Impact of Climate Change on Reservoir Reliability: A Case of Bhumibol Dam in Ping River Basin, Thailand

Allan Sriratana Tabucanon[1], Areeya Rittima[2*], Detchasit Raveephinit[2], Yutthana Phankamolsil[3], Wudhichart Sawangphol[4], Jidapa Kraisangka[4], Yutthana Talaluxmana[5], Varawoot Vudhivanich[6], and Wenchao Xue[7]

[1]*Faculty of Environment and Resource Studies, Mahidol University, Nakhon Pathom 73170, Thailand*
[2]*Faculty of Engineering, Mahidol University, Nakhon Pathom 73170, Thailand*
[3]*Environmental Engineering and Disaster Management Program, Mahidol University, Nakhon Pathom 73170, Thailand*
[4]*Faculty of Information and Communication Technology, Mahidol University, Nakhon Pathom 73170, Thailand*
[5]*Faculty of Engineering, Kasetsart University, Bangkok 10900, Thailand*
[6]*Faculty of Engineering at Kamphaeng Saen, Kasetsart University, Nakhon Pathom 73140, Thailand*
[7]*Department of Energy, Environment and Climate Change, School of Environment, Resources and Development, Asian Institute of Technology, Pathum Thani 12120, Thailand*

ARTICLE INFO

Received: 21 Jan 2021
Received in revised: 18 Mar 2021
Accepted: 16 Apr 2021
Published online: 18 May 2021
DOI: 10.32526/ennrj/19/2021012

Keywords:
Bhumibol Dam/ Climate change/ Hydrological model/ Ping River Basin/ Reservoir reliability

*** Corresponding author:**
E-mail: areeya.rit@mahidol.ac.th

ABSTRACT

Bhumibol Dam is the largest dam in the central region of Thailand and it serves as an important water resource. The dam's operation relies on reservoir operating rules that were developed on the basis of the relationships among rainfall-inflow, water balance, and downstream water demand. However, due to climate change, changing rainfall variability is expected to render the reliability of the rule curves insecure. Therefore, this study investigated the impact of climate change on the reliability of the current reservoir operation rules of Bhumibol Dam. The future scenarios from 2000 to 2099 are based on EC-EARTH under RCP4.5 and RCP8.5 scenarios downscaled by RegCM4. MIKE11 HD was developed for the inflow simulation. The model generates the inflow well (R^2=0.70). Generally, the trend of increasing inflow amounts is expected to continue in the dry seasons from 2000-2099, while large fluctuations of inflow are expected to be found in the wet seasons, reflecting high uncertainties. In the case of standard deviations, a larger deviation is predicted under the RCP8.5 scenario. For the reservoir's operation in a climate change study, standard operating procedures were applied using historical release records to estimate daily reservoir release needed to serve downstream water demand in the future. It can be concluded that there is high risk of current reservoir operating rules towards the operation reliability under RCP4.5 (80% reliability), but the risk is lower under RCP8.5 (87% reliability) due to increased inflow amounts. The unmanageability occurs in the wet season, cautioning the need to redesign the rules.

1. INTRODUCTION

Anthropogenic greenhouse gas emissions have been regarded as the cause for 1.0°C of global warming above pre-industrial levels. The global warming phenomenon has been scientifically related to changing rainfall variability patterns (IPCC, 2018). The IPCC (2012) concluded that climate change is causing the emergence of statistically significant trends in the number of heavy rainfall events, as well as more intense and longer droughts. These findings are also consistent with statistical long-term records of Thailand, including increasing extreme temperature indices (Limsakul, 2020), as well as less frequent but more intense rainfall events (Limsakul and Singhruck, 2016). Raneesh (2014) proposed a variety of factors arising from the challenges in water resources planning and management. The major factor will be the impact of climate change through the alteration of

Citation: Tabucanon AS, Rittima A, Raveephinit D, Phankamolsil Y, Sawangphol W, Kraisangka J, Talaluxmana Y, Vudhivanich V, Xue W. Impact of climate change on reservoir reliability: A case of Bhumibol Dam in Ping River Basin, Thailand. Environ. Nat. Resour. J. 2021;19(4):266-281. (https://doi.org/10.32526/ennrj/19/2021012)

the hydrological cycle, which affects quantity and quality of regional water resources, especially in Asia. These consequences will be further exacerbated by population growth, economic factors, and land use changes (including urbanization). Shiferaw et al. (2014) and Miyan (2015) found that these changes impact the vulnerable and poor, especially those related to agricultural activities. A major reason for the impact is the uncertainty of the capability of reservoir operating rules for dams influenced by the impacts of climate change (Kang et al., 2007; Kim et al., 2009; Ehsani et al., 2017). Reservoir operating rules are generally developed based on the relationship between rainfall-inflow, water balance, and downstream water demand. The rules are applied to ensure appropriate management of flood in the wet season and water scarcity in the dry season. Therefore, understanding future changes of inflow into the dam is important for adaptive management of the rules (Raneesh, 2014; Koontanakulvong et al., 2020).

The objective of this study was to investigate the impact of climate change on the reliability of the current reservoir operating rules of Bhumibol Dam, the largest dam in Thailand, which is an important water resource for agriculture in the central region, especially in the dry season (Kitpaisalsakul, 2018; Koontanakulvong et al., 2020). This is one of two major dams regulating the Chao Phraya River, the major river in Thailand. From a historical perspective, floods frequently occur in Thailand and the 2011 flood was the largest experienced by the country, which was triggered by successive storms that forced the dam to fully release its stored water. The 2011 flood was responsible for economic losses totaling 45.5 billion USD (World Bank, 2012). In contrast, due to inadequate rainfall, there was a severe drought in 2020. It was anticipated that production of sugarcane, off-season rice and cassava were decreased by 27%, 21% and 7%, respectively. This resulted in an extensive decline of the farmers' overall income. The most seriously impacted region was in the central part of the country and was influenced by critically low water level in the dams (Siam Commercial Bank, 2020). The start of the problems in 2020 can be traced to November 2019, when the total reservoir storage of Bhumibol Dam was at a critical level of only 22% (Thana-dachophol et al., 2020).

Kitpaisalsakul (2018), and Sharma and Babel (2013) conducted a climate change impact study on the inflow and water storage of the dam. However, their study lacked consideration of a number of updated climate change scenarios to sufficiently address future uncertainties and reliability of the current reservoir operating rule curves under climate change scenarios. Furthermore, Kure et al. (2013) applied MIKE11 to estimate annual inflow to the Bhumibol Dam, in which a significant increase was detected. Moreover, according to our extensive literature reviews, the research of reservoir operating reliability under recently developed climate change scenarios in the South East Asia (SEA) region is still very limited. In this study, we used MIKE11 rainfall-runoff (RR) and MIKE11 Hydrodynamic (HD) for inflow simulation of the current situation and we incorporated the climate change scenarios that were developed by Ramkhamhaeng University Center of Regional Climate Change and Renewable Energy (RU-CORE). The prediction was based on the simulation of EC-EARTH under RCP4.5 and RCP8.5 scenarios for future inflow simulation. The reliability of the future inflows was then examined, based on the standard operating procedure (SOP) of reservoir operating rules.

The additional information derived from this study can inform water management-related agencies to redesign reservoir operating rules under climate change scenarios to minimize future flood and drought risks. The current incidents and damage impacts triggered by unsatisfactory operation of major dams are evidence of the importance and necessity of redesigning reservoir operation rules with adaptive management strategies under climate change to minimize these disaster risks.

