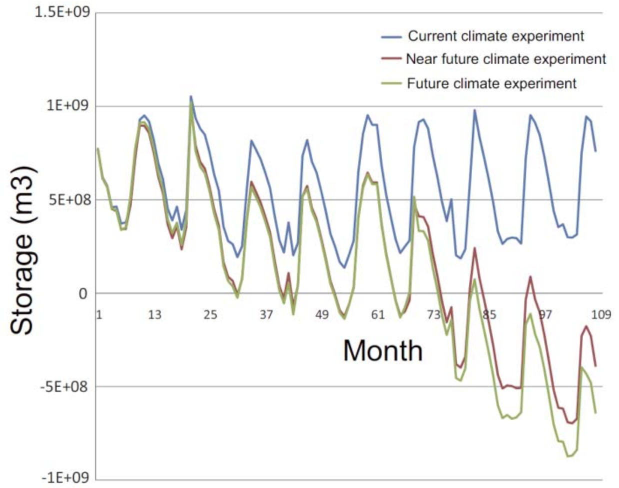

Fig. 17 Change of the Pasak dan storage under climate change scenario (case 1).

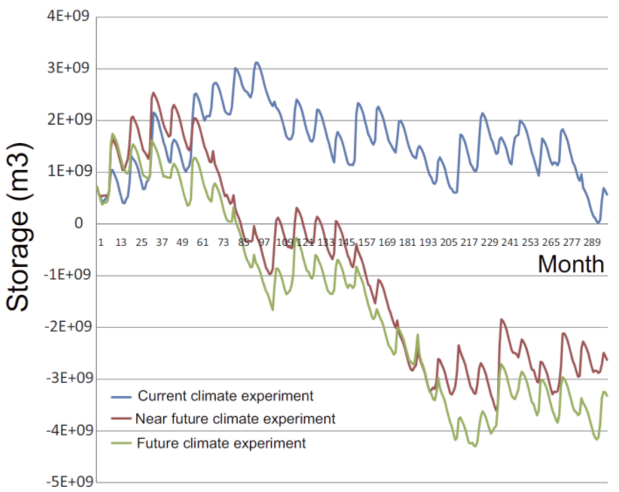

Fig. 18 Change of the Pasak dan storage under climate change scenario (case 2).

To examine the simulation result, another simulation to use inflow projection time series was conducted. At first, the ratio of the observed inflow and the current climate experiment were obtained as:

$$r_i = \overline{I_{o,\iota}}/\overline{I_{c,\iota}}, i = 1, 12$$

Then, the ratio was multiplied to the 25 years inflow projection for each climate experiment. Similar simulation to the above were conducted for 25 years data. Figure 18 shows the change of the simulated storage. The current climate experiment satisfies the rule curve, however, the simulated storage using the near and future climate experiments decreases year to year and after 6 years, the storage becomes zero if the outflow pattern is the same.

6. SUMARRY

The Thailand's Great Flood in 2011 resulted in the great calamity causing tremendous losses impacting livelihood, social, and economics 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. By using the model, the effect of the existing dams operations is numerically evaluated.

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