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ORIGINAL ARTICLE

The Effects of Climate Change on Hydrology based on Dynamically Downscaling and Physically-Based Hydrology Model at Upper Ping River Basin, Thailand

Srisunee Wuthiwongyothin[1*], Su-Hyung Jang[2]
Kei Ishida[3] and M. Levent Kavvas[4]

[1] Faculty of Engineering, Burapha University
169 Long-Hard Bangsaen Road, Saen Sook, Muang, Chonburi 20131, Thailand

[2] Senior Researcher, Korea Insitute of Water and Environment, Korea Water Resoruces,
200 Sintanjin-ro, Daedeok-gu, Deajeon 34350, KOREA

[3] Graduate School of Science and Technolgy, Kumamoto University
2-39-1 Kurokami, Kumamoto 860-8555, JAPAN

[4] Hydrologic Research Laboratory, Department of Civil & Environmental Engineering, UC Davis
One Shields Avenue, Davis 95616, USA

[*]E-mail: srisunee.wu@eng.buu.ac.th

***Abstract*:** One of the major challenges in water resources research is to understand the impact of climate change on hydrology. In Thailand, upper Ping river basin is one of the major resources supply water to a major rice bowl, Chao Phraya basin area. In this study, the effects of climate change on hydrology was utilized by using SRES-climate scenarios during the 21st century under the A1B, A2 and B1. The future hydrologic response water performed by utilizing the dynamical downscaling technique to refine those global scale data to the regional scale at nine kilometer grid resolution over the study via the Watershed Environmental Hydrology-Hydro Climate Model (WEHY-HCM). The downscaled data was corrected its bias, and tested by a well matching of cumulative distribution function between the model and observed flows. Based on the average of SRES-climate scenarios, A1B, A2 and B1, it is found that toward the 21st century the upper Ping basin runoff will increase 13.7% when compared to the average flows from 1988 to 2015. This projected change on hydrological information would be a significant data for water management in Thailand.

Keywords: climate change, dynamically downscaling, physically-based hydrology Model, upper Ping River basin

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1. Introduction

Global climate change is accepted as a key issue which is foreseen to increase water stress globally. Its effects around the world are increasing specifically increasing the numbers of occurrences of extremes hydrological events. This would affect water resources planning and management which typically involve substantial work that deals with many socioeconomic and engineering development activities in particular to ensure meeting the water needs in a specified area. The present study emphasizes the need to assess the effects of climate change on hydrology over the upper Ping river basin (Figure 1), which is a significant head watershed and essential water supply to a major rice bowl area, Chao Phraya River system, in central Thailand. As water resources are highly stressed in the basin due to the evolutionary change in climate conditions.

The term of climate change is generally defined as a long-term change over decades or longer of a statistically significant variation (mean state or its variability) of weather or climate pattern due to changing conditions (IPCC, 2007). Climate is what people can usually anticipate in a certain time period as expressed by Edward Lorenz (1982, a mathematician and meteorologist) that “Climate is what you expect, weather is what you get”. However, future climate is what people want to know for its evolution, vital signs and its effects, especially its unexpected consequences because the future climate evolution may not resemble the past as global temperature is warming, due to increasing CO_2 and changing climate conditions.

Climate change impacts on hydrology and water resources have been quantified in numerous studies corresponding to the development of global climate models, which have been rapid over the last three decades. Changes in the climate system results in perturbing the hydrologic cycle, causing changes in hydrologic regime, altering the timing and magnitude of runoff, affecting soil moisture, disturbing water quality and so on. Studies of these changes provide important implications for future water resource planning and management (Gleick, 1989). The 21st century water resources management and planning would require long range information that relate to the evolution of climate to avoid unexpected losses such as in food or water supply. Time series data are necessary especially for infrastructure design, which usually requires 50 to 100 years or more time horizon to define return periods of extreme events. Other significant implications might help in terms of mitigation and adaptation plans to cope with the uncertainty that would happen. Traditional studies typically depend upon the limited historical recorded data for design or management, for instance for reservoir simulation and operation. Examples such as mass curve analysis were used to define reservoir sizes, as well as deterministic and stochastic approaches were used to synthesize either existing flows or to generate future time series inflows for reservoir operation optimizations. These approaches are mainly based on the observed streamflow data, which are typically of short duration. Moreover, the underlying concept of these traditional methods relies on the statistical information on historical recordings of data (e.g. streamflow) which implies that they will keep the same behavior in the future, specifically the mean values, referred to as statistical stationarity (Lettenmaier, 2013). In reality, the future climate contains uncertainty, and it is best for planners to evaluate the robustness of using statistical parameters that characterize reservoir inflows (e.g. mean and variance) over plausible ranges, instead of using the historical recordings of streamflow observations as the best estimation. Hence, future projections of flows under climate change are the most advantageous for water resources studies that include the possibility of constructing a range of possible values with underlying nonstationary characteristics.

