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Hydrological impact of regional climate change in the Chao Phraya River Basin, Thailand

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Abstract:

The warming of the Earth's atmosphere system will change temperature and precipitation distributions across the globe. This will affect the hydrological cycle and, therefore, the hydrology of river basins worldwide. In this study, we model the stream flow of the Chao Phraya River Basin (CPRB), Thailand, in response to two climate change projection data sets under scenario A1B of the Special Report on Emissions Scenarios. We used Japan Meteorological Research Institute (MRI) atmospheric general circulation model 3.1 and 3.2 output data as input to a watershed hydrologic model to assess the impact of climate change for the basin. We found that, in the future, the mean annual river discharge is likely to increase in the CPRB due to increased rainfall. Furthermore, increases in annual maximum daily flows will occur toward the end of the 21st century.

KEYWORDS climate change; Thailand; Chao Phraya River Basin; watershed hydrologic model

INTRODUCTION

Climate change caused by global warming is a growing public concern throughout the world. Changes in air temperature and precipitation due to climate change may seriously affect the hydrology and water resources of river basins worldwide. Between June and October 2011, five tropical storms and three strong low-pressure systems caused historical levels of flooding and the worst recorded damage in Thailand. Extensive flooding caused the most damage in the capital of Bangkok; in Nakhon Sawan; and in Ayutthaya, the ancient capital located in the Chao Phraya River Basin (CPRB), the largest basin in Thailand. In the CPRB, more than 700 people were killed during the floods of 2011 and approximately 1.8 million pastoral homesteads were damaged. The events of 2011 beg two important questions: 1) was the flooding a direct result of climate change? and 2) with what frequency will such extreme flooding events occur in the future? It is thus important to examine what future changes could happen to the CPRB and its hydrological cycle as a result of climate change, and to quantify these effects so that we might better mitigate future flooding events.

Many regional climate change studies across the world have used hydrologic models with climate projections to simulate the responses of river basins to climate change (e.g., Evans and Schreider, 2002; Milly *et al.*, 2005; Nohara *et al.*, 2006; IPCC, 2007; Kiem *et al.*, 2008; Nakaegawa and Vergara, 2010; Kim *et al.*, 2010; Ma *et al.*, 2010; Tatsumi *et al.*, 2011; Nakaegawa and Nakakita, 2012; Yamashiki *et al.*, 2012; Hunukumbura and Tachikawa, 2012). For example, Milly *et al.* (2005) and Nohara *et al.* (2006) projected global river discharge simulated by a multimodel ensemble of atmospheric general circulation models (AGCMs) under the Special Report on Emissions Scenarios (SRES) A1B scenario. Their results indicated that under changing climate, runoff and river discharge in the CPRB are likely to increase. However, the spatial resolutions of the AGCM outputs used in those studies were too coarse for climate change impact assessment at the local sub-basin scale. To examine local impacts, a spatial downscaling technique, such as dynamical downscaling using a regional climate model, could be applied (e.g., Evans and Schreider, 2002). Another approach would be to employ a super high-resolution atmospheric model (e.g., Japan Meteorological Research Institute [MRI] AGCM) with 20-km spatial resolution to study climate change impacts at sub-basin scales (e.g., Kiem *et al.*, 2008; Nakaegawa and Vergara, 2010; Ma *et al.*, 2010; Kim *et al.*, 2010; Hunukumbura and Tachikawa, 2012). Hunukumbura and Tachikawa (2012) used MRI-AGCM3.1 output data as input to a distributed flow routing model based on the kinematic wave flow model in the CPRB. They showed clear changes in river discharge and found that future flood risk is likely to increase in the CPRB. They also showed a significant decrease in discharge at the Pasak River Basin in the CPRB. These results clearly demonstrate the importance of discharge simulations with high spatial resolution. However, in their study, only one AGCM was employed to project future river discharge, and Manning's roughness coefficient for the flow routing model were determined from typical values derived from Japanese basins. Other AGCMs with calibrated flow routing or watershed hydrologic models should be applied to the CPRB to compare simulation results and reduce uncertainties regarding future climate change.

The main objective of this study was to evaluate the impact of climate change on the hydrology and water resources of the CPRB in Thailand. In particular, we estimated the impact of climate change on river discharges by using a watershed hydrologic model and the outputs from MRI-AGCM3.1 and 3.2.