2. METHODOLOGY

2.1 Study area

Bhumibol Dam is located at 17°14′33″N Latitude and 98°58′20″E Longitude in Sam Ngao District in Tak Province in the northern region of Thailand, as shown in Figure 1. It is a concrete arch gravity dam, with a storage capacity of 13,462 million m^3 (MCM) to receive inflow from the Ping River Basin with an area of 25,370 km^2. The dam is designed for a hydroelectric power plant with a total installed capacity of 779.2 MW. According to Koontanakulvong et al. (2020), the long-term annual inflow over the period between 1969 and 2019 averaged 5,637 MCM. Nevertheless, their study indicated a trend of decreasing inflow after the 2011 flood, with an average annual inflow of only 3,960 MCM between 2012-2019. This highlights the challenge of reservoir management of the Bhumibol Dam, both currently and in the future. A flowchart of

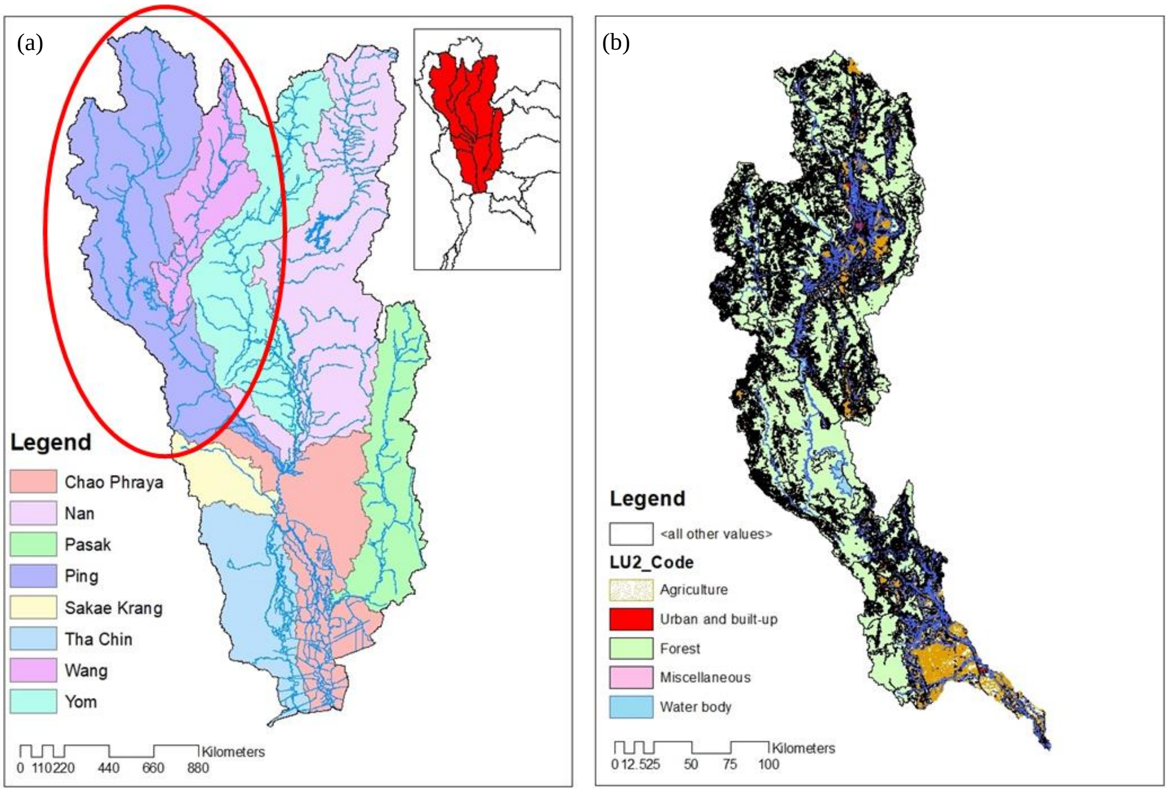


Figure 1. The Greater Chao Phraya River Basin (a) and land use of Ping River Basin in 2013 (b)

the methodology used in this study is given in Figure 2. The methods and tools that were used are described in detail in the following sections.

2.2 Development of hydrological models

The platform of MIKE11 Zero Version 2016, developed by the Danish Hydraulic Institute (DHI), was adopted for simulation of inflow into Bhumibol Dam. The package consists of a variety of hydrological-hydraulic models for use, depending upon the nature of the problem and solution objective. In this study, we selected MIKE11 (Rainfall-runoff) RR NAM model and MIKE11 Hydrodynamics (HD) for inflow simulation. The MIKE11 RR NAM model, the lumped model, was applied for rainfall-runoff simulation in the Ping River Basin. As shown in Figure 3(a), 30 sub-basins were delineated in accordance with the recommendation of the Royal Irrigation Department (RID), as well as Thiessen polygons of 22 daily rainfall stations, namely 070731 and 170181 derived from RID, and 20 stations, namely 300201, 300202, 303201, 303301, 310201, 327301, 327501, 328201, 328202, 328301, 32920,1 373201, 373301, 376201, 376202, 376203, 376301, 376401, 380201, and 400201 derived from the Thailand Meteorological Department (TMD). In addition, daily evaporation data in the study area was obtained from TMD station 48376. The simulated runoff was compared with the observed runoff at RID discharge stations, namely P.4A (Mat Taeng station), P.20 (Chiang Dao station), P.21 (Mae Rim station), P.24A (Mae Klang station), and P.26A (Klong Suan Mak station), as shown in Figure 3(b) for the model setup. The list and adjustment methods of rainfall-runoff parameters can be found in DHI (2017). The adjusted parameters include maximum water content in surface storage (U_{max}), maximum water content in root zone storage (L_{max}), overland flow runoff coefficient (CQOF), time constant for interflow (CKIF), time constants for routing overland flow (CK1,2), root zone threshold value for overland flow (TOF), root zone threshold value for interflow (TIF), time constant for routing baseflow (CKBF), and root zone threshold value for ground water recharge (TG). In this study, the period for model calibration was between 2000 and 2010, in which the auto-calibration function of MIKE11 RR was first applied and followed by manual adjustment to find the best fit with the observations, while the verification period was independently simulated between 2010 and 2018.

The developed MIKE11 RR model was then incorporated with MIKE11 HD. The data input for MIKE11 HD includes MIKE11 RR runoffs and 128 river cross-sections along Ping River, obtained from

RID and Hydro-Informatics Institute (HAII) for hydrodynamic simulation of the inflow into Bhumibol Dam. The model calculation is based on one- dimension flow Saint Venant equation. Furthermore, the river discharge record at P.20 station and water level at P.17 derived from RID were set as upstream and downstream boundaries, respectively. The record of reservoir storage of the dam on 1 January 2000 (9,508.49 MCM) was set as an initial storage condition. As for MIKE11 HD, Manning's coefficients of river channels and flood plains were adjusted to improve the fitness of inflow between simulation and observation.

To evaluate the model's performance, the coefficient of determination (R^2) was applied. In addition, the Q-Q plots of wet season (May-October) and dry season (November-April) were also used to evaluate the simulated inflow performance.