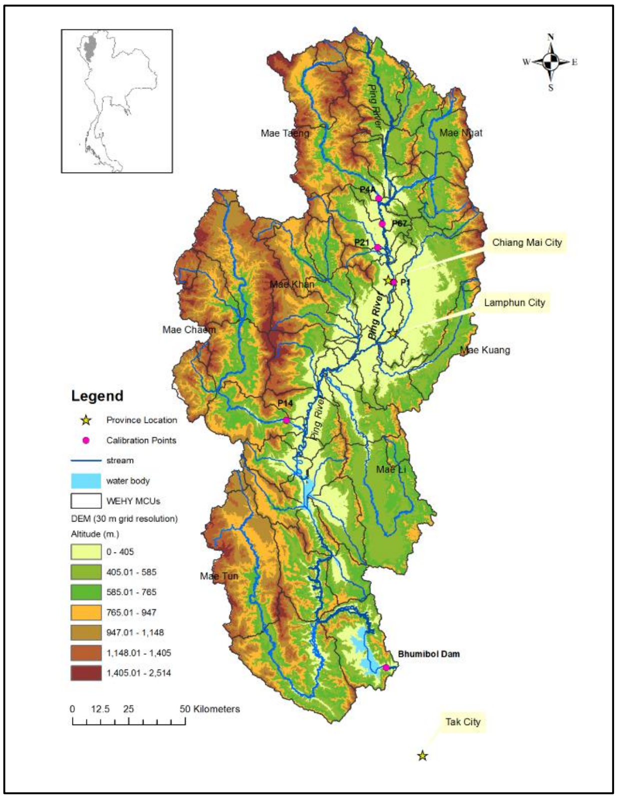

Fig.1 The upper Ping River Basin Topography

Studying about the effect of climate change, uncertainties are still considerate as one major issue. In hydrology and water resources area, uncertainties in a climate change study can arise from many sources such as different GCMs usage, climate scenarios, statistical or dynamical downscaling techniques, choice of RCMs, bias correction approaches, hydrological models or water balance models in the studies, etc. In order to deal with the uncertainty originating from GCMs, RCMs, and hydrology models, ensemble averaging of simulations from multi-models has been suggested (e.g. Hagemann et al., 2013; Kjellstrom et al., 2011). The ensemble mean approach is a better representation for showing the range or tendencies for future climate change (Kjellstrom et al., 2011). Thus, three initial future climate scenarios A1B, A2 and B1 are investigated in this research.

The future climate conditions provided by the Intergovernmental Panel on Climate Change (IPCC), were considered in this study. The IPCC had developed various scenarios based upon projected socio-economic conditions, population growth and energy use issues. The main storylines are A1, A2, B1 and B2. Each main storyline is comprised of sub-scenarios such as A1B, A1B1 forming the A1 family. However, these scenarios were developed mainly by the quantification of future global greenhouse gas emissions (Nakicenovic and Swart, 2000). To simulate the future climate change effect particulars on hydro-climatic conditions under IPCC scenarios over a specified region, one of the most important information resource is the output from General Circulation Model (GCM) climate. This study retrieved the data from the Community Climate System Model version 3.0 (CCSM3).

In this work, the study was mainly based on the physical approach. Most of the study approaches are relied on physical basis which comprises of two main processes, dynamically downscaling and physically-based hydrology model. The dynamical downscaling is based on a process based technique considered over a nested area or limited area by means of a regional climate model (RCM) to extract the local-scale climate data from the large-scale GCM's information (Xu, 1999). Dynamical downscaling means is by using regional climate models (RCMs) that are nested within the domains of GCMs. The advantage is able to solve land-atmosphere interaction under physical principles such as conservation of mass, energy and momentum (Jang and Kavvas, 2013). In other words, dynamical downscaling by means of RCMs relies on dynamics and physics of the climate processes at very fine spatial and temporal scales that can gain incorporate physical information over a watershed scale, and allows more understanding of hydrologic impact studies. Therefore, using downscaling methods to refine the GCM climate data before using such data as the input to a hydrologic model now is sound to be the best choice that seems to be rendering more precise information on studying the impact of various climate scenarios on hydrologic regimes and water resources availability under climate change, despite the fact that there are still remain some limiting conditions with uncertainty.

2. Objectives

The purpose of this study is to assess the effects of climate change on hydrological system during the 21st century in northern Thailand, focusing on the upper Ping River basin. To obtain this goal, we need to develop a physically based modelling system from the global climate to regional climate and to the river basin scale. An integrated approach to climate change impact assessment is also explored by coupling an atmospheric model and a hydrologic model within the hydro-climate modeling framework.

