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Assessment of climate change and forest conservation impact on ecologically relevant flows: A case study in Wang River Bain, Thailand

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Abstract

Climate change is a major threat to river basins and ecosystems, leading to changes in ecosystems due to rising temperatures, expansion or contraction of specific habitat boundaries, and alterations in the timing of the seasons. This study investigated climate and land use changes to predict future hydrological regime in the Wang River Basin (WRB) and its impact on the ecosystem, focusing on key flow properties such as magnitude, duration, and intensity. The flow properties were studied based on the indicators of hydrologic alteration software and environmental flow components, which were separated into five groups and considered for economic and forest conservation scenarios based on the representative concentration pathway (RCP4.5 and RCP8.5) trajectories. The results showed that future climate change in the WRB will involve severe maximum/minimum temperature increases of 2.09–1.95°C and 4.01–4.05°C for RCP4.5 and RCP8.5 respectively, while the annual rainfall trend will decrease during the 2030s and the 2050s and then increase during the 2070s and the 2090s or a change ranging from -1.96 to 6.10% for RCP4.5 and 1.43 to 6.68% for RCP8.5 from 2030s to 2090s. The projected annual discharges for the combined impacts of climate change and land use change during 2030–2090 indicated that the discharge will tend to decrease in the future, especially in the near future (ranging from -9.75 to -12.32%). Furthermore, there will be an increase in the rise and fall rates (120.24-147.11% and 61.24–62.30%). Consequently, these impacts will eventually affect the livelihoods and ecosystems in this river basin.

Keywords: Climate change, The Indicators of Hydrologic Alteration, Hydrological model, Hydrological regime, Land use change, Wang River Basin

1. Introduction

Water is one of the most important resources and the lifeline of various ecosystems which is essential in agriculture, industry, power generation, and many other important human activities. The streamflow regime is a "master variable" that influences river structure and function, and thus riverine ecosystems [1]. Streamflow regime changes can have a significant impact on river biological processes. The minimum flow requirement alone cannot sustain habitat features and characteristic ecological processes; there is an ecological necessity for the complete range of flow changes. All aspects of the streamflow regime, including floods and medium and low flows, are critical to the survival of biodiversity [2-4]. The hydrological alteration of natural streams is considered to have damaging and widespread impacts on river systems. Thus, hydrological indicators are provided to quantify the streamflow regime for appropriate flow management in considering ecological impacts [5]. Generally, the concept of hydrological alteration is used in the context of water management to evaluate the effects of human distortions of river flow regimes. One of the methods and approaches now utilized to evaluate hydrologic alteration and flow variability is the Indicator of Hydrologic Alteration/Range of Variability Approach (IHA/RVA). It was created as a quantitative method for characterizing changes in streamflow regime using 32 hydrologic indicators organized into five groups (magnitude, frequency, duration, timing, and rate of change) that enable a complete investigation of hydrologic alteration and flow variability [6]. These indicators have been used in climate impact assessment studies [4, 7-10] as sensitive parameters of anthropogenic effects on riverine systems. In addition, climate change and land use change are the two major factors affecting the hydrological cycle and streamflow regime [11]. The important effects of climate change have been predicted to have a negative influence on the hydrological cycle in tropical regions [12]. Southeast Asia is particularly vulnerable to climate change and land use change due to the region's heavy reliance on agricultural and water resources [13, 14]. Because of the diversity of Southeast Asia's climates, accurate regional-scale climatic forecasts are crucial for this region.

The Wang River Basin (WRB) is an important river in northern Thailand because it has a diverse ecosystem and is one of the rivers flowing into the central plains region, which is the source of much of the economic activity of the country. As a result, forecasting available flow in the face of land use change and climate unpredictability is a critical issue for this basin. Climate change and land use change not only affect ecosystems and species directly, they also interact with the sustainable development of human society. Consequently, there have been numerous studies on the influence of land use change and climate change on the hydrologic cycle [15, 16]. These researchers discovered that rainfall and extreme (maximum and minimum) temperatures were important factors impacting the streamflow regime and changes in the ecosystem. From research on climate change in the WRB, it was found that the future rainfall

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may increase and decrease during the dry and wet seasons, respectively, with maximum and minimum temperatures being predicted to rise in the future [17]. However, only climate change has been taken into account in these research studies. Shreatha et al. [18] investigated the effects of climate change and land use changes on hydrology and water quality using the SWAT model, with the land use changes considered under an economic and conservation scenario. The results showed that future climate change will result in decreased streamflow and nitrate nitrogen levels. However, land use change under economic and conservation scenario increased the streamflow and decreased the nitrate nitrogen levels, with the study concluding that land use change caused less impact, though its contribution should not be overlooked as it could exacerbate the problem if there were greater unfavorable climatic variation than predicted. Shreatha et al. [19] studied the combined effect of climate change and land use change on sediment yield. Their results indicated that climate change would reduce flow under both the RCP4.5 and 8.5 scenarios. However, the expected land use change under economic and conservation situations increased the sediment yield in both situations. The combined effects of climate and land use change produced a decreased trend in sediment yield. For the WRB, climate and land use changes play different roles. Various studies have suggested that climate and land use changes are the most important factors influencing streamflow [20-25]. These studies have shown that future land use change had less impact on streamflow than climate change, with the influence of land use change being mostly on evapotranspiration and were minimal unless there were considerable changes in land use. The majority of climate impact assessments in hydrology have concentrated on the effects of rainfall patterns and temperature change, which are mostly used in analyzing and evaluating future droughts or floods. There has been little study in the WRB focusing on the river ecosystem and flow variability utilizing ecological flow parameters and hydrological indicators. The flow regime features are critical for studying river variability and freshwater ecosystems, as well as investigating the impact of streamflow and conducting hydrological regionalization evaluation [26]. Additionally, they are important for studying the effects of climate change on flow regime because changes in both rainfall and temperature are the most important physical impacts of climate change on river ecosystems.

Consequently, the current study focused on climate change and land use change to predict the future hydrologic regime in the WRB based solely on changes in annual flows. A more complete investigation of changes in hydrological features caused by climate change and their consequences for riverine ecosystems is lacking. Such information is critical for understanding the various flow properties depending on magnitude, duration, and intensity. Indicator of hydrologic alteration (IHA)-based indicators and environmental flow components were also used to assess hydrological alteration in this study. The outputs should be useful in designing more effective water management policies to allocate water for economic and social development and to preserve biodiversity in the WRB.

2. Materials and methods

2.1 Description of study area

The WRB was selected as study area because it is one of the important tributaries of the greater Chao Phraya River and has a great biodiversity across various ecosystems of Thailand [27]. This basin is shown in Figure 1 (left). The drainage area of this basin is 10,791 km^2. The Wang River originates from the Phi Pan Nam mountain range in Chiang Rai province and flows to join the Ping River about 30 km downstream from the Bhumibol Dam in Tak province [28]. The WRB can be divided into upper, middle, and lower basins that are mountainous, hills or highland areas, and lowland areas, respectively. In addition, the upper and middle parts contain the Kiew Kor Mah (2008), Kiew Lom (1972) Dams, respectively. This basin is mostly covered with forests (73.09%), while 18.29% of basin area is agricultural land. The remaining area is urban land, built-up land areas, and water bodies. The average annual rainfall is approximately 1,098.36 mm and the average annual temperature is 26.49°C [28].

