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Assessment of surface water and groundwater potential under climate change in the Lam Phaniang River Basin

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Abstract

The assessment of surface water and groundwater potential under climate change in the Lam Phaniang River Basin was based on SWAT model for evaluating streamflow, and MODFLOW model for evaluating groundwater flow. The SWAT model was well calibrated and validated with daily discharge measured at E.68A during 2010-2015 and 2016-2021, respectively, with R^2 and Nash-Sutcliffe Efficiency values more than 0.60. The MODFLOW model was also well calibrated and validated with observation data from 16 groundwater wells during May 2021, and 2 groundwater observation wells of Department of Groundwater Resources during 2013-2021, respectively, with r greater than 0.95 and Normalized Root Mean Square Error less than 10%. Future climate analysis (2022-2099) was based on Regional Climate Models (CNRM-CM5, CanESM2, and GFDL-ESM2M), under RCPs 4.5 and 8.5 scenarios. The maximum and minimum temperatures under RCP 4.5 were 34.54 °C and 21.07 °C, respectively, while under RCP 8.5, both temperatures were 35.30 °C and 20.36, respectively. The future mean temperature tended to be higher than present temperature (32.35 °C and 19.28, respectively). The future mean annual rainfall, which were 1,246.37 mm/year and 1,250.01 mm/year under RCPs 4.5 and 8.5, respectively, were lower than the mean annual rainfall recorded between 2002-2021 (1,257.00 mm/year). The surface water under RCPs 4.5 and 8.5 were lower than the present condition (2,175,988,582 m^3/year), while the future groundwater supply was increased from the present (424,418,714 m^3/year). When annual surface water supply was compared with water demand, no water shortage was expected under present condition, while low to moderate levels of water shortage were identified under RCPs 4.5 and 8.5. When compared annual surface and groundwater supply with the demand, no water shortage was detected under present and future conditions. Finally, the obtained results will be useful for surface and groundwater management, in which water-related problems can sustainably be solved.

Keywords: SWAT model, MODFLOW model, Climate change, Regional Climate Model, Representative Concentration Pathways, Water Scarcity Index

1. Introduction

It is important to note that hydrology, which is a fundamental component of the hydrological cycle, is closely linked to the climate system, in which the change in climate change would certainly affect the hydrological components and their spatial distribution [1]. According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), climate change significantly impacts water resources and future adaptation strategies, while rising in temperatures could reduce water availability, increase evaporation rates, and lead to declines in streamflow and groundwater infiltration, etc. [2, 3]. Therefore, the study water resources management and development, with a strong emphasis on quantitative assessments of surface and groundwater systems, is critically important.

The previous mentioned concern is exactly what happened in the study area, i.e., the Lam Phaniang River Basin, especially with severe water scarcity for agriculture by the estimated deficit of 186 million m^3 in drought-prone areas. This is primarily due to the absence of water storage infrastructure, unsuitable landscape conditions, and low rainfall amounts [4]. To optimize water availability in the region, an integrated evaluation of surface and groundwater resources has been initiated. The Lam Phaniang River Basin features diverse geological structures and hydrological characteristics, including steep slopes, plains, and plateaus, which contribute to high

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surface runoff. These conditions affect surface water storage, groundwater infiltration, and groundwater quality, as rainfall plays a significant role in groundwater recharge. The river basin itself contains extensive agricultural areas that require substantial water resources, particularly during the dry season when water scarcity challenges both farming and daily livelihoods. Additionally, surface water bodies in the Lam Phaniang River Basin are generally shallow and lack large-scale water storage infrastructure. Sustainable utilization of groundwater remains a challenge, alongside deforestation caused by cropland expansion and unregulated water usage.

To address these challenges, the Soil and Water Assessment Tool (SWAT) has been employed to assess surface water quantity, in conjunction with the MODular Finite-Difference FLOW (MODFLOW) model for the quantitative evaluation of groundwater under both current and future conditions across different climate change scenarios. This integrated modeling approach provides a comprehensive representation of hydrological systems by incorporating dynamic interactions and key parameters for both surface water and groundwater. It enables the simulation of groundwater-surface water interactions, offering valuable insights into hydrological processes. Based on scientific reviews, groundwater-surface water assessments can significantly enhance integrated water resource management, as detailed in the following sections.

In the literature, there are some studies that provide reasons why MODFLOW was included in this modeling framework, instead of only relying on the application of SWAT model, in order to obtain a realistic hydrological simulations of surface water and groundwater flow and their interactions. Molina-Navarro et al. [5] proposed to use SWAT-MODFLOW instead of SWAT when considering the groundwater processes and groundwater abstraction impacts on nearby surface water resources. This is because in SWAT, the impact of changes in streamflow in relation to the abstraction of volume of water is negligible, while SWAT evaluates the impacts on streamflow only when abstractions are taken from the shallow aquifer, and not from the deep aquifer. Kim et al. [6] integrated the quasi-distributed watershed model (SWAT) with the fully-distributed ground-water model (MODFLOW) since the SWAT model has semi-distributed features in which its groundwater component does not consider distributed parameters such as hydraulic conductivity and storage coefficient, and could result in inaccurate representation of spatial distribution of groundwater levels and recharge rates. Due to the difficulty in calculating the head distribution and the distributed pumping rate, recharge values at steady and unsteady states estimated by SWAT were therefore used in a MODFLOW model by exchanging the characteristics of the Hydrologic Response Units (HRUs) in the SWAT with cells in the MODFLOW model. Of course, there are many more relevant studies that are highly supportive for the application of distributed and physically based MODFLOW modeling system for groundwater flow simulation like [7-10], and many more.