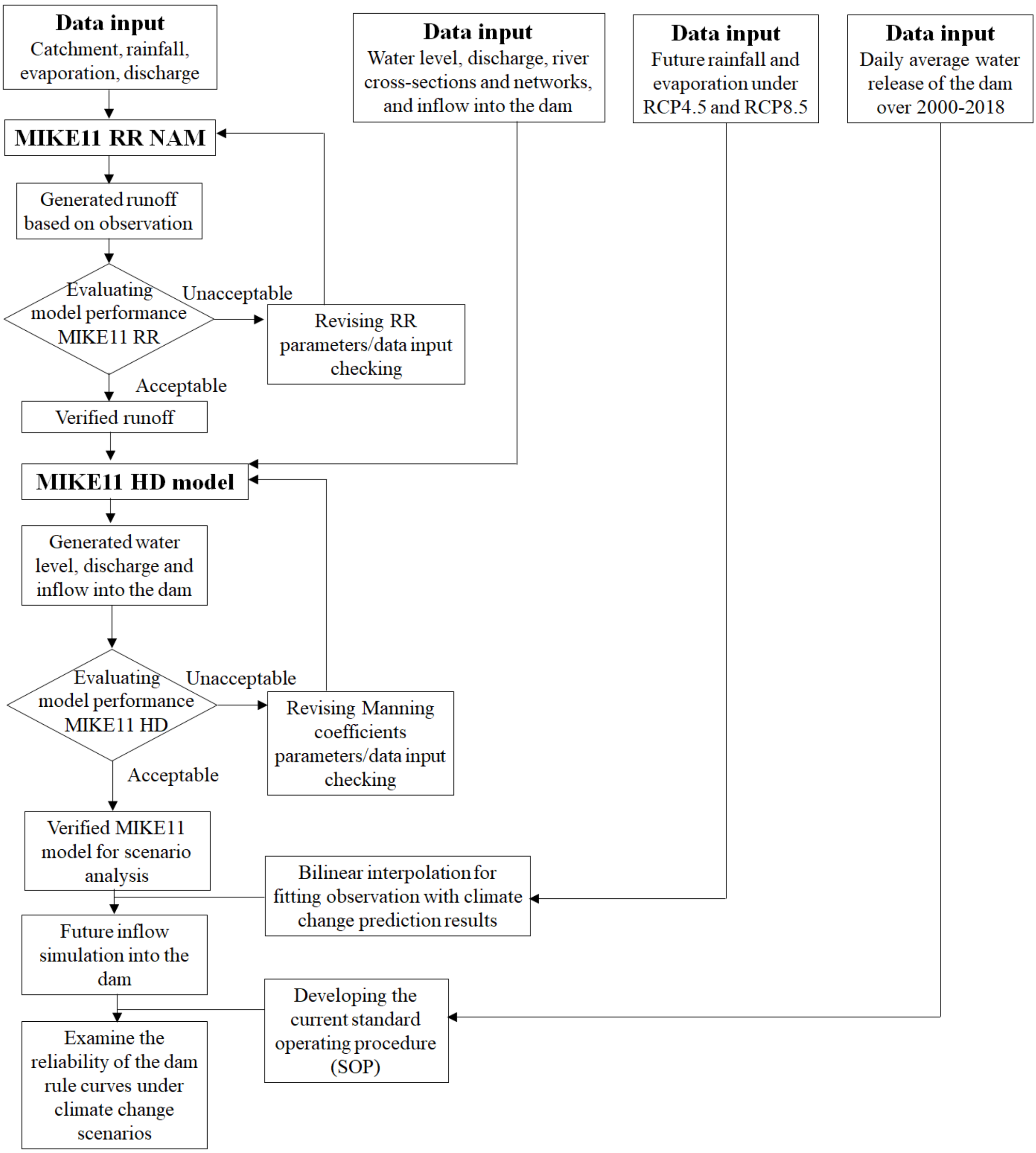


Figure 2. Flowchart of the methodology used in this study

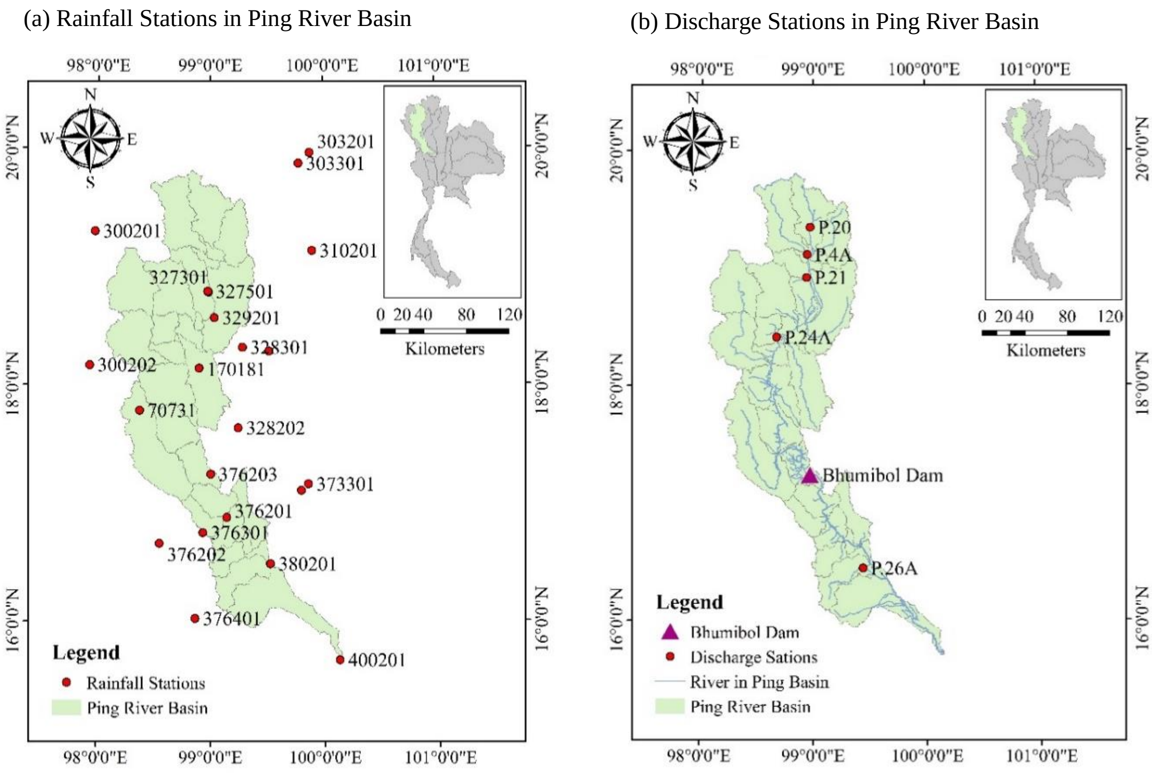


Figure 3. 30-subbasins delineated, selected rainfall (a) and selected discharge stations (b)

2.3 Climate change scenarios

Prediction of rainfall and evaporation under climate change scenarios was extracted from RU-CORE. The prediction was based on the simulation of EC-EARTH under RCP4.5 and RCP8.5 scenarios regionally downscaled by RegCM4 with 25 km × 25 km grid size over the study area (Ngo-Duc et al., 2017; Cruz et al., 2017; Tangang et al., 2019). According to the IPCC glossary, RCP stands for representative concentration pathways, providing possible future scenarios regarding long-term concentrations of greenhouse gases (Moss et al., 2010). RCP4.5 indicates that radiative forcing is stabilized at approximately 4.5 W/m^2 (intermediate intensity level of global warming), while RCP8.5 shows radiative forcing greater than 8.5 W/m^2 by 2100 and continues to rise afterwards (highest possible intensity level of global warming). Rainfall and evaporation data at the stations described in Section 2.2 were extracted in reference to the average values of four grids neighboring the targeted station grid. Murphy (1999) indicated that this method provided more precise rainfall data than the grid over the targeted station. In addition, bilinear interpolation was applied to correct the predicted values, as shown in the following equation:

$$P_{\text{corrected i}} = P_{\text{RU-CORE i}} \times \frac{\mu_{P_{\text{observed i}}}}{\mu_{P_{\text{RU-CORE i}}}}$$

Where; $P_{\text{corrected i}}$ is the corrected daily prediction data in month i, $P_{\text{RU-CORE i}}$ is the average value of four grids neighboring the targeted meteorological station grid in month i, $\mu_{P_{\text{observed i}}}$ is the monthly average of observed value over the targeted period between 2000 and 2018 in month I, and $\mu_{P_{\text{RU-CORE i}}}$ is the monthly average of predicted value over the targeted period between 2000 and 2018 in month i. In this study, predictions were temporally separated into five periods-namely 2000-2020 (baseline), 2021-2040, 2041-2060, 2061-2080, and 2081-2099 to investigate the changes in comparison with the baseline value. The statistical parameters for the analysis include average, standard deviation and the storage at the end of wet season, representing water security in the dry season.

2.4 The reservoir operating policy used in this study

The reservoir operating rules of Bhumibol Dam, developed in 2012, were obtained from the Electricity Generating Authority of Thailand (EGAT). The previous rules were redesigned after the 2011 flood event in Thailand. The procedure to evaluate the reliability of the current rules under climate change scenarios is described as follows.

1) Daily reservoir release was based on the record between 2000-2018. Annual inflow into the

dam was fitted with Gumbel Distribution (Rittima, 2018). The behavior of daily reservoir release was set to be constant across a respective month. The record of annual inflow over 2000-2018 was first categorized into three groups, namely low inflow year (<20th percentile), normal inflow year (20th-80th percentile) and high inflow year (>80th percentile). Each group had its own constant daily release behavior in the respective month, dependent upon inflow year groups, as shown in Table 1. This was done to represent the daily release behavior based on expected amount of river inflow in the following year.

Table 1. Daily release of Bhumibol Dam based on the respective months and inflow year groups

	Daily reservoir release (MCM)		
	Low inflow year	Normal inflow year	High inflow year
Jan	15.77	24.85	19.75
Feb	19.17	27.40	21.58
Mar	17.46	24.26	19.21
Apr	16.22	20.59	16.40
May	24.20	13.59	11.61
Jun	21.08	9.24	9.57
Jul	10.16	9.98	8.67
Aug	7.35	7.57	11.82
Sep	3.54	4.95	9.30
Oct	3.70	3.52	24.30
Nov	10.04	8.11	20.69
Dec	10.70	18.48	25.87
Annual	4832.41	5223.55	6041.38

2) The concept of standard operating procedure (SOP) of reservoir operating rule curves was applied with the following four conditions:

2.1) When storage of the previous day (S_{t-1}) is lower than the value specified by the lower rule curve, the release is regulated to a rate of 5 MCM/day, this value is set to maintain the vitality of downstream ecosystems.