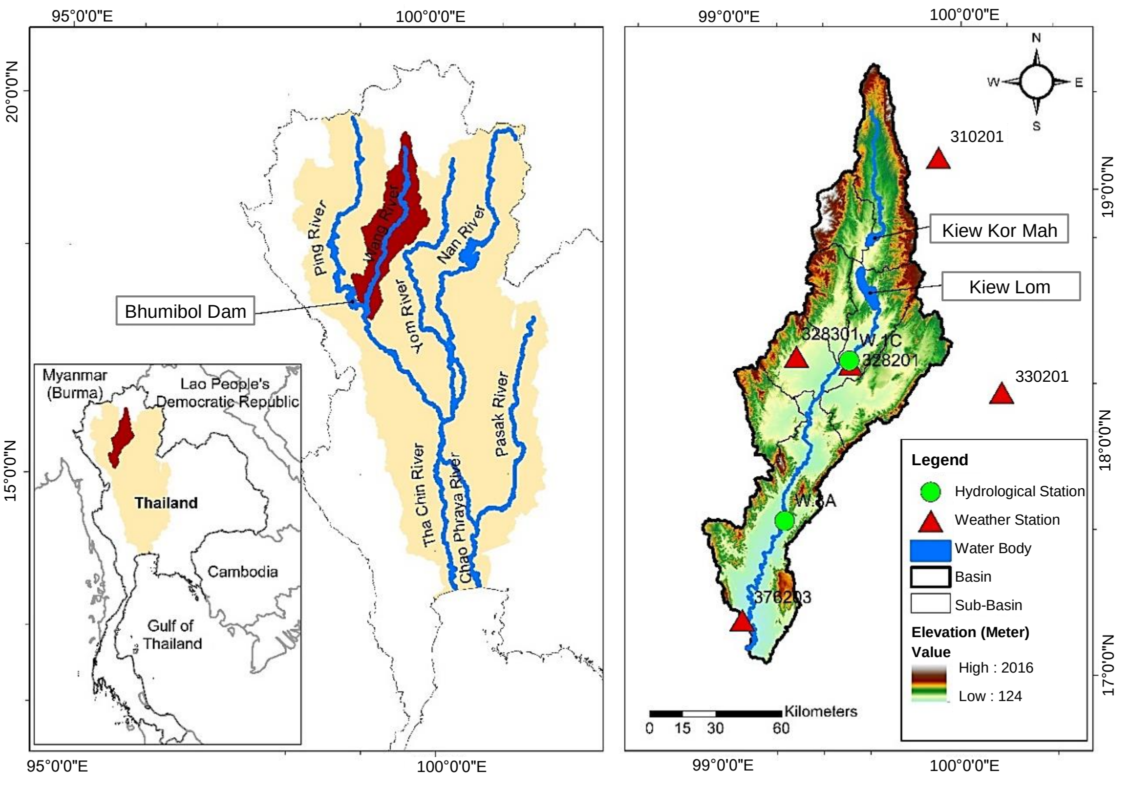


Figure 1 Geographical extent of the study area: location maps of the Greater Chao Phraya River Basin (left) and Wang River Basin (right)

2.2 Data

The primary input data utilized in this study are consisting of meteorological data, hydrological data, topographical data (digital elevation model (DEM) data), land use data, and soil data. The meteorological data used for the climate change projections were rainfall and maximum and minimum temperatures. The study used the Thai Meteorological Department (TMD) meteorological data as observed data during 1970–2021. The Wang River weather stations are shown in Figure 1 (right). Furthermore, telemetering stations (W.3A) that are daily flow discharge data of the Royal Irrigation Department (RID) were utilized as observed data to calibrate and validate the hydrological model. The Land Development Department (LDD) of Thailand provided historical land use maps (2012-2021) and a soil map (2002). Since the soil types have remained unchanged, there have been no updates to the soil data since 2002. The boundary of the WRB was determined using the DEM data at a resolution of 30 m x 30 m, which is adequate for conducting comprehensive hydrological analysis.

The predicted climate data were based on three regional climate models (RCMs) with 0.5° spatial resolution under the two representative concentration pathways (RCPs) 4.5 and 8.5 from the Intergovernmental Panel on Climate Change, namely ACCESS-CSIRO-CCAM, CNRM-CM5-CSIRO-CCAM and MPI-ESM-LR-CAIRO-CCCAM. These models were selected because previous studies [29-31] demonstrated their effectiveness in producing accurate climate projections for Thailand. The future climate data were projected using the different RCPs for the periods 2006–2099 while the baseline period was 1970–2005.

3. Methodology

The methodology of this study comprised four paths: Path A for climate bias correction and projection, Path B for calibration and validation of the hydrological model, Path C for evaluation of future land use, and Path D for analysis of the simulated and future discharge. The methods used in each part are described in Figure 2. The Path A framework was initiated using a linear regression method for bias correction of the climate data from the three RCMs during the baseline period and the future period. The next step of the Path A framework involved the projection of future climate data for four future periods; the 2030s (2020–2039), 2050s (2040–2059), 2070s (2060–2079), and 2090s (2080–2099) under RCP4.5 and RCP8.5. The Path B framework set up the hydrological model (HEC-HMS model) to simulate discharge. The HEC-HMS model's accuracy was calibrated and validated so that it could be used to simulate future discharge. The performance accuracy of this model was verified with statistical indicators (coefficient of determination: R^2, Nash-Sutcliffe efficiency: NSE, Percent bias: PBIAS, and root mean square error: RMSE). The calibration and validation periods for the HEC-HMS model were 1991–2006 and 2007–2017, respectively for the hydrological station (W.3A). The Path C framework commenced the compilation of land use maps from 2012 and 2021 to assess the historical land use change trends under the economic scenario. The next step of Path C applied spatial dynamic modeling using the Future Land Use Simulation (FLUS) model to evaluate future land use change under the economic and forest conservation scenarios. The conservation scenario was based the 20-year Thailand Government Strategy for conserving and rehabilitating biological diversity to protect and expand forest area, which account for approximately 40 percent of the total land area [32]. The FLUS model was verified using the Kappa coefficient statistic before projecting land use. The last path framework (Path D) used the projected climatic data from Path A and the projected land use data from Path C as input data to the HEC-HMS model to simulate future discharge from the WRB under the RCP4.5 and 8.5 options for the four future periods. The Indicators of Hydrologic Alteration (IHA) indicators were applied to identify hydrological extremes (streamflow) in the WRB. The IHA indicators were classified into five groups based on the intensity, magnitude, and duration of river discharge, as shown in Table 1 (group 1 = magnitude of monthly discharge; group 2 = magnitude of annual extreme discharge under different durations; group 3 = timing of annual extreme discharge; group 4 = rate and frequency of discharge change; and group 5 = monthly low flows of EFCs).