A wide range of literature is also available on the application of a linked modeling system between SWAT and MODFLOW for efficiently and integratively simulating spatial and temporal distributions of hydrologic components. For example, Putthividhya and Laonamsai [11] employed the SWAT and MODFLOW models for spatio-temporal surface water simulation and the estimation of groundwater recharge rates in Sukhothai Province of Thailand. It was found that the mean annual recharge (mm) in the upland forested areas and the watershed outlet area is higher than along the main central area of the floodplain. The highest water table elevation of 472 m. (MSL) was found at the mountainous regions of the Yom River, while the lower groundwater level of 181 m. (MSL) was identified along the Yom River and its tributaries. Moreover, the vast majority of groundwater-surface water interaction was also found to be discharged from the aquifer to the stream. Aslam et al. [12] applied the integrated modeling framework of SWAT and MODFLOW models for investigating the projected groundwater changes based on climate change and anthropogenic drivers, e.g., land use change, and abstraction on the groundwater resources in the Lahore, Pakistan. The results revealed the projected increase in minimum and maximum temperature by 2100, while the future rainfall was projected to be decreased in mid future, and increased in near and far future periods, under both RCPs 4.5 and 8.5 scenarios. Under all scenarios, due to the increase in groundwater abstraction and impermeable surface expansion, the groundwater level in bult-up areas was projected to decline from 185 m to 125 m by 2100, while the fluctuation trend with a slight increase in groundwater level was found for agricultural areas due to decreasing abstraction and multiple recharge sources under RCP 4.5-R1S1-SSP1 and RCP 8.5-R1S1-SSP1 combined scenarios. Saurav [13] evaluated the current state of groundwater governance in the rapidly urbanizing Khon Kaen Province in Thailand, which is close to Nong Bua Lam Phu Province where the majority area of the Lam Phaniang River Basin is located. The SWAT and GMS-MODFLOW models were applied to estimate the current and future availability of surface water and groundwater under increasing multiple stresses, i.e., climate, land use, population, and water demand. The results revealed that the groundwater recharge was expected to decrease by 5%-10% and 9%-15%, while the groundwater level was also expected to decrease by 0.8 m-3.0 m and 1.7 m-6.3 m under SSP-245 and SSP-585 scenarios, respectively. In addition, many researchers have also combined the SWAT and MODFLOW models together to simulate the interactions between surface water and groundwater including [14-16], etc.

Regarding the impacts of climate change on the water budget and the interaction between surface water and groundwater in the Lam Phaniang River Basin, climate change projection data during 2022-2099, excluding socio-economic influences, was utilized. Finally, the main findings obtained from this study are crucial for ensuring the sustainable management of water resources within the river basin.

2. Materials and methodology

2.1 Study area

The Lam Phaniang River Basin, which is confined in the S-shaped, narrow morphology, and situated between two mountain ranges [17], is a sub-basin of the Chi River Basin located in northeastern Thailand, with the total area of 1,936.63 km^2 (3.93% of the Chi River Basin [18]. It encompasses 33 subdistricts across five districts in Nong Bua Lam Phu and Loei Provinces, while the Lam Phaniang River is the main river with the total length of 150 kilometers, originating from Phu Pha Wiang in Na Duang District, Loei Province, and flows southeastward through Na Wang, Na Klang, Mueang Nong Bua Lam Phu, Non Sang, and Si Bun Rueang Districts before draining into the Ubol Ratana Dam. The upper part of the basin features elevations generally exceeding 600 meters above mean sea level (AMSL), while the central region ranges from 100 to 200 meters AMSL [19] (see Figure 1 for details).

According to data from the Upper Northeastern Meteorological Center, Thai Meteorological Department (2002-2021), the mean temperature in the Lam Phaniang River Basin is 32.35°C, with the lowest recorded temperature at 19.28°C. The 30-year (1988-2017) mean annual rainfall is 1,409.2 mm, with 1,182.4 mm occurring in the wet season (May to October) and 226.8 mm in the dry season (November to April). The mean annual streamflow is 325.8 million cubic meters (MCM), with 282.2 MCM occurring during the wet season and 43.6 MCM in the dry season, equivalent to 5.3 liters/second/square kilometer [18]. The land use in the Lam Phaniang River Basin consists of five main categories: (1) agricultural land, which covers 68.5% of the total area, including paddy fields (27.4%), cropland (28.4%), perennial crops (11.6%), orchards (1.1%), and horticulture (0.1%); (2) urbanized areas (5.6%); (3) forested land (19.8%); (4) water bodies (3.3%); and (5) miscellaneous land use (2.7%) [18].

According to the data from [4], the Lam Phaniang River Basin faces significant hydrological challenges, including 608 hectares of flood-prone areas, 32,784 hectares of drought-prone areas, and 160 hectares vulnerable to both flood and drought risks, affecting approximately 18,800 households. To deal with water-related problems, the Lam Phaniang River Basin was incorporated into the water management plan of the Chi River Basin in 2006 [20] and later included in the water scarcity network project, along with 19 other areas, under the strategic study of the Kong-Chi-Mun project in 2014 [21]. The aforementioned plan and project highlight the severity of water-related challenges in the region. According to the Department of Groundwater Resources, extensive groundwater well drilling and development have been undertaken in the Lam Phaniang River Basin (1,013 licensed wells for agricultural and utility purposes and 36 observation wells) by government agencies, private organizations, and individuals, which shows the attempt to solve the water shortage problem and also underscores the importance of groundwater resources for mitigating water scarcity in the study area [22]. Based on the information from [23], the groundwater quality in the Lam Phaniang River Basin is considered suitable for consumption according to groundwater quality standards with the concentration of Total Dissolved Solid (TDS) of less than 600 mg/L or not exceeding 1,200 mg/L, except in areas affected by salinity, while the mean annual groundwater pumping volume is 13.39 MCM.

