Hydrologic evaluation and effects of climate change on the Nong Han Lake Basin, northeastern Thailand

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ABSTRACT

The purpose of this study is to investigate the future runoff into the Nong Han Lake under the effects of climate change. The hydrological model Soil and Water Assessment Tool (SWAT) has been selected for this study. The calibration and validation were performed by comparing the simulated and observed runoff from gauging station KH90 for the period 2001–2003 and 2004–2005, respectively. Future climate projections were generated by Providing Regional Climates for Impacts Studies (PRECIS) under the A2 and B2 scenarios. The SWAT model yielded good results in comparison to the baseline; moreover, the results of the PRECIS model showed that both precipitations and temperatures increased. Consequently, the amount of runoff calculated by SWAT under the A2 and B2 scenarios was higher than that for the baseline. In addition, the amount of runoff calculated considering the A2 scenario was higher than that considering the B2 scenario, due to higher average annual precipitations in the former case. The methodology and results of this study constitute key information for stakeholders, especially for the development of effective water management systems in the lake, such as designing a rule curve to cope with any future incidents.

Key words | climate change, Nong Han Lake, PRECIS, runoff, SWAT

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INTRODUCTION

Climate change has become more severe in the last few decades, as confirmed by the accelerating increase in global temperatures linked to the greenhouse effect and known as global warming (IPCC 2013). The occurrence of higher temperatures enhances the evaporation process (Attarod *et al.* 2015), increasing the intensity and duration of droughts, as well as the amount of water vapor in the atmosphere (responsible for storms and heavy rains). Overall, these alterations influence the amount of energy involved in the hydrological cycle and can affect seasonal changes (Trenberth 2011). For example, a previous study indicated that climate change will affect the monsoon season in Southeast Asia, delaying it, but also increasing its frequency and intensity (Loo *et al.* 2015). Climate changes strongly influence both human societies and the environments they live in, including water resources, agriculture practices, forests, human health, and natural disasters. The effects of climate change on water resources are direct: variations in the annual amount of rainfall and in rain distribution, temperature, as well as wind speed and direction, are indicators of the amount of runoff in watersheds. The results of the Variable Infiltration Capacity (VIA) water cycle model, which uses projected future climate data obtained from the Conformal Cubic Atmospheric Model, indicate that the quantity of water in most subbasins of the Mekong River in Lao PDR and in Thailand will be higher due to an increase in future rainfall (Snidvongs 2006). Likewise, a study on global climate change and water resources in Thailand suggested that, by the year 2050, the runoff will increase considerably during the highest flow

doi: 10.2166/wcc.2019.040

period (i.e., June–August; Arnell 1999). Another study indicates that in northeastern Thailand the summer period will last longer around the Chi-Moon Basin and the Sonkram watershed (Chinvanno & Choengbunluesak 2006; Chinvanno 2009).

The Nong Han Lake is the largest natural water source in northeastern Thailand, storing water from neighboring areas and creeks including Huay Nakae, Lam Nam Pung, Huay Deak, and Huay Muang. Moreover, Nong Han contributes to Lam Nam Kam, which flows into the Mekong River at the That Phanom district (Nakhon Phanom Province). These wetlands are extremely important in Thailand, constituting the main water resource for the livings of more than 240,000 people (e.g., fundamental for agriculture, fishery, etc.). These resources are fundamental even for local communities directly situated along the lake, like the Nakhon Sakon Nakhon and Tha Rae municipalities, which employ the Nong Han waters in their water supply system (Sukthanapirat *et al.* 2017). For these reasons, the study of future runoff and its responses to climate change will provide key information for the management of water resources in the Nong Han watershed (e.g., for local consumption, industry use, design of water control structures, flood control and drought prevention, and reservoir operation rule curve design; Prasanchum & Kangrang 2017). Therefore, the purpose of this study is to project the changing quantity of runoff into the Nong Han Lake caused by the climate change during 2021–2050 using the simulated climate data from the Providing Regional Climates for Impacts Studies (PRECIS) scenario and the future runoff forecast with the hydrological Soil and Water Assessment Tool (SWAT) model. The scope of this study focuses on the change in future runoff characteristics within the regional basin and the future runoff flowing directly into the Nong Han Lake.