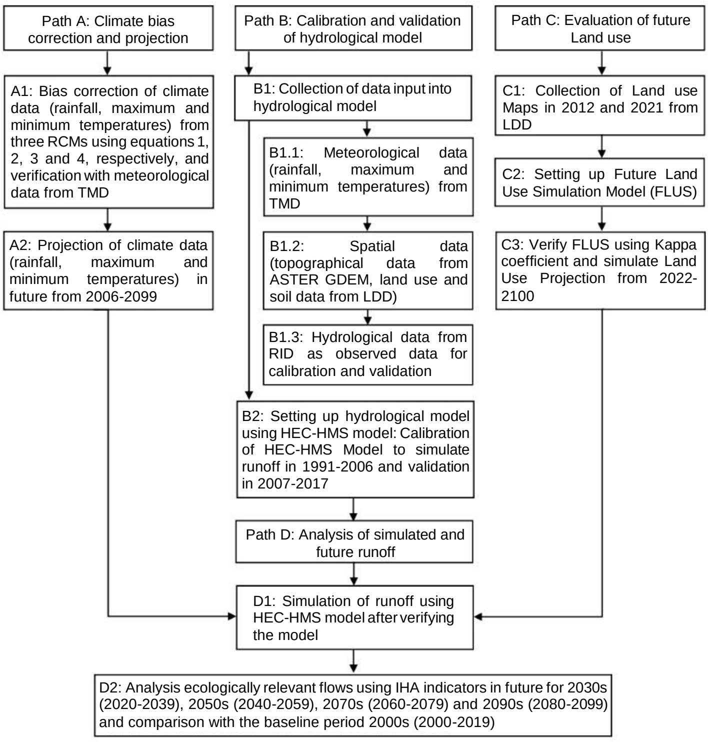


Figure 2 Methodological framework used

Table 1 IHA hydrological parameters

IHA parameter group	Hydrological parameters
Group 1: magnitude of the monthly discharge (12 parameters)	Mean monthly flow from January to December
Group 2: magnitude of the annual extreme discharge under different durations (10 parameters)	1-day, 3-day, 7-day, 30-day, and 90-day minimum flow and maximum flow
Group 3: timing of the annual extreme discharge (2 parameters)	Julian date of the annual 1-day minimum flow and maximum flow
Group 4: rate and frequency of the discharge change (2 parameters)	Rise rates: mean or median of all positive differences between consecutive daily values Fall rates: mean or median of all negative differences between consecutive daily values
Group 5: monthly low flows of EFCs (12 parameters)	EFCs: monthly low flow from January to December

3.1 Bias correction for climate data projection

Bias correction is a technique to match simulated and observed data to improve simulated data precision [17]. In this study, the linear scaling approach was chosen to address biases in rainfall and temperature data with observed data from the TMD. This approach, known for its simplicity and effectiveness in adjusting biases, was selected to improve the precision of simulated data, as reported in other studies [33-39]. Equations (1) and (2) were used to correct and match the historical and simulated data from each RCM with the observed rainfall data. Equations (3) and (4) were applied to the maximum and minimum temperature data to correct and match the historical and simulated data from each RCM with the observed data. The standard deviation (SD), root mean square error (RMSE), and the mean are sensitivity performance parameters that were used quantify the dispersion and central tendency.

Rainfall correction formulas: $P'_{his,d} = P_{his,d}\left[\frac{\mu_m \cdot P_{obs,d}}{\mu_m \cdot P_{his,d}}\right]$ (1)

$$P'_{sim,d} = P_{sim,d}\left[\frac{\mu_m \cdot P_{obs,d}}{\mu_m \cdot P_{his,d}}\right] \quad (2)$$

Temperature correction formulas: $T'_{his,d} = T_{his,d} + \left[\mu_m \cdot T_{obs,d} - \mu_m \cdot T_{his,d}\right]$ (3)

$$T'_{sim,d} = T_{sim,d} + \left[\mu_m \cdot T_{obs,d} - \mu_m \cdot T_{his,d}\right] \quad (4)$$

Where, P is the rainfall, T is the temperature, d is the daily unit, μ_m is the monthly unit, obs is the observed data, his and sim are historical and simulated RCM data, respectively, and $'$ is the corrected value.

3.2 Land use change model

The Future Land Use Simulation FLUS model is commonly used for projecting future land use [35, 40, 41]. It can simulate various types of land use change under environmental and anthropogenic effects. The FLUS model is based on two components: a multiple cellular automata (CA) allocation model and an artificial neural network (ANN) algorithm [35]. The multiple CA allocation model was prepared to assess future spatial land use patterns as a result of land use change and demand based on historical trends and anthropogenic effects [17]. The ANN algorithm defined the complex relationships of the influential human and environmental characteristics driving future land use types. The future land use map based on the FLUS model was set up based on separate economic and a conservation case studies. The economic case study was based on the land use maps from 2012 to 2021 sourced from the LDD to establish land use change projections during 2022–2100. The forest conservation case study used the Thailand Government Strategy for conserving and restoring biological variety to protect and expand forest area. Land use change was classified into five categories: agricultural, forest, miscellaneous, urban and built-up land, and water body. The simulated land use map was calibrated against the observed land use map in 2021 using Kappa statistical analysis (K), as shown in equation (5). K has a value in the range 0–1, where 1 indicates the strong agreement between the simulation and observation [17].

$$K = \frac{\Pr(a) - \Pr(e)}{1 - \Pr(e)} \quad (5)$$

Where, Pr(a) is observed relative agreement amongst all raters and Pr(e) is the hypothetical probability of chance of agreement.

3.3 Hydrological modeling

The Hydrological Modeling System (HEC-HMS) [42] was established to simulate the runoff from rainfall while accounting for the topography and surface characteristics of the simulated area. This model was developed to be usable over a wide topographical range and to solve as many problems as possible.

3.3.1 Model set-up

In this study, HEC-HMS was used to simulate runoff under various climatic and land use scenarios. HEC-GeoHMS, an extension of HEC-HMS, was used with the ArcGIS to prepare the data and parameters for simulation in HEC-HMS by delineating hydrological components, such as sub-basins, river networks, and basin characteristics. The SCS curve number was applied to calculate the infiltration loss. Each year, the impervious percentage from land use type and soil maps, as well as simple canopy and surface equations were utilized to define water detention and surface storage. The surface runoff simulation, based on time of concentration and storage coefficient, was calculated using the Clark Unit Hydrograph method. The base flow method was used to calculate consistent monthly flow statistics from the streamflow discharge data. The Thiessen polygon modification approach was used to compute the weighting factor of each weather station in the sub-basin. The configuration of the HEC-HMS models for the Wang River is shown in Figure 3.

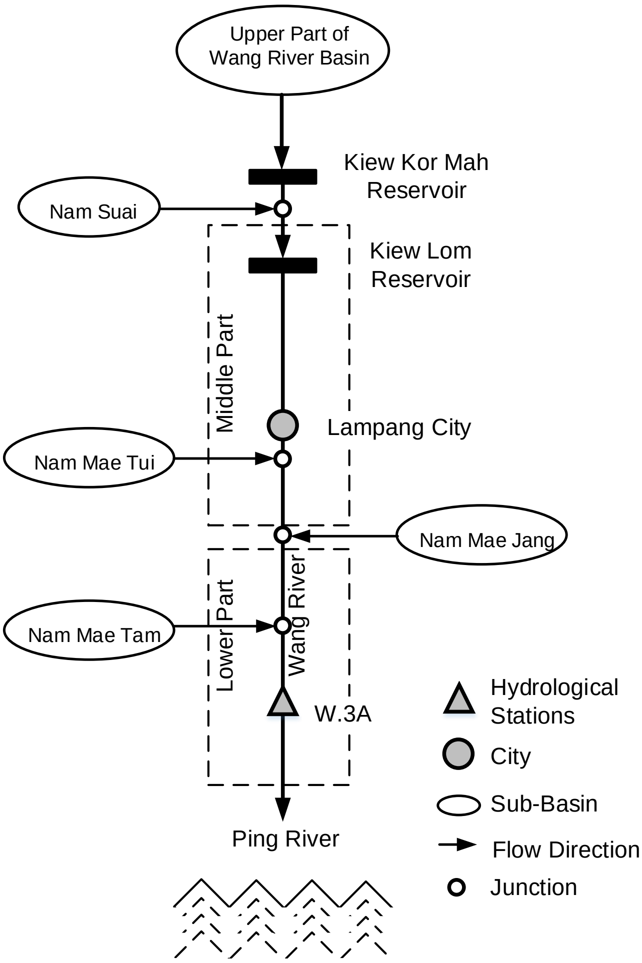


Figure 3 Configuration of HEC-HMS model for Wang River

3.3.2 Calibration, validation, and assessment of model performance

The HEC-HMS outputs consisted of daily streamflow discharge from converting the daily rainfall data, as well as maximum and minimum temperatures. For calibration, these results at a hydrological station (W.3A) were compared to observed data from RID during 1991–2006, and 2007–2017 for validation. The performance of the HEC-HMS model was assessed based on a graphical comparison and statistical indices for goodness-of-fit: R^2, NSE, PBIAS, and RMSE. This model was used to forecast future discharge in the WRB under future climatic and land use change options.