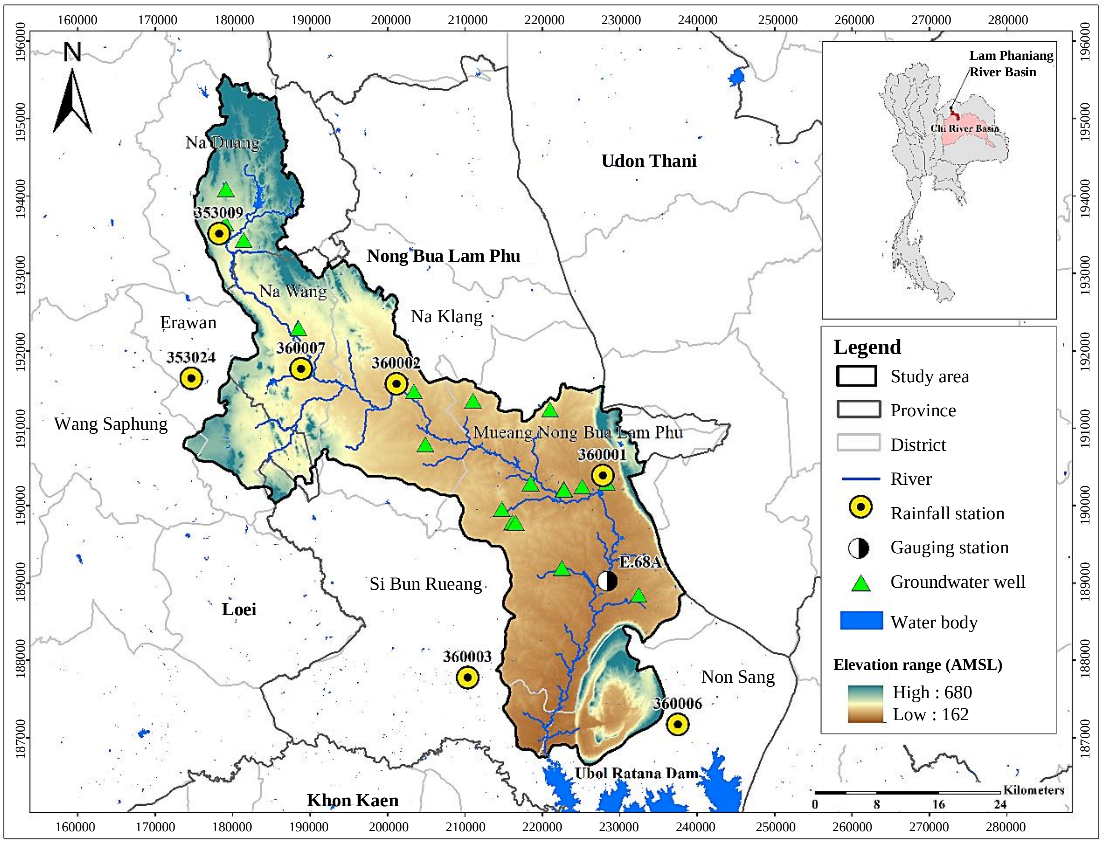

Figure 1 The Lam Phaniang River Basin

2.2 Brief description of the methodology

This research examined the relationship between the hydrologic system and climate change impacts on surface and groundwater quantity in the Lam Phaniang River Basin, focusing specifically on quantitative assessments without considering socio-economic aspects. The study applied SWAT and MODFLOW models to integratively evaluate surface and groundwater quantity, respectively, in which the simulated aquifer recharge extracted from the HRU output files of SWAT were used as recharge rates in the cells of MODFLOW. The projected global climate change using Regional Climate Models (RCMs), i.e., CNRM-CM5, CanESM2, and GFDL-ESM2M, under two Representative Concentration Pathways (RCPs 4.5 and 8.5) were incorporated in the linked SWAT-MODFLOW model. The analysis of climate projections covered the period from 2022 to 2099 and compared with the historical baseline of 2002-2021, while the details of the methodology used in this study can be shown in Figure 2.

2.3 Assessment of surface water quantity using SWAT hydrological model

In this study, the SWAT model, which is suitable for complex small and large basins and is based on water balance and water cycle concepts [24], was applied to evaluate the surface water quantity in the Lam Phaniang River Basin. The detailed SWAT model setup can be described as follows. Firstly, the watershed delineation was undertaken using a 30-meter spatial resolution Digital Elevation Model (DEM) for delineating the stream network and basin outlet points. The flow direction was then defined and the Lam Phaniang River Basin was divided into 36 sub-basins. Secondly, each sub-basin was discretized into a series of HRUs based on the combination of unique land use, soil, and slope characteristics [25], in which about 1,083 HRUs were identified for the Lam Phaniang River Basin (thresholds of 10% in land use, 10% in soil type, and 5% in slope). Thirdly, the daily weather data of a 20-year period (2002-2021), retrieved from the Upper Northeastern Meteorological Center, Thai Meteorological Department, were used as model inputs (see

Table 1 for the summary), in which the rainfall, and maximum and minimum temperature, were saved as ".txt" files individually, while solar radiation, relative humidity, and wind speed data were estimated using the SWAT weather generator. Fourthly, the SWAT model was calibrated and validated on a daily basis using historical streamflow recorded at E.68A gauging station over the periods 2010-2015 for calibration and 2016-2021 for validation. The coefficient of determination (R^2) and Nash-Sutcliffe Efficiency (NSE) were used as model performance metrics with satisfactory levels set at 0.60 and 0.50, respectively [26-28] (see Table 2 for more details).

