A NEAR FUTURE CLIMATE CHANGE IMPACTS ON WATER RESOURCES IN THE UPPER CHAO PHRAYA RIVER BASIN IN THAILAND

***Naphol YOOBANPOT*[1] *and Weerayuth PRATOOMCHAI*[2 *]**

DOI: 10.21163/GT_2022.172.16

ABSTRACT:

This paper focused on regional climate change impacts on hydro-meteorological variables in the Upper Chao Phraya River basin located in northern Thailand. The five global climate models were used with a number of 15 experiments to assess near future water resources over the period 2026-2040. The impacts of climate change were quantified in percentages relative to a retrospective period (1986-2000). On average, the surface temperature tends to increase by 1.45, 1.48, and 1.80 °C under the lowest (RCP2.6), intermediate (RCP4.5), and highest (RCP8.5) CMIP5 greenhouse gas emission scenarios, respectively. Mathematical model called H08 was used, the coupling of three modules did a very good job on mimicking river discharge with high Nash-Sutcliffe and Index of Agreement. The projections of rainfall and its response to surface runoff and groundwater recharge exhibit relatively uneven distributions. The upper basin tends to face extremely heavy rainfall and taking place of serious flood, while the lower areas are expected to cope with drought. Based upon ensemble averages over the entire area, relative changes of -1.7% (-6.4%), -0.1% (-5.2%), and -2.0% (-9.3%) in the mean annual rainfall (groundwater recharge) are shown under the RCP2.6, RCP4.5, and RCP8.5 scenarios, respectively. This study included a groundwater recharge assessment indicating potential available groundwater use, which is considered to be a key resource for climate change adaptation. Based on these findings, implementing such an artificial groundwater recharge system is needed in order to harvest surplus water and making for coping with water stress in the dry season.

Key-words: *Climate change, Drought, Flooding, Groundwater recharge, Water resources management*

1. INTRODUCTION

Climate change is real and is now an international problem. It has a broad and spatially distributed impact on multiple sectors. Observations of air temperature rises and a number of extreme hydrological events, for example 2022 drought across Europe, 2022 Pakistan flood as well as people’s perceptions on the impacts of climate change show an increasing trend (Kiguchi et al., 2021; IPCC, 2018; Magramo, 2022; Hansen et al., 2010; Heim, 2015; Manandhar et al., 2015; Pratoomchai et al., 2015b). The consequences of climate change impacts on hydro-meteorology related to water variability and hazard are complicated. In addition, these impacts are uncertain and difficult to predict. Therefore, understanding how potential climate change effects alter the distribution and availability of hydro-meteorological variables at a regional or basin scale is crucial and necessary to frame resilient measures to provide and formulate better water resource management such as conjunctive water use.

In Thailand, extreme floods and droughts are common (Pavelic et al., 2012 and Kiguchi et al., 2021). During the period 1991-2011, approximately 8,300 million US dollars were spent toward flooding damage (Department of Disaster Prevention and Mitigation, 2011). On the other hand, the depletion of river discharge and widespread drought-affected areas were reported, for example, in 1986, 1987, 1990, 1993, 1998, 2003, 2005, 2012, 2015 and 2018.

[1] *King Mongkut's University of Technology North Bangkok, Faculty of Engineering, Department of Civil Engineering, Bangkok, Thailand, naphol.y@eng.kmutnb.ac.th*

[2*] *King Mongkut's University of Technology North Bangkok, Faculty of Engineering, Department of Civil Engineering, Bangkok, Thailand, weerayuth.p@eng.kmutnb.ac.th*

More recently, over two consecutive years (2014 and 2015), the annual rainfall over Thailand was 8% and 12%, respectively, below the 30-year average (from 1981-2010). Because of the hydrological conditions in Chao Phraya River basin, changes on the order of a few percentages of rainfall can lead to a significant impact on the runoff volume (Kotsuki and Tanaka, 2013). In this case, the volume of water storage in major reservoirs was low in an approximately 30-year return period; therefore, irrigation water was not allocated to grow rice during the dry season, which had a large impact on more than ten million people who were primarily farmers.

Regarding the potential of climate change impact studies, Kotsuki et al. (2014), Pratoomchai et al. (2014), and Watanabe et al. (2014) noted that both flooding and drought periods in the Chao Phraya River basin tend to be amplified adversely compared to the last decade. The number of rainy days might decrease, but the amount and intensity of precipitation tend to increase. Hydrologically extreme events and their aftermath, e.g., extreme precipitation-induced landslides, are likely to be exacerbated (Kuraji et al., 2009; Limsakul and Singhruck, 2016; Ono et al., 2015). Thorough assessments are consequently needed with a high horizontal resolution (Kiguchi et al. 2021). It will be more practical and useful if an assessment provides information at a sub-basin scale or at monitoring/warning points, e.g., main gauging stations. Furthermore, groundwater is rarely studied in Thailand, but its potential is now being considered as a buffer for the available water supply to cope with water stress. Thus, a projection of climate change impacts, including impacts with regard to groundwater flux (recharge), is needed to evaluate basin threats and resilience. Therefore, investigating the temporal and spatial distributions of hydro-meteorological variables affected by climate change to provide scientific, region-based information for adaptation options is mandatory for intensive agriculturally based countries such as Thailand. Key hydro-meteorological variables, i.e., surface temperature, rainfall, runoff, river discharge, and groundwater recharge, were subjected to investigation in this study to reveal hydro-meteorological changes at a sub-basin and grid-based scale as well as at monitoring gauging stations. Accordingly, decision makers, community leaders, and people who are interested in how anthropogenic climate change might shape future water resources can benefit from this paper.

2. THE UPPER CHAO PHRAYA RIVER BASIN

Thailand is a country that plays a significant role in supplying agricultural products such as rice, which is a staple food for global food demand. However, the trend in the rice yield is currently decreasing because of an increasing number of hot days (≥ 37.5 °C, Pratoomchai et al., 2015, 2020) and less water for allocating to irrigation area. The Upper Chao Phraya River basin (UCP), which is associated with the Ping, Wang, Yom, and Nan sub-basins (comprising 12 provinces) in the northern part of the country shown in **Fig. 1a**, is a major source for rice growth. Its basin covers a total massive land area of approximately 109,973 km^2. The altitude varies from that of a mountain range (the upper region) with a maximum elevation of approximately 2,570 m (above mean sea level, msl) to that of a lowland area at approximately 14 m (msl) at the basin outlet.

The basin lies in a tropical zone that is usually dominated by two distinct monsoon seasons: the rainy southwest monsoon (May-July) and the northeast monsoon (August-October), wherein approximately 82% of the average annual rainfall occurs during the rainy season. On average, the base-wide annual rainfall is 987 mm. Kuraji et al. (2009) showed that the annual high-altitude rainfall reaches approximately 1,300 mm and demonstrates an increasing trend. Flooding is the most severe natural disaster threat over the lowland area. Based on satellite image data that were analyzed by the Geo-Informatics and Space Technology Development Agency (GISTDA) of Thailand, the area of maximum flood inundation varied between 1,455 km^2 and 9,490 km^2. The light-blue shaded area (**Fig.1b**) represents the extent of maximum flood inundation of the 2011 extreme flood event. Deforestation, especially in the headwaters of the Nan sub-basin, is expected to accelerate and contribute to an increased flood volume downstream.