2.2) When S_{t-1} is in the range between the value of lower and upper rule curves, the release is regulated based on daily reservoir release behaviors that was previously described.

2.3) When S_{t-1} is higher than the value specified by the upper rule curve, the release is regulated to a rate of 69.76 MCM/day, which is the maximum release capacity of the dam.

2.4) When S_{t-1} is higher than the normal high-water level value of the dam, which is 13,462 MCM, the exceedance value above 13,462 MCM is regarded as spilled water and the storage of the following day will remain at 13,462 MCM.

The reliability of reservoir operation was calculated by the following equation (Rittima, 2018);

$$\text{Rl} = 1.00 - \frac{\text{FL}}{\text{n}}$$

Where; Rl is the reservoir reliability, FL is the failure of reservoir storage to maintain in the range between lower and upper rule curves, and n is the total number operation days.

3. RESULTS AND DISCUSSION

3.1 Performance of the developed hydrological models

The results of MIKE11 RR calibration and verification are, respectively, shown in Figure 4 and Figure 5. For calibration, R^2 ranged between 0.29 and 0.55. It was apparent that there is an overestimation of runoff at P.21 at low runoff periods and an underestimation at high runoff periods. These may be due to a limited number of rainfall stations representing the sub-basin. Other factors may include unknown hydraulic structures in the P.21 sub-basin that can decelerate runoff and also correction of sub-basin delineation size by the governments. Therefore, an additional field survey is required for improvement. In addition, MIKE11 RR can capture the observed runoff patterns at other stations well. Considering the verification period, R^2 ranged between 0.39 and 0.53. To be consistent with calibration results, the runoff simulation at P.21 was still problematic. Furthermore, runoff simulation at P.4A and P.20 was overestimated while simulated runoff at P.26A and P.24A can capture the observed runoff patterns well. Additional information regarding a number of rainfall stations and operations of weirs and small-to-middle sized reservoirs can improve the results in this section.

Concerning MIKE11 HD, adjusted Manning's coefficients of channel flow ranged between 0.040 in downstream and 0.066 in upstream areas, which are consistent with the study of Sriwongsitanon (1997). In the case of flood plain flows, the values were between 0.060 in downstream and 0.100 in upstream areas.