METHODOLOGY

Study area

The Nong Han Lake, located in the Muang and Phon Na Kaeo districts (107°6′ N, 104°8′ E–104°18′ E; Sakon Nakon Province), covers an area of ~123 km^2 (Figure 1). The Nong Han Basin covers several watersheds, for a total area of 1,655 km^2. The height of the Nong Han Basin, obtained from the digital elevation model (DEM) map (Figure 2), comprises between +142 and +629 m above mean sea level

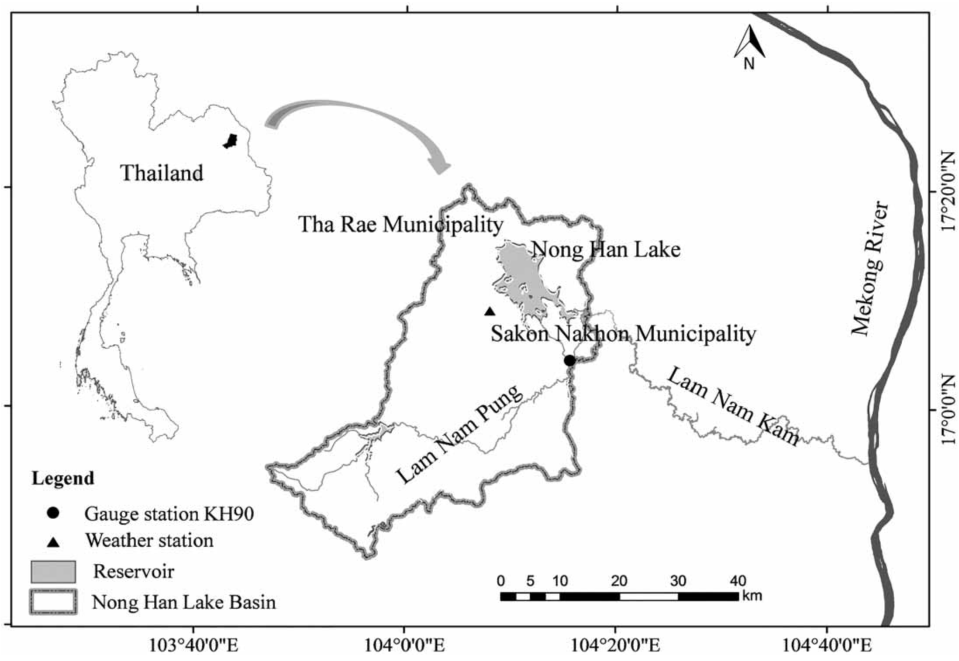

Figure 1 | Study area of the Nong Han Basin.

