River discharge assessment under a changing climate in the Chao Phraya River, Thailand by using MRI-AGCM3.2S

Supattana Wichakul1, Yasuto Tachikawa2, Michiharu Shiiba3 and Kazuaki Yorozu2

1TEAM Consulting International Co., Ltd., Thailand
2Department of Civil and Earth Resources Engineering, Kyoto University, Japan
3Runoff Forecasting Research Institute, Japan

Abstract:

Several studies have shown the change of future river flow projection in the Chao Phraya River basin; however, these researches focused on the natural river flow. In this study, to obtain a realistic river flow projection for the Chao Phraya River basin, bias corrected GCM outputs were given to a regional distributed hydrological model including dam operation and flood inundation components. The projected river flow data was analyzed to assess the change of drought and flood risk. The GCM outputs used were precipitation and evapotranspiration projected by MRI-AGCM3.2S, which is a 20 km spatial resolution general circulation model developed by the Meteorological Research Institute, Japan Meteorological Agency. The results obtained from the projected river flow at the Nakhon Sawan station are as follows: 1) mean monthly discharge tends to increase in both the near-future and far-future projection periods for all months; 2) low-flow exceeding 99% of a mean daily flow duration curve for the near-future and far-future periods tends to decrease; and 3) a flood frequency analysis using the annual maximum daily flow series indicates that the flood risk in the near-future and far-future projection periods becomes higher.

KEYWORDS climate change; river flow projection; Chao Phraya River; regional distributed hydrological model; MRI-AGCM3.2S

INTRODUCTION

General circulation models (GCMs) have been widely used in climate change impact studies. Nowadays hydrologic prediction studies using GCM outputs are indispensable to assess future water resources and analyze the risk of water-related disasters. MRI-AGCM3.2S (Mizuta et al., 2012) is a high-resolution atmospheric general circulation model developed by the Meteorological Research Institute (MRI), Japan Meteorology Agency. The outputs of MRI-AGCM3.2S and its former version MRI-AGCM3.1S have approximately 20 km spatial resolution, which were widely used for impact studies of water resources because of the non-necessity of spatial downscaling due to their high spatial resolution modeling.

Several impact studies were conducted at the Chao Phraya River Basin (CPRB) in Thailand. Hunukumbura and Tachikawa (2012) used the runoff projected by MRI-AGCM3.1S, which showed the increase of extreme discharge at the upper part of CPRB and the decrease of monthly discharge in October at the Pasak River basin. Kure and Tebakari (2012) showed the increased tendency of the mean annual river discharge and annual maximum daily flow at the Nakhon Sawan station located at the downstream of the four major rivers in the CPRB using the precipitation and temperature projected by MRI-AGCM3.1S and MRI-AGCM3.2S. Champathong et al. (2013) assessed the uncertainty of river flow projections using the outputs of MRI-AGCM3.1S and MRI-AGCM3.1H. Kotsuki et al. (2014) found the increase of runoff at the Nakhon Sawan area using a land surface model forced by outputs from six bias-corrected CMIP5 GCMs. Watanabe et al. (2014) projected natural river flow using newly developed bias-corrected outputs of nine GCMs and showed the increase of future river discharge in September to reference simulations.

These studies focused on natural river flow to examine the effect of climate change on river discharge excluding anthropogenic flow change. However, the river flow in the CPRB is highly regulated by the large dam reservoirs, and thus river flow projection studies need to incorporate the effect of river flow regulations into hydrologic and hydraulic simulation modeling. Wichakul et al. (2013a) showed the difference of simulated hydrographs for the 2011 flood with and without the Bhumibol and Sirikit dam operations using the same hydrologic modeling framework as used in this research. It shows the 23% increase of the flood volume at the C.2 station (the Nakhon Sawan station) for the case without dam operations. The difference of the daily peak discharge was 5,500 m³ s⁻¹ and 4,500 m³ s⁻¹ for the cases with and without the dam operation models. Mateo et al. (2014) also clarified the significant effect of the operation of the Bhumibol and Sirikit dam reservoirs on the total volume of flooded water and the flooded area in the floodplain in the CPRB for several historical floods using a physically based hydrologic model H08-CaMa with a reservoir operation component. Sayama et al. (2015) showed a considerable impact of the dam reservoir operation on river flow and inundation volume through long-term runoff and inundation simulations using a rainfall-runoff-inundation model RRI. These researches clearly show the importance of the introduction of dam reservoir operations for the historical river flow simulations in the CPRB. For future river flow projections, to suppose the current dam operations and inundation situation is the primary hydrologic modeling scenario to be considered. Therefore, impact studies of future water resources using GCM outputs in the CPRB also need to use a hydrologic and

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Correspondence to: Yasuto Tachikawa, Department of Civil and Earth Resources Engineering, Kyoto University, Nishikyo-ku, Kyoto 615-8540, Japan. E-mail: tachikawa@hywr.kuciv.kyoto-u.ac.jp

Received 16 July, 2015
Accepted 9 October, 2015

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hydraulic simulation model incorporating such human activities on the hydrologic cycle. Thus, this study aims to analyze the change of river flow due to climate change using a regional distributed hydrologic model introducing a dam reservoir operation and flood inundation component.