3. Methodology

Under the physical based processes, a methodology to refine the spatial scale from the GCM output, called “downscaling”, is necessitated, and it has been widely applied to date for most user applications (Cozzetto et al., 2011). Downscaling seems to be a standard method to refine GCMs' output in such studies (e.g. Bastola and Misra, 2014; Xu and Yang, 2012). The technique is essential to bridge the gap of the mismatched scales between GCM-supplied climate variables and the required detailed information of a region, especially at a watershed scale for studying the impact of climate change on hydrology and water resources. In practical, two broad downscaling techniques, statistical and dynamical downscaling, have been used to study climate change impact on hydrology and water resources of regions. A number of comparative studies for different statistical bias correction approaches, for different dynamical downscaling resolutions, for statistical-dynamical downscaling approach comparison, and their reviews have been reported in the literature (e.g. Chen et al., 2011a; Fowler et al., 2007; Marke et al., 2011; Wood et al., 2004; Xu and Yang, 2012). However, there is no clear consensus as to whether statistical or dynamical downscaling is better in applications. In the assessment of climate effect on water-related processes, dynamical downscaling may be superior in the physical sense and was chosen approach in this research. However, a statistical approach such as bias correction is unavoidable to adjust some bias in dynamical downscaling results that are intrinsic from the GCM simulation data that provides the initial and boundary conditions for downscaling. Advantages and disadvantages of the statistical and dynamical downscaling methods still remains. Nonetheless, results from various studies have shown that the downscaling method can improve and refine the GCMs' coarse data when studying the impact of climate over a region or a watershed (e.g. Marke et al., 2011; Teutschbein et al., 2011).

In this research, dynamical downscaling by means of the atmospheric model the PSU/NCAR MM5, fifth generation mesoscale model, developed by the U.S. National Center for Atmospheric Research (NCAR) and Pennsylvania State University in the 1970's (Anthes and Warner, 1978) was performed. This version of the fifth generation mesoscale model is the latest development in its series (there is a newer NCAR model known as the “WRF model”, developed by NCAR). However, MM5 still can be used as the atmospheric component of a regional hydro-climate model in this study, as it has been used for a longer period of time. Thus, its strengths and limitations are more established. MM5 is a limited-area, nonhydrostatic, terrain-following sigma-coordinate model designed to simulate or predict regional scale atmospheric circulation. In short, the model competencies include (i) the capability of multiple-nesting, (ii) nonhydrostatic dynamics, which allows to model at a few-kilometers grid scale, (iii) multitasking capability on shared and distributed memory machines, (iv) a four dimensional data assimilation capability and (v) many atmospheric physics options (Dudhia et al., 2005). The biggest advantage of MM5 is its ability to dynamically downscale data to as small as 0.5-1 km resolution, allowing better representation of the impact of steep topography, orographic effects, and land surface/land use conditions of a watershed on local atmospheric conditions. Therefore, in this study the MM5 was used to refine the GCMs output of climate projections in time and space over the Ping River basin. MM5 is able to translate the physical conditions of climate, as simulated by GCMs at coarse grid size (about 200x200 km grid size) to a finer scales. A 9 km grid size was chosen based on the intent to realistically account for local effects including topography and orographic features, but study limitations with respect to time and computational resources prevented an even smaller grid size. Furthermore, the 9 km grid size is roughly the size of a typical cumulus convective cloud. Resolution finer than 9 km would require a more detailed description of cloud microphysics, a highly uncertain modeling area, and greatly increased computational resources.

Then, the downscaled atmospheric data over the region was incorporated in to a fully physically-based hydrologic model, the Watershed Environmental Hydrology-Hydro Climate Model (WEHY-HCM). WEHY-HCM has a unique module of a land-surface process, which is able to account for the heterogeneity of the physiographic information (e.g. soil vegetation, land use types) on the ground surface level. WEHY-HCM was developed consider the interaction between the atmospheric and land hydrologic processes, in which the hydrologic cycle is closely related to the atmosphere and is a part of the earth's atmospheric complex system. Moreover, the model is useful at watersheds that naturally have non-homogeneous topography and land use/cover, because the model is based on areally-averaged, scalable conservation equations and parameters in order to quantify and account for the effect of heterogeneity within watersheds. WEHY-HCM is able to model vertical interaction with the atmosphere (precipitation, radiation, wind, sensible heat flux, evaporation/ET, and vertical soil water flow), lateral hydrologic processes (subsurface storm flow, overland flow, groundwater flow) at hillslope scale, and dynamic interaction of the open channel flow and groundwater flow at the watershed scales (Kavvas et al., 2013). The WEHY-HCM has been developed at the Hydrologic Research laboratory (HRL), UC Davis. The detail description of the WEHY-HCM model are given by Kavvas et al. (2004; 2006; 2013) and Chen et al. (1994a; 1994b).