4. Results and discussions

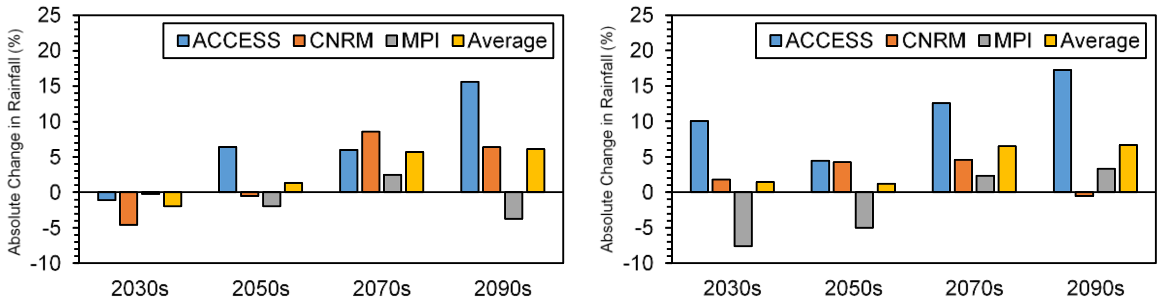
4.1 Climate bias correction and projection

The WRB climate was projected using only three climatic variables: average daily rainfall and maximum and minimum temperatures. Three regional climate models (RCMs) were used namely ACCESS, CNRM, and MPI, to predict the future climate under the RCP4.5 and 8.5 models based on the baseline period 1970–2005. The TMD provided meteorological data from stations: 310201, 328201, 328301, 330201, and 376203. These TMD stations were utilized to provide baseline observation data on rainfall and temperature that were modified for bias correction using a linear scaling method. As indicated in Table 2, the mean and standard deviation (SD) were used to define the central tendency and dispersion, respectively, of the observed and simulated climatic data for the baseline and three RCMs. Additionally, the RMSE is displayed in Table 2. It was found that all meteorological stations from TMD had mean rainfall values in all RCMs that were equal to the observed mean rainfall values. CNRM had SD values quite close to the observed SD values for almost all TMD stations. Although the RMSE values of all TMD stations were higher than the observed RMSE values of all RCMs, the RMSE values remained close to the observed RMSE values. All the TMD stations had mean temperature values in all RCMs equal to the mean observed temperature values. The MPI maximum temperatures and ACCESS minimum temperatures from all TMD stations had SD values closer to the observed SD values than the other RCMs. All the TMD stations had maximum and minimum temperature RMSE values in all RCMs that were lower than the observed RMSE values. All RCMs had sufficient accuracy and precision for use as input into the hydrological model to predict future discharge. The average method was applied to increase the accuracy of the predicted data and decrease the central tendency. Therefore, the input data were used as the average daily rainfall and maximum and minimum temperatures in the hydrological model.

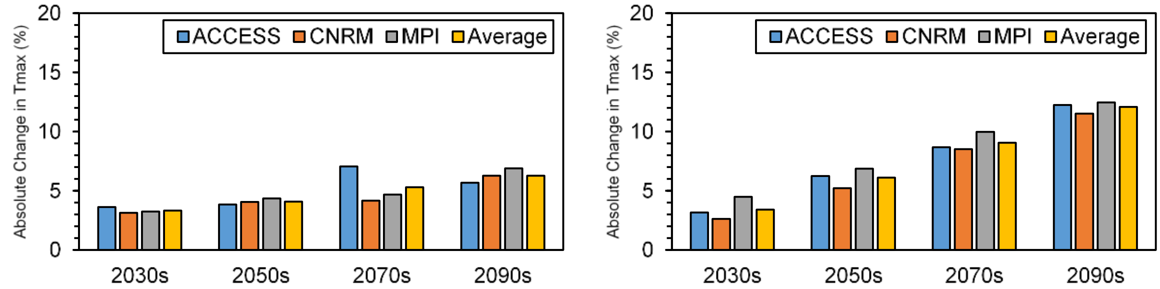
The results based on the Lampang meteorological station (328201) are presented in Figure 4 to show the relative change trend of the future climate projection period from baseline period (1970–2005) in the WRB. This station contributes more than 35.88% of the WRB's spatially distributed rainfall compared to other stations, as determined using the Thiessen polygon method. The future climate was projected for four periods: 2030s (2020–2039), 2050s (2040–2059), 2070s (2060–2079), and 2090s (2080–2099) under the RCP4.5 and RCP8.5 trajectories. Future annual rainfall trends in WRB fluctuated from the baseline under RCP4.5 and 8.5. From the baseline period, the mean annual rainfall was 1,066.66 mm, which was almost in the range 1,045.80–1,131.70 mm or change -1.96 to 6.10 % in the 2030s–2090s for RCP4.5. For RCP8.5, the annual rainfall extreme was the range 1,079.77–1,137.95 mm or change 1.43 to 6.68 % in the 2030s–2090s. Future maximum temperature trends in the basin indicate a continue increase rise about 2.09 and 4.01 °C or change 6.28 and 12.07 % for the RCP4.5 and RCP8.5 trajectories, respectively. The mean annual maximum temperature for the baseline was 33.20 °C, which increased from 34.31 (2030s) to 35.29 °C (2090s) or change 3.33 to 6.28 % and from 34.34 (2030s) to 37.21 °C (2090s) or 3.42 to 12.07 % from the baseline under RCP4.5 and 8.5 respectively. Additionally, the trends for the future minimum temperature under RCP4.5 and 8.5 showed steady increases by about 1.95 and 4.05°C from the baseline (about 20.75 °C). The minimum temperature increased from 21.67 (2030s) to 22.70 °C (2090s) or change 4.43 to 9.41 % and then from 21.85 (2030s) to 24.80°C (2090s) or change 5.30 to 19.50 % from the baseline under RCP4.5 and 8.5 respectively. In other studies in the same region, their projected climatic data presented a fluctuating trend for rainfall and an increasing trend for the maximum and minimum temperatures [17, 33, 43, 44].