Wichakul et al. (2013a, 2013b) developed a regional distributed hydrologic model based on the concept of the variable infiltration capacity and a kinematic wave flow routing model including effects of dam operation and inundation, and projected river flow using MRI-AGCM3.2S without bias correction (Wichakul et al., 2014). The result showed the increase of river discharge in the CPRB all year round both in the wet and dry seasons in the far-future projection period. In this study, we introduce a bias correction method to daily precipitation and evapotranspiration in the MRI-AGCM3.2S outputs on a monthly basis to obtain river flow projection in a realistic basin condition. For the GCM daily precipitation and evapotranspiration, a distribution mapping method and a linear scaling method were applied, respectively. The bias-corrected daily precipitation and evapotranspiration were given to a regional distributed hydrological model, which consists of a rainfall-runoff model, and a flow routing model including inundation effect and dam operation. The long-term river flow projections were analyzed in terms of drought risk using annual duration curves of daily flow and flood risk using a flood frequency analysis for the annual maximum daily flow series.

INPUT DATA AND STUDY AREA

We used the MRI-AGCM3.2 outputs from three different climate experiments: the present climate experiment using the Super high resolution Present climate GCM version A (SNA, 1979–2008), the near-future climate experiment (SNA, 2015–2044), and the far-future climate experiment (SFA, 2075–2104). The GCM outputs used in the research were the projected rainfall reaching to the soil layer (PRCSL) and the projected evapotranspiration which is the summation of evaporation from the bare soil (EVPDSL) and transpiration from root zone (TRNSL). The GCM grids covering the CPRB were a total of 1,120 grids (28 columns and 40 rows) with the spatial resolution 0.1875 degrees (about 20 km), located between the latitude of 12 degrees 5 minutes and 19 degrees 24 minutes north and the longitude of 98 degrees 3 minutes and 103 degrees 7 minutes east.

To prepare the input data for a regional distributed hydrological model, the GCM outputs were processed by a distribution mapping method for daily precipitation and a linear scaling method for evapotranspiration. In the bias correction processes, the APHRODITE daily precipitation data (Yatagai et al., 2012) and a reference crop evapotranspiration data provided by the Royal Irrigation Department of Thailand (RID) from a total of twenty six stations throughout the basin. The reference crop evapotranspiration was estimated using the FAO Penman-Monteith method (Allen et al., 1998) with recorded climatology data for the 30 years from 1981 to 2010 to be the truth reference data. Corresponding to the APHRODITE data available for 1979–2007, the bias correction and the hydrological simulation were carried out for 1979–2007 (SPA, the present climate experiment), 2015–2043 (SNA, the near-future climate experiment), and 2075–2103 (SFA, the far-future climate experiment).

For the bias correction of GCM daily precipitation data, the distribution mapping method (Teutschbein and Seibert, 2012) was slightly modified and the following correction equation was applied for each month:

\[ r_{cor,i} = r_{pi} \left( \frac{F_{n}^{-1}(F_{n}(r_{pi}))}{F_{n}^{-1}(F_{n}(r_{pi}))} \right) \]

(1)

where \( r_{pi} \) is the i-th rank projected daily rainfall, \( r_{cor,i} \) is the bias corrected daily rainfall, \( F_{p}(, \), \( F_{cor}(,) \) and \( F_{n}(,) \) are cumulative distribution functions of daily rainfall for observation, GCM output of the present climate experiment (baseline values), and GCM output of the near-future and far-future climate experiments (projected values), respectively. For the bias correction of daily GCM evapotranspiration, the linear scaling method is applied. The method corrects the GCM outputs with an additive term based on the difference of long-term monthly mean reference evapotranspiration and the GCM evapotranspiration as

\[ e_{cor} = e_{pi} + c \]

(2)

where \( e_{pi} \) is the i-th day future projected daily evapotranspiration, \( e_{cor} \) is the bias corrected daily evapotranspiration, and \( c \) is the correction factor for each month.

The discharge monitoring station is the C.2 station located at the latitude 15 degrees 40 minutes north and the longitude 100 degrees 6 minutes east about 5 km downstream of the Ping River and Nan River confluence, which is the beginning of the Chao Phraya River as shown in Figure 1. The river discharge projections at the C.2 station represent the overall characteristics of the change of the flow regime in the Chao Phraya River basin.