3.1 GCM Climate Projections

To evaluate the impacts of climate change on hydrologic system of the upper Ping River basin, future climate change scenarios from the special report on emissions scenarios (SRES) A1B, A2 and B1, acquired from CCSM3. These future climate projections are based on the assumption of increasing greenhouse gas emission due to the development in global and regional economies together with the change in world demography and environment technology innovation. The CCSM3 GCM is the Community Climate System Model version 3.0 (CCSM3), a general circulation model of the US National Center for Atmospheric Research (Collins et al., 2006). CCSM3 has generated and provided three different projections of A1B, A2 and B1. In addition, the model has provided four-dimensional atmospheric data at a six-hour time scale (able to capture daily diurnal effect) which are required as realistic boundary conditions for regional atmospheric model simulations. This CCSM3-GCM also supply a historical control run (focusing in 1971-2000) which can be used to quantify model historical climate simulations that contain biases due to model uncertainties. The future (2001-2099) global meteorological data then can be downscaled and simulate to study the effect of climate change on upper Ping watershed hydrology.

3.2 MM5 Atmospheric Model Set up and Model Configuration

To set up MM5 model over the upper Ping basin, three nested domains were created. The model outer domain and the intermediate domain cover the whole watershed and surrounding areas (starting at the basin's centroid) and have horizontal grid spacing at 81x81 and 27 x 27 respectively. The inner domain was refined to 9 x 9 grid resolution covering the focus watershed. The larger grid domain is called a parent domain for the next, smaller grid domain. Each nested domain has a spatial resolution of 1/3 of the parent grid required by MM5 (MM5 user documentation). In this way, initial and boundary conditions from outer domains can be refined and computed to obtain atmospheric variables, supplying these data to the second domain. The inner domain was simulated utilizing simulation results of the intermediate domain model, which provided the boundary conditions for the inner domain. The inner domain covered the specified region at the required scale of 9 x 9 km grid resolution.

Next, the MM5 has several physical parameterization options inside, therefore the model must be calibrated to obtain an optimal configuration at first. To determine the optimal configuration, the combination of the MM5 model options were simulated, and those downscaled precipitation results were then compared to available observed rainfall at specific grid points. The data used for this comparison is retrieved from NCEP/NCAR reanalysis1 coarse-resolution climate data, and compared with observed rainfall for the year 2004. Result shows that the best physical combination is the Kain-Fritsch 2, Reisner graupel, and MRF which can prodice reliable atmospheric vairables over the upper Ping basin.

3.3 WEHY Model Set up

In the upper Ping watershed, the WEHY-HCM was applied to model land surface and hydrologic flow processes. The atmospheric input is obtained by dynamical downscaling from MM5. The watershed hydrology module in WEHY-HCM requires basin physical parameters and the meteorological (obtained from MM5). Spatial data such as a topographic map in digital elevation map, a soil dataset, vegetation cover and land use and leaf area index was used to prepare model parameters. Hydro-meteorology data such as precipitation, radiation, wind, sensible heat flux, evaporation/ET, and vertical soil water flow was used prepare atmospheric input file.

Preparation and processing of required and available data (i.e. collecting, checking, assembly, analysis), and steps in setting up the WEHY model in order to simulate the hydrologic system of the upper Ping Basin runoff and to estimate the basin runoff at the outlet which, in turn, flows to the Bhumibol Dam (a focused dam in this study). In order to model the study watershed, the WEHY model requires the specified Model Computation Units (MCUs), which are the hillslopes or first order watersheds. MCUs are the model computational grid areas. The MCUs are used to prepare and specify the watershed's physical and geomorphologic parameters (i.e. stream reaches, rills, inter-rills, MCUs and their geometry) and to estimate other parameters within each MCU for upscaling WEHY parameters to the MCU grid (i.e. vegetation and land cover, soil properties). Flows from each MCU are toward the stream network and to the watershed outlet. The topographic map in a digital elevation model (DEM) format, at 30-meter grid resolution of the Ping River basin was altered to make a 100-meter grid resolution for computational efficiency to delineate MCUs. Using a GIS analysis tool (HEC Geo-HMS) the watershed stream reaches, stream network, and MCUs were delineated (more detail for this step is discussed in (Chen et al., 2004a; Chen et al., 2004b)). The study catchment area is about 26,111 sq.km, and is comprised of 69 sub-basins, 69 reaches, and 138 MCUs. In addition, geographic parameters were obtained, including flow direction, flow accumulation, degree of slope, elevation and their geometries.

After MCUs were specified, the prepared vegetation and land use/cover map, LAI map and soil map were overlaid on the MCUs to obtain the average vegetation and land cover parameters, and soil parameters, in each MCU. The vegetation and land cover parameters are LAI (averaged from 10 years on monthly average during 2003 to 2012), surface roughness, root depth, and crop coefficient. The WEHY average soil parameters in each MCU are 1) mean saturated hydraulic conductivity (Ks), 2) variance of Ks, 3) mean total porosity, 4) mean residual water content at saturation, 5) mean pore size distribution index, 6) mean bubbling pressure, and 7) mean soil depth. These parameters were averaged in each MCU.