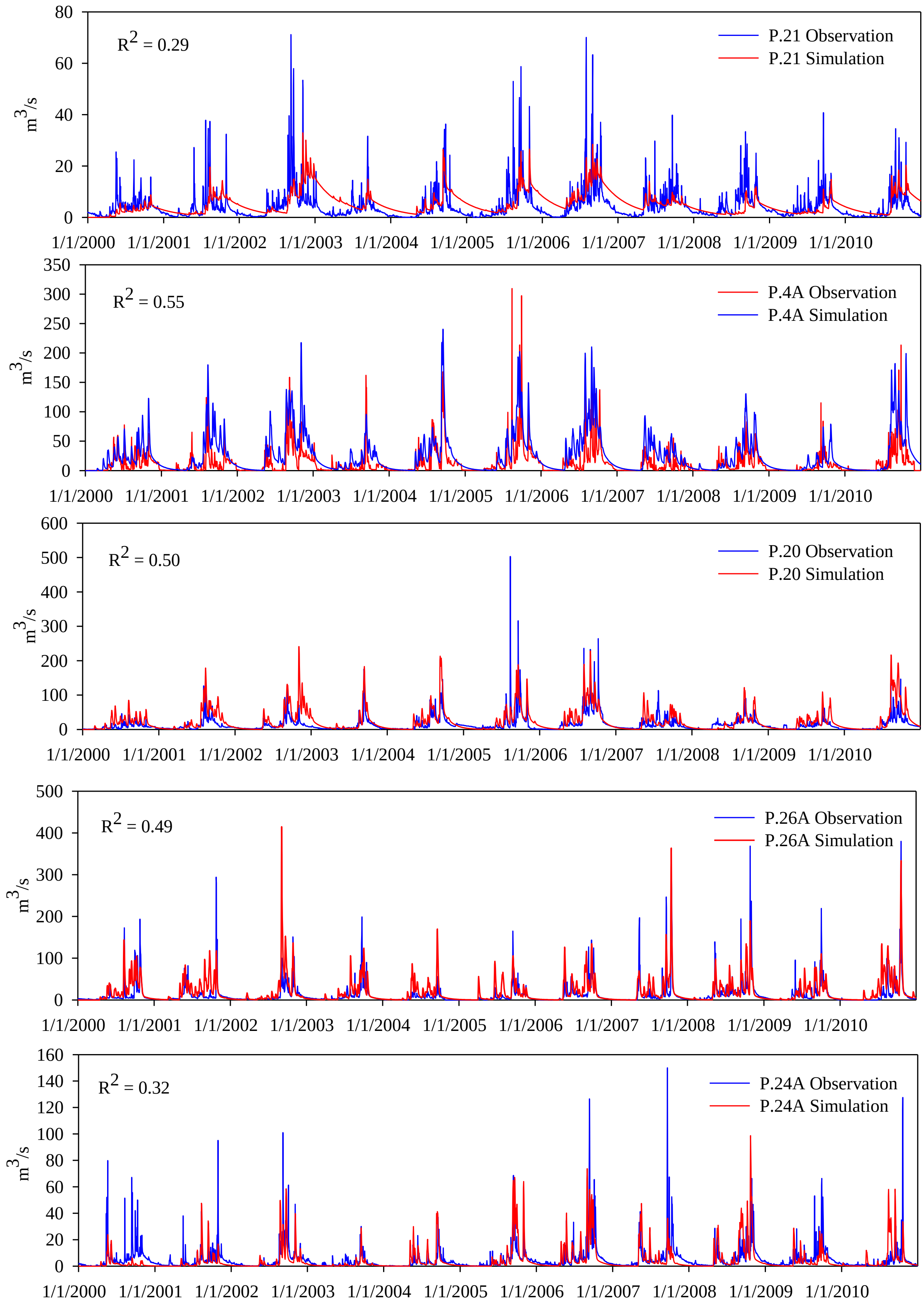


Figure 4. Calibration results of MIKE11 RR

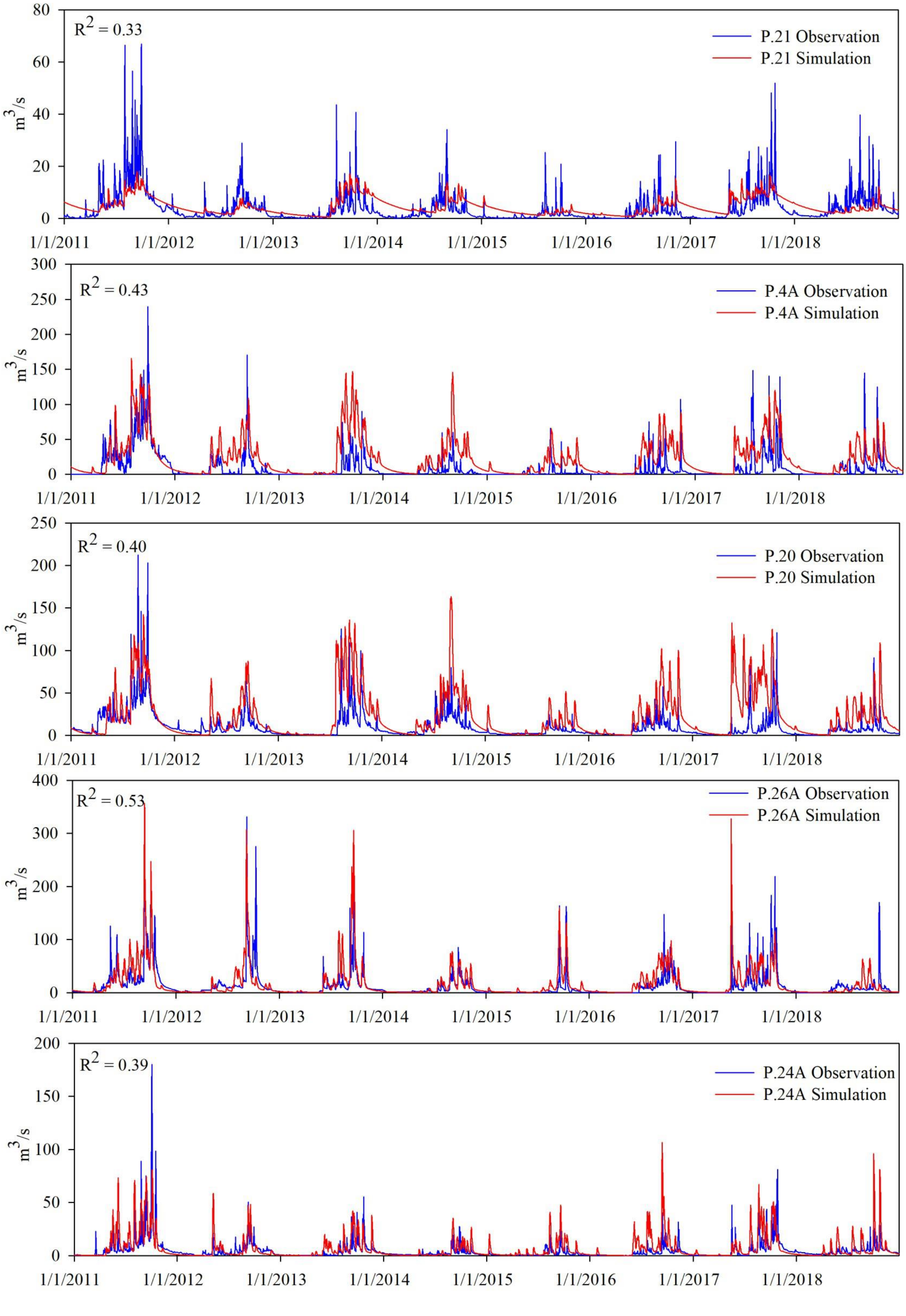


Figure 5. Verification results of MIKE11 RR

According to our land use data collection in Ping River Basin between 1989 and 2016 as shown in Figure 6, we found gradual changes in land uses. Therefore, Manning's coefficients were not different from Sriwongsitanon (1997). According to the results of the simulated daily inflow into Bhumibol Dam as shown in Figure 7, the predicted inflow matched the actual inflow well over the period between 2000 and 2018 (R^2=0.70). Nevertheless, the simulation was not capable of capturing high inflow rate periods, which are typical limitations for hydrological modelling, especially for daily rainfall input. To simulate extreme events, hourly rainfall data is necessary. The results of seasonal inflow Q-Q plot are shown in Figure 8. It was found that the model can calculate monthly inflows in the wet season well, and the model only underestimated the values in extreme events. However, in the dry season, the simulated inflow was overestimated. This was due to the unknown characteristics of the operated weirs and small-to-middle sized reservoirs in the study area, which can decelerate the river flow rate.

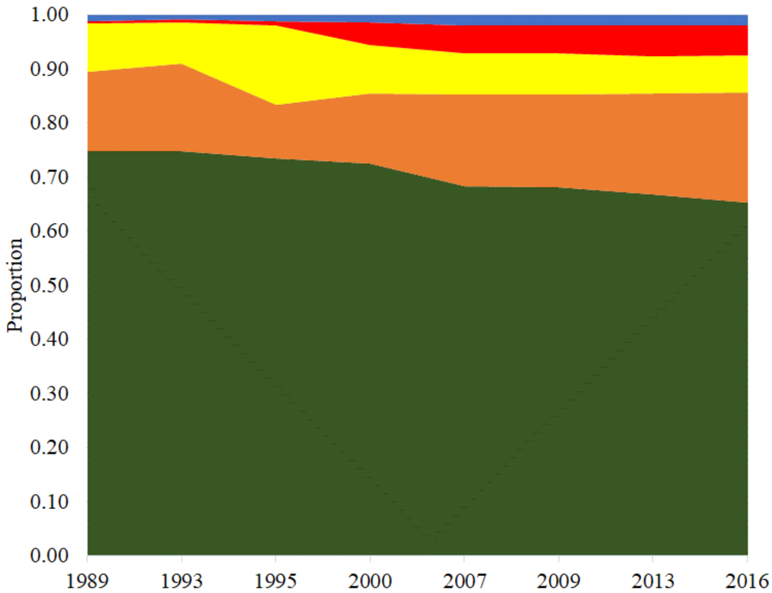


Figure 6. Proportion of land use change between 1989 and 2016. Blue, red, yellow, orange and green denote percentage proportion of water, urban, paddy land, upland agriculture and forest, respectively. (Source: Land Use Development Department, Thailand)

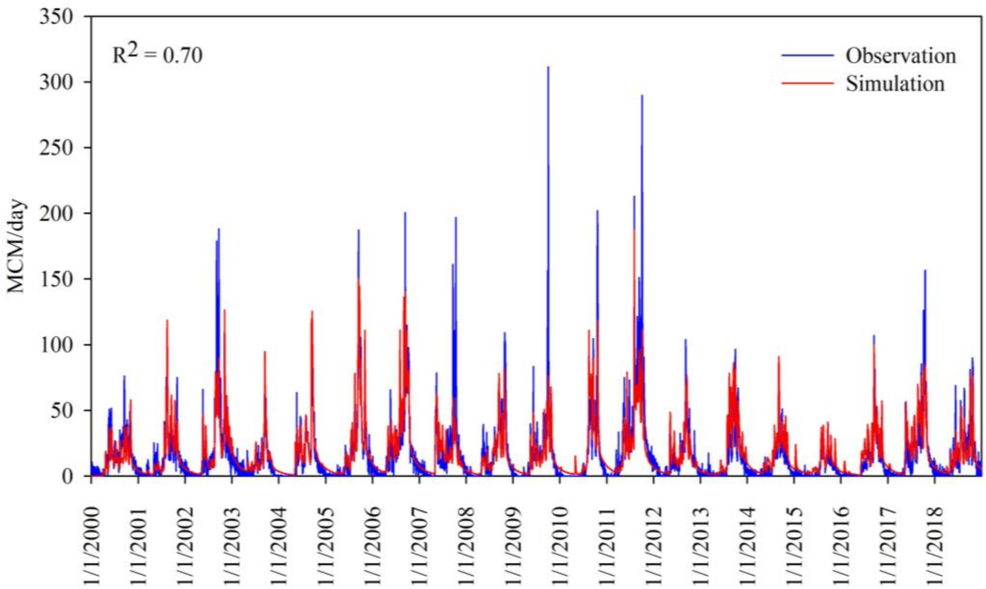
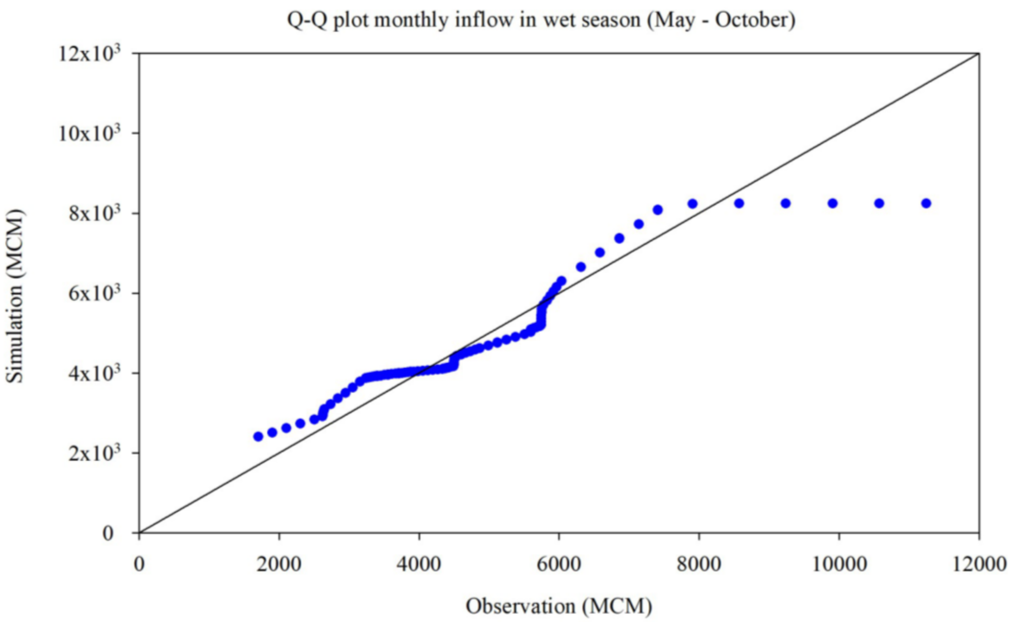


Figure 7. Comparison of simulated and observed inflows into Bhumibol Dam between 2000 and 2018 based on MIKE 11 HD