Generally, the river delineation and flow are from north to south, which is the same direction of the storm paths. The Wang River merges with the Ping River, the Yom River joins with the Nan River, and the Ping and Nan Rivers have a confluence at the C.2 gauging station in the Nakhon Sawan

Province with an observed mean river discharge of 734 $m^3 s^{-1}$ (during the 2011 event, the maximum daily peak was 4,686 $m^3 s^{-1}$, or approximately 1,200 $m^3 s^{-1}$ over its channel capacity). Overall, approximately 82% of the annual rainfall is evaporated back into the atmosphere (Pratoomchai et al., 2015).

There are 2 major artificial storages (i.e., the Bhumibol reservoir on the Ping River, which is not far upstream from the Ping-Wang confluence, and the Sirikit reservoir on the Nan River, **Fig. 1b**) with a total storage of approximately 23 km^3 within the basin. Both reservoirs were considered in this study. However, other artificial storages that are also situated within the upper Ping and Wang sub-basins were not considered in our assessment because their capacities are relatively small compared with those of the Bhumibol and Sirikit reservoirs.

There are a couple of reasons to select UCP as the study area. First, based on statistical data, the content of the UCP basin tends to increase in terms of both magnitude and frequency with both flooding and droughts (e.g., Ekkawatpanit et al., 2013; Kuraji et al., 2009; Mateo et al., 2014; Pavelic et al., 2012; Pratoomchai et al., 2014, 2015a; Gopalan et al., 2021). Second, approximately 80% of the agricultural areas that are mainly used for rice in the basin are rain-fed. There is explicit plan to develop new irrigation areas in these rain-fed that requiring more water budget (Royal Irrigation Department, 2010). Furthermore, there has been very strong and aggressive protesting from the local populace on the construction of a new reservoir in the Yom sub-basin because of natural and environmental concerns. Nevertheless, prior to a couple of years ago, groundwater irrigation promoted and played a distinguished role in the growth of rice (Department of Groundwater Resources, 2012; National Research Council of Thailand, 2022). Therefore, the abovementioned factors will push the UCP into a critical hydro-meteorological state that will eventually impose negative impacts upon the residents.

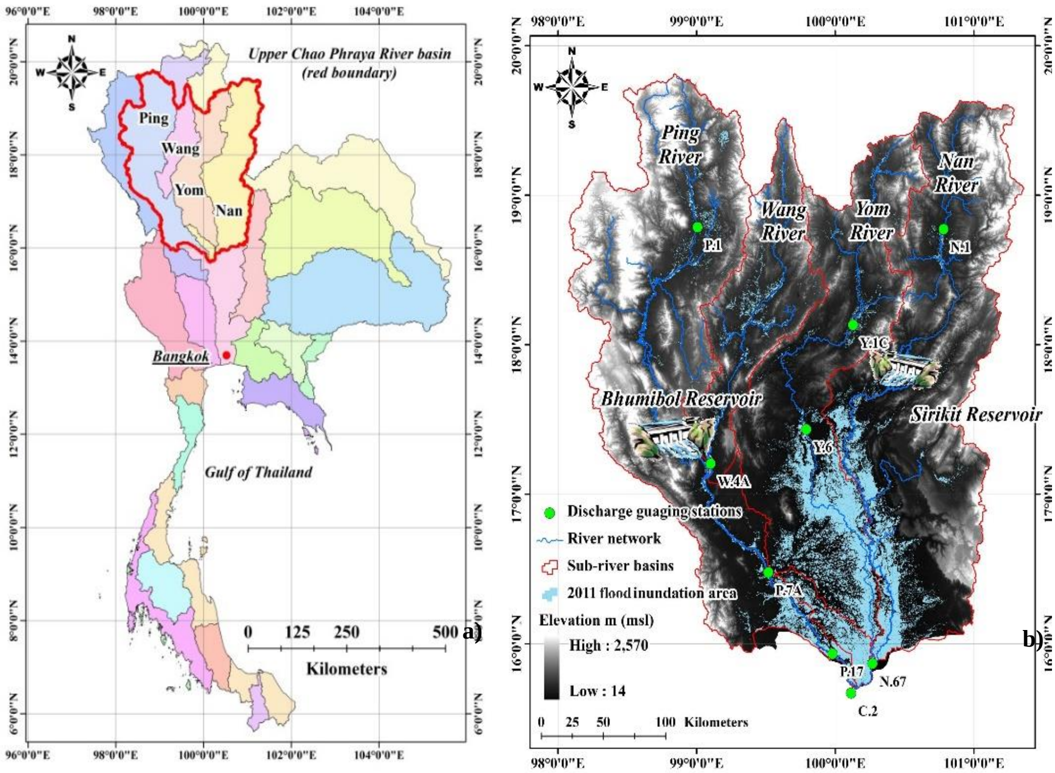


Fig. 1. Study area: a) the main river basins in Thailand and b) the Upper Chao Phraya River basin.

3. METHODOLOGY AND DATA

3.1. Mathematical model

This study took advantage of the Integrated Study Project on Hydro-Meteorological Prediction and Adaptation to Climate Change in Thailand (the IMPAC-T project, http://impact-www.eng.ku.ac.th/cc/), which downscaled the water resource model known as H08 (Hanasaki et al., 2008) from a $1.0^\circ \times 1.0^\circ$ to a $5' \times 5'$ spatial resolution that is more reasonable for a regional-scale assessment (Hanasaki and Mateo, 2012; Hanasaki et al., 2014). Three modules of the H08 model, i.e., land surface, river routing, and reservoir operation modules, were conducted in this study (**Fig. 2**). The technical details and limitations of H08 are available in Hanasaki et al., 2014; Mateo et al., 2014. However, a brief description of each particular module will be outlined below.

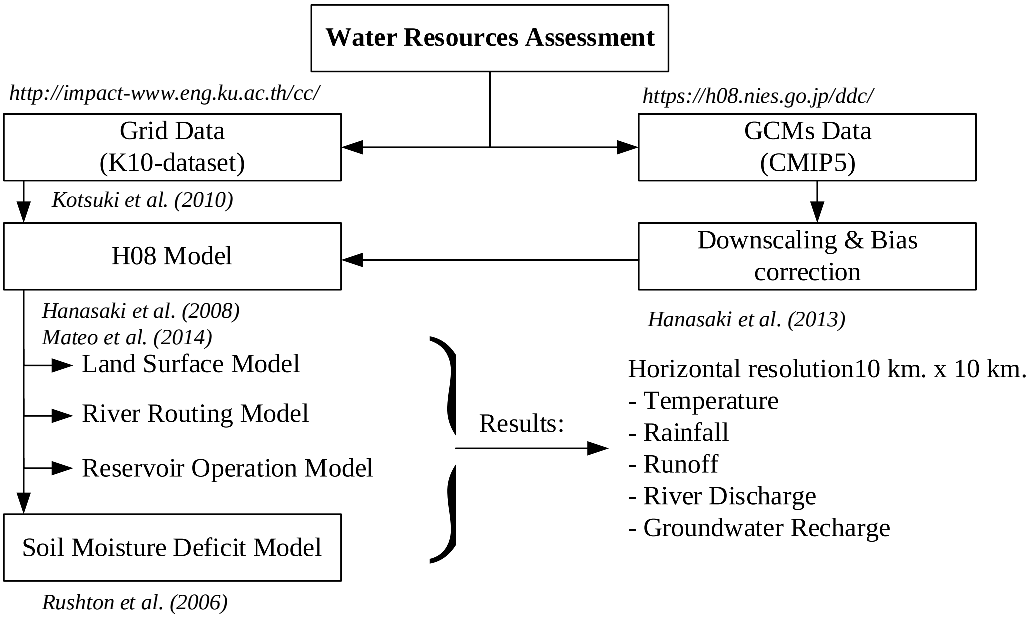


Fig. 2. Schematic diagram of methodology.