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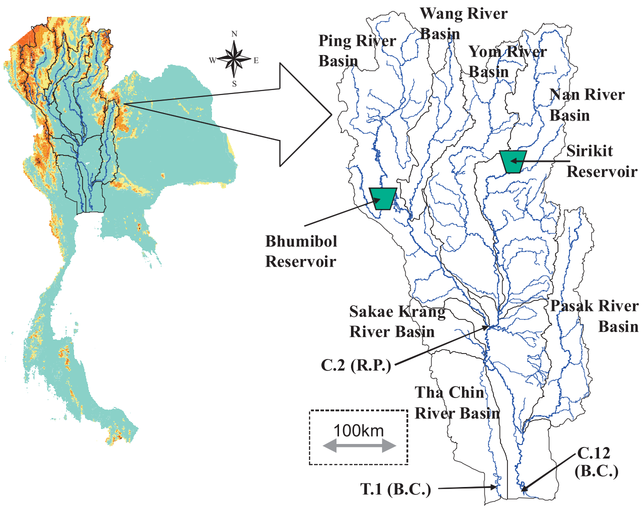

Figure 1. Thailand and the Chao Phraya River Basin (C.2: Nakhon Sawan, T.1: Nakhon Pathom, and C.12: R.I.D. Bangkok).

STUDY AREA

The CPRB (Figure 1), located in the heart of Thailand, covers roughly 31% of the country's land surface and is the largest river basin in the country. The locations of the main dams in the CPRB are also shown in Figure 1. The Chao Phraya River system consists of four principal tributaries: the Ping (36,018 km^2), the Wang (11,708 km^2), the Yom (24,720 km^2), and the Nan (34,557 km^2). Both the Wang and Yom tributaries and the Ping and Nan tributaries join in the upper third of the CPRB. The Ping and Nan meet at Nakhon Sawan (C.2) to form the Chao Phraya River, which flows down through the lower basin (through Ayutthaya and Bangkok) before discharging into the Gulf of Thailand. Due to the Asian summer monsoon, rainfall distribution over the CPRB varies distinctly between the rainy (May–October) and dry (November–April) seasons. Mean rainfall during the rainy season accounts for about 90% of mean annual rainfall in the CPRB (see Figure S1 in the supplemental material S1).

METHODOLOGY

Super high-resolution atmospheric model

The latest AGCM, MRI-AGCM20, was used to project the future hydrological impacts on the CPRB that we examine in this study. The MRI-AGCM20 was developed by the Japanese Meteorological Agency and the MRI of Japan (Mizuta *et al.*, 2006, 2012; Kitoh *et al.*, 2009). One advantage of using the MRI-AGCM20 is that it produces an output with spatial resolutions of 20 km, which allows regional climate change assessment to be evaluated in great detail. Rainfall and air temperature components from MRI-AGCM20 outputs were used as input data to the watershed hydrologic model in this study. The MRI-AGCM20 provides present-term (1980–2004), near future-term (2015–2039), and future-term (2075–2099) outputs. In this study, we used outputs from ver. 3.1 and 3.2 of the MRI-AGCM20 (MRI-AGCM3.1 and MRI-AGCM3.2) under the SRES A1B scenario. Various new parameterization schemes were introduced to MRI-AGCM3.2 to simulate extreme weather events (Mizuta *et al.*, 2012). MRI-AGCM3.1 and MRI-AGCM3.2 were treated as different models in this study to increase the number of future projections.

Bias correction

We employed two bias correction methodologies for rainfall projections in this study. The hybrid statistical bias correction (HSBC) method was developed by the International Centre for Water Hazard and Risk Management (ICHARM), Public Works Research Institute of Japan, and compares MRI-AGCM20 daily rainfall output with observed ground rainfall data using a non-exceedance probability (Inomata *et al.*, 2011). The other method uses the monthly climatology (CLM) of sub-basins (Ohara *et al.*, 2011). In this method, AGCM20 and observed rainfall data were compared for each sub-basin during the model's calibration period (1980–1996), giving a mean monthly ratio of rainfall for each sub-basin. Model validation results of bias correction are discussed in the supplemental material S1.