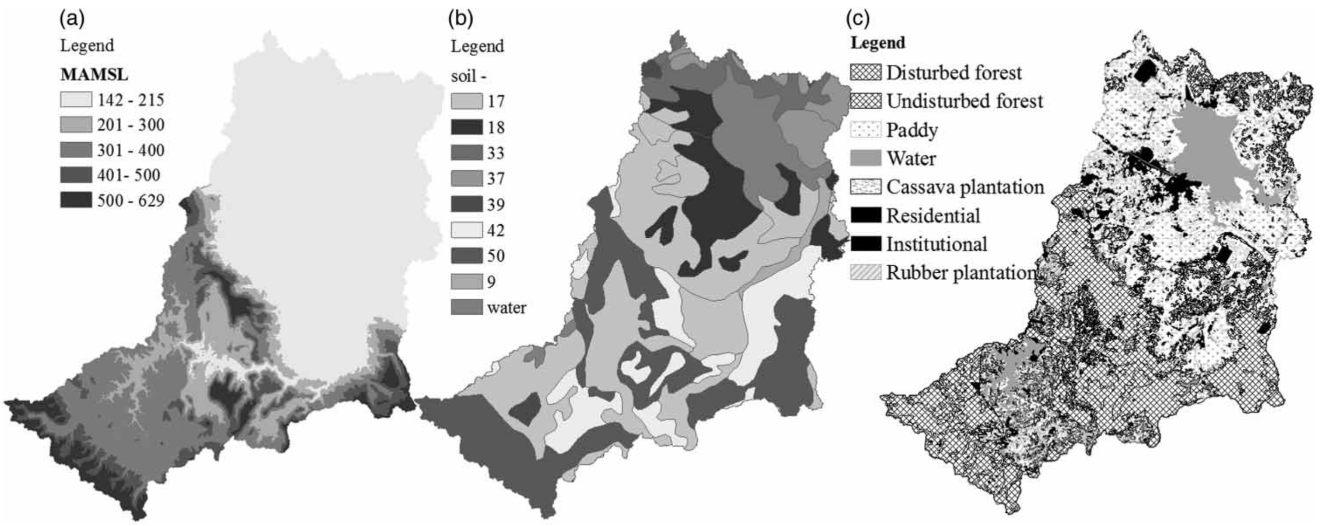

Figure 2 | DEM, soil type, and land cover of the Nong Han Basin.

(MAMSL). The meteorological data concerning this basin have been collected at the Sakon Nakhon Province station; they included temperature (annual average = 26.7 °C), relative humidity (annual average = 72%), wind speed (annual average = 3.69 m/s), and rainfall (annual average = 1,666 mm). Most of the basin soil is represented by a fine alluvial loam, which has quite bad drainage and low fertility. The remaining soil is represented instead by a moderately fine loam, which has good drainage and low fertility. Moreover, most of the basin area is covered by forests, rice fields, and wetlands. Figure 2 shows the DEM, soil type, and land cover characteristics of the basin; details of the land cover and soil types are shown in Tables 1 and 2.

The PRECIS model

The PRECIS model is a regional climate model (RCM) dynamically downscaled from the Global Climate Model (GCM, also called 'ECHAM4' model), developed by the Met Office Hadley Centre for Climate Change (United Kingdom). PRECIS has been widely accepted and used the most in order to investigate the future climate changes of Thailand and Southeast Asia (Inthacha 2011; Lacombe *et al.* 2012; Lauri *et al.* 2012; Sentian & Kong 2013; Shrestha 2014; Masud *et al.* 2016). This model was able to calculate climate data for the period 1960–2100 (140 years), with a spatial resolution of 0.22° (~20 km × 20 km), under the climate change scenarios A1B, A2, and B2. The calculated climate

Table 1 | Land cover

Land cover type	Area (ha)	%	Land cover type	Area (ha)	%
Paddy field	54,644	33.01	Perennial land	213	0.13
Residential	8,247	4.98	Horticulture	113	0.07
Range brush	2,313	1.40	Rubber plantation	2,576	1.56
Disturbed forest	58,356	35.25	Cassava plantation	8,781	5.30
Institutional	2,786	1.68	Undisturbed forest	10,069	6.08
Miscellaneous	1,467	0.89	Sugarcane plantation	1,045	0.63
Water	13,169	7.95	Orchard	1,307	0.79
Pasture	458	0.28			
				165,545	100