First, the land surface module (LSM) was constructed under a soil water balance concept (Hanasaki et al., 2008), which is able to simulate a diurnal soil-surface water balance. Second, a virtual straight-line river element concept from the Total Runoff Integration Pathways (TRIP) model, which was developed by Oki and Sud (1998), was implemented into the river routing module. Lastly, a simple reservoir operation module, consisting of the mean seasonal released flows (i.e., of the wet and dry seasons), was determined from historical operating data (Bhumibol and Sirikit reservoirs) for normal regulation. In extreme circumstances (i.e., droughts and flooding), the module will output a zero-discharge value if the storage volume is less than the dead reservoir storage (i.e., 3.80 and 2.85 km^3 for the Bhumibol and Sirikit reservoirs, respectively) and will output more discharge to maintain the water level in the reservoir below that which is allowed by the upper rule curve if a large amount of runoff volume flows into the reservoirs (Hanasaki and Mateo, 2012; Mateo et al., 2014).

To provide groundwater recharge calculations, we simplified an approach known as the soil moisture deficit (SMD) method and focused on the distribution of groundwater recharge as driven by rainfall (Rushton et al., 2006). Groundwater recharge is generated on days when the SMD estimate reaches a negative value. If the SMD becomes zero, it represents the state wherein the soil is at 100% saturation and ready to free the recharged volume Groundwater recharge is therefore the quantity of water in excess of that required to saturate the soil. The model structure, calculation steps, and parameters as well as the initial conditions can be found in Pratoomchai et al. (2014 and 2015a).

There were some limitations of our model. Only the Bhumibol and Sirikit reservoirs were included in the reservoir operation module while small reservoirs in the Ping, Wand, and Nan sub-basins were not considered. Land use land cover in the UCP for the projected climate change period (2026-2040) and reference period (1986-2000) was assumed the same, no land use change. The study focused on only climate change impacts on water resources, socio-economic changes did not include.

3.2. Forcing climate data

Kotsuki et al. (2010, 2014) collected observed data (1981 to 2004) from the Thai Meteorological Department (TMD) and Royal Irrigation Department (RID) and created the 10 km. x 10 km. horizontal resolution in binary format. This data-set known as K10-data and contributed (**Table 1**), free of charge, for researchers under the international IMPAC-T project (http://impact-www.eng.ku.ac.th/cc/). To simulate the LSM, K10-dataset was used for the model input. The observed river discharge provided by RID were used for model calibration and validation.

Table 1.

Forcing climate data for the H08 model.

Data	Grid size	Temporal resolution	Sources
Surface air temperature	10 km. x 10 km.	Daily	K10-data set (http://impact-www.eng.ku.ac.th/cc/)
Specific humidity	10 km. x 10 km.	Daily	
Wind speed	10 km. x 10 km.	Daily	
Surface air pressure	10 km. x 10 km.	Daily	
Short-wave downward radiation	10 km. x 10 km.	Daily	
Long-wave downward radiation	10 km. x 10 km.	Daily	
Rainfall	10 km. x 10 km.	Daily	
River discharge	Gauging stations	Daily	Royal Irrigation Department

3.3. Global climate model (GCM) selection, climate change scenarios, and bias correction of GCMs

As a consequence of an incomplete knowledge of the earth's systems and an unforeseeable future (e.g., Hanasaki et al., 2013; Jackson et al., 2011), there is no universally applicable GCM that is recommended for conducting studies to assess climate change. Applying an increased number of GCMs is common for projecting climate change impacts because each GCM has been developed and treated using a different technique. The results obtained from multiple GCMs might reflect and encompass a broader possible range of the future assessment.

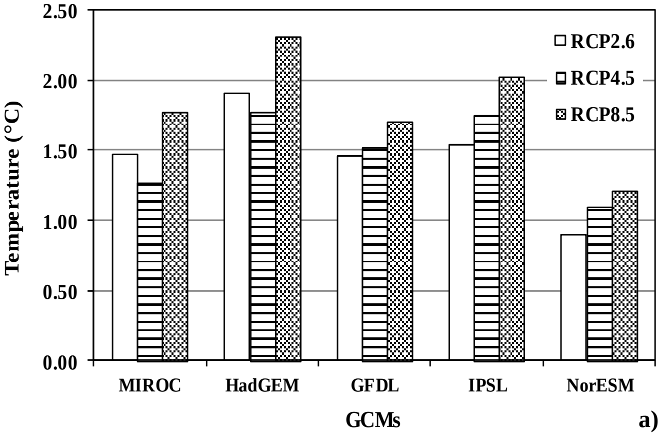
In this paper, 5 GCMs were selected, namely, 1) MIROC-ESM-CHEM (MIROC), 2) HadGEM2-ES (HadEM), 3) GFDL-ESM2M (GFDL), 4) IPSL-CM5A-LR (IPSL), and 5) NorESM1-M (NorESM), which were selected from the World Climate Research Program's Coupled Model Inter-Comparison Project phase 5 (CMIP5). All of these GCMs are earth system models, the results of which were cross-checked in the Inter-Sectoral Impact Model Intercomparison Project (http://www.isi-mip.org/). These 5 GCMs from different climate research institutes were selected to reflect uncertainties within the models. Three scenarios (i.e., representative concentration pathways, or RCPs), including low (RCP2.6), intermediate (RCP4.5), and high (RCP8.5) levels of emissions, were used to project the future climate for the period 2026-2040, which represents the near future, in order to ignore the effects of land use change. Since multiple GCMs and scenarios were considered, a plausible range and pattern of hydro-meteorological variables due to the forcing of climate change should be revealed.

For the projection and simulation of climate change, the systematic biases from 3 variables (i.e., temperature, rainfall, and longwave downward surface radiation) that were collected from the GCMs were corrected. A shifting and scaling technique previously used by researchers, including Hanasaki et al. (2013), was applied to remove the systematic bias of the 3 variables. This is one of the simplest and most popular techniques for GCM bias correction. In short, a time series of current climate data can be modified by adding or multiplying climate elements that are affected by climate change in order to create a new climate variable time series under a particular scenario or set of climate change conditions.

4. RESULTS AND DISCUSSION

4.1. Surface temperature and rainfall changes

Fig. 3a shows the spatial average of the mean annual surface air temperature variations over the entire UCP in 2026-2040. It shows the differences between the projection period and the reference period (1986-2000), which had a 25.38 °C mean annual surface air temperature (**Fig. 3b**). In general, these projections show good agreement with the degree of greenhouse gas emissions. There were changes (anomaly) of 1.45, 1.48, and 1.80 °C under the RCP2.6, RCP4.5, and RCP8.5 scenarios, respectively, which all exhibit an increasing trend. All scenarios projected a rising trend in every single area. The projected results show good agreement with the forcing conditions, which are the lowest in the RCP2.6 scenario and the highest in the RCP8.5 scenario. In fact, the values shown above were averaged from the 5 GCMs for each scenario to express a general trend and overcome the uncertainty within the GCMs (e.g., Jackson et al., 2011).