Watershed hydrologic model

We used the watershed hydrologic model DHI MIKE 11 (e.g., Woltemad and Potter, 1994) to perform river runoff projections in the CPRB because this model has been successfully implemented and calibrated in previous studies (Tebakari *et al.*, 2006). We selected the Nedbor-Afstromnings model (Refsgaard and Knudsen, 1996) as the rainfall runoff module because it is suitable for long-term simulations as it simulates rainfall runoff processes in each sub-basin by continuously accounting for the water content in four different, mutually interrelated, water storages that represent different physical elements of the catchment. For flood routing of the river, the unsteady flow simulation module (Saint Venant equations) was used.

Due to data limitations, we adopted the Blaney-Criddle method (Brouwer and Heibloem, 1986), which requires only daily mean air temperature as climate data, to compute potential evapotranspiration. Evapotranspiration rates for potential evapotranspiration at each sub-basin during each month were determined by trial and error based on observed discharge data during the model calibration processes. Then, bias-corrected rainfall data and evapotranspiration data were used as input data to the watershed hydrologic model.

Boundary conditions were included in the model for the hydrological station C.12 (Royal Irrigation Department [RID], Bangkok) on the Chao Phraya River about 40 km upstream from the river mouth, and at hydrological station T.1 (Nakhon Pathom) along the Tha Chin River about 50 km upstream from the river mouth (Figure 1). A time series of historical daily mean water level was also available for each station, and these data were used as the boundary conditions of the simulation during the historical and future periods. The flow evaluation points used in this paper were located more than 300 km upstream from the river mouth, so that the lower boundary conditions did not affect the simulation results.

For model validation, comparison was made between model runs and observed daily discharge rates during the model calibration (1956–1959) and validation (1960–1962)

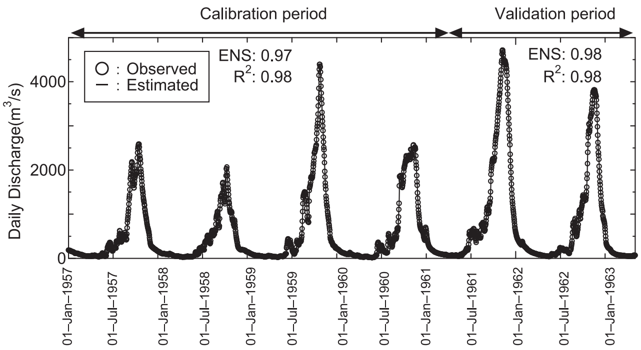

Figure 2. Comparison of simulated and observed daily flow at Nakhon Sawan (C.2) station in the Chao Phraya River Basin during the model calibration (1957–1961) and validation (1961–1963) periods.

periods. These periods were selected as there were very few hydraulic facilities operated in the basin during these period and we did not consider gate operations of dam reservoirs in the models due to a lack of available information. Thus, the hydrologic simulation was made assuming that land and cover conditions have not changed from 1962 until present and that estimated discharge denoted only natural flows in the basin. Hydraulics facilities affect base flows and high flows in the CPRB (Tebakari *et al.*, 2006). However, in this study, our aim was to compare results for the historical and future periods without including the effects of dam operations.

Observed rainfall and pan evaporation data were used as input data to the watershed hydrologic model for calibration and validation of the model. Flow discharge data provided by the RID were also used for calibration and validation. Figure 2 shows graphical comparisons of the simulated daily discharge against observations at Nakhon Sawan (C.2) station in the CPRB during the calibration and validation periods. The Nash-Sutcliffe efficiency coefficients (ENS) and the coefficient of determination (R^2) are 0.97 and 0.98 for the calibration period and 0.98 and 0.98 for the validation period, respectively. As shown by Figure 2 and these values, the simulated discharge matches corresponding observations very well at the daily time scale.

Evaluation of the simulation results

The changes in mean monthly and annual rainfall and mean daily discharge for the historical (1980–2004), near future (2015–2039), and late future (2075–2099) periods were examined statistically with Student's *t*-test. Flood frequency analysis using annual maximum daily flows for the historical and future periods was also conducted. Return periods and non-exceedance probabilities were determined by the Hazen plotting position using 50-year river runoff projection simulations (i.e., 50 data for each period) from two realizations (ver. 3.1-HSBC and ver. 3.2-HSBC) during the 25-year period. Only the HSBC bias correction method was employed for this analysis because that method captured extreme daily rainfall events well.