Table 2 Performance parameters for projected daily rainfall and maximum and minimum temperatures with bias correction at five meteorological stations

Station	Var.	Rainfall (mm)				Maximum Temperature (°C)				Minimum Temperature (°C)			
		Obs	ACCESS	CNRM	MPI	Obs	ACCESS	CNRM	MPI	Obs	ACCESS	CNRM	MPI
310201	Mean	3.13	3.13	3.13	3.13	31.62	31.62	31.62	31.62	20.18	20.18	20.18	20.18
	SD	9.36	7.69	9.37	8.77	3.39	4.19	4.30	4.13	4.46	4.60	4.69	4.66
	RMSE	10.05	11.55	12.59	12.34	4.26	4.10	4.23	4.13	3.61	3.26	3.33	3.30
328201	Mean	2.75	2.75	2.75	2.75	33.54	33.54	33.54	33.54	20.90	20.90	20.90	20.90
	SD	8.41	10.03	6.41	6.46	3.25	4.03	4.10	3.96	4.01	4.25	4.30	4.27
	RMSE	9.20	12.72	10.08	9.98	4.22	3.96	4.01	3.95	3.29	3.00	3.03	3.04
328301	Mean	3.07	3.07	3.07	3.07	32.59	32.59	32.59	32.59	20.50	20.50	20.50	20.50
	SD	8.71	9.78	8.48	9.43	3.38	4.17	4.25	4.13	3.69	3.90	3.97	3.92
	RMSE	9.45	12.59	11.53	9.43	4.30	4.07	4.16	4.06	3.15	2.94	2.96	2.96
330201	Mean	2.95	2.95	2.95	2.95	33.20	33.20	33.20	33.20	21.48	21.48	21.48	21.48
	SD	9.52	7.32	6.94	6.10	3.11	3.93	3.99	3.86	3.98	4.14	4.20	4.15
	RMSE	10.01	11.54	11.26	10.72	4.08	3.90	3.93	3.85	3.14	2.95	2.99	2.98
376203	Mean	2.69	2.69	2.69	2.69	33.57	33.57	33.57	33.57	22.41	22.41	22.41	22.41
	SD	9.21	7.95	8.77	8.85	3.39	3.97	4.00	3.94	3.41	3.48	3.53	3.51
	RMSE	9.83	11.74	12.19	12.20	4.53	3.97	3.98	3.98	3.14	2.76	2.82	2.83

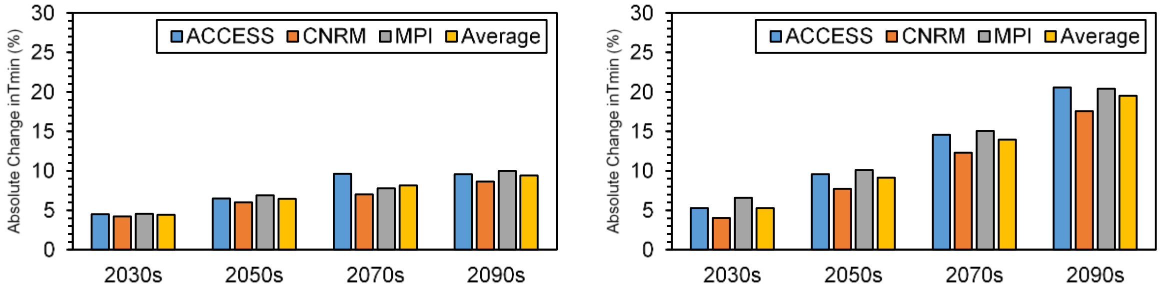


(a) Absolute change in annual rainfall



(b) Absolute change in maximum temperature

Figure 4 Relative absolute change in rainfall (a), maximum temperature (b) and minimum temperature (c) under RCP4.5 (left) and RCP8.5 (right) scenarios at Lampang meteorological station (328201)



(c) Absolute change in minimum temperature

Figure 4 (continued) Relative absolute change in rainfall (a), maximum temperature (b) and minimum temperature (c) under RCP4.5 (left) and RCP8.5 (right) scenarios at Lampang meteorological station (328201)

4.2 Land use projection

The future land use projections were simulated using economic and conservation scenarios. The historical land use change patterns were evaluated using the land use maps from 2012 to 2021, taking into account future urbanization and population growth at 2030, 2050, 2070, and 2090. Land use was divided into five land use categories: agricultural, forest, miscellaneous, urban and built-up land, and water body. The historical land use analysis from 2012, 2015, 2018, and 2021 in the WRB was found that the annual percentage change in agricultural land (0.14%), urban and built-up land (0.02%), and water body (0.01%) increased, whereas the annual percentage change in forest (-0.17%) and miscellaneous land (-0.01%) decreased. The K parameter was used to compare and correct the 2021 land use map with the observed land use map. The K parameter was 0.96, which is very close to 1 indicating acceptance and sufficient accuracy of the future predictions. The annual land use change for both scenarios is shown in Figure 5. The projected land use changes in the economic scenario were 32.25% for agricultural land, -12.71% for forest land, 11.26% for miscellaneous land, 9.81% for urban and build-up land, and 2.95% for water body in 2090 with respect to the baseline map of 2021. In the conservation scenario, the projected land use changes were -23.46% for agricultural land, 8.58% for forest land, 1.06% for miscellaneous land, -0.77% for urban and built-up land, and -6.94% for water body in 2090 with respect to the baseline map of 2021. The largest increase in land change occurred in agricultural land under the economic scenario, followed by miscellaneous land, urban and built-up land and water body, respectively. Otherwise, forest land showed a tendency to decrease compared to the past. This aligns with a previous study on land use changes in the Mae Soi sub-basin of WRB by Somphor et al. [45], these findings are consistent with the projected land use change in the economic scenario, where forested land is projected to decrease while agricultural, miscellaneous, urban and built-up land, and water body areas are projected to increase. For the conservation scenario, there would be no change in forest land and water body in the future following the 20-year Thailand Government Strategy.

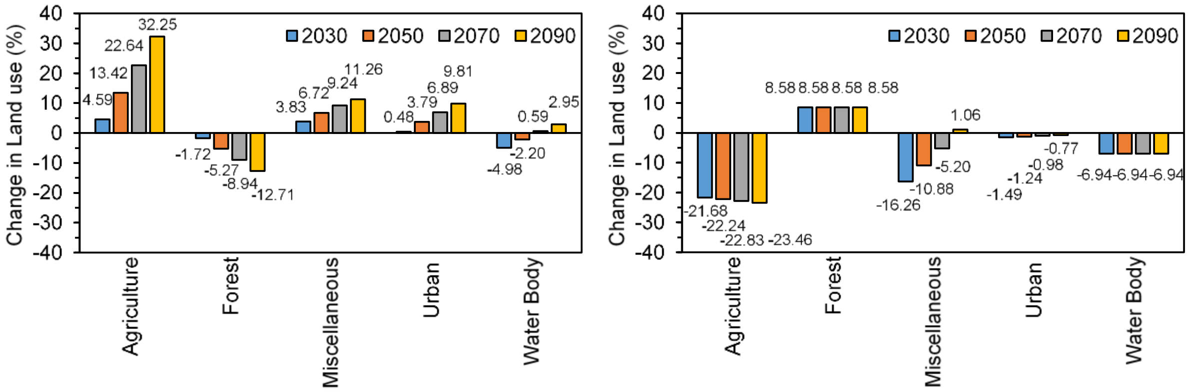


Figure 5 Relative change in land use under economic (left) and conservation (right) land use change scenarios for 2030, 2050, 2070 and 2090 with respect to 2021 baseline

4.3 Hydrological model calibration and validation

The HEC-HMS model simulated the daily discharge in the WRB. The simulated and observed discharge data at station W.3A from RID were evaluated during the calibration (1991–2006) and validation (2007–2017) periods. The results are displayed using the statistical performance indicators. The R^2 and NSE values should be close to 1 for acceptable model performance, while the PBIAS and RMSE values should be close to 0 for high model performance. If PBIAS is $\pm$25%, the model performance is often satisfactory. The current results were R^2=0.80, NSE=0.79, PBIAS=5.85%, and RMSE=38.85 cms for the calibration period, indicating very good performance by the model. Similarly, these indicators during the validation period showed there was very good agreement with R^2=0.82, NSE=0.82, PBIAS=4.95%, and RMSE=33.37 cms. Figure 6 compares the observed and simulated daily discharge at station W.3A, with the discharge simulated from HEC-HMS model being consistent with the observed data for both the calibration and validation period. The model performance was highly accurate in terms of data dispersion and central tendency. The discharge simulated by the HEC-HMS model closely matched observations, showing performance indicators similar to those found in previous studies [17, 29, 43]. As a result, this model was suitable to simulate discharge in the WRB under difference climatic and land use change scenarios.

