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Assessment of Agricultural Water Sufficiency under Climate and Land Use Changes in the Lam Takong River Basin

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Abstract: To narrow the gap of agricultural water insufficiency in the Lam Takong River Basin, Thailand, we conducted an assessment of water availability and agricultural water demand under climate and land use changes. The water availability was estimated by SWAT, which was calibrated and validated during 2008–2012 and 2013–2018 against the observed daily discharge at the M.164 station. Measured and simulated discharges showed good agreement during calibration and validation, as indicated by values of 0.75 and 0.69 for R^2 and 0.74 and 0.63 for Nash–Sutcliffe Efficiency, respectively. The results of GCMs (IPSL-CM5-MR, NorESM1-M, and CanESM2) under RCPs 4.5 and 8.5 were calculated to investigate changes in rainfall and temperature during 2020–2099. The warming tendencies of future maximum and minimum temperatures were projected as 0.018 and 0.022 °C/year and 0.038 and 0.045 °C/year under RCPs 4.5 and 8.5, respectively. The future rainfall was found to increase by 0.34 and 1.06 mm/year under RCPs 4.5 and 8.5, respectively. As compared to the 2017 baseline, the future planted areas of rice, maize, and cassava were projected to decrease during 2020–2099, while the sugarcane plantation area was expected to increase until 2079 and then decline. The top three greatest increases in future land use area were identified as residential and built-up land (in 2099), water bodies (in 2099), and other agricultural land (in 2059), while the three largest decrease rates were paddy fields (in 2099), forest land (in 2099), and orchards (during 2059–2079). Under the increased reservoir storage and future climate and land use changes, the maximum and minimum increases in annual discharge were 1.4 (RCP 8.5) and 0.1 million m^3 (RCP 4.5) during 2060–2079. The sugarcane water demand calculated by CROPWAT was solely projected to increase from baseline to 2099 under RCP 4.5, while the increase for sugarcane and cassava was found for RCP 8.5. The future unmet water demand was found to increase under RCPs 4.5 and 8.5, and the highest deficits would take place in June and March during 2020–2039 and 2040–2099, respectively. In this context, it is remarkable that the obtained results are able to capture the continued and growing imbalance between water supply and agricultural demand exacerbated by future climatic and anthropogenic land use changes. This research contributes new insight for compiling a comprehensive set of actions to effectively build resilience and ensure future water sufficiency in the Lam Takong River Basin.

Keywords: agricultural water sufficiency; unmet water demand; agricultural water demand; General Circulation Model; climate change; land use change; SWAT model; CROPWAT model

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1. Introduction

It is of paramount importance to emphasize that water is a vital natural resource and is an indispensable component for the maintenance of livelihood on Earth. There are various primary sectors of water consumption, i.e., domestic, agriculture, industry, etc. However, the combination between a deficiency in rainfall and increased human water demand is the major cause of any drought, which can affect most seasonally dry areas recurrently and severely. This corresponds to the findings presented in the IPCC

6th Assessment Report (AR6); the increasing frequency of rainfall deficits in South East Asia was projected based on the increasing frequency of extreme weather events such as droughts triggered by El Nino and anthropogenic effects of climate change [1]. Therefore, addressing future climate shifts in both rainfall patterns and increases in temperature is challenging especially for climate change and biodiversity hotspots since they are two major components of ongoing climate change [2,3]. As with most other parts of Thailand, the northeastern part of Thailand (henceforth referred to as the Northeast) is being affected by droughts almost every year [4–6]. Drought leads to a crop water shortage, wilt, desiccation, growth retardation, poor quality of crop yield, etc., and conditions could worsen if a more extensive dry spell continues. The expansion of agricultural areas for both irrigated and non-irrigated fields is also the cause of water shortage and drought, which induces a higher water demand. The expansion clearly resulted in the forest cover loss in the Northeast, as indicated by the observation of the Office of the National Economic and Social Development Council [7], which is a key contributor to human-caused climate change. Consequently, the projected changes in temperature and rainfall are likely to affect the crop productivity and crop water demand. This reflects the fact that afforestation is considered to be a readily available mitigation option to potentially limit climate change to the lowest possible levels, as stated by Doelman et al., 2020 [8]. The drought effects on domestic and agriculture are becoming more severe and persistent in some provinces in the Lower Northeast, i.e., Buriram, Surin, and Sisaket, due to a lack of large reservoir storage sites and low rainfall [9]. Likewise, some parts of the Lam Takong River Basin within the boundary of Nakhon Ratchasima Province have also suffered from drought every year due to the insufficient storage of the Lam Takong Reservoir, especially during the rainy season of 2019, which has 30% less rainfall compared to the average rainfall of the same period between 1997 and 2019. As a result, the inflow to the Lam Takong Reservoir during the rainy season of 2019 was found to be the lowest; the storage to be managed was about 18.9 million m^3, decreasing from its average value of 30–40 million m^3 [10]. Together with the increase in population, the pressure on land utilization and water demand is on the rise, leading to problems related to land use change and water shortage during the dry season [11]. In addition, the change in climate, which affects the spatial and temporal changes in the water budget, is also likely to result in crop yield and production instability [12].