RESULTS

The bias-corrected rainfall and air temperature projections from MRI-AGCM3.1 and 3.2 were analyzed and used as input variables for our watershed hydrologic model. According to the projections, mean annual air temperature (mean values of ver. 3.1 and 3.2) will increase by 2.8°C for the late future period 2075–2099. Table I lists mean monthly and annual rainfall for the CPRB and mean daily discharge (m^3 s^{-1}) at Nakhon Sawan (C.2) for each month during the historical period (1980–2004), near future period (2015–2039), and late future period (2075–2099) based on 1980–2004 data. Mean values from two bias correction methods, HSBC and CLM, are shown in the table. Comparisons of mean daily discharge at points upstream of the Bhumibol and Sirikit dams and the outlet points of the Yom, Pasak, and Wang River basins are also shown in Table SII.

Near future (2015–2039)

As shown by Table I, significant differences at the 5% level in mean monthly and annual rainfall at the CPRB were not detected in results by MRI-AGCM3.1 in the near future. However, significant differences at the 5% level in mean monthly rainfall at the CPRB in June and significant differences at the 10% level in July, September, and December were shown by MRI-AGCM3.2 in the near future. Significant increases at the 5% and 10% levels in mean daily discharge were detected only by MRI-AGCM3.2 at Nakhon Sawan (C.2) in the near future. However, MRI-AGCM3.2 detected no significant differences at the 5% or 10% level in mean daily discharge upstream of Sirikit dam in the Nan River Basin or at the outlet of the Yom River Basin (see Table SII). Mean daily discharge in the Pasak River Basin decreased in MRI-AGCM3.1 in the near future, but not at a statistically significant level. However, it is significantly increased in MRI-AGCM3.2 from January through June. These differences originated from the projected rainfall differences at each sub-basin between the two AGCMs. The differences in future discharge changes at neighboring sub-basins demonstrate the importance of using several AGCMs with fine spatial resolution to assess regional climate change impacts at the local sub-basin scale. Different GCMs may provide different results for future rainfall at the local sub-basin scale.

Late future(2075–2099)

Significant increases at the 5% level in mean annual rainfall at the CPRB were detected by both MRI-AGCM3.1 and 3.2 in the late future period (2075–2099). Significant increases at the 5% level in mean daily discharge were also shown by both MRI-AGCM3.1 and 3.2 at Nakhon Sawan (C.2) in the late future. However, significant differences at the 5% level in mean daily discharge were not detected upstream of Sirikit dam or at the outlet of the Yom River Basin by MRI-AGCM3.2 in the late future (see Table SII). In addition, mean daily discharge in the Pasak River Basin decreased in MRI-AGCM3.1 in the future but increased in MRI-AGCM3.2, although these differences were not statistically significant.

The annual increase in volume at Nakhon Sawan (C.2) was also calculated from these simulation results and is roughly 3 billion m^3 for the late future period, which is

Table I. Changes in rainfall (mm) in the CPRB and in mean daily discharge (m^3/s) at Nakhon Sawan (C.2) station during future periods (2015–2039 and 2075–2099), based on 1980–2004 data. Difference results significant by Student's *t*-test at the 10% and 5% levels are written in the bold font and bold font with double underlines, respectively.

Rainfall [mm] at CPRB														
Ver3.1		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual
1980–2004	Mean	3.6	10.0	27.9	59.7	155.5	130.9	139.8	178.1	211.2	130.8	36.7	7.8	1091.6
2015–2039	Change	0.6	0.7	−1.7	1.2	2.3	1.2	0.4	3.3	6.9	−8.2	−7.1	−2.4	−2.8
2075–2099	Change	−0.3	0.1	−0.4	**5.7**	**4.9**	**8.3**	**16.9**	**19.3**	**8.8**	**−0.7**	**−0.4**	**4.0**	**66.1**
Ver3.2														
1980–2004	Mean	3.5	9.3	25.9	58.0	155.1	129.6	138.7	177.8	212.1	127.3	36.1	7.8	1081.0
2015–2039	Change	2.3	0.7	−3.5	−0.8	−0.8	**17.0**	**−17.0**	3.8	**15.2**	12.4	−7.6	**−4.0**	17.7
2075–2099	Change	3.5	−0.7	−4.4	2.6	2.7	**28.5**	−2.6	**18.4**	−0.4	23.3	−7.1	0.6	**64.3**
Daily Discharge [m^3/s] at Nakhon Sawan station														
Ver3.1		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual
1980–2004	Mean	129.5	79.4	57.6	42.8	41.2	80.5	178.2	460.9	1174.6	1838.2	1213.1	404.4	475.0
2015–2039	Change	−11.2	−1.0	−0.4	−0.2	−1.7	−3.9	−35.6	−20.2	104.7	57.0	−51.8	−63.4	−2.3
2075–2099	Change	16.5	**14.9**	**12.4**	**10.4**	**10.6**	10.3	11.7	**121.9**	**413.7**	**306.8**	143.5	16.6	**90.8**
Ver3.2														
1980–2004	Mean	167.8	105.3	75.3	54.7	52.4	112.6	210.7	499.0	1464.4	1979.9	1218.3	421.2	530.1
2015–2039	Change	16.8	**24.9**	16.5	11.8	**23.0**	**53.6**	**97.7**	46.2	62.8	275.2	84.0	−17.4	57.9
2075–2099	Change	26.9	27.3	20.0	14.2	8.7	24.4	91.0	**174.3**	**329.5**	318.2	132.2	2.3	**97.4**