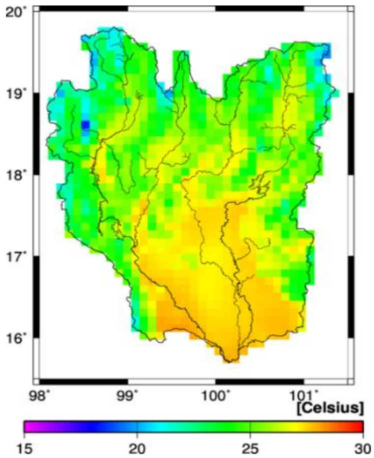


Fig. 3. a) Projection of annual surface air temperature changes in 2026-2040 and b) spatial distribution of the past mean annual temperature (1986-2000).

All of the GCMs were also applied to project the spatial mean annual rainfall, runoff, and evaporation, as shown in **Table 2**. The GCMs and scenarios that revealed decreasing trends are presented in italics. In general, we observe that the projected trends depended upon the GCMs rather than the scenarios. The MIROC and NorESM GCMs showed an increasing trend for all variables. Rainfall acts like an input into the system, for which the projected variability or ranges from -10.5 to +7.5%, -11.5 to +6.4%, and -10.2 to +10.2% corresponding to the RCP2.6, RCP4.5, and RCP8.5 scenarios, respectively, relative to the reference period (987 mm). Using a simple average among the GCMs for each particular scenario, we can quantify potential -1.7%, -0.1%, and -2.0% changes in the mean annual rainfall under the RCP2.6, RCP4.5, and RCP8.5 scenarios, respectively. Based on the projected results, rainfall tends to decrease, and the other variables (runoff and evaporation) are associated with rainfall.

Table 2.

Mean annual rainfall, runoff, and evaporation in 2026-2040 under the modeled climate change conditions.

Scenarios	GCMs	Mean annual projections					
		Rainfall		Runoff		Evaporation	
		mm	% changes	mm	% changes	mm	% changes
RCP2.6	MIROC	1,057.50	7.14	189.20	6.89	868.30	7.20
	HadGEM	*883.30*	*-10.51*	*137.10*	*-22.54*	*746.10*	*-7.89*
	GFDL	*925.20*	*-6.26*	*161.80*	*-8.59*	*763.40*	*-5.75*
	IPSL	*923.30*	*-6.45*	*144.00*	*-18.64*	*779.20*	*-3.80*
	NorESM	1,060.60	7.46	196.80	11.19	863.80	6.64
RCP4.5	MIROC	1,045.10	5.89	188.20	6.33	856.90	5.79
	HadGEM	*938.90*	*-4.87*	*153.60*	*-13.22*	*785.30*	*-3.05*
	GFDL	*873.00*	*-11.55*	*138.80*	*-21.58*	*734.20*	*-9.36*
	IPSL	*1,032.90*	4.65	*186.50*	5.37	*846.40*	4.49
	NorESM	1,049.80	6.36	188.10	6.27	861.70	6.38
RCP8.5	MIROC	1,088.20	10.25	205.60	16.16	882.60	8.96
	HadGEM	*885.90*	*-10.24*	*135.70*	*-23.33*	*750.30*	*-7.37*
	GFDL	*904.40*	*-8.37*	*152.00*	*-14.12*	*752.40*	*-7.11*
	IPSL	*888.40*	*-9.99*	*140.80*	*-20.45*	*747.60*	*-7.70*
	NorESM	1,070.50	8.46	201.10	13.62	869.40	7.33

Fig. 4 shows the spatial distributions of the average annual rainfall, runoff, and evaporation. The figures show the spatial average from the past (left, 1986-2000), the ensemble average using the 5 GCMs under the RCP8.5 scenario (middle, 2026-2040), and the difference between the projected and reference periods (right). Both increases and decreases in the projected rainfall changes are observed, except within the projection under the RCP4.5 scenario. This scenario demonstrates that rainfall over the entire basin might be reduced by 20 mm to 50 mm relative to the period 1986-2000. However, all scenarios showed agreement that the lower part of the UCP is likely to be subject to a reduction in the amount of rainfall, especially in the lower Ping sub-basin. On the other hand, RCP2.6 suggests that rainfall will increase in the Ping sub-basin in the future. The spatial distributions of evaporation and runoff show the same patterns as rainfall because the rainfall is the input into the system. More rainfall means more available water for evaporation, while the rest contributes to runoff.

However, the results based on the 5 GCMs can be changed when we consider a greater number of GCMs, but there is no rule of thumb on this matter. Since the projections were focused on the near future to avoid the effects of land use change, the signals of climate changes may not be clearly observable within the projected period. However, the projected models imply that the first monsoon tends to decrease, while the second monsoon season shows an increasing trend. This interannual variability might induce both drought (i.e., an insufficient water supply for good crop growth over the period from May to July) and flooding during the second monsoon.

4.2. River discharge changes

Fig. 5 shows a comparison between river discharge rates (i.e., from observation and simulation) at the selected 8 gauging stations over the period 1986-2000 as a result of the coupling of 3 modules (LSM, river routing, and reservoir operation) in a daily time-step. Two objective functions, i.e., the Nash-Sutcliffe coefficient (Ef) and index of agreement (IOA), were applied to quantitatively show the model performance. Both the Ef and IOA are likely close to unity; thus, we note that our model very capably predicted the river discharge rates at the various observed stations. Thus, adapting the validated model to assess the river discharge under different climate change conditions should be reasonable.