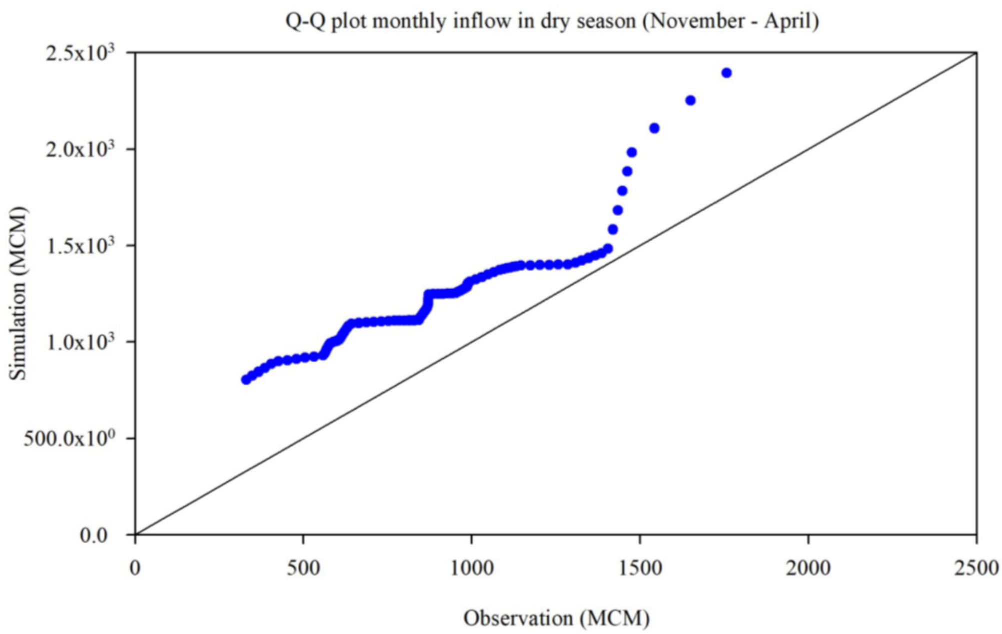


Figure 8. Q-Q plot of monthly inflow into Bhumibol Dam in wet (upper) and dry seasons (lower) between 2000 and 2018

3.2 Changes in monthly and seasonal inflow

The prediction of inflow into Bhumibol Dam under RCP4.5 and RCP8.5 is summarized in Tables 2 and 3, respectively. In comparison with the baseline period (2000-2020), RCP4.5 scenarios indicate increases in inflow in dry season by +0.07%, +10.00%, +15.42%, and +6.25% in 2021-2040, 2041-2060, 2061-2080, and 2081-2099, respectively. However, the results are generally converse in the wet season because the changes are expected to be -10.44%, +9.60%, -13.01%, and -2.63%, respectively. In the RCP8.5 scenario, the results in dry season are generally consistent with RCP4.5 in which the changes compared with the baseline period are expected to be -5.03%, +8.14%, +8.15%, and +22.71% in 2021-2040, 2041-2060, 2061-2080, and 2081-2099, respectively. In contrast to RCP4.5, RCP8.5 in the wet season also shows fluctuating results which are projected to be -4.68%, +20.17%, -10.13%, and +18.04%, respectively. The findings in this study do not correspond with Kitpaisalsakul (2018), who applied bias corrected MRI-GCM climate data and concluded a slightly decreasing trend of annual inflow into Bhumibol Dam in both seasons through the near future (2015-2039) at the slope rate of -5.744 MCM/year and the far future (2075-2099) at

Table 2. Summary of percentage change in statistical indicators compared with the baseline period (2000-2020) under RCP4.5

							Average								
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Wet	Dry
2021-2040	-0.64%	-1.89%	-8.67%	45.44%	44.21%	-32.29%	-11.48%	-19.49%	-12.34%	-5.35%	-1.30%	-6.61%	-8.74%	-10.44%	0.07%
2041-2060	7.09%	5.44%	8.29%	28.22%	77.19%	54.53%	-3.22%	-2.53%	5.08%	-1.55%	12.83%	3.65%	9.67%	9.60%	10.00%
2061-2080	9.04%	1.56%	133.76%	35.26%	23.83%	-16.32%	-19.88%	-7.40%	-21.51%	-10.33%	1.87%	6.64%	-8.40%	-13.01%	15.42%
2081-2099	10.97%	2.79%	-7.63%	17.20%	16.42%	9.42%	0.15%	-10.31%	-0.71%	-8.71%	9.16%	0.60%	-1.19%	-2.63%	6.25%
							Standard deviation								
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Wet	Dry
2021-2040	12.58%	12.55%	-18.63%	58.56%	82.67%	-9.40%	45.47%	-35.76%	38.98%	23.64%	-4.85%	3.59%	-2.53%	12.75%	8.49%
2041-2060	6.78%	3.49%	-3.55%	39.79%	134.19%	77.73%	-11.10%	-42.74%	37.37%	2.79%	41.81%	-11.05%	6.18%	14.43%	19.38%
2061-2080	54.55%	36.45%	911.78%	45.86%	34.77%	13.69%	-23.50%	-44.10%	23.93%	3.18%	73.54%	96.97%	-2.10%	-5.71%	146.93%
2081-2099	15.78%	-11.28%	-44.44%	74.93%	71.72%	88.84%	29.47%	-41.97%	34.00%	-18.97%	-14.19%	-36.42%	-9.61%	9.63%	-4.19%
							Storage at the end of wet season								
2021-2040	-10.44%														
2041-2060	9.60%														
2061-2080	-13.01%														
2081-2099	-2.63%														

Table 3. Summary of percentage change in statistical indicators compared with the baseline period (2000-2020) under RCP8.5

							Average								
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Wet	Dry
2021-2040	-4.91%	-2.80%	-9.06%	-28.34%	-1.47%	-11.83%	-36.68%	2.28%	-14.92%	16.18%	-3.66%	0.80%	-4.74%	-4.68%	-5.03%
2041-2060	11.93%	13.35%	7.03%	-16.37%	8.42%	6.59%	3.30%	131.09%	3.00%	2.73%	10.65%	8.04%	18.20%	20.17%	8.14%
2061-2080	15.73%	8.90%	0.77%	-26.91%	-56.47%	-37.78%	-31.99%	17.52%	-12.32%	5.13%	15.08%	4.90%	-7.15%	-10.13%	8.15%
2081-2099	13.11%	15.64%	9.08%	61.47%	39.31%	10.19%	24.59%	76.45%	1.42%	6.95%	21.72%	23.88%	18.80%	18.04%	22.71%
							Standard deviation								
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Wet	Dry
2021-2040	5.86%	12.89%	-15.69%	-76.78%	17.93%	-25.30%	-23.38%	49.15%	18.73%	65.67%	-11.44%	28.26%	44.32%	16.79%	-18.71%
2041-2060	20.02%	23.62%	-6.75%	-70.15%	8.48%	-1.50%	-6.77%	346.47%	35.56%	27.10%	8.94%	29.00%	62.78%	53.03%	-6.81%
2061-2080	77.98%	43.98%	2.36%	-80.03%	-62.32%	-19.75%	-15.07%	95.60%	5.49%	80.80%	85.01%	38.75%	34.32%	14.94%	27.48%
2081-2099	30.26%	37.67%	3.69%	82.13%	113.54%	25.83%	69.48%	184.66%	10.92%	35.76%	49.55%	76.38%	73.58%	57.77%	55.40%
							Storage at the end of wet season								
2021-2040	-4.68%														
2041-2060	20.17%														
2061-2080	-10.13%														
2081-2099	18.04%														

the slope rate of -23.03 MCM/year. The results closely relate with predicted decreasing rainfall in those periods. Similarly, the results are dependent upon the studied location. For example, Harraki et al. (2020) indicated a decrease in the total average supply between 9% and 12% for mid-term scenario (2046-2065) and 20% to 27% for the long-term scenario (2081-2100) for the Sebou Basin in Morocco. Our results correspond with the work of Sharma and Babel (2013), especially in the dry season. The work applied bias corrected and downscaled ECHAM4/OPYC and indicated continuous decreases in inflow rate in the wet season by -29.0% in the period between 2023-2027 and -27.0% in 2093-2097 under A2, as well as -23.0% and -27.0% under B2. As for dry season, insistent increases in inflow rate were detected by +10.0% and +6.0% under A2, as well as +19.0% and +24.0% under B2. In addition, our study also had the same finding that the peak flows in the future would be shifted from September to October, which was more apparent in RCP8.5. Giesen et al. (2010) also found a shift of ending rainy season to later periods under climate change in the Volta Basin, West Africa.