Table 2 | Soil type

Soil type	Area (ha)	%	Soil type	Area (ha)	%
Soil-9	2,071	1.25	Soil-37	6,684	4.04
Soil-17	56,248	33.98	Soil-39	364	0.22
Soil-18	16,056	9.7	Soil-42	19,792	11.96
Soil-33	8,425	5.09	Soil-50	42,232	25.51
			Water	13,673	8.26
				165,545	100

data included maximum and minimum temperature, precipitation, wind speed, wind direction, and solar radiation (Jones *et al.* 2003). These data can be obtained from the Southeast Asia START Regional Center. In particular, Thailand has been included in a group of nations characterized by moderate–high income, and whose economy and social development are particularly close to those described in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) A2 and B2 scenarios. The A2 scenario puts emphasis on economic development, in particular on growing regional collaborations; in this scenario, people will tend to live more isolated while the total population and the energy consumption will gradually increase. On the other hand, the B2 scenario entails parallel environmental and economic developments, with the establishment of sustainable solutions for local economies, society, and environmental problems; in this scenario, the human population does not grow continually as in A2, and environment conservation is promoted at regional and local levels (IPCC 2013).

The SWAT model

The SWAT model was developed by the Agricultural Research Service (ARS) of the U.S. Department of Agriculture (USDA) for basin water management. This model assesses the runoff, sediments, and water quality (e.g., nutrient and chemical substances) of rivers. The SWAT model has been used internationally, including in Thailand (Pongpetch *et al.* 2015; Faksomboon & Thangtham 2017; Tumkoon *et al.* 2017). Moreover, it is a license-free model, functioning in both licensed (ArcGIS) and license-free (QGIS) geographic information systems. The SWAT model can divide a basin into several subbasins, based on their geographical characteristics, and then use the relationships between land cover, soil series, and areal slope (i.e., the hydrologic response units (HRUs)) to calculate its results. For water balance calculations, the model needs to know the soil water content in shallow and deep aquifers, whereas the evaporation can be separately calculated from plants' soil and water use. The evaporation from soil can be estimated from the exponential relationship between soil depth and soil moisture, while the plants' evaporation can be derived from the potential evapotranspiration, the leaf area index, and the root depth. The hydrological processes in a watershed can be divided between two phases: a land phase and a routing phase. For the land phase, the model simulates eight categories of data: hydrological, climatological, sedimentary, soil temperature, plant growth, nutrient, pesticide loading, and agricultural management. Afterwards, it simulates the runoff, sedimentation, and pollution from each HRU to the main channel in each subbasin. For the routing phase, the model calculates the movement of water, sediments through the channel, and the distribution of different chemical contaminants in the stream. Generally, the amount of runoff is calculated using a modified SCS curve number method, which considers the types of soil and land use; at the same time, the runoff in a stream can be calculated using either the variable storage or the Muskingum method (Srinivasan *et al.* 1998).

Data source

The data used in this study include three categories: (1) spatial data (i.e., DEM with resolution = 30 m × 30 m distributed by Open Topography; soil data, and land cover data from the Land Development Department (LDD)); (2) Meteorological data (i.e. rainfall, relative humidity, solar radiation, wind direction, and wind speed) from 1992 to 2015 at the Sakon Nakhon weather station obtained from the Thai Meteorological Department (TMD); (3) daily runoff data for model calibration and validation, collected by the Royal Irrigation Department (RID) at station KH90, between 2001 and 2005. Additional details are presented in Table 3.

Table 3 | Data input

	DEM	Land cover	Soil type	Weather	Runoff
Data source	Open topography	LDD	LDD	TMD	RID
Scale	30 × 30 m	1:50,000	1:50,000	Daily	Daily

Model calibration and validation

The model's accuracy has been tested applying standard statistical calibration and validation methods: the coefficient of determination (R^2) and the Nash–Sutcliffe efficiency (NSE) index. R^2 is always between 0 and 1: for R^2 values close to 1, the data are considered strongly correlated; for R^2 values close to 0, instead, the data are considered non-correlated. The NSE is always between $-\infty$ and 1. For NSE = 1, the model is considered accurate; on the other hand, if NSE is <0, the model's prediction is considered less accurate than the average predicted value.