The step after finishing of preparation the physical parameters and the hydro-meteorological time series, are calibration and validation. These calibration and validation are needed to evaluate model performance and reliability. Calibration was completed by adjusting and/or refining the corresponding parameter set (e.g. initial soil moisture condition, Chezy and Manning's roughness coefficients at each stream network segment in each model computational unit) to fit the hydrologic processes (by comparison with the watershed runoff observations) of the upper Ping watershed. Validation is necessary to confirm that the model can represent the study area's hydrologic system well and is capable to reproduce realistic hydrologic projections. In this work at the upper Ping Basin, the WEHY hydrologic module was calibrated during 2004-2006 (3 years). Another critical step to assure the model accuracy is by validation, which was performed during 2000-2012 (10 years excluding 2004-2006). The calibration and validation results were compared with the daily observed stream discharge including branches stream and on Ping river stream in total of six stations, P.4A, P67, P.21, P.1, P.14 and at the Bhumibol. The plot for theses calibration and validation period are displayed in Figures 2.

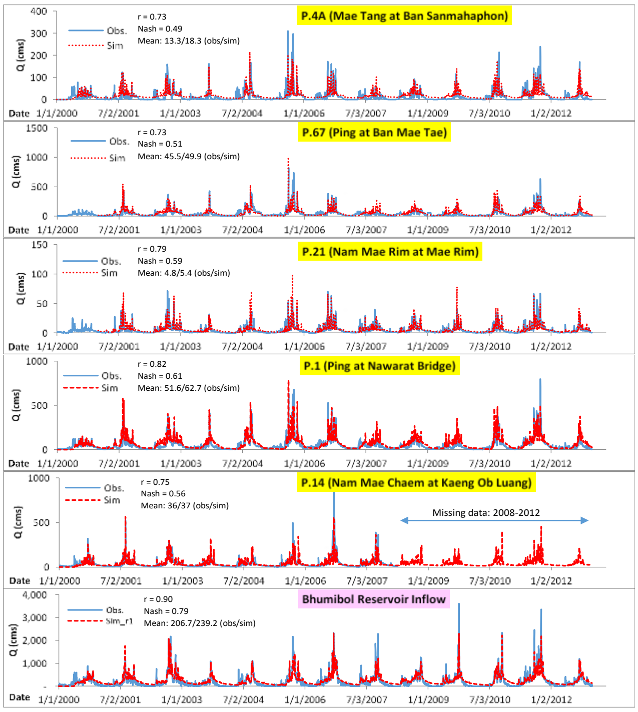

Fig.2 WEHY hydrology model calibration and validation by comparing the daily mean discharge between simulated and observed flows

3.4 CCSM3-GCM Model Performance

Typically, the GCM's climate model contain model uncertainty due to the model functions and the historical climate data. In order to simulate the 21st century future climate projections, it is necessary to test the GCMs' downscaled climate data after bias correction. This study, bias factors are estimated by comparing the average monthly rainfall of the upper Ping Basin from the GCM-simulated historical data to the observed data. The corrected rainfall data, along with other atmospheric variables, are fed into the WEHY-HCM which simulates the basin hydrologic flows. By comparing the simulated flows with inputs from the corrected GCM-simulated historical control run climate data, with the observed flows during 1971-2000, the GCM's performance can be evaluated to determine whether the downscaled bias-corrected GCM data can achieve consistency and reliability in producing future climate variables. In this manner, the performances of the CCSM3-GCM was evaluated by average monthly flow and the cumulative distribution function of the GCM-based historical simulated flows and the observed flows of the upper Ping Basin at the outlet which is the Bhumibol Dam location, as shown in Figure 3 and 4 respectively.

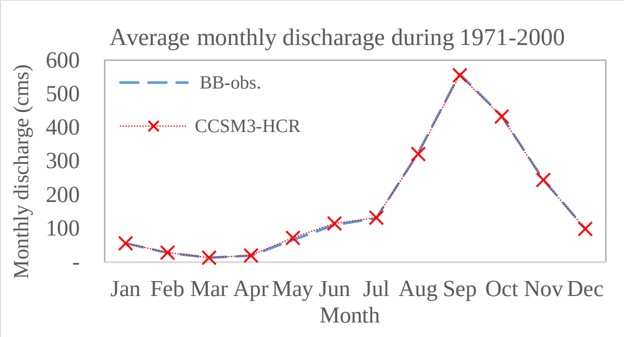

Fig.3 Comparisons of mean monthly flow of CCSM3-average flows with the observed flow during the historical period.