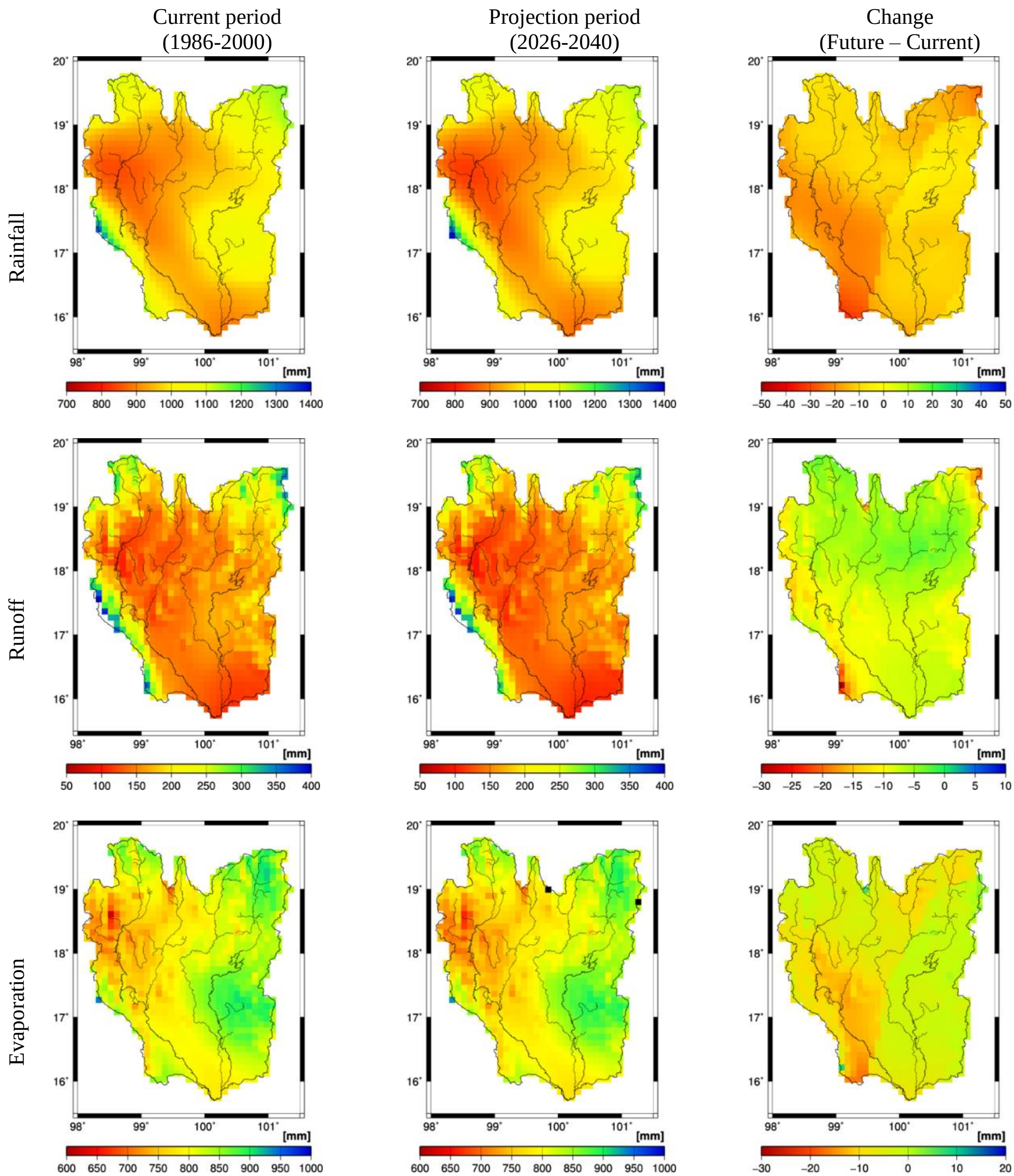


Fig. 4 Spatial distribution of average annual rainfall, runoff, and evaporation under the RCP8.5 scenario using the ensemble average from the 5 GCMs.

As shown in the figure, Ef and IOA were not calculated for the P.17 and N.67 stations because of incomplete observed data. For the IOA values (0.89 – 0.98), the model did a very good job on mimicking discharge observation. The other objective function (Ef) also showed good performance on producing model results with Ef values between 0.76 and 0.95. However, W.4A station (Outlet of the Wang sub-basin), Ef coefficient (0.49) reveled relatively low due to the fact that there are two dams in this sub-basin but we did not consider in our model since their total capacity is very small compare to the Bhumibol and Sirikit reservoirs.

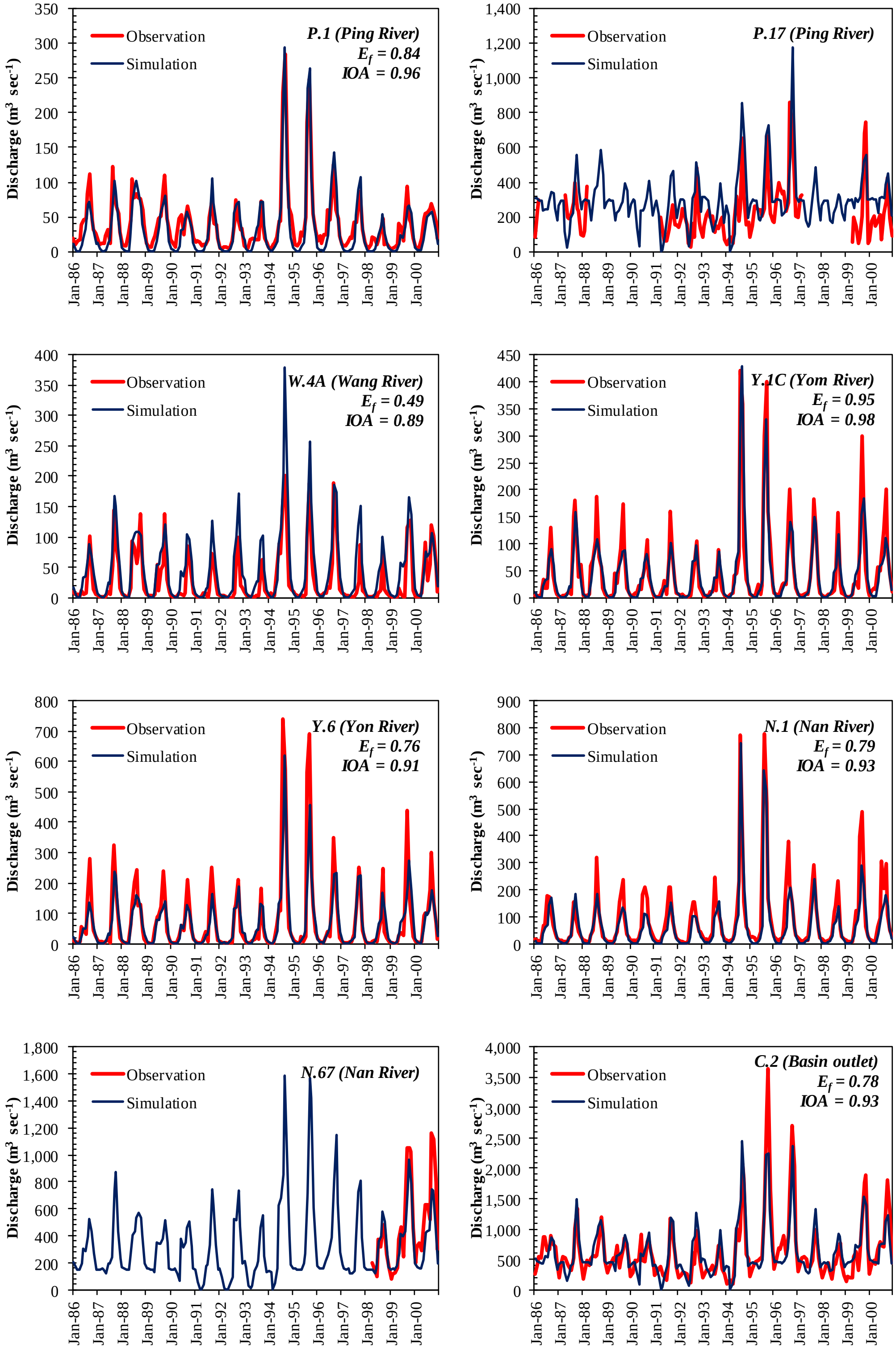


Fig. 5. Comparison of monthly river discharge rates at the main gauging stations in the UCP.

Overall, the model performance able to capture the general patterns of river discharge in the UCP. It was confirmed by model result at C.2 station (UCP outlet), 0.78 and 0.93 for the Ef and IOA, respectively. However, for an extreme event (1995 flood event), the model did not capture the peak well (under estimate) because of special reservoir operation policy and it is a limitation of our model. Under the climate change conditions (**Fig. 6**), at the basin outlet (station C.2), the black dashed line was quite stable from January to May (approximately 390 m^3 sec^{-1}) because this period was governed by reservoir operations.