RESULTS AND DISCUSSION

SWAT calibration and validation results

The SWAT calibration compared the calculated and the actual measured values. The actual value was taken from the runoff dataset collected by the RID at station KH90: Lam Nam Pung that regularly measured the runoff flowing into Nong Han Lake. The data used in the model calibration were recorded between 2001–2003 and 2004–2005 for the model validation. The adjusted parameters included: the baseflow alpha factor (ALPHA_BF), the SCS runoff curve number for moisture condition II (CN2), the plant uptake compensation factor (EPCO), the soil evaporation compensation factor (ESCO), the groundwater delay (GW_DELAY), the deep aquifer percolation fraction (GW_REVAP), the threshold water depth in the shallow aquifer required for the occurrence of the return flow (GWQMN), the deep aquifer percolation fraction (RCHRG_DP), and the groundwater 'revap' coefficient (REVAPMN). The calibration and validation results on the monthly runoff at station KH90 (as illustrated in Figure 3 and Table 4) have R^2 and NSE values equal to 0.77, 0.79 and 0.75, 0.61, respectively. The results in 2001, 2002, 2003, and 2005 showed that the R^2 and NSE were 0.71–0.91 and 0.61–0.89, respectively. While in 2004, it was found that the pattern of simulated hydrograph was different from observation, as shown in Figure 3. However, the five-year results were significantly acceptable to be representative of the model simulation.

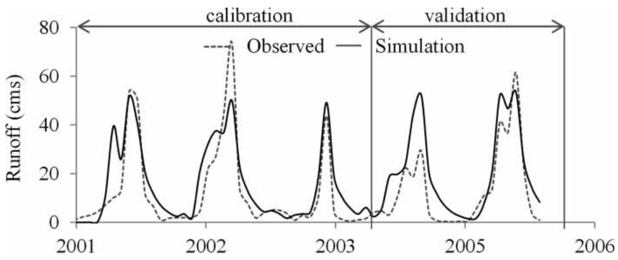

Figure 3 | Comparison between simulated and observed monthly data.

Adjustment of climate data by bias correction

The PRECIS is an RCM that was downscaled from the GCM, in order to apply it to regional data. Nevertheless, the calculated results are raw and not suitable for further applications (e.g., limited to a small basin; Chen *et al.* 2011). Accordingly, the downscaled data need to be adjusted by bias correction. In this study, we used the change factor (CF) method to adjust the downscaled climate data by comparing them with previously measured data and using Equation (1) for temperature and Equation (2) for rainfall, respectively.

$$Tadj = Tobs, d + (Tobs, m - Tds, m) \quad (1)$$

$$Padj = Pobs, d \times (Pobs, m/Pds, m) \quad (2)$$

where *Tadj* and *Padj* are the corrected temperature and rainfall values, *Tobs* and *Pobs* the previous temperature and

Table 4 | Statistical agreement between simulated and observed data

Period	r^2	NSE
Calibration period (2001–2003)	0.77	0.75
Validation period (2004–2005)	0.79	0.61

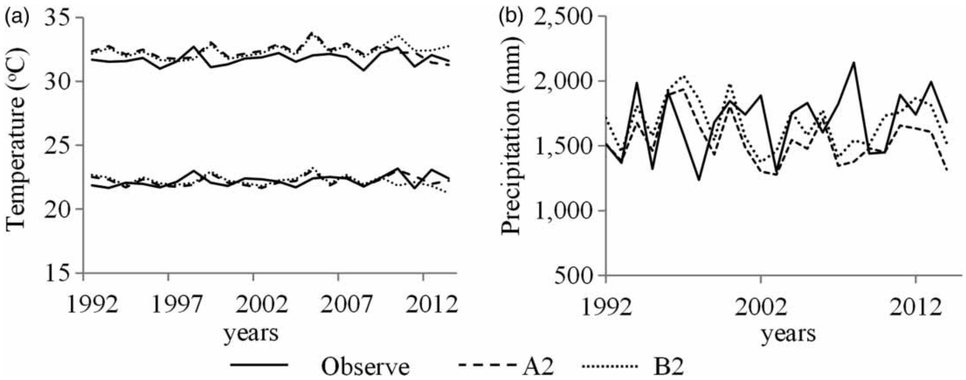

Figure 4 | Adjusted climate data: (a) mean annual maximum and minimum temperatures and (b) mean annual precipitation.