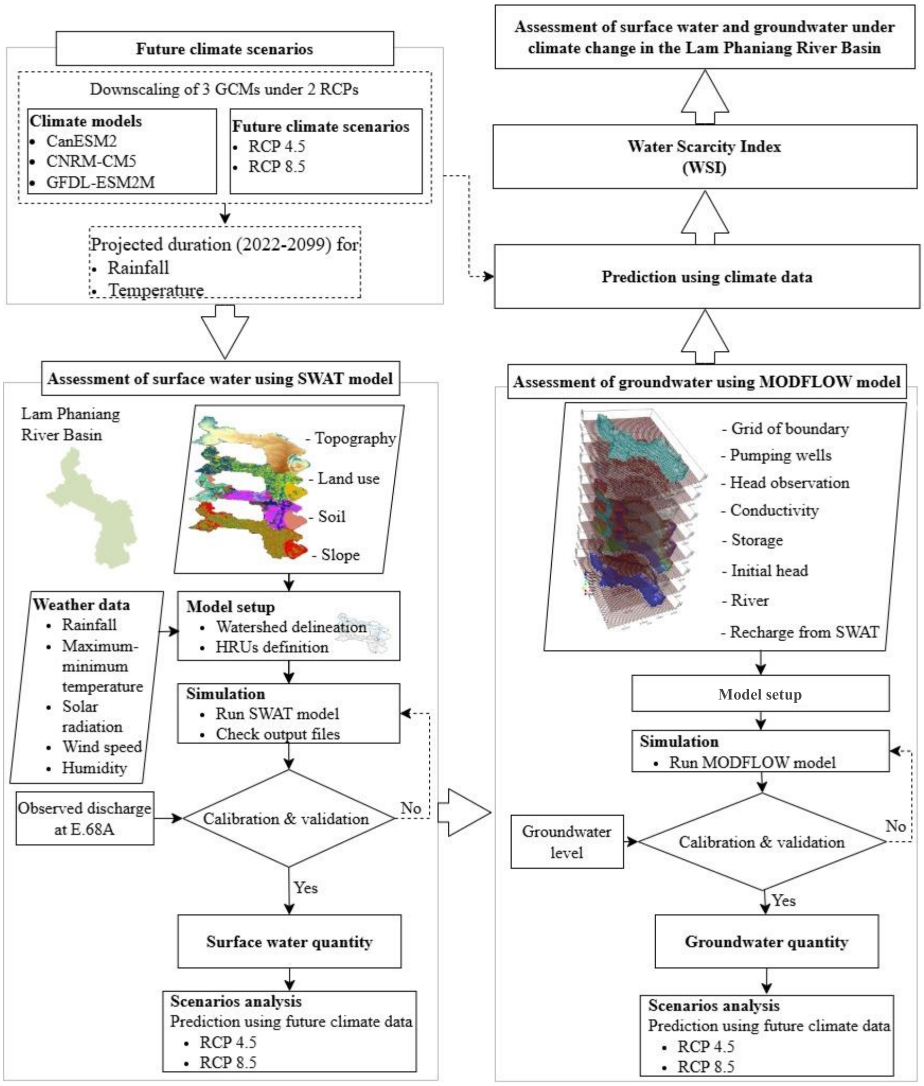

Figure 2 The assessment of surface water and groundwater potential under climate change in the Lam Phaniang River Basin

Table 1 Input data for the SWAT and their sources

Data	Description	Resolution/Period	Source
Topography	Digital Elevation Model (DEM)	30 m x 30 m	USGS website
Land use	Land use map	Scale 1:50,000	Land Development Department
Soil	Soil map	Scale 1:50,000	Land Development Department
Weather data	Rainfall, max/min temperature	Daily (2002-2021)	Thai Meteorological Department
Discharge	Discharge	Daily (2010-2021)	Royal Irrigation Department

Table 2 Classification of statistical indices [27, 28]

NSE	R^2	Classification
$0.75 < NSE \leq 1.00$	$R^2 > 0.85$	Very good
$0.65 < NSE \leq 0.75$	$0.75 < R^2 \leq 0.85$	Good
$0.50 < NSE \leq 0.65$	$0.60 < R^2 \leq 0.75$	Satisfactory
$NSE \leq 0.50$	$R^2 \leq 0.60$	Unsatisfactory

2.4 Assessment of groundwater quantity using MODFLOW groundwater flow model

The MODFLOW model, which is based on Darcy's law and the mass conservation law as fundamental principles for calculations [29], was set up for the simulation of groundwater potential in the Lam Phaniang River Basin. Initially, the process began by defining the groundwater flow simulation period from 2002 to 2021 under transient flow conditions. The delineation of boundary conditions, which is crucial for obtaining a correct water balance for the groundwater basin, was then performed. Then, the model input data were incorporated as can be seen in Table 3 for the detailed input data sets). The observation well information, i.e., monitoring groundwater level and fieldwork collected data, was employed for the calibration and validation of developed MODFLOW groundwater model for assessing the groundwater fluctuations (see Figure 1 for observation well locations). The model performance was assessed using statistical metrics, including the correlation coefficient (r) and the Normalized Root Mean Square Error (NRMSE), with the evaluation results presented in Tables 4 and 5. Finally, future groundwater conditions were simulated under projected climate change scenarios, incorporating defined pumping rates to estimate groundwater availability and determine the optimum pumping rate for sustainable future use.

Table 3 Input data for the MODFLOW

Data	Description
DEM	The topographic data obtained from USGS website with a resolution of 30 m and aggregated to a uniform grid resolution of 1 km for deriving the top surface of the model
Geological characteristics	Lithology and aquifer thickness
Hydraulic conductivity	The main hydrogeological property, which refers to the ability of the aquifer to receive the infiltrated water, for each geological unit in the x, y, and z coordinate axes.
Specific yield	The values must be greater than or equal to 0
Specific storage	The values must be greater than or equal to 0
Initial head	Groundwater level from the observation well
Groundwater well information	Locations and depths of the production wells (groundwater levels and depths from ground surface to water table), and pumping rates
Physical properties	Geometric parameters such as stream width and depth, water levels, used for the calculation of conductance (K) or hydraulic connection between the stream and the aquifer
Groundwater recharge rate	The values obtained from SWAT simulations based on annual groundwater simulations and the spatial distribution of HRUs and sub-basins

Table 4 Correlation coefficient descriptions [30, 31]

r	Description	r	Description
+1.0	Perfect positive	-0.0 to -0.5	Weak
+0.8 to +1.0	Strong	-0.5 to -0.8	Moderate
+0.5 to +0.8	Moderate	-0.8 to -1.0	Strong
+0.0 to +0.5	Weak	-1.0	Perfect negative

Table 5 Normalized Root Mean Square Error classification [32]

Classification	NRMSE range value
Excellent	≤10%
Good	10% to 20%
Fair	20% to 30%
Poor	> 30%

2.5 Analysis of the Water Scarcity Index (WSI)

The degree of water scarcity in the Lam Phaniang River Basin was evaluated using the statistics of water availability from 2002 to 2021, in conjunction with the Water Scarcity Index (WSI), which describes the relationship between water demand and water supply [33]. The water demand for agricultural and household uses was only considered in this study. In detail, the amount of water needed for agriculture was determined by the rate of evapotranspiration in mm/day, calculated by the Penman-Monteith method in SWAT. The household water demand was calculated by multiplying the population served with the per capita water demand per day, in which the average household consumption for the area within the town municipality was based on the design use of 200 liters per capita per day (lpcd), 120 lpcd for the area within the subdistrict municipality, and 50 lpcd for the area outside of the municipality. The details related to WSI calculation can be presented in Eq. (1), with the corresponding threshold values listed in Table 6.

$$\text{WSI} = \frac{\text{Water demand - Water supply}}{\text{Water supply}} \quad (1)$$

where Water demand is the demand for agricultural and household uses, and Water supply is the surface water and groundwater quantity.