Several studies were undertaken corresponding to the previously mentioned concerns. Al-Bakri et al., 2013 [13], investigated the impact of climate change and land use change on water resources and food security in Jordan. The crop production using crop simulation process-oriented and statistical models and water resources under anticipated climate change and population growth was considered, in which the changes in land use from cultivated land to urbanization were detected using remote sensing data. The results revealed that the decrease in irrigated areas would lead to less food production and food security, while the agricultural water demand is projected to be increased as a result of increased air temperature and reduced rainfall by the years 2030 and 2050. Koch et al. (2015) [14] analyzed the changes in land use patterns derived by the open-source land system model MAgPIE, agricultural production, and climate, and their effects on water demand and availability in the São Francisco River Basin (Brazil) using the mesoscale ecohydrological Soil and Water Integrated Model (SWIM), in which the global driver of population growth, economic development, and trade liberalization were taken into consideration. It was found that under the A2 climate scenario, cropland area in the São Francisco River Basin almost doubles until 2035 compared to 2005 at the expense of natural vegetation, whereas under scenario B1, with large nature conservation areas, the size of the cropland area does not change. In addition, under both scenarios, the crop mix changes, in which irrigated sugar cane increases mainly because of increased demand and favorable conditions. Lastly, based on a wetter future climate with wetter rainy seasons and drier dry seasons during 2021–2050, the water availability for irrigated agriculture is high, while hydropower generation declines by 3.2% and 1.7% for the A2 and B1 climate scenarios, respectively, as compared to the reference (1984–2003). Wiberg et al. (2017) [15] assessed the impacts of

changes in socioeconomic and climatic conditions on water security through the development of a hydro-economic classification system that aggregates indicators of hydrological challenges and adaptation capacities. Based on the combination of the impacts of changes in climate under two Representative Concentration Pathways (RCPs 4.5 and 6.0) and land use, the estimated increase in irrigation water use in the Asia and Pacific region becomes 14.3% to 19.9% in 2050 and 16.3% to 30.1% in 2080 compared to the base year, 2010. As a result, the total crop production would increase by 30–36% in 2050 and by 46–50% in 2080 compared to 2010. Furthermore, Song et al., 2018 [16], also estimated the future agricultural water demand in 2030 on Jeju Island under changes in land use extracted from satellite images at 5-year intervals and future climate (RCP 4.5). The trend analysis method during the interval from 1980 to 2014 was employed to characterize the variation in land use in 2030. By multiplying the target area of the water supply excluding the area not in use in the winter season by the basic unit of water demand, the monthly maximum agricultural water demand on Jeju Island was observed in August of 2030 with a subtropical climate, while the total agricultural water demand in 2030 was estimated to be 1,848,010 m^3/day. The above findings are coherent and consistent with the results of other studies, such as those by Knox et al., 2013 [17], Bisselink et al., 2018 [18], Afzal and Ragab, 2019 [19], Afzal et al., 2021 [20], etc., which can be useful for worthwhile relevant problems for further investigation in the case of the Lam Takong River Basin. Therefore, the main objective of this study was to assess the agricultural water sufficiency based on changes in climate and land use in the Lam Takong River Basin. In this manner, the framework used in this study lies in integrating the new insights from multiple variations and interaction analyses that were not addressed in earlier studies in the Lam Takong River Basin, thus contributing to the novelty of this work. The effects of future climatic and anthropogenic drivers of change were incorporated to further systematize and consolidate findings concerning the growing imbalance between water supply and agricultural demand at the river basin level, where more than 880,000 people reside [21] and rapid urbanization and intensive farming are more prevalent [22]. Eventually, the obtained results from this study will be beneficial for the provision of useful insights and guidelines for effective water allocation, which will lead to the sustainable management of water resources in the Lam Takong River Basin.