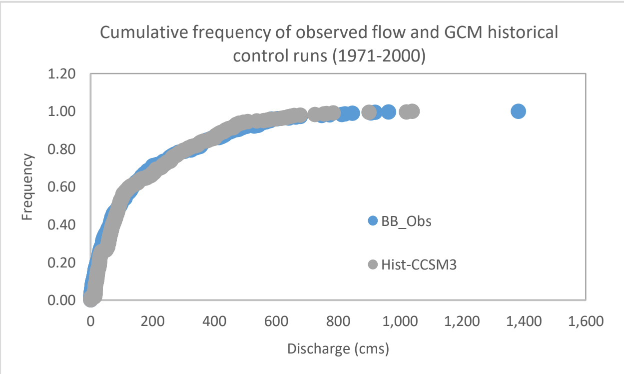

Fig.4 Comparison of simulated flow based on CCSM3-GCM historical control runs and observed flow at the upper Ping Basin outlet

The CCSM3-GCM provide the climate change projections from 2001 to 2099, thus the generated flows during 2001-2015 can be extracted and compared to the observations in order to verify the performance of these GCMs. It is noted that the future projected flow simulations driven by the GCM are based on climate driving forcing assumptions, which are not used for climate prediction purposes. Hence, the expectation is that the future hydrologic flows under various climate scenarios should give a plausible range covering the observed flows instead of providing accurate forecasts for flows. The statistics of the flows generated using data from the CCSM3-GCM during 2001-2015 are presented in Table 1 and Figure 5.

Table 1. Statistical values of the simulated flows based on the CCSM3 GCMs' historical control runs and the observed monthly flows during 1997 to 2000 and during their validation period 2001 to 2015 (cms).

Data Source	Time Period	Average	Standard Deviation
Historical observed flows	**1971-2000**	**174.13**	**238.1**
Historical control run	1971-1999	174.1	186.82
Present period observed flows	**2001-2015**	**184.67**	**238.1**
Average CCSM3 projected flows A1B, A2, B1	2001-2015	160.33	169.6

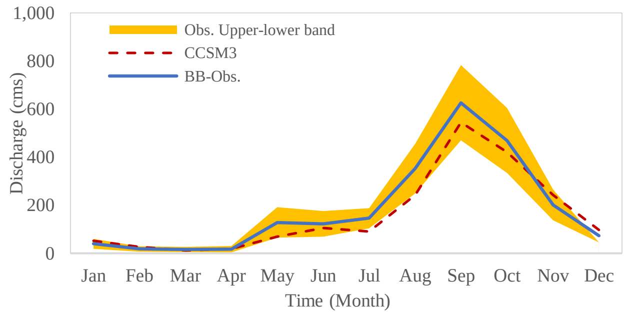

Fig5. Comparisons of mean monthly flow of CCSM3-average flows with the observed flow during 2001-2015, along with 95% confidence band (shade color) of the observed mean monthly flow

In summary, the historical control runs (1971-1999) of CCSM3-GCM performs well. The flow projections, based on the climate projections of the present period (2001-2015) as shown in table 1 is also satisfactory relationship with the observations. Both table 1 and Figure 5 show that the overall average of the GCMs' generated flows is also close to the observed mean within the range of 95% confidence band. Thus, the CCSM3 can used to represent and project the future water flow during the 21st century for the upper Ping Basin.

4. Results and Discussion

As mention before, climate change is expected to impact the hydrologic flows in the Ping River basin and one of the most important functional hydraulic structures, Bhumibol Dam. The future projected flows from the upper Ping River basin are considered as the dam inflows. Future projected monthly inflows under A1B, A2 and B1, which flow into the Bhumibol Dam from 2016 to 2099 are plotted in figure 6. The result shows that scenario A1B will produce higher monthly discharge comparing to the other two scenario A2 and B1.

However, it is clearly seen by plotting ten year moving average of CCSM3-GCM historical control runs and of the observation together with the future flow projection shown in figure 7 that at the late 21^{st} century A2 scenario will produce the maximum floods in this study area. The three projected flows of CCSM3 in plot shows the variability range of about 136.0 cms throughout the 21st century. This implies that based on CCSM3-GCM A1B, A2 and B1 climate scenarios, the future projected flows based on the average of these three projection has an upward trend toward the end of the 21^{st} century with 95% confidence level using Mann-Kendall trend test.

For comparison purposes, the generated series of future flow projections are divided into three periods, each of which contains 28 years. The near future period is from 2016 to 2043, the mid future period is from 2044 to 2071, and the far future or late 21st century period is from 2072 to 2099. The present period (called the baseline period), with the most recent 28-year observed flows is chosen to be from 1988 to 2015. Table 2 shows statistical results of each future period as well as the baseline period (from observed flow data). The results clearly show that the average of the three future projected flows and their accumulated flow volumes increase in every future peroid when compared to the baseline period. The increase are at about 8.7%, 14.5% and 32.3 % in the near-future, mid-future and far-future respectively. Hence, from this result it can be concluded that during the 21^{st} century in the upper Ping River basin, there will be higher streamflow values at about 13.7% on average throughout the century due to climate change effect, specifically at the end of the 21^{st} century.