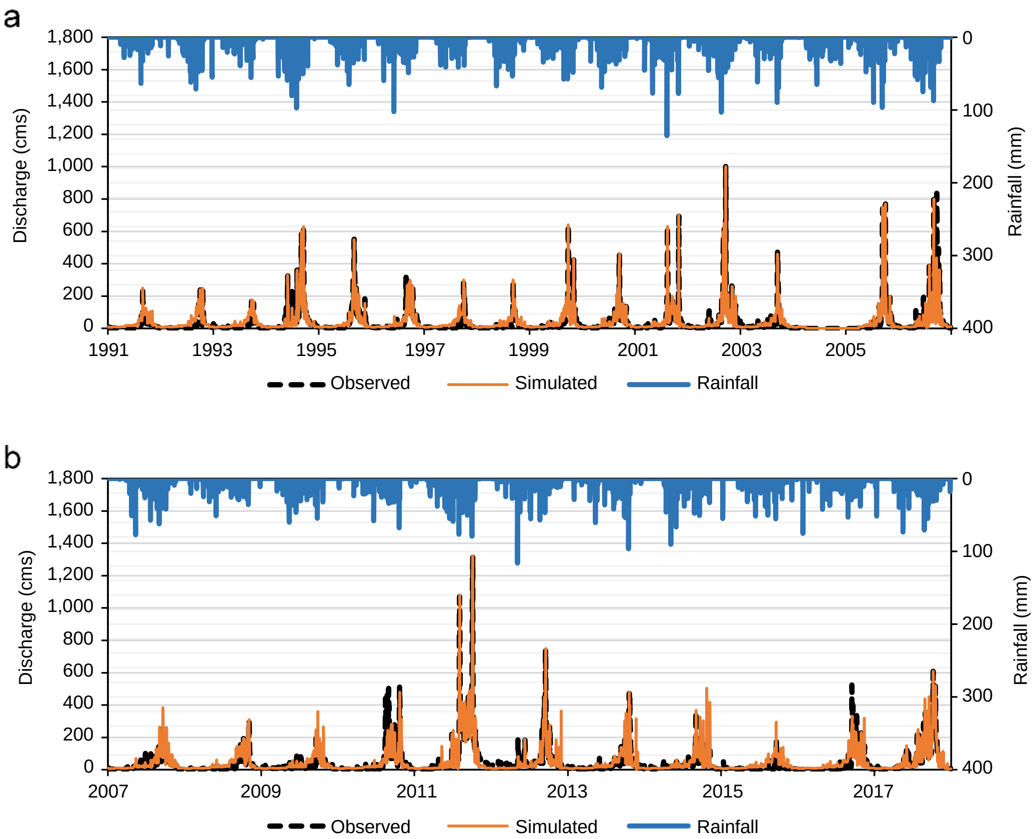


Figure 6 Comparison of observed and simulated daily discharge at W.3A hydrological station (a) calibration period (1991–2006) and (b) validation period (2007–2017)

4.4 Future climatic and land use impacts on streamflow discharge

The future rainfall and maximum and minimum temperatures impacted the discharge in the WRB. In this study, the annual flow discharge was projected under combined climate and land use change scenarios for different RCPs over four time periods: 2030s, 2050s, 2070s, and 2090s. The climatic data analysis indicated that the expected annual rainfall tended to progressively fluctuate, while the temperatures tended to increase. The future discharge in this basin was projected for four conditions, with conditions 1 and 2 involving the combined impacts of climate change and economic land use change under the RCP4.5 and RCP8.5 trajectories, respectively, and conditions 3 and 4 involving the combined climate change and conservation land use change under RCP4.5 and RCP8.5, respectively.

The annual flow discharge in the WRB was assessed in relation to the projected rainfall and temperatures for the future periods (2030s, 2050s, 2070s, and 2090s), as shown in Table 3. The projected annual discharges for the combined impacts of the climate change and economic scenarios in the 2030s, 2050s, 2070s, and 2090s were 16,156 cms, 16,668 cms, 17,523 cms, and 17,661 cms, respectively for RCP4.5 and 15,999 cms, 16,465 cms, 17,231 cms, and 17,281 cms, respectively, for RCP8.5. Similarly, the projected annual discharges for the combined impacts for the climate change and conservation scenarios in the 2030s, 2050s, 2070s, and 2090s were 16,467 cms, 16,698 cms, 17,462 cms, and 17,439 cms, respectively, for RCP4.5 and 16,306 cms, 16,490 cms, 17,166 cms, and 17,078 cms, respectively, for RCP8.5. The observed discharge during 2000–2019 (2000s) in the WRB was 18,246 cms. The annual discharge change rate under the climate change and economic scenarios in the 2030s, 2050s, 2070s, and 2090s tended to decrease by -11.46%, -8.65%, -3.97%, and -3.21%, respectively, for RCP4.5 and -12.32%, -9.76%, -5.56%, and -5.29%, respectively, for RCP8.5 comparing the future discharge to the observed discharge. Under the climate change and conservation scenarios, the annual discharge change rates in the 2030s, 2050s, 2070s, and 2090s had the same decreasing trend for the climate change and economic scenarios of -9.75%, -8.49%, -4.30%, and -4.43%, respectively, for RCP4.5 and -10.64%, -9.63%, -5.92%, and -6.40%, respectively, for RCP8.5. Therefore, it can be concluded that under both climate change and land use change scenarios for RCP4.5 and RCP8.5, there is a projected trend of reduced annual discharge in the WRB, which will impact ecosystem flows and water management [46]. In particular, in the near future (2030s and 2050s), the annual discharge tended to decrease more than in the middle future (2070s) and far future (2090s) for both RCPs. The trend of a decreasing discharge for RCP8.5 was greater than for RCP4.5 in both the economic and conservation scenarios. Furthermore, the economic scenarios had a greater impact on reducing discharge than the conservation scenario in the 2030s and 2050s for both RCPs, while in the 2070s and 2090s the economic scenario had less impact on reducing discharge than the conservation scenario for both RCPs, aligning with findings from Somphor et al. [45]. They studied climate variability and land use changes impact on discharge in Mae Soi sub-basin of WRB and found that forest area can increase discharge in the future. However, under the climate change and conservation scenario for RCP8.5, the percentage of discharge decrease in the far future was slightly higher than in the middle future. Moreover, their other study in the same region discovered a similar decreasing trend in discharge [29].

Table 3 Projected annual flow discharge and ensemble annual change under combined climate and land use change scenarios

Times	RCP 4.5				RCP 8.5			
	Economic Scenario		Conservation Scenario		Economic Scenario		Conservation Scenario	
	Annual Discharge	Change (%)	Annual Discharge	Change (%)	Annual Discharge	Change (%)	Annual Discharge	Change (%)
2030s	16,156	-11.46	16,467	-9.75	15,999	-12.32	16,306	-10.64
2050s	16,668	-8.65	16,698	-8.49	16,465	-9.76	16,490	-9.63
2070s	17,523	-3.97	17,462	-4.30	17,231	-5.56	17,166	-5.92
2090s	17,661	-3.21	17,439	-4.43	17,281	-5.29	17,078	-6.40

4.5 Climate change impact on water condition based on IHA indicators

This section analyzed the differences in discharge mean values for each IHA indicator, divided into five groups under the economic and conservation scenarios for both RCPs.