2. Materials and Methods

2.1. Study Area

The Lam Takong River Basin, which originates from the Dong Phaya Yen Range and divides the river basins of Mun, Pasak, and Nakhon Nayok, is a tributary located in the west of the Mun River Basin. The drainage area is about 3295 km^2 (5% of the entire Mun River Basin), covering the areas of Mueang District of Nakhon Nayok Province and Nakhon Ratchasima Province for the districts of Kham Thale So, Chaloem Phra Kiat, Pak Thong Chai, Pak Chong, Mueang, Sikhio, and Sung Noen. The Lam Takong River is the main river of the Lam Takong River Basin and it flows approximately 220 km from its source to its confluence with the Mun River at Tha Chang Sub-district in Chaloem Phra Kiat District, Nakhon Ratchasima Province. The Lam Takong Dam, which is the largest earthen dam in the Lam Takong River Basin with a storage capacity of 314.5 million m^3, is the main water source for 24,671.2 hectares of irrigated area, domestic consumption in Nakhon Ratchasima Province, and hydropower generation operated by the Electricity Generating Authority of Thailand (Provincial Office of Natural Resources and Environment Nakhon Ratchasima, 2020 [11]) (see Figure 1). The topography of the Lam Takong River Basin is steep at the upstream, especially the upper part of the Lam Takong Dam, while the terrain downstream is flat. The climate of the Lam Takong River Basin is under the influence of the southwest and northeast monsoons. There are three kinds of seasons that exist in the area, i.e., dry (mid-February to mid-May), rainy (mid-May to mid-October), and winter seasons (mid-October to next February). According to the information from the Provincial Office of Natural Resources and Environment Nakhon Ratchasima (2020) [11], the annual average rainfall is about 1200.4 mm, of which 976.7 mm and 223.7 mm are recorded in the rainy and

dry seasons, respectively. The annual average runoff is estimated to be 467.5 million m^3, while the average runoff can reach 359.6 million m^3 and 107.9 million m^3 in the rainy and dry seasons, respectively. Based on the meteorological records of the historical years, the annual average temperature is about 25.4 °C. Lastly, based on the Soil Service Repository of the Land Development Department (2017) [23], there are five main land use types, namely, agriculture (59.7%), forest (17.6%), urban and built-up (15.3%), water body (2.1%), and miscellaneous (5.3%).