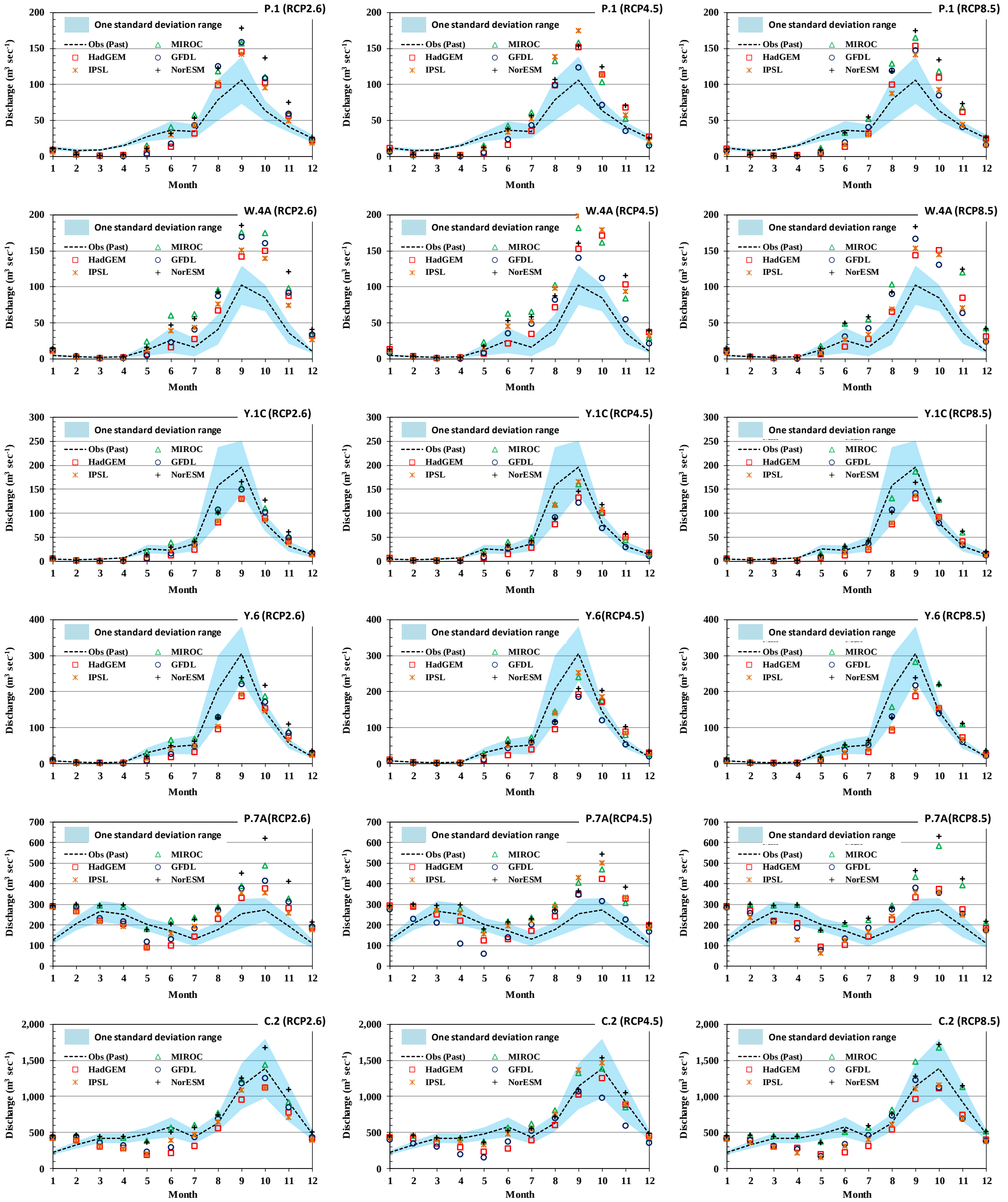


Fig. 6. Comparison of past (1986-2000) and projected (2026-2040) river discharge rates. The light blue shaded area represents a band of one standard deviation using the observed data for analysis.

During the wet season (May to October), the river discharge at the basin outlet station reached its peak in October (approximately 1,400 m^3 sec^{-1} from an average of 15 years), but the rainfall reached a maximum in September. It can be roughly estimated that the travel time of surface water in the UCP is approximately 1 month. However, for the stations that are not subject to reservoir effects, almost zero discharge was observed during the dry season. From January to May, the projections of river discharge rates resulting from the multiple GCMs and scenarios were decreased for these stations (i.e., P.1, W.4A, Y.1C, and Y.6). In contrast, during the second monsoon period (August to October), the river discharge rates in the upper area (i.e., the mountainous region) showed a significant increase, as their projected results (e.g., for stations P.1 and W.4A) exceeded the one standard deviation range.

NorESM GCM projected the highest discharge while HadGEM GCM showed relatively low discharge rate for all scenarios. The degree of climate change impact on river discharge in the UCP is not much difference between climate change scenarios, for example, projected maximum monthly discharge at P.1 (headwater) and C.2 (UCP outlet) stations are approximately 180 and 1,600 m^3 s^{-1}, respectively. For the sub-basin scale, the Ping, Wang, and Nan sub-basins showed increasing in runoff volume but the Yom sub-basin yielded less discharge compared to the based-period. These projected patterns showed consistency for all scenarios.

In addition, an increasing trend of rainfall in the upper Ping region has been observed (Kuraji et al., 2009). To alleviate the expected flood volume, a reservoir operation option was modeled and simulated by Mateo et al. (2014), the results of which revealed that, because of the operation of the Bhmibol and Sirikrit reservoirs, approximately 8.6 billion m^3 of the 2011 downstream flood volume was reduced. Further adaptations of the reservoir rule curves were examined. If the proper rule curve had applied during the flood, approximately 2.4 billion m^3 would have been further reduced.

In terms of their spatial distributions, the projections show an increasing river discharge in the upper basin with a decreasing trend in the lower area. This is especially clear if we look at the spatial distributions of the runoff. It is optimistic that the lower basin can take advantage of the reservoir storage capacities (i.e., the Bhumibol and Sirikit reservoirs), and therefore, climate change impacts on river discharge rates might not much change except for within the Yom sub-basin.

4.3. Groundwater recharge changes

Based on the model results, nearly 100% of the recharge occurred between May and October. The maximum groundwater recharge time frame for both the reference and projected periods occurred during August-September, which was coincident with the second monsoon period. Approximately 93 mm of the mean annual groundwater recharge accounted for 9.4% of the mean annual rainfall (1986-2000). Meanwhile, there is no observation of groundwater recharge within the UCP or in Thailand. However, the amount of the calculated groundwater recharge was consistent with amounts reported in other studies, such as Ramnarong and Wongsawat, 1999, Döll (2009), and Koontanakulvong et al. (2010). The future projections show a large range in the mean annual groundwater recharge from 70.8 mm (a -24% decrease) to 105 mm (a +13% increase). These findings are consistent with the results of Döll (2009), who obtained a range in the projected changes in groundwater recharge in Thailand from -30% (decrease) to +10% (increase) by 2050 under the ECHAM4 and HadCM3 models with scenarios A2 and B2. Overall, we note that the projections varied predominantly according to the GCM utilized rather than by the scenario. This emphasizes that the projections are sensitive to the GCMs used (e.g., Döll, 2009; Jackson et al., 2011).

Fig. 7 shows the spatial distributions of the mean annual groundwater recharges over the projected period. In addition, the ensemble averages (Jackson et al., 2011) of the spatial distributions for each scenario are presented. Decreases of 87.0 (-6.4%) mm, 88.1 (-5.2%) mm, and 84.3 (-9.3%) mm relative to the reference period were observed for the RCP2.6, RCP4.5, and RCP8.5 scenarios, respectively. The maximum projected decrease in the mean annual groundwater recharge is approximately -22.2 mm (24%), which was obtained under the HadGEM model for the RCP8.5 scenario corresponding to the extreme decrease in the projected rainfall. On the other hand, the same experiment (RCP8.5) under the MIROC model projected a 13% increase in the mean annual groundwater recharge relative to the period 1986-2000.