Table 6 Classification of Water Scarcity Index values [34]

Water Stress Index (-)	Classification
WSI < 0.1	No water stress
0.1 to 0.2	Low water stress
0.2 to 0.4	Moderate water stress
0.4 to 0.8	High water stress
WSI > 0.8	Very high water stress

2.6 Analysis of future climate scenarios

The assessment of surface water and groundwater potential under future climate change scenarios in the Lam Phaniang River Basin was determined based on the downscaled rainfall and temperature (minimum and maximum) data obtained from the Regional Climate Models (RCMs) from the Coordinated Regional Climate Downscaling Experiment (CORDEX). The selection of RCMs was based on their applicability, acceptance, and suitability for the study area. A total of 12 RCMs from the CORDEX were considered under both a moderate projection scenario (RCP 4.5) and an extreme projection scenario (RCP 8.5). The selection process was guided by previous studies evaluating the efficiency of these models using statistical metric, namely Root Mean Square Error (RMSE) [35-39]. The rainfall data from seven meteorological stations were used to assess the accuracy of the RCMs, covering the period from 2002 to 2021. The first three climate models with the lowest RMSE values for rainfall were considered the most suitable for capturing the variability accurately, which were CNRM-CM5 (256 × 128 grid cells with a uniform horizontal resolution of 1.4° latitude × 1.4° longitude), CanESM2 (128 × 64 grid cells with a uniform horizontal resolution of 2.8° latitude × 2.8° longitude), and GFDL-ESM2M (144 × 90 grid cells with a uniform horizontal resolution of 2.0° latitude × 2.5° longitude) with the RMSE of 54.7, 64.5, and 83.2 mm/month, respectively. These models were used to project future climate conditions for four time periods, i.e., 2022-2041, 2042-2061, 2062-2081, and 2082-2099. The CMhyd (Climate Model data for hydrologic modeling) tool was also applied for climate downscaling to obtain more accurate rainfall and temperature data at local scales, and are in consistent with past climate conditions. In detail, the Linear Scaling (LS) bias correction approach was employed to ensure comparability with observed data and local applicability, and also to best represent the extreme climate conditions, while the statistical downscaling approach was applied to bridge the gap between the large and local scales with high-resolution climate projections.

3. Results and discussion

3.1 SWAT model calibration and validation

The model calibration and validation were performed using observed daily streamflow data during 2010-2015 and 2016-2021, respectively, at gauging station E.68A. The model evaluation yielded the R^2 value of 0.84 for calibration and 0.65 for validation, while the NSE values were 0.82 and 0.63, respectively, indicating a satisfied correlation between observed and simulated streamflow. The calibration process was performed both manually and using the SWAT-CUP modeling tool, incorporating nine key parameters, i.e., GW_DELAY, ALPHA_BF, GWQMN, ESCO, EPCO, CH_N2, CH_K2, TRNSRCH, and CH_N1 (see Table 7 for calibrated parameter descriptions, and Figures 3a and 3b for calibration results).

Table 7 Summary of calibrated SWAT parameters used for daily streamflow simulations in the Lam Phaniang River Basin

Category	Parameter	Description	Range	Calibrated value
Groundwater	GW_DELAY	Delay time for aquifer recharge (day)	0-500	15
	ALPHA_BF	Baseflow alpha factor (day^{-1})	0.00-1.00	0.37
	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	0-5,000	100
Evapotranspiration	ESCO	Soil evaporation compensation factor (unitless)	0.01-1.00	0.98
	EPCO	Plant uptake compensation factor (unitless)	0.00-1.00	0.00
Channel	CH_N2	Manning's "n" for the main channel (m$^{-1/3}$ s)	0.01-0.30	0.30
	CH_K2	Effective hydraulic conductivity of channel (mm h^{-1})	0-500	100
	TRNSRCH	Fraction of transmission losses from main channel that enter deep aquifer (unitless)	0.00-1.00	0.40
Time of concentration	CH_N1	Manning's "n" for tributary channels (m$^{-1/3}$ s)	0.014-0.400	0.400

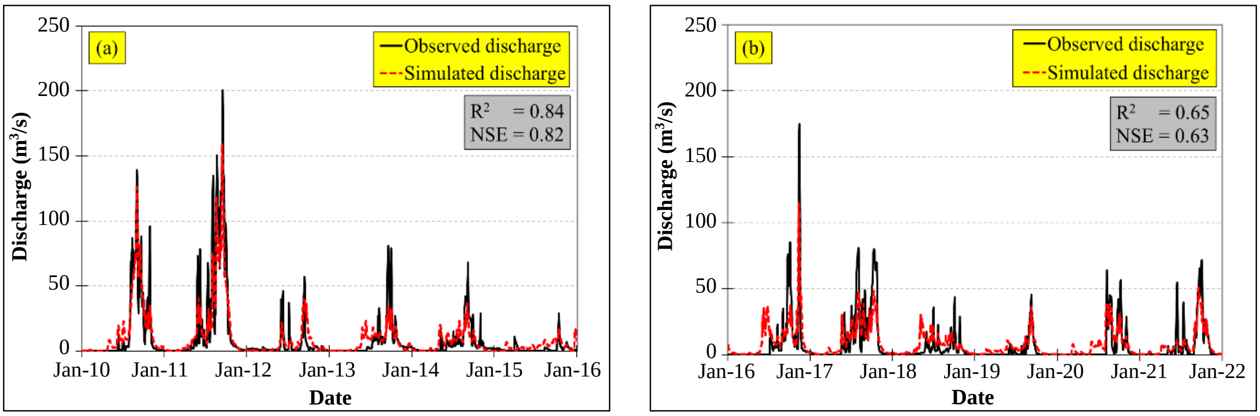

Figure 3 Observed and simulated daily discharge during (a) calibration (2010-2015) and (b) validation (2016-2021), at gauging station E.68A

3.2 MODFLOW model calibration and validation

The developed MODFLOW model was calibrated and validated under transient state conditions using groundwater level data from 16 groundwater wells observed during the field measurements in May 2021, as well as the data from two groundwater monitoring wells constructed and maintained by the Department of Groundwater Resources, Thailand, covering the period 2013-2021. For model calibration and validation, the computed groundwater heads were compared with the observed heads at 18 monitoring wells at the time steps corresponding to the simulation time of 7,080 days and 4,800 days, respectively (note: the time step was set in days and counted from the start of the SWAT simulation, i.e., January 1, 2002). The r values were 0.97 for calibration and 0.98 for validation, while the NRMSE values were 7.67% and 6.79%, respectively. These statistical metrics indicated excellent performance of the MODFLOW model simulation. Additionally, the analysis of the scatter plot revealed that the calculated heads closely matched the observed heads at the monitoring sites during both the calibration and validation periods. The data points followed a 1:1 line, further confirming the model's accuracy (see Figures 4a and 4b).