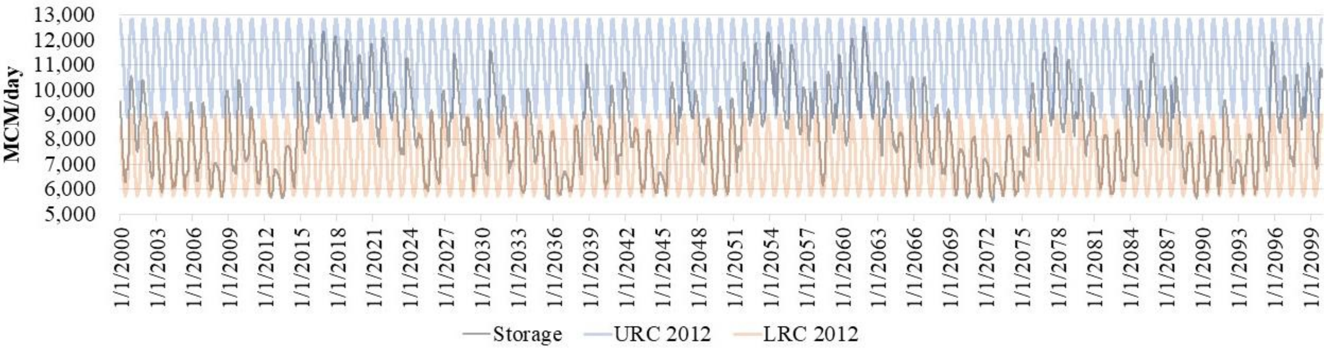
In terms of inflow variation, a large change in standard deviation indicates increasing difficulty for reservoir managers to estimate and regulate appropriate release to control the storage within the range between lower and upper rule curves. Under RCP4.5, in comparison with the baseline period, the deviation will be less at the annual change rate of -2.53%, +6.18%, -2.10%, and -9.61% in 2020-2040, 2041-2060, 2061-2080, and 2081-2099, respectively. This implies more stability of water inflow into the dam, leading to better estimation for the appropriate release. In contrast, RCP8.5 is challenging due to a large increase in the deviation rate at +44.32%, +62.78%, +34.32%, and +73.58%, respectively.

Regarding the results of storage at the end of wet season (May-October), this indicates water security for utilization in the dry season, especially for agricultural activities. The results show high uncertainties in which RCP4.5 provides change rates of -10.44%, +9.60%, -13.01%, and -2.36% in 2020-2040, 2041-2060, 2061-2080, and 2081-2099, respectively. While for RCP8.5, the changes are expected to be -4.68%, +20.17%, -10.13%, and +18.04%, respectively. Therefore, with an understanding of climate change impacts, the adaptive or flexible management of the reservoir operating rule curves should be considered to be able to be proactively redesigned under uncertain conditions (Adeloye and Dau, 2019; Fletcher et al., 2019).

3.3 Reliability of current reservoir operating rules

Daily reservoir storage of Bhumibol Dam based on the standard operating rules under RCP4.5 and RCP8.5 is illustrated in Figure 9. Under RCP4.5, the reliability of reservoir operation throughout 2000-2099 will be 80%. This indicates high failure risk (20%) in reservoir operation reliability quality, in which the acceptable percentage is 80% (Rittima, 2018). Interestingly, RCP8.5 indicates higher reliability with the rate of 87%. The results are consistent with the findings of Park and Kim (2014), who suggested that under the new climatic conditions, the reliability of water and hydropower supply from the Chungju Multipurpose Dam in South Korea would be generally improved as a consequence of increased dam inflow. In addition, the study of Zolghadr-Asli et al. (2019) found similar results in which the dam reliability for power generation will be generally improved through 2010-2099 due to climate change because of the increased inflow from four hydropower projects in the Karkheh River Basin in Iran.

Considering reservoir operation reliability, the dominant cases will be the storage below the lower rule curve accountable for 92% for RCP4.5 and 86% for RCP8.5. The monthly failure ratios are summarized in Table 4. Under RCP4.5, the apparent failure rates above 10% would occur in January (11.87%), August (10.72%), September (11.50%), October (13.09%), November (14.20%), and December (13.93%). In case of failure of upper rule curve, the frequent flood risks would occur in June (20.80%), July (35.88%), August (12.65%), and October (10.75%). Under RCP8.5, the failure to be below the lower rule curve would apparently occur in July (11.01%), August (12.66%), September (12.01%), October (12.78%), November (15.25%), and December (12.31%), while the failure of upper rule curve management would be in June (14.88%), July (23.07%), August (22.77%), September (18.45%), and October (15.63%). The major cause of these failures would be due to high fluctuation of average and deviation rates of monthly rainfall between April and September through 2021 to 2099, in which the monthly rainfall pattern is relatively different from the current situation (2000-2020); as can be seen in Tables 2 and 3. The results indicate that the failure of lower and upper rule curves generally



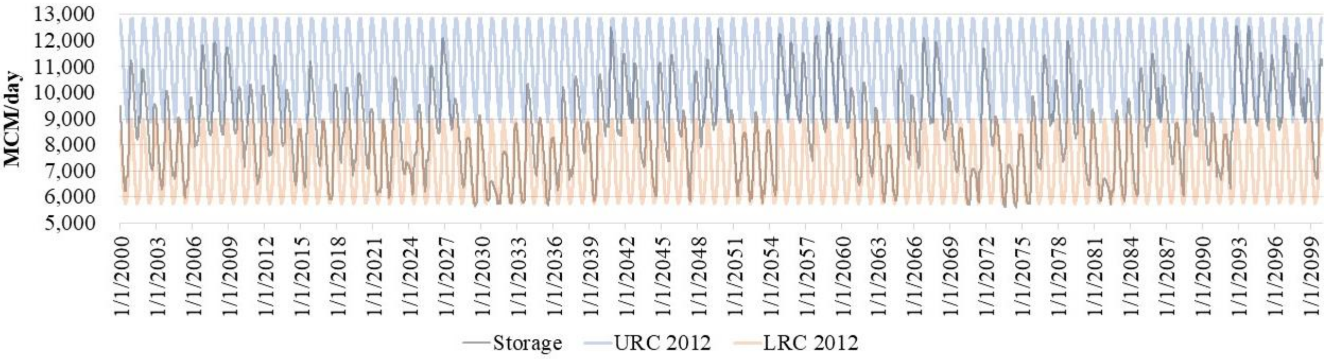


Figure 9. Simulated daily reservoir storage with current lower rule curve (LRC) and upper rule curve (URC) under RCP4.5 (upper) and RCP8.5 (lower) between 2000 and 2099.

Table 4. Monthly reservoir operation failure ratios under climate change scenarios (2000-2099)

	RCP4.5		RCP8.5	
	Lower	Upper	Lower	Upper
Jan	11.87%	0.00%	9.47%	0.00%
Feb	6.20%	0.00%	5.81%	0.00%
Mar	3.00%	0.00%	3.07%	0.00%
Apr	1.24%	0.00%	1.35%	0.45%
May	1.33%	1.56%	0.67%	3.42%
Jun	4.55%	20.80%	3.61%	14.88%
Jul	8.38%	35.88%	11.01%	23.07%
Aug	10.72%	12.65%	12.66%	22.77%
Sep	11.50%	17.68%	12.01%	18.45%
Oct	13.09%	10.75%	12.78%	15.63%
Nov	14.20%	0.69%	15.25%	1.34%
Dec	13.93%	0.00%	12.31%	0.00%
Total	100.00%	100.00%	100.00%	100.00%

occurs in the wet season, especially between the month of June and October. This suggests that the dam regulator should revise the rule curves, especially in the wet season.

Our study heavily relies on SOP, which may not be able to reflect the real reservoir release response situation. However, we can successfully demonstrate that SOP would be a relatively more inappropriate operation in the future. The Hedging Rule (HR), an advanced/developed form of SOP, can also be considered for further study, in which operating rules can be designed to ration water supply in an appropriate preparation for potential low inflows in the near future (You and Cai, 2008). Hedging aims at distributing the anticipated water shortage uniformly to reduce severity in reservoir management so that it can cope well with impact of drought and consequent shortage in current and future water supply (Jain and

Singh, 2003). Advanced research and technology, including further climate change impact studies with various future scenarios and application of artificial intelligence (AI), could support improvement of water regulation through adaptive management of rule curves, which are highly recommended for further study. For example, Kompor et al. (2020) found that changing the reservoir operation plan with seasonal prediction adopted from Centre for Medium-Range Weather Forecasts could decrease the peak river discharge in the Chao Phraya River by 20% under the 2011 flood rainfall scenario. Therefore, integration of climate change scenarios should be further included in future studies to understand and minimize climate change uncertainties, which would be useful information for decision-makers in the development of appropriate rule curves.