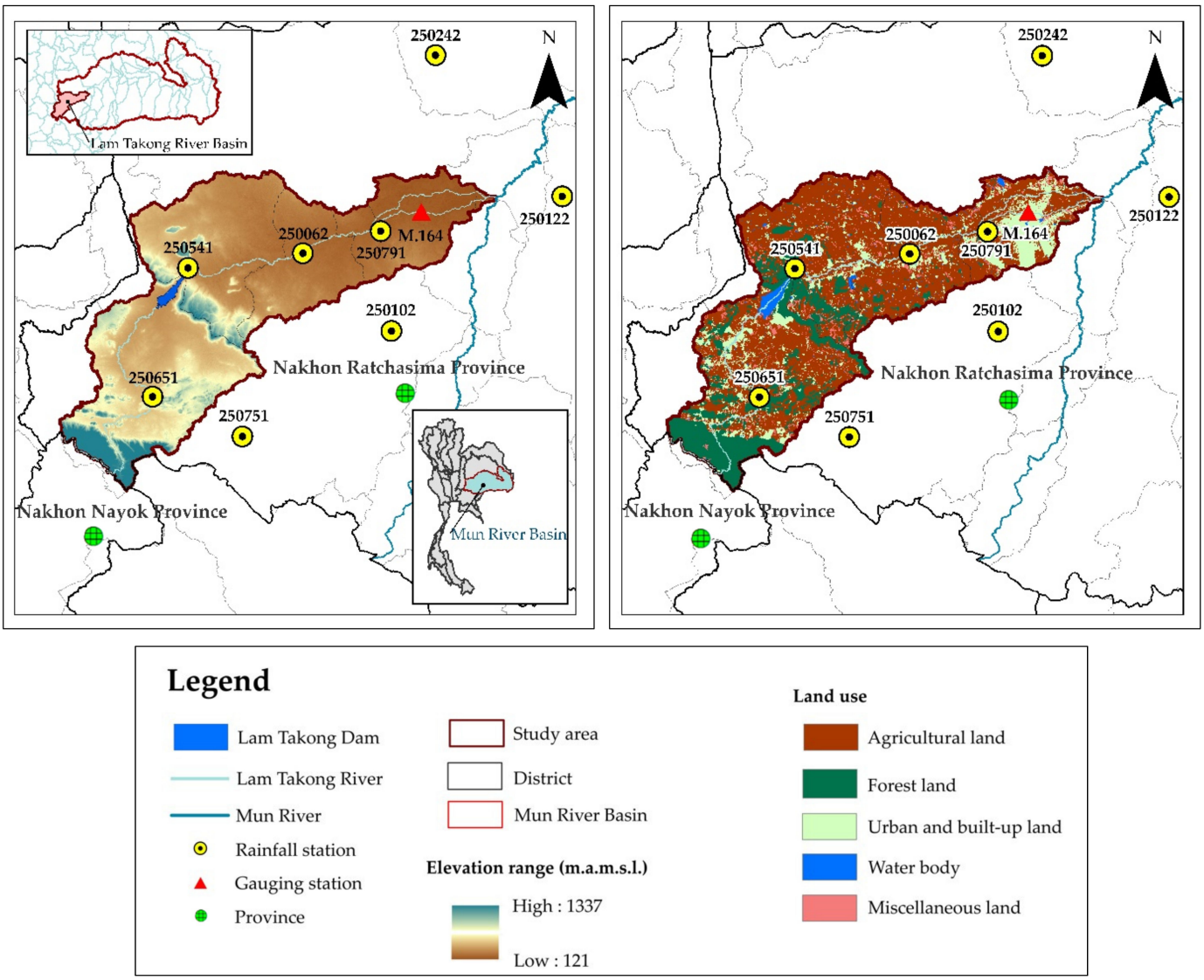

Figure 1. The Lam Takong River Basin, including its topography and land use.

2.2. Data Collection

The basic data required for this study were obtained from various sources. In particular, the daily rainfall data observed at eight rain gauge stations were obtained from the Thai Meteorological Department, and the daily discharge observed at the M.164 gauging station was obtained from the Royal Irrigation Department, with time series in text file format over the period 1993–2018 (see Figure 1). The 2017 digital dataset of land use and soil group with a spatial resolution of 30 m was acquired from the Land Development Department (LDD). The 30 m resolution Digital Elevation Model (DEM) from the Shuttle Radar Topographic Mission (SRTM) was downloaded from the Earth Explorer Web Page of the United States Geological Surveys (USGS) [24]. The Crop Water Requirements (CWRs) of major cash crops, namely, rice, maize, sugarcane, and cassava, were calculated based on monthly climatic

parameters in text file format acquired from the Nakhon Ratchasima Meteorological Station, e.g., time series of maximum and minimum temperature, humidity, wind speed, sunshine, and rainfall. In view of crop-related information, the planting dates, cropping patterns, and yields were gathered from the Royal Irrigation Department (2017) [25]. The other inputs for CWR calculations for each crop, such as length of growth period, crop coefficients of each growth stage, total available water, maximum infiltration rate, maximum rooting depth, initial soil moisture depletion, and initial available soil moisture, were obtained from the guidelines presented in the FAO 56 report by Allen et al. (1998) [26]. It is worth mentioning that the datasets used in this study were reliable as they have been updated and verified by relevant agencies and officials, and the record was generally complete over the Lam Takong River Basin. However, some rainfall data at stations 250062 Sung Noen (year 1999), 250102 Pak Thong Chai (years 2010 and 2013), and 250122 Chakkarat (years 2009–2011) were missing during the study period due to various reasons and were estimated by using the SPSS program.

2.3. Calculation of Crop Water Requirement (CWR) Using CROPWAT Model

The calculation of crop water requirement was carried out by the FAO CROPWAT computer program under the interactions between soil, climate, and crop data. The estimated requirements were then used for the provision of water supply taken from the water resource development projects in the Lam Takong River Basin. Together with the development plan of the Lam Takong River Basin, a comprehensive approach for appropriate and sufficient water allocation, appropriate planting dates, and suitable crop rotation for various crops can be achieved. In this study, the total amount of monthly crop water requirement for selected cash crops was then multiplied by the cropping area for the determination of water demand, which was further compared with the water supply for evaluating the sufficiency of water for agriculture (see Equation (1)).

$$\text{Total water demand} = \sum_{i=1}^{n} A_i \times CWR_i \quad (1)$$

where CWR_i refers to the crop water requirement of crop i, and A_i stands for the cropping area of crop i.

2.4. Assessment of Streamflow Using SWAT Hydrological Model

The simulation of water resources management scenarios in the Lam Takong River Basin was performed using the Soil and Water Assessment Tool (SWAT) model. The obtained water budget was then compared with the crop water requirement for the evaluation of water scarcity and water sufficiency in the Lam Takong River Basin. The various steps of running SWAT model are as follows:

- The automatic watershed delineation was carried out by using the 30 m DEM, which was used to define the outlet point of the river basin. The 18 sub-basins were then delineated, in which the location of the Lam Takong Reservoir was also incorporated during the delineation process.
- The sub-basins were subdivided into various homogenous units called "Hydrological Response Units (HRUs)" based on a threshold value of 10% each for land use, soil, and slopes, and a total of 168 HRUs were created.
- Daily climate datasets, i.e., rainfall and maximum and minimum temperature, were fed into the SWAT model as weather input files, while the solar radiation, humidity, and wind speed were calculated in SWAT using the weather generator tool.
- Calibration and validation of the SWAT at daily time steps was undertaken, in which a systematic modification of the most sensitive model parameters was made to match simulated outputs with observed historical discharge data at the M.164 gauging station during 2008–2012 and 2013–2018 for calibration and validation, respectively (note: a long time series of observations was unavailable because the installation of gauge and monitoring process started later in April 2007). In this study, the corre-

lation coefficient (R^2) and the Nash–Sutcliffe Efficiency coefficient (NSE) were used to evaluate the goodness-of-fit plots. As suggested by Santhi et al. (2001) [27] and Moriasi et al. (2007) [28], the SWAT model performance is judged as satisfactory and reliable when R^2 and NSE values are greater than 0.6 and 0.5, respectively, which imply that the model simulation results are reliable and could be used for further simulations.

2.5. Modeling the Impacts of Future Scenarios on Water Availability

The simulations of future scenarios, i.e., climate and land use changes, which might affect streamflow in the Lam Takong River Basin, were performed to examine the scarcity/sufficiency of available water supply in relation to future agricultural water demand and a future action plan for water resources management and development. Future scenarios of climate changes under RCPs 4.5 and 8.5 for 2020–2099 were predicted using three bias-corrected General Circulation Models (GCMs) from the archive of Coupled Model Intercomparison Project Phase 5 (CMIP5), namely, IPSL-CM5-MR, NorESM1-M, and CanESM2. It should be noted that the data from the climate models were bias-corrected via the Linear Scaling method, as suggested by Crochemore et al. [29], using the Climate Model Data for Hydrologic Modeling (CMhyd) tool developed by Rathjens et al. [30] in order to remove the systematic biases in the observed and historical downscaled rainfall and maximum and minimum temperature datasets from 1993 to 2018. It is also important to emphasize that for impact studies of climate change, the spatial resolution of GCM outputs is known to be too coarse to properly represent the local climate variations. Hence, the coarse GCM outputs would then need to be downscaled to a finer scale through statistical Regional Climate Models (RCMs), which is necessary, especially in the areas with complex terrain conditions, as highlighted by Tolika et al., 2016 [31], Stefanidis, 2021 [32], etc. To analyze future land use changes, the Cellular Automata–Markov chain model (CA-Markov) in the TerrSet software suite Eastman (2020) [33]—which relies on Markov matrices to calculate the land use transition matrix between two periods—the Multi-Criteria Evaluation (MCE) module for producing suitability maps for each category, and a CA process for spatially allocating the transition of a cell by defining the neighborhood with the standard 5×5 contiguity type were applied. Based on the transition area matrix and suitability maps from 2000 to 2009, the land use of 2017 was simulated. In addition, the classification accuracy was also checked by using the Overall Accuracy (OA) and Kappa Hat (KH) coefficient to measure the agreement between the simulated land use mapping of 2017 predicted from historical land use of years 2000 and 2009 with the 2017 land use map obtained from the Land Development Department. Thereafter, the trends of land use changes over the periods 2000–2017, 2020–2039, 2040–2059, 2060–2079, and 2080–2099 were analyzed. To investigate how the climate and land use changes will affect both water supply and demand, the downscaled climate data from GCMs with two RCPs each (RCPs 4.5 and 8.5) and scenario-based land use projection were then used in both SWAT and CROPWAT models for future simulations.

3. Results and Discussion

3.1. Prediction of Future Climate

The projected future climate change in the Lam Takong River Basin was assessed by considering the differences in mean annual rainfall and mean annual maximum and minimum temperature from the reference period of 1993 through 2018. To determine the tendency of future changes, the aforementioned climate data obtained from the ensemble average of three bias-corrected and downscaled GCMs (IPSL-CM5-MR, NorESM1-M, and CanESM2) under CMIP5-RCP 4.5 and 8.5 scenarios, at a 25 km resolution, were analyzed since uncertainty would arise from an individual climate model. Thereafter, the statistically downscaled climate scenarios were then simulated with the SWAT model to generate the future daily discharge and CROPWAT model to estimate the future agricultural water demand. The description and climate prediction results of future climate change scenarios can be summarized as follows.