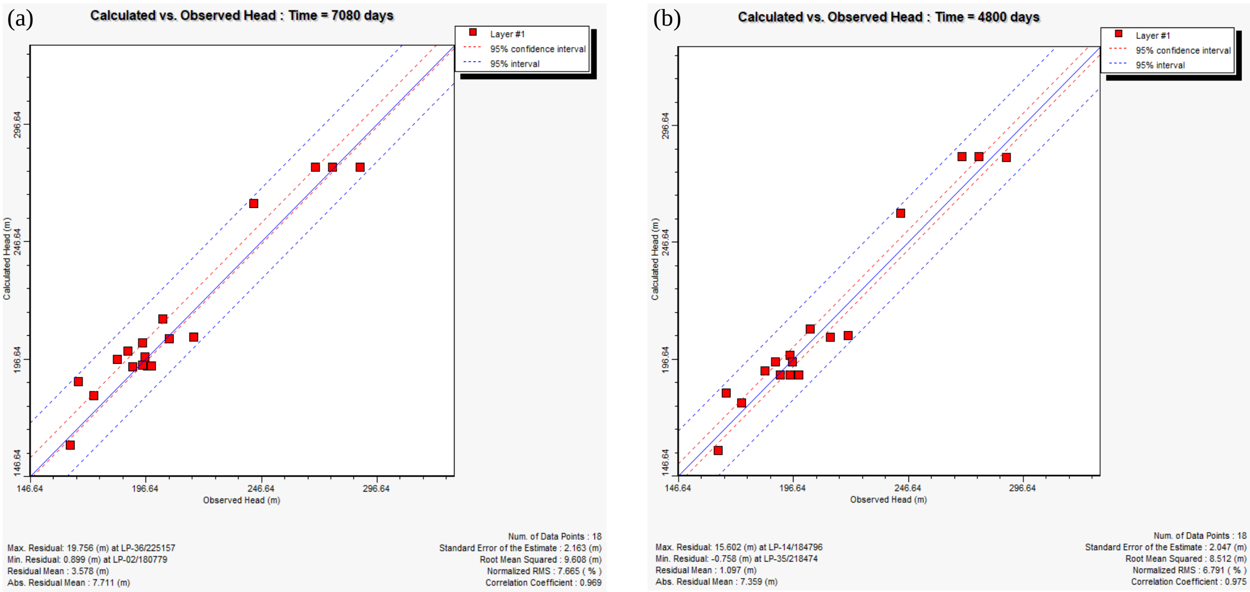

Figure 4 Comparison of calculated and observed heads during the calibration and validation periods at time steps (a) 7,080 days and (b) 4,800 days, respectively

3.3 Prediction of future climate variability

The comparison of minimum and maximum temperatures from the three selected climate models indicated the increasing trend in future temperature in comparison to the current mean minimum and maximum temperatures of 19.28°C and 32.35°C, respectively. Under RCP 4.5, the projected minimum and maximum temperatures were expected to be 21.07°C and 34.54°C, respectively, and by about 20.36°C and 35.30°C, respectively, under RCP 8.5 (see Figures 5a and 5b for more details).

The daily rainfall amounts observed at seven weather stations, i.e., Mueang (360001), Na Klang (360002), Suwannakhuha (360003), Non Sang (360006), Na Wang (360007) Districts, Nong Bua Lam Phu Province, and Na Duang (353009) and Erawan (353024) Districts, Loei Province, were also compared to the corresponding values derived from three selected RCMs during the period 2002-2021. The results showed a strong correlation between observed and simulated rainfall data according to the lowest RMSE values described in section 2.6. However, in some months, the simulated rainfall values were higher than the observed ones, while the projected rainfall trends under RCPs 4.5 and 8.5 were markedly similar. For future rainfall variation, the mean annual rainfall was analyzed using the Thiessen method for the period 2022-2099 under RCPs 4.5 and 8.5. The results indicated a decreasing trend in rainfall under the CNRM-CM5, CanESM2, and GFDL-ESM2M climate models compared to the current mean annual rainfall of 1,257.00 mm/year. The projected mean annual rainfall under RCPs 4.5 and 8.5 were 1,246.37 mm/year and 1,250.01 mm/year, respectively. The maximum projected rainfall was 1,598.32 mm under RCP 8.5, which remained lower than the RCP 4.5 maximum projected rainfall of 1,851.95 mm (see Figure 5c for a detailed description).

3.4 Climate change impacts on future surface water and groundwater quantity in the Lam Phaniang River Basin

Through the linkage between SWAT and MODFLOW models, the surface water and groundwater quantity under climate change projections for RCPs 4.5 and 8.5 were estimated for the period 2022-2099 and compared to the current water quantity (2002-2021). Under climate change projections, the surface water exhibited a declining trend, whereas the annual groundwater trend increased compared to the baseline period. The finding related to the increasing groundwater trend is in line with the information revealed by [40], which stated that Nong Bua Lam Phu Province where the Lam Phaniang River Basin is mainly located, is characterized by a high groundwater potential. Quantitatively, the current average surface water volume was 2,175,988,582 m^3, while the groundwater quantity was 424,418,714 m^3. Under the RCP 4.5, the average annual surface water quantity was projected to be 1,805,604,927 m^3, with a groundwater quantity of 613,730,888 m^3. When considering the RCP 8.5, the projected average annual surface water quantity was 1,811,450,740 m^3, while the groundwater quantity was 600,034,711 m^3. The results indicated that the surface water quantity under RCP 8.5 was higher than under RCP 4.5, while the groundwater quantity under RCP 8.5 was lower than under RCP 4.5. Clearly, the future projections implied that climate change-driven average decrease in rainfall, which corresponded to the average decrease in surface water availability. Meanwhile, a high infiltration rate, which allowed more surface water to percolate through the ground quickly, also contributed to a decrease in surface runoff and highlighted the potential to augment groundwater storage.

With respect to the RCP 4.5, the surface water quantity peaked at 3,815,807,731 m^3 in 2099, while the lowest value of 948,796,064 m^3 occurred in 2061. The groundwater quantity reached its maximum of 943,641,600 m^3 in 2050 and its minimum of 312,809,472 m^3 in 2061. Under the RCP 8.5, the highest surface water quantity was 2,966,166,362 m^3 in 2080, whereas the lowest of 888,163,917 m^3, was recorded in 2073. The groundwater quantity varied between a maximum of 918,165,504 m^3 in 2050 and a minimum of 325,453,824 m^3 in 2037 (see Figure 6 for further details).

When analysing trends over eight consecutive 10-year periods (2022-2031, 2032-2041, 2042-2051, 2052-2061, 2062-2071, 2072-2081, 2082-2091, and 2092-2099), climate change influences were evident in surface water fluctuations. Under RCP 4.5, the surface water quantity notably increased by 74.72% during 2052-2061 compared to the baseline period, while the groundwater availability was projected to rise, with a peak increase of 53.57% during 2032-2041. In contrast, under RCP 8.5, surface water showed an overall decline, with a significant reduction of 23.36% during 2042-2051 in relation to the baseline period. However, the groundwater quantity demonstrated an upward trend, reaching a 32.30% increase during 2032-2041.