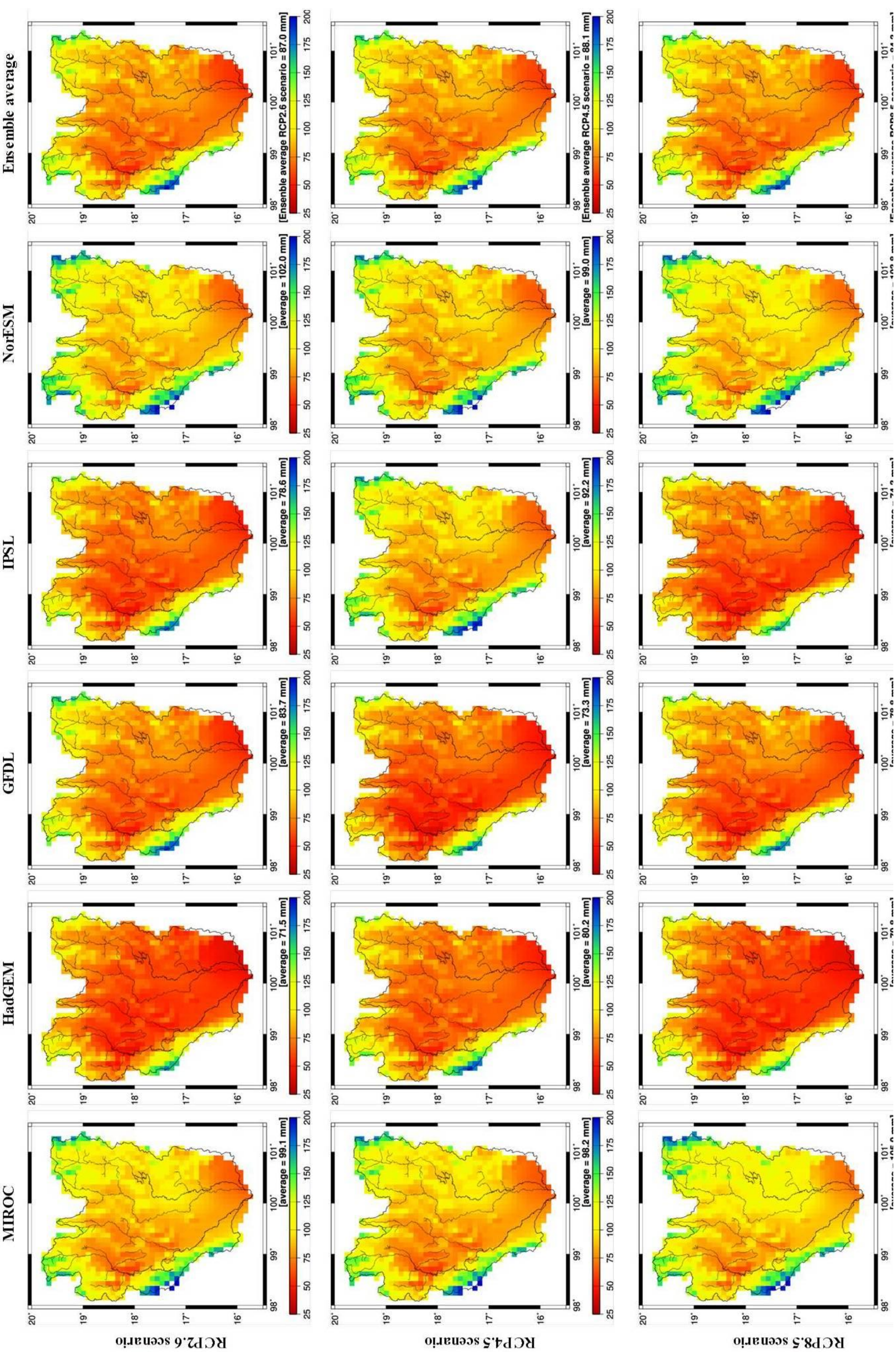


Fig. 7. Spatial distribution of the average annual groundwater recharge rates under different climate change conditions.

However, it should be noted that the decreasing rate of groundwater recharge is evidence of the effect of evaporation that is driven by increasing surface air temperatures. If we compare the range of the projected changes in the mean annual rainfall (from -11.5% to +10.2%) with those of the groundwater recharge (from -24% to +13%), we see that the range in the projected change of the groundwater recharge is larger.

There is a clear interrelationship between flood inundation and induced groundwater in a floodplain area (e.g., Kazama et al., 2007). Thus, a flood harvesting scheme should be implemented in order to take advantage of this phenomena to buffer droughts during the dry season. As suggested by Pavelic et al. (2012), the allocation of areas ranging from 70 km^2 to 340 km^2 (depending on the infiltration rate) in the lower Yom and Nan sub-basins should be considered for constructing infiltration ponds. In fact, groundwater use is now playing an important role in alleviating surface water shortage (National Research Council of Thailand, 2022). However, the observed fluctuations of groundwater levels in the wet and dry seasons showed a larger range during consecutive years given the high volume of extracted groundwater (Pratoomchai et al., 2015b). Thus, a measure to induce additional groundwater recharge to compensate for high groundwater drafting is needed to avoid groundwater depletion.

5. CONCLUSIONS

Key hydrological variables, i.e., temperature, rainfall, runoff, river discharge, and groundwater recharge, were projected under different climate change conditions over the near period 2026-2040 because it was reasonable to ignore the effects of land use change. An increased temperature ranges from 1.45-1.80 °C was expected relative to the period 1986-2000. Rainfall was projected to increase under the MIROC and NorESM GCMs, but the HadGEM, GFDL, and IPSL GCMs suggested a decrease in the rainfall trend. Using ensemble averages, the future annual rainfall was expected to decrease by approximately 20 mm under the highest greenhouse gas emission scenario (RCP8.5). In terms of its spatial distribution, only the upper Ping sub-basin showed an increasing rainfall trend. The rest of the basin, the majority of which is the UCP, was subjected to decreasing rainfall; therefore, the runoff and groundwater recharge, on average, were projected to show 5.6% (10 mm) and 9.3% (8.7 mm) reductions under the RCP8.5 scenario. Among the 4 sub-basins, the Yom sub-basin is the most vulnerable area and going to face with drought because of pronounced climate change impacts, low river discharge and groundwater recharge, and a lack of artificial storage, e.g., a reservoir. Therefore, a structural measure to secure flood water in the wet season and release downstream in the dry season is now not available for this area.

Climate change might cause or induce more flooding (e.g., the upper Ping and Wang sub-basins during the second monsoon) and drought (e.g., the lower basin, especially in the Yom sub-basin). Considering the advantages of reservoir storage and their proper operation is one possible option to alleviate the problems related to flooding (Mateo et al., 2013, Gopalan et al., 2021). On the other hand, enhancing the use of groundwater is one possible option to cope with drought (Pratoomchai et al., 2015a). However, to ensure that groundwater will not be depleted and thereby induce other problems, increasing the groundwater recharge rate by means of floodwater harvesting schemes (i.e., allocating low-lying areas in the lower Yom and Nan sub-basins for temporary natural flood ponds) is recommended during the second monsoon (September-October). In addition, a law or policy to control groundwater extraction should be implemented.