3.1.1. Change in Potential Future Temperature

There is no doubt that understanding how both future maximum and minimum temperatures might change is a vital element towards for determining possible changes in the water supply and demand. As shown in Figure 2a,b, from the base period until 2099 over the entire Lam Takong River Basin, there is a progressive rise in both future maximum and minimum temperatures through the given time interval. Considering a 95% significance level, the statistically significant increasing trends in both future minimum and maximum temperatures under RCPs 4.5 and 8.5 for an 80-year time span (2020–2099) over the study area were detected, and the *p*-value was found to be less than 0.05. The future maximum temperature was found to be increasing at the rate of 0.038 °C/year under RCP 8.5, which is higher than 0.018 °C/year under RCP 4.5. The rate of the future minimum temperature was also reported to increase by 0.022 °C/year and 0.045 °C/year under RCPs 4.5 and 8.5, respectively. By 2099, above the 2019 conditions, the future minimum and maximum temperatures were noticed to rise by 1.76 °C and 1.45 °C, respectively, as per RCP 4.5, and also continue to increase by 3.59 °C and 3.02 °C, respectively, according to RCP 8.5.

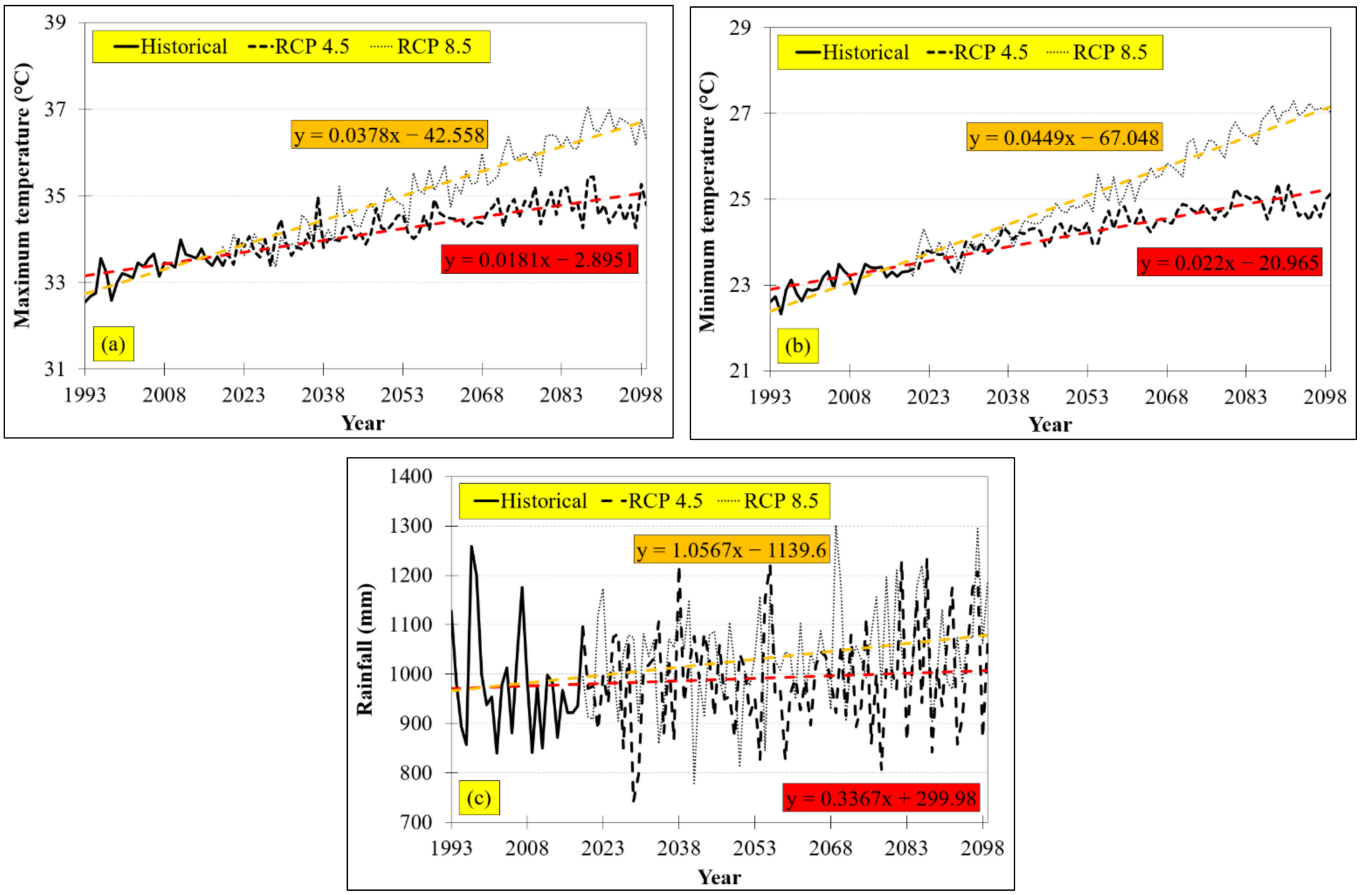

Figure 2. Projected average annual maximum and minimum temperature (**a**,**b**) and projected average annual rainfall (**c**) under RCPs 4.5 and 8.5 until the end of the century in the Lam Takong River Basin.