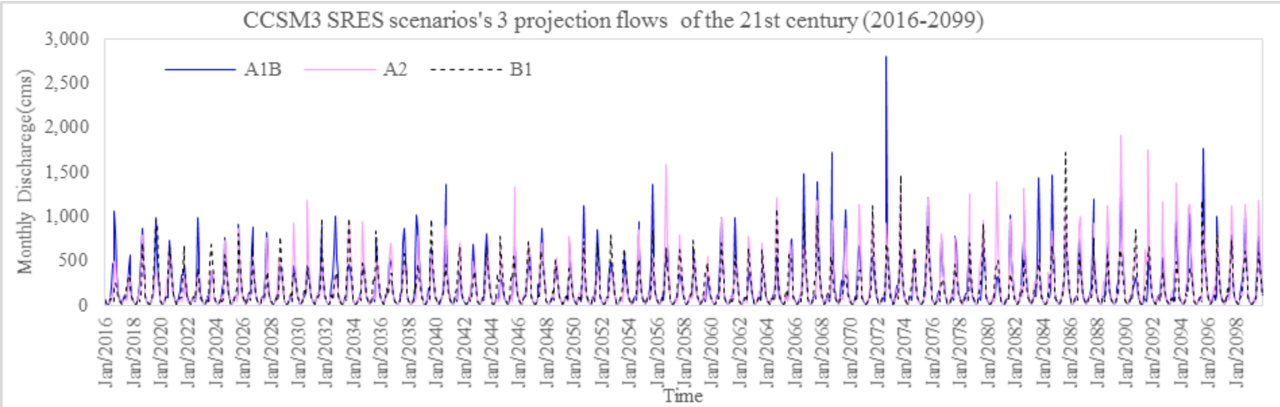

Fig.6 Future projected flows under CCSM3- SRES scenarios

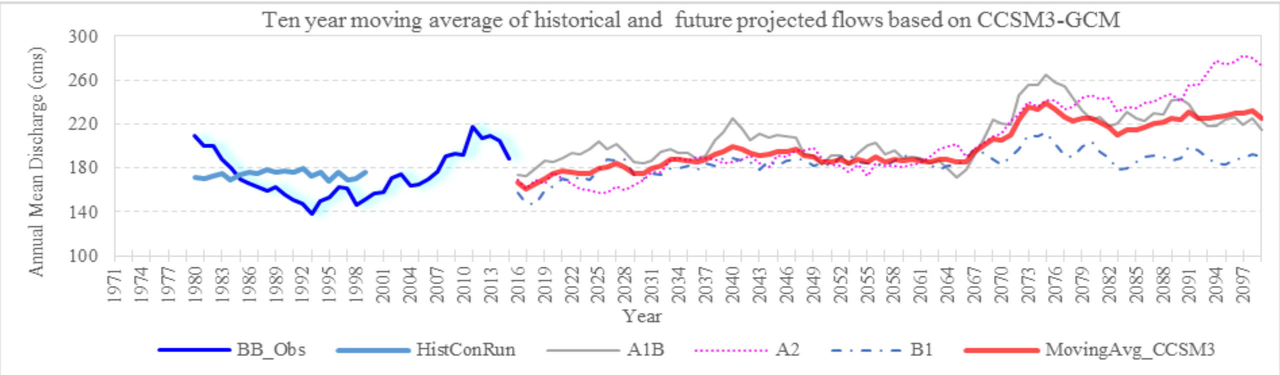

Fig.7 Ten year moving average of future flow projections under CCSM3- SRES scenarios

Table 2. Comparison of statistical results of the baseline period and the three future periods based on monthly future projected flows (cms).

Time period	Min	Max	Standard Deviation	Average montlhy flows	Accumulated annual flow	%
	(cms)	(cms)	(cms)	(cms)	(mcm)	Change
Baseline (1988-2015)	0	1153.6	215.3	171.2	5,421	-
Near future (2016-2043)	12.6	906.3	197.7	186.2	5,888	8.6%
Mid Future (2044-2071)	13.3	1194.4	223.6	196.1	6,197	14.3%
Far Future (2072-2099)	12.6	1465.5	267.7	226.6	7,158	32.0%
Aveage	**9.625**	**1180**	**226.075**	**195.025**	**6165.95**	**13.7%**

Figure8 shows the plot of average future period's trend of the mean accumulated annual inflows into the Bhumibol Dam reservoir comparing in each period based on the ensemble average of the three realizations (A1B, A2 and B1) as well as the inflow trend corresponding to the baseline period.