Further suggestions and projections with an uncertainty analysis are a crucial component to improve the qualitative understanding of potential climate change impacts on water resources at a local scale. A number of small reservoirs in the Ping and Wang sub-basins and land-use/land-cover changes should be included in the mathematical model. Moreover, an integrated assessment between climate change and socio-economic change impacts on water sector will provide a clearer picture for what should do to cope with the era of changing climate (Kiguchi et al. 2021). Finally, we hope that this study will provide useful guidance for decision makers managing of water resources in helping to secure and alleviate water problems induced by climate change in the UCP.

ACKNOWLEDGEMENTS

The authors are very pleased with and appreciate the funding provided by Faculty of Engineering, King Mongkut's University of Technology North Bangkok, under grant number ENG-64-108.

REFERENCES

Department of Disaster Prevention and Mitigation (2011) Statistics of flood and droughts in Thailand (in Thai). Bangkok, Thailand.

Department of Groundwater Resources (2012) Groundwater and sustainable agriculture in Thailand (in Thai). Bangkok, Thailand.

Döll P. (2009) Vulnerability to the impact of climate change on renewable groundwater resources: a global scale assessment. Environmental Research Letters 4: 035006.

Ekkawatpanit C, Kazama S, Sawamoto M, Sarukkalige P. (2013) Evaluation of the inequality of water resources. Water Management 166: 303-314.

Green TR, Taniguchi M, Kooi H, Gurdak JJ, Allen DM, Hiscock KM, Treidel H, Aureli A. (2011) Beneath the surface of global change: impact of climate change on groundwater. Journal of Hydrology 405: 532-560.

Gopalan S.P., Hanasaki N., Champathong A., Tebakari T. (2021) Impact assessment of reservoir operation in the context of climate change adaptation in the Chao Phraya River basin. Hydrological Processes. https://doi.org/10.1002/hyp.14005

Hanasaki N, Mateo CM. (2012) H08 regional application: Case study of the Chao Phraya River. H08 supplemental documentation 1.

Hanasaki N, Kanae S, Oki T, Masuda K, Motoya K, Shirakawa N, Shen Y, Tanaka K. (2008) An integrated model for the assessment of global water resources Part1: Model description and input meteorological forcing. Hydrology and Earth System Sciences 12: 1007-1025.

Hanasaki N, Fujimori S, Yamamoto T, Yoshikawa S, Masaki Y, Hijioka Y, Kainuma M, Kanamori Y, Masui T, Takahashi K, Kanae S. (2013) A global water scarcity assessment under shared socio-economic pathways – Part2: Water availability and scarcity. Hydrology and Earth System Sciences 17: 2393-2413.

Hanasaki N, Saito Y, Chaiyasaen C, Champathong A, Ekkawatpanit C, Saphaokham S, Sukhapunnaphan T, Sumdin S, Thongduang J. (2014) A quasi-real-time hydrological simulation of the Chao Phraya River using meteorological data from the Thai Meteorological Department automatic weather stations. Hydrological Research Letters 8(1): 9-14.

Hansen J, Ruedy R, Sato M, Lo K. (2010) Global surface temperature change. Reviews of Geophysics 48: RG4004

Heim RR. (2015) An overview of weather and climate extremes – products and trends. Weather and Climate Extremes 10: 1-9.

IPCC (2018). In V. Masson-Delmotte, et al. (Eds.), Global Warming of 1.5° C. An IPCC Special Report on the impacts of global warming of 1.5° C above pre-industrial 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.

Jackson CR, Meister R, Prudhomme C. (2011) Modelling the effects of climate change and its uncertainty on UK Chalk groundwater resources from an ensemble of global climate model projections. Journal of Hydrology 399: 12-28

Kiguchi et al. (2021) A review of climate-change impact and adaptation studies for the water sector in Thailand. Environmental Research Letters 16 023004

Kazama S, Hagiwara T, Ranjan P, Sawamoto M. (2007) Evaluation of groundwater resources in wide inundation areas of the Mekong River basin. Journal of Hydrology 340: 233-243.

Koontanakulvong S, Suthidhummajit C, Roodpai S. (2010) The assessment report impact of climate change to irrigation and groundwater: Case study in Plaichumpol Irrigation Project. Final report (in Thai), Chulalongkorn University, Bangkok, Thailand.

Kotsuki S, Tanaka K, Kojiri T, Hamaguchi T. (2010) The water budget analysis with land surface model in Chao Phraya River basin. In Proceedings of Japan Society of Hydrology and Water Resources, 23rd annual conference, 44-45.

Kuraji K, Mei G, Kowit P. (2009) Inter-annual and spatial variation of altitudinal increase in rainfall over Mount Inthanon and Mae Chaem watershed, Northern Thailand. Hydrological Research Letters 3:18-21.

Magramo K. (2022) A third of Pakistan is underwater amid its worst floods in history. Here’s what you need to know. CNN (access September 2022)

Manandhar S, Pratoomchai W, Ono K, Kazama S, Komori D. (2015) Local people’s perceptions of climate change and related hazards in mountainous areas of northern Thailand. International Journal of Disaster Risk Reduction 11: 47-59.

Mateo CM, Hanasaki N, Komori D, Tanaka K, Kiguchi M, Champathong A, Sukhapunnaphan T, Yamazaki D, Oki T. (2014) Assessing the impacts of reservoir operation to floodplain inundation by combining hydrological, reservoir management, and hydrodynamic models. Water Resources Research 50: 7245-7266.

Oki T, Sud YC. (1998) Design of total runoff integrating pathways (TRIP)-A global river channel network. Earth Interact 2: 1-37.

Pavelic P, Srisuk K, Saraphirom P, Nadee S, Pholkern K, Chusanathas S, Munyou S, Tangsutthinon T, Intarasut T, Smakhtin V. (2012) Balancing-out floods and droughts: Opportunities to utilize floodwater harvesting and groundwater storage for agricultural development in Thailand, Journal of Hydrology 470-471: 55-64.

Prajamwong S, Suppataratarn P. (2009) Integrated flood mitigation management in the Lower Chao Phraya River basin. Expert group meeting on innovative strategies towards flood resilient cities in Asia-Pacific.

Pratoomchai W, Kazama S, Ekkawatpanit C, Komori D. (2015a) Opportunities and constraints in adapting to flood and drought conditions in the Upper Chao Phraya River basin in Thailand. International Journal of River Basin Management 13: 1-15.

Pratoomchai W, Kazama S, Hanasaki N, Ekkawatpanit C, Komori D. (2014) A projection of groundwater resources in the Upper Chao Phraya River basin in Thailand. Hydrological Research Letters 8(1): 20-26.

Pratoomchai W, Kazama S, Manandhar S, Ekkawatpanit C, Saphaokham S, Komori D, Tongduang J. (2015b) Sharing of people’s perceptions of past and future hydro-meteorological changes in the groundwater use area. Water Resources Management 29: 3807-3821.

Ramnarong V, Wongsawat S. (1999) Groundwater resources in Thailand (in Thai). Thai Hydrologist Association Journal, vol. 1.

Royal Irrigation Department Thailand (2010) The system of irrigation plan under the framework of 60 million Rai. Summary report (in Thai), Bangkok, Thailand.

National Research Council of Thailand (2022) Drought risk assessment and crop damage using geographic information system (in Thai), Bangkok, Thailand.

Rushton KR, Eilers VHM, Carter RC. (2006) Improved soil moisture balance methodology for recharge estimation. Journal of Hydrology 318: 379-399.