around 12.5% of the total storage capacity of the Bhumibol and Sirikit dam reservoirs (24 billion m^3).

Flood frequency analysis

Flood frequency analysis using annual maximum daily flows for the historical (1980–2004), near future (2015–2039), and late future (2075–2099) periods was conducted for Nakhon Sawan (C.2) and points upstream of the Bhumibol and Sirikit dams. The annual maximum daily flow discharge corresponding to various return periods during the historical, near future, and late future periods at the three flow stations is shown in Figure 3. Flood frequency distributions change markedly and increases in high flows are apparent upstream of Bhumibol dam in the near future under the changing climate projections, as shown in Figure 3. However, apparent increases in high flows were not detected upstream of Sirikit dam and Nakhon Sawan in the near future. Flood frequency distributions were projected to change markedly in the late future under the changing climate projections, as shown in Figure 3. Increases in high flows are apparent in the late future at Nakhon Sawan and upstream of Bhumibol dam (Figure 3). However, increases in high flows were not detected upstream of Sirikit dam in the late future, as also found in the near future period (2015–2039). It can be seen from Figure 3 that 100-year return period daily annual maximum flows upstream of Bhumibol and Sirikit dams in the late future are smaller than those in the near future. However, this change is not seen at Nakhon Sawan (C.2). This is because the largest rainfall events at the Nan and Ping River basins in the near future period are much larger than those in the late future period. This result suggests that future flood situations and magnitudes will differ among neighboring sub-basins in the CPRB. This result also shows the importance of using an AGCM with fine spatial resolution to assess regional climate change impacts at local sub-basin scales. However, the largest

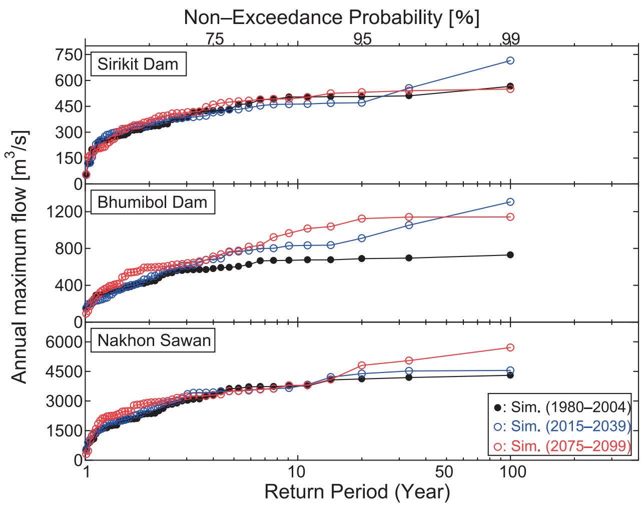

Figure 3. Frequency of annual maximum daily flow at Nakhon Sawan (C.2; lower) and points upstream of Bhumibol (middle) and Sirikit (upper) dams in the Chao Phraya River Basin.