4.5.1 Group 1 (Magnitude of mean monthly flows)

The magnitude of mean monthly flows is defined in Group 1 and shown in Table 1. The changes in the mean monthly flow (Group 1) in the WRB for each future period and scenario are shown in Figure 7. The future discharge in the 2030s was expected to reduce by approximately 0–27.43 cms for both RCPs in the economic scenario and by 0–21.61 cms for both RCPs in the conservation scenario, especially during May–October and December. Similarly, the future discharge was predicted to decrease by approximately 0–22.85 cms in the 2050s, by 0–17.22 cms in the 2070s, and by 0–22.00 cms in the 2090s for both RCPs in the economic scenario and by 0–24.13 cms in the 2050s, by 0–24.30 cms in the 2070s, and 0–21.82 cms in the 2090s for both RCPs in the conservation scenario. In contrast, the future discharge in November was expected to increase by approximately 25.98 cms in the 2030s, by 2.05 cms in the 2050s, by 5.43 cms in the 2070s, and by 22.46 cms in the 2090s for both RCPs in the economic scenario and by 6.37 cms in the 2030s, by 3.24 cms in the 2050s, by 4.07 cms in the 2070s, and by 26.72 cms in the 2090s for both RCPs in the conservation scenario. However, the future discharge in June and September in all future periods had both increases and decreases for both RCPs and scenarios. These discharge changes were mostly caused by changes in rainfall, with the rainfall expected to decrease in the rainy season, particularly in the months of July, August, and September. This conclusion aligns with the findings of a study on rainfall patterns in Northeast Thailand, which predicts a reduction in rainfall during these months [47].

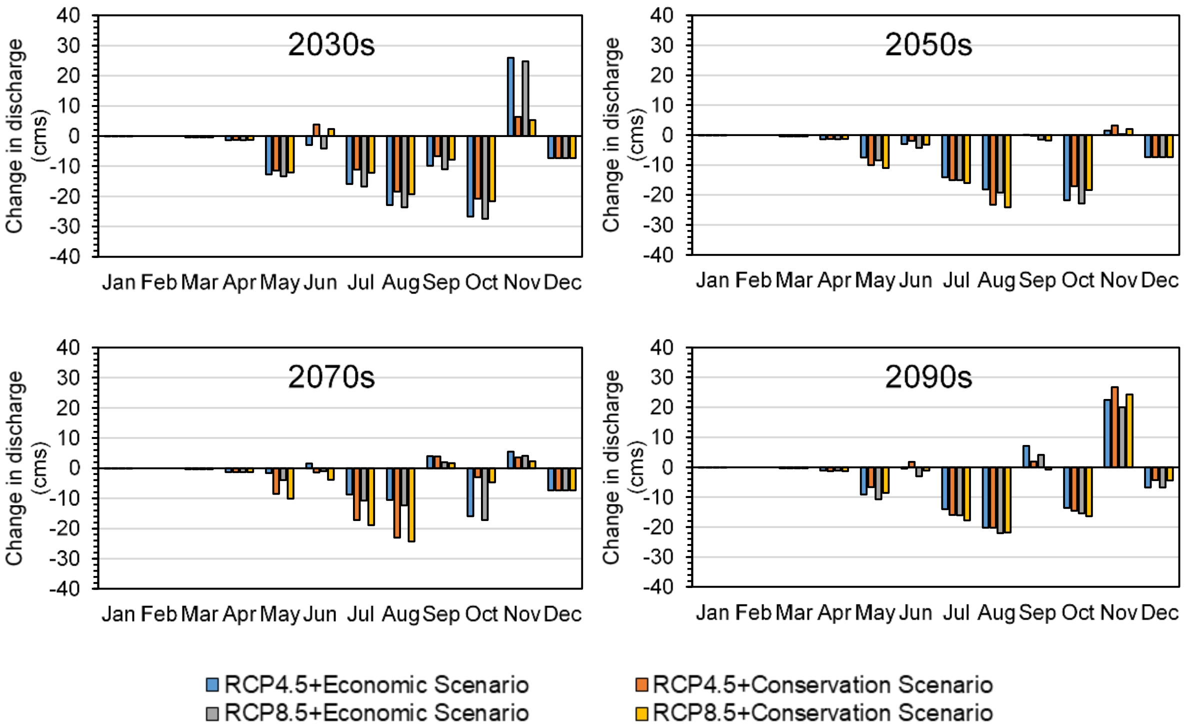


Figure 7 Changes in mean monthly flow (Group 1) in WRB in 2030s, 2050s, 2070s and 2090s

4.5.2 Group 2 (Magnitude and duration of annual extreme water conditions)

The were 10 different parameters of magnitude of extreme (maximum and minimum) annual water condition of various durations, ranging from daily (1, 3, and 7 days) to seasonal (30 and 90 days), in Group 2, as shown in Table 1. For the baseline period (2000-2019), the 1-, 3-, 7-, 30- and 90-day annual maxima were 1,006.30, 765.80, 468.35, 352.06, and 242.17 cms, respectively, while the 1-, 3-, 7-, 30-, and 90-day annual minima were 9.00, 4.30, 1.84, 0.43, and 0.14 cms, respectively. The mean change value for the annual minima showed minimal variation across all durations due to the long-term stability of annual minimum streamflow volume during the dry season. In contrast, the mean change value of the annual maxima varied substantially across all durations due to the differing maximum streamflow volume each year.

The changes in the average values of the 1-, 3-, 7-, 30-, and 90-day annual maxima for RCP4.5 were predicted to be by 31.24% in the 2030s, by 9.39% in the 2050s, by 10.07% in the 2070s, and by -2.20% in the 2090s under the economic scenario and by 29.64% in the 2030s, by 6.95% in the 2050s, by 8.42% in the 2070s, and by -6.80% in the 2090s under the conservation scenario. For RCP8.5, by -30.93% in the 2030s, by 3.01% in the 2050s, by 2.87% in the 2070s, and by -3.35% in the 2090s under the economic scenario and by -31.47% in the 2030s, by 1.20% in the 2050s, by -0.07% in the 2070s, and by -6.14% in the 2090s under the conservation scenario. In addition, the average values of the 1-, 3-, 7-, 30-, and 90-day annual minima were expected to increase by 65.71% under both RCPs and scenarios for all future periods. In summary, for all future periods, the annual maximum change was high for the short-term duration period, consistent with studies by Masud et al. [48] and Manton et al. [49], which found a decrease in the number of rainy days and a significant increase in the proportion of total rainfall from extreme rainfall from 1960 to 2099.

4.5.3 Group 3 (Timing of annual extreme flow conditions)

Group 3 contained two parameters critical for the seasonal characteristics of the hydrological conditions: the Julian dates of the annual 1-day maximum and minimum flow conditions. The annual extreme flows timings for RCP4.5 and 8.5 were similar to the baseline period. The Julian date of the annual 1-day minimum flow was expected to be 20 days earlier for RCP4.5 and 20 days later for RCP8.5, whereas the Julian date of the annual 1-day maximum flow was expected to be 1 day earlier for RCP4.5 and 1 day later for RCP8.5. Thus, these indicators predicted that this basin would experience extreme changes in the annual flow which would have a direct impact on the life cycles of plants and aquatic species, inducing stress on aquatic life and many other factors.