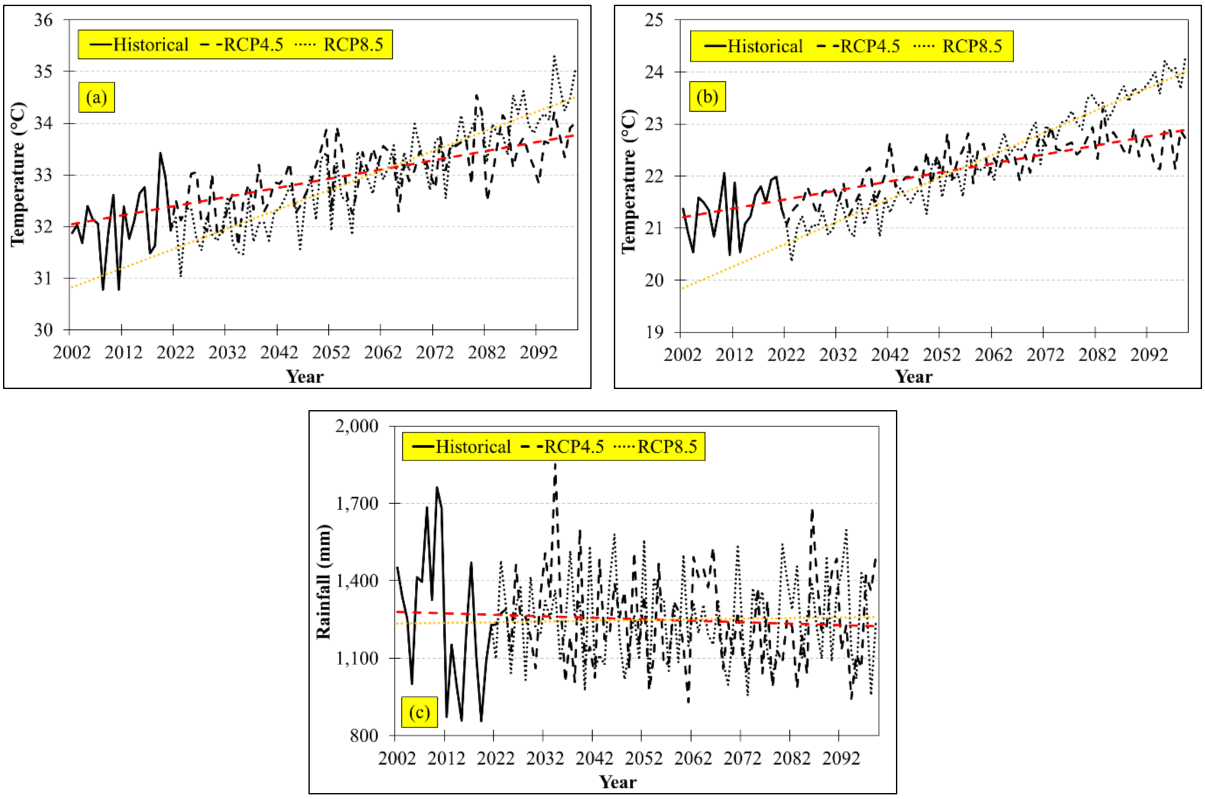

Figure 5 Mean annual maximum and minimum temperatures (a, b), and mean annual rainfall (c) under RCPs 4.5 and 8.5

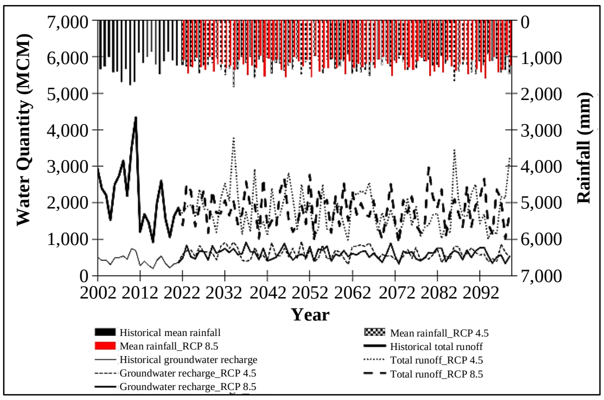

Figure 6 The comparison of total surface water, groundwater recharge and mean annual rainfall under RCPs 4.5 and 8.5 climate scenarios.

3.5 Assessment of surface water and groundwater quantity

The water budget determination for average surface water and groundwater was evaluated using the SWAT and MODFLOW models under RCPs 4.5 and 8.5, in conjunction with the mean rainfall data. In this case, the analysis was divided into four periods: present or baseline (2002-2021), near-future (2022-2051), mid-future (2052-2071), and far-future (2072-2099). Compared to the baseline rainfall of 1,302 mm, rainfall under RCP 4.5 was projected to decline to 1,254 mm in the near-future, 1,228 mm in the mid-future, and 1,204 mm in the far-future, with the greatest reduction occurring in the far-future period. The average surface water quantity was expected to decrease from the baseline amount of 2,176 MCM to 1,925 MCM, 1,763 MCM, and 1,708 MCM in the near-future, mid-future, and far-future periods, respectively. In contrast, the average groundwater quantity was projected to increase from the baseline value of 424 MCM to 643 MCM, 624 MCM, and 575 MCM in the corresponding future periods. Under the RCP 8.5 scenario, the mean rainfall was also expected to be lower than the baseline period, with values of 1,221 mm, 1,232 mm, and 1,244 mm for the near-future, mid-future, and far-future periods, respectively. The average surface water quantity was projected to decline to 1,817 MCM, 1,844 MCM, and 1,783 MCM, respectively. Meanwhile, the average groundwater quantity was anticipated to be higher than the baseline period, reaching 620 MCM, 612 MCM, and 570 MCM for the near-future, mid-future, and far-future periods, respectively (see Table 8 for more details).