3.1.2. Change in Potential Future Rainfall

Before assessing the possible changes in future rainfall, the mean observed and statistically downscaled daily time series of rainfall over the Lam Takong River Basin were calculated using the Thiessen method. Based on the eight rain gauge stations in and around the catchment, a weighting factor for each station was proportionally defined in a representative Thiessen polygon for the entire river basin area. The weighted average rainfall of the Lam Takong River Basin was then estimated by multiplying each station's rainfall

amount by its assigned percentage of the area and summing the weighted averages for all rainfall stations.

As presented in Figure 2c, an insignificant trend towards future average annual rainfall change under RCP 4.5 was evident, while the trend became significant (p-value < 0.05) for RCP 8.5. This means that no trend was detected in future average annual rainfall under RCP 4.5 with the small increase of 0.34 mm/year, and the statistically significant positive increase trend was noted by 1.06 mm/year under RCP 8.5 covering an 80-year time period (2020–2099) over the Lam Takong River Basin. In 2099 compared to the present year (2019), there was a slight change observed in future annual rainfall, as it was projected to increase to 26.94 mm under RCP 4.5 and 84.54 mm under RCP 8.5. The obtained findings indicated above are in agreement with the findings of Khadka et al. (2021) [34], who stated that no significant changes in future annual rainfall were projected in Northeast Thailand.

3.2. Trends and Projections of Future Land Use

To provide insight into the trends and projections of future land use, the land use data acquired from the Land Development Department were employed as a baseline for understanding historical conditions. Then, the CA-Markov model in the TerrSet software package was applied to determine how much land would be transferred from the later date to the specified future date, as presented in more detail below.

3.2.1. Land Use Pattern and Its Changes during 2000–2017

The obtained land use data of the Lam Takong River Basin in 2000, 2009, and 2017 were categorized into the following types: agriculture, forest, residential and built-up land, water body, and miscellaneous. After examining the land use changes between 2000, 2009, and 2017, with a maximum change in 2017 compared to 2000, the agricultural land indicated the same decreasing trend of 17.6%, while the same increasing trends were observed for the residential and built-up land and water body of 113.0% and 109.1%, respectively (see Table 1 for more details). There was not much change in forest area during the entire period under analysis, except a large expansion of miscellaneous land (mainly shrubland) of 633.7% was detected mostly during 2000–2009. As investigated above, the conversion of land used for agriculture into urban areas and settlement is consistent with the local trend reported by Chotchaiwong and Wijitkosum (2019) [35] and Wijitkosum and Sriburi (2008) [36] for Nakhon Ratchasima Province covering the majority of the study area.

Table 1. Change in the spatial extent of land use in the Lam Takong River Basin during 2000, 2009, and 2017.

Land Use Type	Area (km^2)			% Change		
	2000	2009	2017	2000–2009	2009–2017	2000–2017
Agriculture	2387.9	2003.7	1968.2	−16.1	−1.8	−17.6
Forest	611.0	617.5	578.7	+1.1	−6.3	−5.3
Residential and built-up land	237.2	427.3	505.1	+80.2	+18.2	+113.0
Water body	33.6	61.5	70.3	+83.2	+14.2	+109.1
Miscellaneous	25.2	184.8	172.5	+633.7	−6.6	+585.0
Total	**3294.8**	**3294.8**	**3294.8**	**-**	**-**	**-**

3.2.2. Comparison of Different Land Use Areas Predicted by the CA-Markov Model with Actual Land Use Map of 2017

To evaluate the validity of the CA-Markov model, the predicted land use map of 2017 was compared with the 2017 reference land use map obtained from the Land Development Department. Referring to Table 2, over the specified time period (2017), the areas (in square kilometers) that are expected to convert from each land use type to another are listed in the transition area matrix. In this table, the sums of each column and row represent the area of each land use type in 2017 of reference and predicted land use maps, respectively.