rainfall, and ($Tobs, m - Tds, m$) and ($Pobs, m/Pds, m$) the temperature and rainfall factors (Chen *et al.* 2011).

In this study, the climate data collected during the years 1992–2014 were used and compared with the PRECIS model results. Figure 4 shows the comparison between simulated and observed temperature and precipitation data.

Future climatic changes

The data relative to future climatic changes were corrected based on the observed data between the years 1992 and 2014. We found that the mean annual maximum temperature value was 3–5% higher than those recorded during the observation period. Consequently, the average temperature calculated under the A2 scenario was higher than that calculated under the B2 scenario. Similarly, the mean annual minimum temperature value was 3–8% higher than the observation period and the A2 scenario was higher than the B2 scenario. The mean annual precipitation increased and its average value under the A2 scenario was higher than under the B2 scenario, as shown in Figure 5(a). The results are similar to those of a previous study on the Chi-Moon and Song Kram watersheds, which have similar geographical characteristics to the northeastern areas of Thailand (Chinvanno & Choengbunluesak 2006; Chinvanno 2009).

Considering the monthly changes within each decade, the average monthly maximum temperature in summer (March–May) should be higher than that during the observation period, under both IPCC scenarios: by 13% under the A2 scenario, and by 10% under the B2 scenario (Figure 6(a)–6(c)). The average monthly minimum temperature is projected to slightly increase under the A2 scenario, whereas the temperature is predicted to decrease considerably compared to the observation period under the B2 scenario (Figure 6(d)–6(f)).

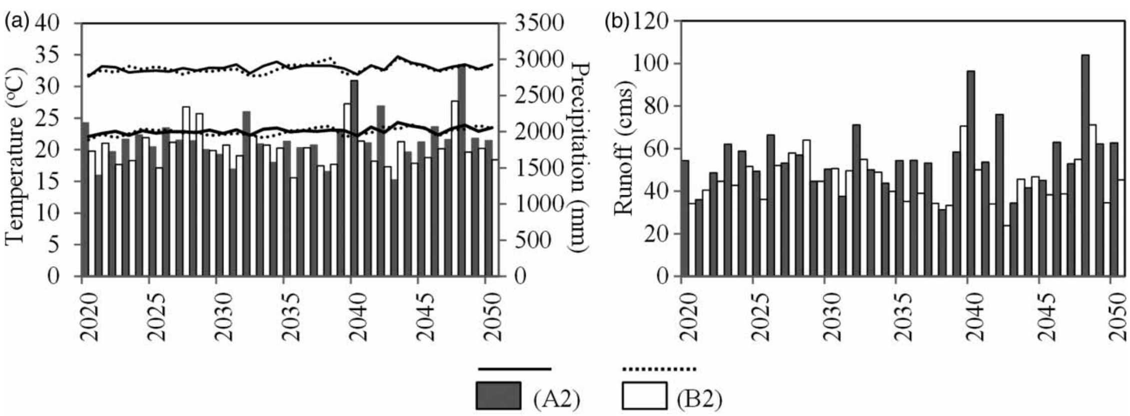

Figure 5 | Projected climate data and runoff: (a) mean annual maximum, minimum temperature, and mean annual precipitation; (b) mean annual runoff.