In view of the assessment of surface water and groundwater potential in the Lam Phaniang River Basin using the Water Scarcity Index (WSI), it was based on the relationship between the water budget and demand for agricultural and household uses. The water demand was estimated from crop water requirements using the SWAT model in combination with the household water needs, which have been increasing in recent years (see Figure 7). At present, there was no water scarcity in the Lam Phaniang River Basin, as the Surface Water Scarcity Index (WSI_S) ranged from -0.03 to -0.75, and the Surface Water and Groundwater Scarcity Index (WSI_{SG}) ranged from -0.20 to -0.78. According to Table 6, WSI values below 0.1 indicated no water scarcity, aligning with drought risk data from [18], which categorized drought severity as low to moderate. The future projections under RCPs 4.5 and 8.5 indicated increasing drought risks. In detail, under RCP 4.5, the WSI_S values of 0.15, 0.15, and 0.10 were projected for 2053, 2061, and 2083, respectively, with water scarcity estimated at 148.69 MCM, 141.89 MCM, and 102.21 MCM. Under RCP 8.5, the WSI_S values of 0.10, 0.12, and 0.17 were expected in 2053, 2069, and 2084, respectively, corresponding to water shortages of 97.22 MCM, 124.48 MCM, and 182.64 MCM. Additionally, in 2073, the WSI_S was projected to reach the value of 0.29, indicating moderate water stress, with the shortage of 261.21 MCM. However, when considering the WSI_{SG} values under both RCPs 4.5 and 8.5, there was no projected water scarcity, as the values remained below 0.1 (refer to Table 6). The WSI_{SG} ranged from -0.14 to -0.77 under RCP 4.5 and from -0.05 to -0.78 under RCP 8.5, confirming that combining surface and groundwater resources could help mitigate scarcity risks. However, if a severe drought occurs in the future, the small and medium-sized water storage systems in the Lam Phaniang River Basin with the total capacity of 31.4 MCM [40], could help alleviate shortages. Additionally, the groundwater resources could also further be developed to meet increasing water demands.

Table 8 The comparison of mean annual rainfall, surface water, and groundwater quantity for the present and future periods under RCPs 4.5 and 8.5 scenarios

Period	RCP 4.5			RCP 8.5		
	Mean annual rainfall (mm)	Mean annual surface water (MCM)	Mean annual groundwater (MCM)	Mean annual rainfall (mm)	Mean annual surface water (MCM)	Mean annual groundwater (MCM)
2002-2021 (Present)	1,302	2,176	424	1,302	2,176	424
2022-2051 (Near-future)	1,254	1,925	643	1,221	1,817	620
2052-2071 (Mid-future)	1,228	1,763	624	1,232	1,844	612
2072-2099 (Far-future)	1,204	1,708	575	1,244	1,783	570

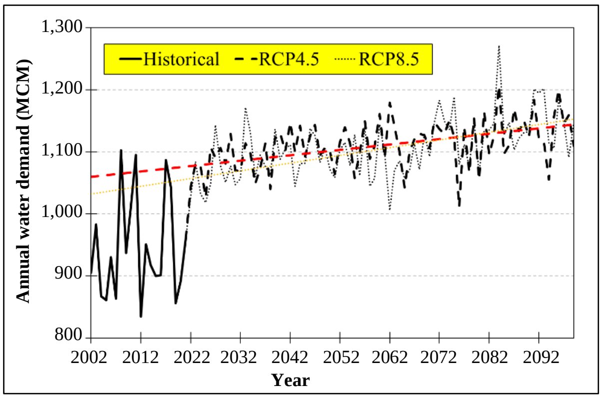

Figure 7 The annual water demand in the Lam Phaniang River Basin

4. Conclusions

The study of rainfall, surface water, and groundwater quantity under future climate change in the Lam Phaniang River Basin, compared to baseline conditions, indicated a declining trend in rainfall under both RCPs 4.5 and 8.5 across the near-future, mid-future, and far-future periods. The average surface water quantity under both RCP scenarios was projected to decrease, with RCP 8.5 showing a higher surface water quantity than RCP 4.5. In contrast, the average groundwater quantity under both RCPs 4.5 and 8.5 was expected to increase, with the RCP 4.5 scenario to have a higher groundwater quantity than RCP 8.5.

For the projected climate under RCPs 4.5 and 8.5, the evaluation of surface water and groundwater potential in the Lam Phaniang River Basin indicated a decreasing trend in surface water quantity compared to the baseline period. When considering 10-year periods, under RCP 4.5, the most significant decrease in average surface water quantity was expected to occur during 2052-2061, with the reduction of up to 74.72%. In contrast, the average groundwater quantity was projected to increase compared to the baseline, with the most significant rise of 53.57% occurring during 2022-2031. Under RCP 8.5, the greatest decline in average surface water quantity was expected during 2042-2051, with the reduction of up to 23.36%. Meanwhile, the average groundwater quantity was projected to increase compared to the baseline, reaching its highest increase of 32.30% during 2032-2041.

The evaluation of surface water and groundwater potential was also conducted to assess the water scarcity in the Lam Phaniang River Basin using the Water Scarcity Index under both baseline and future climate change conditions. No water scarcity was identified during the baseline period. However, the water scarcity was projected to occur under future climate change conditions, specifically in 2053, 2061, and 2083 under RCP 4.5, and in 2053, 2069, 2073, and 2084 under RCP 8.5. When considering both surface water and groundwater budgets for water scarcity evaluation, no significant water scarcity was expected under either baseline or future climate conditions. The results also revealed that the surface water scarcity could emerge as a concern in the Lam Phaniang River Basin. However, the groundwater development, which is expected to enhance the efficiency and sustainability of water management in the Lam Phaniang River Basin, can also serve as an alternative water resource to mitigate water scarcity, particularly where surface water storage development is limited.

In summary, the obtained findings from this study highlighted the adverse effects of accelerating climate change on interconnected surface water-groundwater flow system, which can likely exacerbate water security and scarcity concerns in the Lam Phaniang River Basin that is already under water stress. This will lead to key suggested actions and practical recommendations to integrate climate change adaptation and mitigation in water resources management, by involving all stakeholders at political, institutional, technical, administrative, and other relevant levels. Nonetheless, it is understandable that the nature of water resources management is diverse and specific, and there is no one size fits all solutions for future mitigation, adaptation, and resilience under climate change. It is therefore necessary to determine which recommendations are applicable to this study context, e.g., 1) aligning climate change policy with other related policies, 2) promoting water-efficient crops, community-based water planning, and transboundary water cooperation, 3) assessing the impacts of nature-based adaptation and mitigation interventions like recharging groundwater via wetlands, sustainable land management etc., and 4) implementing Managed Aquifer Recharge (MAR) and conjunctive use of surface and groundwater.

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