4. CONCLUSION

According to the results of this study, it can be concluded that there is high risk of current reservoir operating rules moving towards reliability failure under RCP4.5, but the risk will be lower under RCP8.5 due to increased inflow amounts. The failures obviously occur in the wet season, due to a large fluctuation of the rainfall amount and standard deviation, which cautions the need to redesign the rules. Therefore, it is necessary to revisit the rule curves, especially in the wet season, to maximize reliability. A limitation of this study is the assumption of SOP representing reservoir release behaviors, which is fixed and inflexible. In addition, unknown future water demand in the downstream area was not considered. For future study, adaptive management of rule curves through application of artificial intelligence (AI), such as fuzzy logic model or neuro fuzzy optimization model, is a promising alternative to cope with high uncertainties under climate change.

ACKNOWLEDGEMENTS

This work is financially supported by the Thailand Science Research and Innovation and National Research Council of Thailand, under Grant No. SIP6230022. The authors would like to express their sincere gratitude to Thailand government agencies, including Electricity Generating Authority of Thailand, Royal Irrigation Department, Hydro-informatics Institute and Thai Meteorological Department, for their kind support and sharing of data input for analysis in this study.

REFERENCES

Adeloye AJ, Dau QV. Hedging as an adaptive measure for climate change induced water shortage at the Pong Reservoir in the Indus Basin Beas River, India. Science of The Total Environment 2019;687:554-66.

Cruz FT, Narisma GT, Dado JB, Singhruck P, Tangang F, Linarka UA, et al. Sensitivity of temperature to physical parameterization schemes of RegCM4 over the CORDEX-Southeast Asia region. International Journal of Climatology 2017;37:5139-53.

Danish Hydraulic Institute (DHI.) MIKE 11 User Guide [Internet]. 2017 [cited 2021 Jan 12]. Available from: https://manuals.mikepoweredbydhi.help/2017/Water_Resources/MIKE11_UserManual.pdf.

Ehsani N, Vörösmarty CJ, Fekete BM, Stakhiv EZ. Reservoir operations under climate change: Storage capacity options to mitigate risk. Journal of Hydrology 2017;555:435-46.

Fletcher S, Lickley M, Strzepek K. Learning about climate change uncertainty enables flexible water infrastructure planning. Nature Communications 2019;10:1782.

Giesen NVD, Liebe J, Jung G. Adapting to climate change in the Volta Basin, West Africa. Current Science 2010;98(8):1033-7.

Harraki WEL, OUAZAR D, Bouziane A, Hasnaoui D. Climate change observations and trends overview: Focus on Morocco with a case-study of a future reservoir's response to climate change. E3S Web Conference 2020;150.

Intergovernmental Panel on Climate Change (IPCC). Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Preindustrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. In Press; 2018.

Intergovernmental Panel on Climate Change (IPCC). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge, England: Cambridge University Press; 2012.

Jain SK, Singh, VP. Water Resources Systems Planning and Management. New York, USA: Springer; 2003.

Kang B, Lee SJ, Kang DH, Kim YO. A flood risk projection for Yongdam Dam against future climate change. Journal of Hydro-environment Research 2007;1:118-25.

Kim S, Tachikawa Y, Nakakita E, Takara K. Reconsideration of reservoir operations under climate change: case study with Yagisawa Dam, Japan. Annual Journal of Hydraulics Engineering 2009;53:115-20.

Kitpaisalsakul T. Impact of climate change on irrigation water management by the Bhumibol Dam in Thailand. Journal of Thai Interdisciplinary Research 2018;13:49-54.

Koontanakulvong S, Vudhivanich V, Rittima A, Phankamolsil Y, Tabucanon AS, Sawangphol W, et al. Lesson learnt from past to present and water storage potential in future for Bhumibol and Sirikit Dams. Proceedings of the 13th THAICID National E-Symposium; 2020 Jul 31; Studio of Irrigation Development Institute, Bangkok: Thailand; 2020.

Kompor W, Yoshikawa S, Kanae S. Use of seasonal streamflow forecasts for flood mitigation with adaptive reservoir operation: A case study of the Chao Phraya River Basin, Thailand, in 2011. Water 2020;12(3210):1-19.

Kure S, Tenakari T, Okabe M. Spatial and seasonal differences in the response of flow to climate change in the Chao Phraya

River Basin, Thailand. Journal of Japan Society of Civil Engineers, Ser.B1 (Hydraulic Engineering) 2013;69(4):55-60.

Limsakul A, Singhruck P. Long-term trends and variability of total and extreme precipitation in Thailand. Atmospheric Research 2016;169:301-17.

Limsakul A. Trends in Thailand's extreme temperature indices during 1955-2018 and their relationship with global mean temperature change. Applied Environmental Research 2020; 42:94-107.

Miyan MA. Droughts in Asian least developed countries: Vulnerability and sustainability. Weather and Climate Extremes 2015;7:8-23.

Moss R, Edmonds J, Hibbard K, Manning M, Rose S, Vuuren D, et al. The next generation of scenarios for climate change research and assessment. Nature 2010;463:747-56.

Murphy J. An evaluation of statistical and dynamical techniques for downscaling local climate. Journal of Climate 1999;12:2256-84.

Ngo-Duc T, Tangang FT, Santisirisomboon J, Cruz F, Trinh-Tuan L, Nguyen-Xuan T, et al. Performance evaluation of RegCM4 in simulating extreme rainfall and temperature indices over the CORDEX-Southeast Asia region. International Journal of Climatology 2017;37:1634-47.

Park JY, Kim SJ. Potential impacts of climate change on the reliability of water and hydropower supply from a multipurpose dam in South Korea. Journal of the American Water Resources Association 2014;50:1273-88.

Raneesh J. Impact of climate change on water resources. Earth Science and Climatic Change 2014;5(3):1-5.

Rittima A. Reservoir Systems and Operation Planning. Bangkok, Thailand: Mittrapopkarnpim; 2018.

Sharma D, Babel MS. Application of downscaled precipitation for hydrological climate-change impact assessment in the upper Ping River Basin of Thailand. Climate Dynamics 2013; 41:2589-602.

Shiferaw B, Tesfaye K, Kassie M, Abate T, Prasanna BM, Menkir A. Managing vulnerability to drought and enhancing livelihood resilience in sub-Saharan Africa: Technological, institutional and policy options. Weather and Climate Extremes 2014;3:67-79.

Siam Commercial Bank. EIC evaluates that the 2020 drought could extend to June with severe impacts on sugarcane, off-season rice, and cassava [Internet]. 2020 [cited 2021 Jan 12]. Available from: https://www.scbeic.com/en/detail/file/product/6660/fl65yywwln/EIC-Note_drought_EN_20200302 .pdf.

Sriwongsitanon N. The study of the flood conditions of the Upper Ping River Basin by an application of MIKE 11 model (part 1). Kasetsart Engineering Journal 1997;11:74-87 (in Thai).

Tangang F, Santisirisomboon J, Juneng L, Salimun E, Chung J, Supari S, et al. Projected future changes in mean precipitation over Thailand based on multi-model regional climate simulations of CORDEX Southeast Asia. International Journal of Climatology 2019;39:5413-36.

Thana-dachophol T, Teamsuwan V, Udomsap L, Wongsamut W, Chamnankaew U. An analysis of water management in 2020 drought conditions. Proceedings of the 13th THAICID national esymposium; 2020 Jul 31; Studio of Irrigation Development Institute, Bangkok: Thailand; 2020.

The World Bank. Thai flood 2011, Rapid Assessment for Resilient Recovery and Reconstruction Planning. The World Bank; 2012.

You JY, Cai X. Hedging rule for reservoir operations: 1. A theoretical analysis. Water Researches Research 2008: 44:W01415.

Zolghadr-Asli B, Bozorg-Haddad O, Chu X. Effects of the uncertainties of climate change on the performance of hydropower systems. Journal of Water and Climate Change 2019;10.3:591-609.