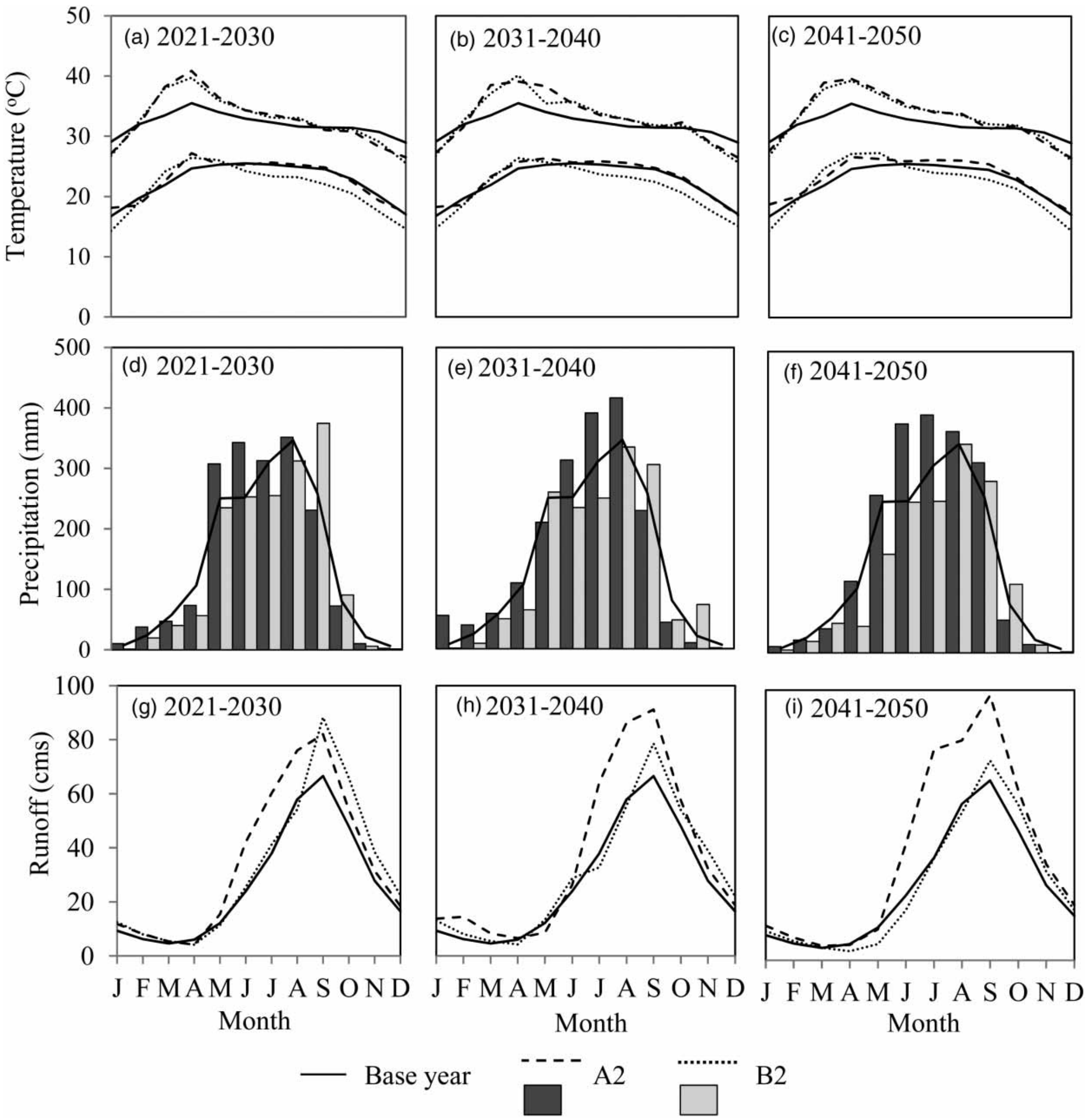

Figure 6 | Average monthly temperature, precipitation, and runoff.