MODELING APPROACH

A regional distributed hydrological model, which consists of a rainfall-runoff model and a flow routing model including dam operation (Wichakul et al., 2013a, 2013b), was used to project future river discharge. The rainfall-runoff model used is the simplified Xinanjiang model (Nirupama et al., 1996), which estimates runoff intensity based on the concept of the variable infiltration capacity. The flow routing model used is the modified 1K-FRM (Tachikawa and Tanaka, 2013), which is a flow routing model using a kinematic wave approximation including the reservoir operations at the Bhumibol and Sirikit dams and inundation effect in low land areas to obtain realistic discharge projections for the CPRB (Wichakul et al., 2013b). Figure 2 explains an algorithm of the dam operation model. In the dry season from January to April water release was determined by the lower rule curve and downstream requirement. The downstream requirements were derived from observed data for 200 m³ s⁻¹ and 250 m³ s⁻¹ for the Bhumibol and the Sirikit dam, respectively. In the rainy season from May to December water release was determined by the upper and lower rule curves and spillway capacity. When the reservoir storage is lower than upper rule curve, the Bhumibol and the Sirikit dams release approximately 15% and 30% of the dam inflow to maintain downstream flow, respectively. Figure 3 shows the framework of the model simulation.
The bias-corrected daily precipitation and evapotranspiration were given to the simplified Xinanjiang model to generate runoff intensity for 1,120 grid cells (28 columns and 40 rows with 0.1875 degrees spatial resolution) covering the CPRB. Then, the runoff intensity data was input to the modified 1K-FRM represented by the 288,000 computational grid cells (480 columns and 600 rows with 30 seconds spatial resolution). Finally, the projected river discharge was extracted at the grid cell representing the C.2 station.

**RESULTS AND DISCUSSION**

River discharge assessment under a changing climate

By using the bias corrected precipitation and evapotranspiration as input to the regional distributed hydrological model, we generated a series of daily discharge for twenty-nine years in each climate experiment period for the 288,000 grid cells covering the CPRB. Mean monthly discharge at the C.2 station was calculated to detect a trend of stream flow change under a changing climate as shown in Figure 4. In the dry season, the simulated river flow at the C.2 station is more than 450 m$^3$ s$^{-1}$ due to dam release, which should be almost zero if the dam operation model is not included. Projected mean monthly discharge for the near-future and far-future climate experiments showed a significant increase of about 10% to 41% compared to the present climate experiment. For the near-future experiment, most of the mean monthly discharge also showed an increase of about 10% to 25% compared to the present climate experiment. The discharge of the near-future climate experiment increased in October at the same rate of increase as the far-future climate experiment. Only in May, the mean discharge did not change. According to the Thailand climatology, May is the end of a dry season and the beginning of a rainy season and the natural runoff in May is the smallest among other months. Thus, the river discharge in May is highly controlled by the dam release and the changes of rainfall and evapotranspiration intensity have less effect on the mean discharge in May.

Figure 5 presents mean annual daily-flow duration curves with standard deviations for the three climate experiments.

Figure 1. Diagram of the Chao Phraya River Basin including the inundated area during the 2011 flood

Figure 2. Flow chart of dam operation model

Figure 3. Framework of a regional distributed hydrological model including an inundation model and a dam operation model

Figure 4. Flow chart of dam operation model

Figure 5. Mean annual daily-flow duration curves with standard deviations for the three climate experiments.
The mean annual duration curve is obtained by calculating the mean daily flow of the same calendar date during the projected periods for each experiment. It clearly shows that the magnitudes and the variances of river flow considerably increase for the high flow part with the exceedance probability less than 0.4 in both the near-future and far-future climate experiments. This means the magnitude of river discharge and its variance in the far-future period have a tendency to increase for all rainy season months.

River discharge during the low flow months in the dry season is influenced by the artificial dam release. To consider the river flow regulation, the dam operation models at the Bhumibol dam and the Sirikit dam were embedded in the flow routing model. For the low flow part with the exceedance probability larger than 0.6, there is also slight increase signal for the near-future and far-future climate experiments. This means the magnitude of river discharge and its variance in the far-future period have a tendency to increase for all rainy season months.