4.5.4 Group 4 (Rate and frequency of water conditions)

Group 4 had two parameters: the mean rate and frequency of the change in water conditions, which could be positive or negative. In the future climate scenarios, the streamflow was predicted to rise and fall at a faster rate with a high percentage change, as shown in Figure 8. Considering both RCPs and scenarios, the streamflow rise rate continuously increased with future periods. The change in rise rate was expected to increase by 124.73–146.85% (RCP4.5) and by 122.26–147.11% (RCP8.5) under the economic scenario and by 122.54–141.45% (RCP4.5) and by 120.24–142.78% (RCP8.5) under the conservation scenario during 2030-2090. Similarly, the streamflow fall rate was predicted to increase equally under both RCPs and scenarios for all future periods. The change in the fall rate was expected to increase by 61.24–62.30% under both RCPs and scenarios for all future periods. As the rise and fall rates increased with higher percentages, it would be likely that the WRB would experience frequent flooding and droughts. This is confirmed by Yang et al. [25], who found that the Upper Chao Phraya River Basin, which includes the WRB, is expected to face more frequent floods and droughts in the future.

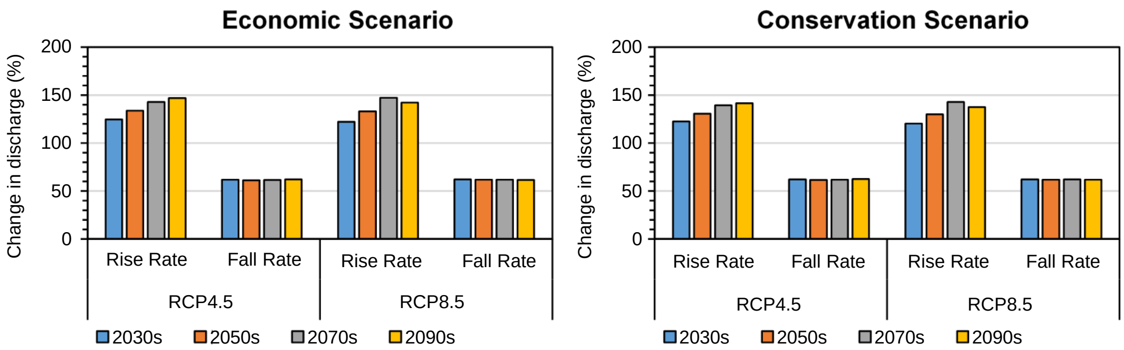


Figure 8 Change in rate and frequency of streamflow (Group 4) in 2030s, 2050s, 2070s, and 2090s

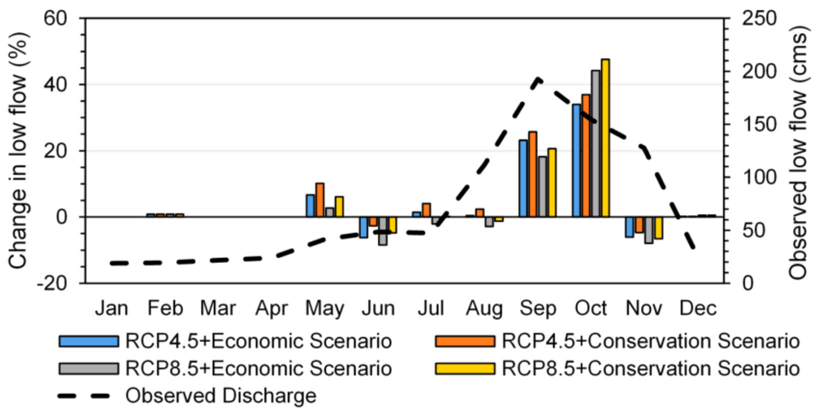


Figure 9 Change in monthly low flow (Group 5) in WRB in 2030s, 2050s, 2070s, and 2090s

4.5.5 Group 5 (Monthly low flows)

The monthly low flow of EFCs is described in Group 5, as shown in Table 1. This Group had twelve parameters, consisting of the mean low flow for each month. The change in monthly low flow in WRB is displayed in Figure 9. Under RCP4.5 and 8.5 for the economic scenario, there were expected decreases in the monthly low flow in June by -6.23% and -8.42%, respectively, compared to the observed low flow. The monthly low flows in November under RCP4.5 and 8.5 for the economic scenario were predicted to reduce by -6.08% and -7.94%, respectively. Similarly, the low flows in June and November under RCP4.5 and 8.5 for the conservation scenario would decrease by -2.72–4.80% and -4.73–6.54%, respectively. In contrast, the monthly low flows would increase in February, May, and July–October (in July and August the increase would only be under RCP4.5 for both the economic and conservation scenarios). The monthly low flows in October were predicted to have maximum increases by 34.03% (RCP4.5) and 44.23% (RCP8.5) for the economic scenario and by 36.94% (RCP4.5) and 47.62% (RCP8.5) for the conservation scenario. The monthly low flows were expected to increase in the future by a high percentage in the rainy and winter seasons, meaning that even during the low flow season, the WRB would not have a good environment for aquatic organisms, plants, fisheries, and terrestrial animals, among others. This aligns with the results of predicted streamflow discharge in the Mae Soi sub-basin of the WRB, where January to May is anticipated to face no or low monthly flows, remaining unchanged from the past decade [45].

5. Conclusions

This study focused on projecting the hydrological regime in the WRB, based on three different drivers: rainfall, temperature and land use change. The linear bias correction approach was used to adjust rainfall and temperature from three RCMs under the RCP4.5 and 8.5 strategies. Land use change was assessed under economic and conservation scenarios using past land use. The FLUS model was used to forecast land use change, whereas the HEC-HMS model was applied to simulate future discharge projections. The results predicted future extreme temperatures would increase by approximately 2.09–1.95 °C for RCP4.5 and by 4.01–4.05 °C (maximum/minimum temperatures) for RCP8.5 from the baseline. The predicted annual rainfall trend in the WRB would reduce and increase from the baseline under RCP4.5 and 8.5, respectively. From baseline period, the annual rainfall under RCP4.5 was from -1.96 to 6.10 % for the 2030s though to the 2090s. For RCP8.5, the annual rainfall was from 1.43 to 6.68 % for the 2030s through to the 2090s. It was concluded that the expected rainfall trend was consistent with those from other studies in the same and surrounding regions [17, 22, 34]. The land use projection analysis showed that agricultural land would change the most under the economic scenario, with no change in forest land under the conservation scenario. The annual discharge was estimated in this study under integrated climate change and land use change scenarios based on the RCP4.5 and RCP8.5 strategies for four future periods: the 2030s, the 2050s, the 2070s, and the 2090s. The predictions were for a trend of decreasing discharge, with the annual discharge dropping more in the 2030s to the 2050s than in the 2070s to the 2090s for both RCPs. Similarly, the rainy season had a lower discharge from the baseline for the climate change and both land use change scenarios, whereas discharge changed little in the remaining seasons. The declining discharge trend would have an impact on flows and affect the ecology and water management for agriculture in the WRB.

The IHA-based hydrological indicators and environmental flow components were utilized to assess flow parameters that were divided into five groups and considered under economic and conservation scenarios for the RCP4.5 and 8.5 trajectories in the WRB. The major findings of this study can be summarized as follows:

- The discharge fluctuations would be mostly caused by changes in rainfall and temperature, which were projected to decrease throughout the rainy season, affecting the ecosystem of the streamflow regime.
- The annual maximum and minimum flows would increase and reduce by more than 30% in the future. Flooding events and soil erosion would became more common, both of which could impact aquatic organisms and livelihoods.
- Considering the timing of annual extreme flow, the minimum flow event would be 20 days earlier and the maximum flow event would be 1 day later, which would have major impacts on ecosystems and agriculture.
- Monthly low flows would decrease during the dry season, so there may not be sufficient water for agriculture and to maintain environmental flows for aquatic and terrestrial animals.

The results of this study could inform more effective water management policies in the WRB to allocate water by considering the impact of climate change on the hydrological cycle, agriculture, and ecosystems.

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