The average monthly rainfall in the future will be higher than that of the observation period under both IPCC scenarios, especially starting from the middle of the century (2040–2050) and under the A2 scenario. In relation to the Sakon Nakhon flood event (between July 28–August 2, 2017) the rainfall data of the Meteorological Department (collected at the Sakon Nakhon station) report the occurrence of continuous heavy rain for 5 days, for a total amount of 400 mm. For the prediction from 2020 to 2050 under the A2 scenario, this same amount of rainfall may occur five times, with more intensity and longer duration; under the B2 scenario, instead, such an event is projected to occur only once.

Future runoff

The SWAT calculation used the average data collected from 2001 to 2014. The runoff during this period was equal to 416.32 million m^3 per year (MCM/yrs); the runoffs for the period 2020–2050 instead were projected to be 569.16 MCM/yrs and 464.67 MCM/yrs under the A2 and B2 scenarios, respectively. Apparently, the future runoff was higher under the A2 scenario than under the B2 scenario (Figure 5(b)). This finding is in agreement with those of Graiprab *et al.* (2010) regarding the effects of climate change on the At Samat watershed (northeastern Thailand), where the runoff yield in the watershed was projected to increase by 3–5%. These results were also similar to those of Ligaray *et al.* (2015) regarding the Chao Phraya watershed (Thailand). The seasonal changes are presented in Figure 6. The graph (Figure 6(a)–6(c)) shows that in both summer and rainy seasons, the average monthly maximum and minimum temperature was drastically higher than what was found in the observation period from those two scenarios. The data comparison indicates that the average runoff in the summer was slightly changed and seemed to decrease in the case of the B2 scenario. Particularly during 2041–2050, it was obviously lower than the result from the observation period. On the contrary, the runoff during the rainy season seemed to increase, especially in the case of the A2 scenario, where the results in each period (2021–2030, 2031–2040, and 2041–2050) were increased 36%, 39%, and 56%, respectively, from the baseline. In the meantime, the result from the B2 scenario during 2021–2030 was increased 15% from the observation period and slightly changed afterwards. In this case, the maximum future runoff for those two scenarios would be found in September, the same as the observation period. The monthly runoff significantly increased in the projections, especially under the A2 scenario in the middle of the century (severe floods are indicated in Figure 6(g)–6(i)). Notably, the runoff under the A2 scenario seemed to increase since the beginning of the rainy season; the maximum runoff was higher than in the observation period. The increased runoff would cause flood with severe impact on the commercial area in Sakon Nakhon Municipality and agricultural damage, especially in the irrigation area around Nong Han Lake. From this study, the water management of the Nong Han reservoir must be reconsidered; the new reservoir operation rule curve should be to release water from the reservoir during the beginning of the rainy season to reduce the impact of flooding, including water allocation to irrigated areas in the dry season. Furthermore, a well-managed disaster warning system is strongly recommended. At this point, the B2 scenario that has been developed with care for the environment could efficiently simplify the water management within the basin.

CONCLUSIONS

This study aimed at estimating the runoff into Nong Han Lake in response to the climatic changes for years 2021–2050 under the A2 and B2 IPCC scenarios. The future rainfall and runoff are projected to increase under both scenarios. Under the B2 scenario, which focuses on the environment, the runoff was higher but its level of severity was lower than under the A2 scenario. Under the A2 scenario, instead, the annual average data indicated that the runoff was higher than in the observation period, whereas the monthly average data confirmed the rapidly and highly increased runoff. Hence, this scenario necessarily requires an adjustment before being applied to flood prevention and management.

ACKNOWLEDGEMENTS

This research was financially supported by Rajamangala University of Technology Isan. The authors acknowledge the Thai Meteorological Department, the Land Development Department, and the Royal Irrigation Department and Material services provided by the Open Topography Facility with support from the National Science Foundation under the NSF Award Numbers.

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First received 21 February 2019; accepted in revised form 26 July 2019. Available online 29 October 2019