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**Frequency analysis of annual maximum daily discharge series**

A frequency of the occurrence of the extreme floods was analyzed by fitting the probability distribution functions to the annual maximum daily discharge series. The distribution functions used in this study were the square-root exponential type maximum distribution (SQRT-ET), the generalized extreme value distribution (GEV), and the Gumbel distribution. The distribution function of the SQRT-ET distribution (Etoh et al., 1987) is:

\[
F(x; \beta, \lambda) = \begin{cases} 
-\lambda \left(1 + \sqrt{\beta x} \right) \exp \left(-\sqrt{\beta x} \right) & x \geq 0, \\
0 & x < 0.
\end{cases}
\]

(3)

where \( \beta \) is a scale parameter; \( \lambda \) is a frequency parameter; and \( x \) is an annual maximum daily discharge. The GEV distribution has a distribution function for \( k \neq 0 \) as:

\[
F(x; a, c, k) = \frac{1}{1 + k} \left[ \frac{1}{a} \left(1 + \left(\frac{x - c}{a}\right)^{-1/k} \right) \right] \left(1 + k \left(\frac{x - c}{a}\right)^{-1/k} \right)^{\frac{1}{k}-1} 
\]

(4)

where \( a \) is a positive scale parameter; \( c \) is a location parameter; and \( k \) is a negative shape parameter. In the case of \( k = 0 \), the GEV distribution is equivalent to the Gumbel distribution shown as:

\[
F(x; a, c) = \exp \left[-\exp \left(\frac{x - c}{a}\right) \right] 
\]

(5)

The annual maximum series of daily river discharge at the C.2, Y.16, N.67 and P.17 stations were extracted from three periods of projections to fit with the distribution functions as mentioned above. The Y.16, N.67 and P.17 stations are the representative flow stations at the Yom, Nan and Ping River basins located at the upper part of the C.2 station. The Y.16, N.67 and P.17 stations are located at latitude 16 degrees 45 minutes north and longitude 100 degrees 7 minutes east, latitude 15 degrees 52 minutes north and longitude 100 degrees 15 minutes east, and latitude 15 degrees 56 minutes north and longitude 99 degrees 58 minutes east, respectively (see Figure 1). The standard least-squares criterion, SLSC (Takara and Takaso, 1998) was used to evaluate the goodness of fit for each distribution function to the annual maximum daily discharge. Table I shows a comparison of the goodness-of-fit for the annual maximum daily discharge at the C.2, Y.16,
Changes of the $T$-year annual maximum daily discharge for the different periods are illustrated in Figure 7 for the C.2, Y.16, N.67 and P.17 stations. The return periods around 50-years corresponds to the design level of flood control structures such as irrigation structures and urban drainage systems. Referring to Figure 7(a), the magnitude of the extreme flood events at the C.2 station significantly increase for the near-future and far-future climate experiments. The change in flood magnitude at the Y.16, N.67 and P17 stations as shown in Figures 7(b), (c), and (d) also shows similar characteristics. The reliability of the estimated quantile decreases when the corresponding return period is longer than the period of data. In Figure 7(a), (c) and (d) the quantiles of the far-future experiment are smaller than the near-future experiment. This could be caused by the shorter data durations (29 years). However, the overall trend shows the flood risk increases in the future.

CONCLUSIONS

Many researchers analyzed the change of naturalized river flow at the Chao Phraya River basin due to climate change. However, the river flow in the CPRB is highly regulated by large dam reservoirs and future river flow projection studies
need to incorporate the effect of human activities in hydrologic simulation modeling. In the research, the change of river flow characteristics including a real basin situation such as dam reservoir control and inundation was analyzed. To obtain a river flow projection for a realistic basin condition at the Chao Phraya River basin, bias-corrected precipitation and evapotranspiration projected by the MRI-AGCM3.2S were applied to the regional distributed hydrological model including inundation and dam operation components. The findings from the analysis of the projected river discharge at the Nakhon Sawan station (C.2 station) are as follows: 1) the mean monthly discharge tends to increase in both the near-future and far-future projection periods for all months; 2) low-flow exceeding 99% of a mean daily flow duration curve for the near-future and far-future periods tends to decrease; and 3) a flood frequency analysis with the GEV distribution using the annual maximum daily flow series indicates that the flood risk in the near-future and far-future projection periods becomes higher. These findings of our study are compatible with the previous studies by Hunukumbura and Tachikawa (2012), Kure and Tabei (2012), Kotsuki et al. (2014), and Watanabe et al. (2014). The result is different from the study by Champhong et al. (2013), which may arise from the difference of used GCM outputs, with and without bias correction for input data, and different hydrologic model settings. The analysis shows the increase of flood risk in the near-future and far-future projection periods and the possibility of the extreme low flow for the far-future period.

ACKNOWLEDGMENTS

We acknowledge the Royal Irrigation Department of Thailand for providing the rainfall, evapotranspiration, and river discharge data. This work was conducted under the framework of the “Precise impact assessments on climate change” supported by the SOUSEI Program of the Ministry of Education, Culture, Sports, Science, and Technology.

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