rainfall and flood events for the sub-basins might have some uncertainties arising from the AGCMs, gas emission scenario, and watershed hydrologic model employed in this study. It is noted that we could not calculate the confidence intervals for the historical and future analysis data due to the shortage of the number of data (50 data for each period). It means that the confidence interval for the analysis data might have wide ranges and the statistical significances of the future flood changes were not detected in this study. It is preferable to use several AGCMs with fine spatial resolution, gas emission scenarios, and watershed hydrologic models for the climate change impact assessment at the sub-

basin scale to reduce the uncertainties of extreme flood events by increasing the number of ensemble members (i.e., the number of data used for the flood frequency analysis). This should result in more accurate evaluation of 100-year return period annual maximum flow with confidence intervals in the target area in the future periods under projected changes in climate. However, as shown in Figure 3, the magnitudes of the daily high flows in the late future period are, in general, higher than their counterparts during the historical period (1980–2004). From this result, it can be said that extreme flooding and high-flow discharge events in the CPRB are likely to become more frequent toward the end of the 21st century.

DISCUSSION AND SUMMARY

In this study, hydrological responses to climate change in the CPRB were analyzed based on the watershed hydrologic model with bias-corrected MRI-AGCM3.1 and 3.2 projections.

The mean annual flow discharge clearly increased in the late future (2075–2099) at Nakhon Sawan (C.2) upstream of the Bhumibol dam and at the outlet point of the Wang River Basin in both MRI-AGCM3.1 and 3.2 due to increased rainfall. Furthermore, flood frequency analysis showed increases in annual maximum daily flow toward the end of the 21st century at Nakhon Sawan and points upstream of the Bhumibol dam. The magnitudes of the daily high flows in the late future period were, in general, higher than their counterparts during the historical period (1980–2004). The projected annual volume increase at Nakhon Sawan for the late future period is about 3 billion m^3, which is about 12.5% of the total main dams' reservoir storage capacity (24 billion m^3).

These results imply that extreme flooding and high-flow discharge events, such as those that occurred in the summer of 2011, will become more frequent in the future due to the high projected rainfall values. The risk of conurbations becoming inundated with floodwater may increase due to the increase in the magnitude of flood events caused by the change in climate conditions. These results indicate that a new flood management and mitigation plan, including the construction of new dam reservoirs and alterations to dam gate operation rules, will likely be necessary in the CPRB to better prepare the region for future flood events.

The results of this analysis basically agree with those of studies previously performed in the CPRB (Milly *et al.*, 2005; Nohara *et al.*, 2006; Hunukumbura and Tachikawa, 2012). Hunukumbura and Tachikawa (2012) used MRI-AGCM3.1 and found a significant decrease in discharge in the Pasak River Basin in the CPRB. However, in this study, MRI-AGCM3.2 showed an increase in river flow discharge in the Pasak River Basin in the late future, although the differences in mean daily discharge were not statistically significant. Further studies should include other high- and low-emission scenarios and different AGCMs to provide a fuller range of possible outcomes. Uncertainties in the climate change modeling in this study included the GCM model structure, the reliability of the emission scenario, and the internal variability of the nonlinear Earth systems. In this study, a conceptual *ET* calculation method, the Blaney-Criddle method, was employed and only air temperature data were used to simulate evapotranspiration. To precisely analyze future drought conditions at the CPRB under changing climate, a physically based *ET* calculation method may be required because, in addition to air temperature, atmospheric components such as shortwave and longwave radiation and wind speed may also change and affect *ET* values.

We used the same calibrated parameter values in the watershed hydrologic model for the simulation of historical and future conditions. In addition, land cover/land use conditions were the same in both historical and future simulations. Furthermore, activities such as water supply for irrigation and gate operations of the dam reservoirs were not taken into account in the model simulations due to a lack of available information. We recommend that future studies examine the impact of human use of water in the region.

ACKNOWLEDGMENTS

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SUPPLEMENTS

S1. Supplementary document describing the bias correction of rainfall and providing figures and tables.

- Figure S1. Comparison of bias-corrected and observed mean monthly basin-averaged rainfall values in the Chao Phraya River Basin.
- Figure S2. Comparison of simulated and observed daily basin-averaged rainfall in the Chao Phraya River Basin using the probability of non-exceedance and a relative frequency histogram.
- Table SI. Statistical comparison of observed and bias-corrected monthly rainfall values during the model validation period (1980–1996).
- Table SII. Changes in mean daily discharge (m^3/s) at the Chao Phraya River Basin. Points upstream of Bhumibol and Sirikit dams and outlet points of the Yom, Pasak, and Wang River basins during the future periods (2015–2039 and 2075–2099), based on 1980–2004 data.

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