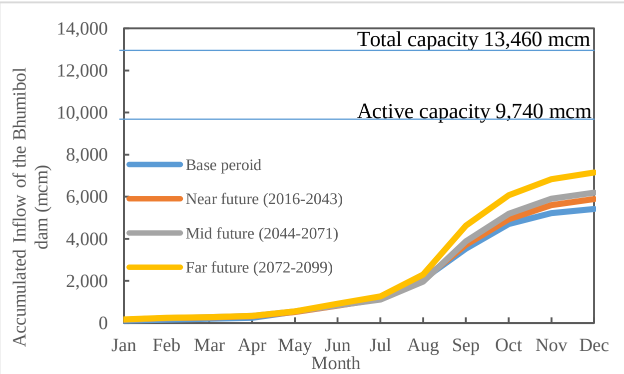

Fig.8 Comparisons of the mean accumulated inflow to the Bhumibol Dam reservoir in the present baseline period, and during each future period (near future, mid future and far future) based on the projected ensemble average flows

Figure 9 illustrates the mean monthly flows in each future period compared to the baseline period (1988-2015). In general, all the future flow projections yield similar hydrograph patterns as the average monthly historical hydrograph. The CCSM3-GCM flow projections of the near-, mid-, and far-future periods show clear differences from the baseline period, especially in September in which case the baseline period has an average flow of 564.58 cms while the near-, mid-, and far-future periods have higher values of about 643.44, 809.21 and 814.52 cms, respectively.

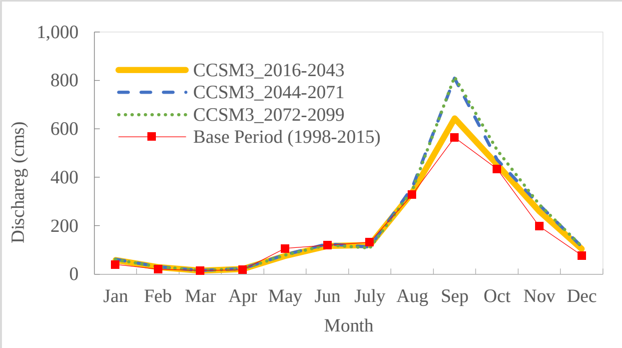

Fig.9 Comparisons of future mean monthly discharges and the baseline period flow

In sum, the overall future flow projections based on the ensemble average of CCSM3 under the A1B, A2 and B1 gas emission scenarios indicate that the future mean monthly flows will increase continuously while having a hydrograph pattern similar to the historical one and peaking in September.

5. Conclusion

The effects of climate change on hydrology based on dynamically downscaling and Physically-Based hydrology model was performed in the upper Ping River basin via the Watershed Environmental Hydrology Hydro-Climate Model. The dynamical downscaling, at 9-km spatial and hourly time resolutions, of the climate projection outputs from CCSM3-GCM under A1B, A2 and B1 have been examined both for their retrospective control runs and the 21st century projections. The downscaled climate information was quantified and bias-corrected for the downscaled historical climate simulations from the CCSM3-GCM, which was then validated by the observed streamflow during the historical period from 1971 to 2000. The results showed that the GCMs' historically-based model outputs, after downscaling, are well matched with the observed flows at the upper Ping watershed's focus point, or at the Bhumibol Dam. Thus, the bias-corrected GCM outputs can be used to project future flows under various climate conditions for assessing the effects of future climate change on the hydrology of this region.

The future projected flows of the 21st century for the upper Ping River basin display a significant trend based on the annual projected flows' ensemble average of the three CCSM3-GCM projections, whereas the historical observed flows show no significant trend (slightly decline as in Fig.7). The CCSM3-projected flows throughout the 21st century produce a great variability (maximum and minimum range) of about 136 cms,

The ensemble average accumulated annual flow is found to increase in the future compared to the baseline period (1988-2015) flow volume of 5.4 billion m^3. The future periods of the accumulated flow volume based on the ensemble average (3 realizations) yield the following projected mean annual flow volumes: 1) in the near-future period (2016-2043) the flow volume is projected to be 5.9 billion m^3 (8.6% increase), 2) in the mid-future period (2044-2071) the flow volume will reach 6.2 billion m3 (14.3% increase), and 3) at the far-future period (2072-2099) the projected flows will increase to 7.1 billion m3 (32% increase), which is still less than the Bhumibol Reservoir's storage capacity (9.76 and 13.46 billion m^3 of active storage and total capacity, respectively) as shown in Figure 8. Future flow volumes tend to be increase at about 13.7% on average throughout the century. Meanwhile, considering the internal variability based on the mean monthly flows, specifically in September, the future monthly flow projections are found to be higher than the baseline period flows

This projected change on hydrological information would be a significant data for water management in Thailand. During the 21st century, the study basin together with the Bhumibol Dam might encounter more severe droughts and flood disasters. Therefore, the Bhumibol Reservoir's operation, the dam's gates'regulations and its structure must be studied in detail by investigating flood risks in order to mitigate the high discharges or extreme floods that may occur as a result of the effect of climate change. The reservoir's water supply reliability and the effects of droughts are also important, and need to be investigated in order to mitigate the high discharges or extreme floods that may occur as a result of the effect of climate change.

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