The extent of the residential and built-up land was found to be 530.7 km^2, while 85.9 km^2 of agriculture, 1.4 km^2 of forest, 6.9 km^2 of water body, and 15.9 km^2 of miscellaneous were expected to transform into residential and built-up land (note: the values indicated along the diagonal elements of the matrix represent the areas of the reference land use type i that were also predicted as type i). The 2017 modeling results given by the CA-Markov model clearly correspond with the findings of Chotchaiwong and Wijitkosum (2019) [35] and Wijitkosum and Sriburi (2008) [36], which indicate that the lost agricultural land was transformed into urban land. Moreover, the error matrix (or confusion matrix) that compared the classification layer with the verification reference data was also used to calculate the accuracy metrics, i.e., Overall Accuracy and Kappa Hat coefficient, for assessing the classification accuracy (note: the Overall Accuracy takes into account only diagonal elements of reference and predicted maps, while the Kappa Hat coefficient also considers the off-diagonal element as a product of the row and column of the error matrix). The results showed that the Overall Accuracy was 86.60%, while the Kappa Hat coefficient was 0.78. It can be said that a good agreement between the projected 2017 land use map generated from the CA-Markov model and the reference data is achieved, as stated by Congalton (1991) [37], who reported that an Overall Accuracy value greater than 70% is judged to be acceptable and a Kappa Hat coefficient value ranging from 0.40 to 0.85 indicates reliable agreement.

Table 2. Comparison of land use in 2017 obtained from the Land Development Department and CA-Markov model.

Simulated Land Use for 2017 Using CA-Markov Model	Existing Land Use in 2017 from the Land Development Department					
	Agriculture	**Forest**	**Residential and Built-Up Land**	**Water Body**	**Miscellaneous**	**Total**
Agriculture	1724.0	7.9	60.1	6.3	45.7	**1843.9**
Forest	44.9	566.4	6.4	0.8	20.6	**639.0**
Residential and built-up land	85.9	1.4	420.7	6.9	15.9	**530.7**
Water body	19.9	0.0	0.6	52.5	0.8	**73.8**
Miscellaneous	93.6	3.0	17.4	3.8	89.6	**207.4**
Total	**1968.2**	**578.7**	**505.1**	**70.3**	**172.5**	**3294.8**
Overall Accuracy (%)	**86.6**					
Kappa Hat Coefficient (%)	**77.8**					

3.2.3. Future Land Use Projections in the Lam Takong River Basin for the Years 2039, 2059, 2079, and 2099

Based on the land use data for two periods (2009 and 2017), the prediction of future land use patterns and changes in the Lam Takong River Basin was carried out by using the CA-Markov model for the years 2039, 2059, 2079, and 2099. The change detection process was performed to compare the quantities of variation in each land use type for each time interval. The findings revealed both increases and decreases in areas of different land use types from 2017 to 2099 (see Table 3). When only considering the major cash crop plantations, the areas of rice (paddy) farming, maize, and cassava were projected to drop from near- to far-future periods by 0.8–53.8% river basin-wide from the baseline (2017). On the contrary, the sugarcane area was expected to continue to rise until 2079 and decline in the following 20 years. Besides that, the largest increase in future land use was identified as residential and built-up land, with a maximum increase of approximately 104.0% in 2099. The second and third largest increases were water body and other agricultural land, with maximum increases of about 86.0% in 2099 and 26.5% in 2059, respectively. The land use patterns with the three largest decrease rates were paddy field, forest land, and orchard, with maximum decreases of about 53.8% in 2099, 41.4% in 2099, and 37.5% during 2059–2079, respectively.

Table 3. Land use change analysis for every twenty years from 2039 to 2099 compared to 2017.

Land Use Type	Area (km^2)					% Change between 2017 and			
	2017	2039	2059	2079	2099	2039	2059	2079	2099
Paddy field	424.4	311.8	256.4	219.6	196.0	−26.5	−39.6	−48.3	−53.8
Maize	292.7	260.9	251.7	247.6	237.4	−10.8	−14.0	−15.4	−18.9
Sugarcane	218.0	239.5	229.3	220.1	214.9	9.9	5.2	0.9	−1.4
Cassava	615.6	610.5	598.2	585.9	569.6	−0.8	−2.8	−4.8	−7.5
Horticulture	31.1	32.6	33.2	30.1	29.1	4.6	6.6	−3.3	−6.6
Perennial	80.0	92.6	96.4	92.3	88.2	15.8	20.5	15.4	10.3
Orchard	117.5	80.6	73.4	73.4	74.4	−31.4	−37.5	−37.5	−36.6
Other agricultural land	189.0	236.1	239.2	235.1	229.0	24.9	26.5	24.4	21.1
Forest land	578.7	491.6	427.1	378.0	339.1	−15.0	−26.2	−34.7	−41.4
Residential and built-up land	505.1	684.3	822.6	931.1	1030.5	35.5	62.8	84.3	104.0
Water body	70.3	90.9	108.1	122.5	130.7	29.4	53.9	74.3	86.0
Miscellaneous land	172.5	163.3	159.2	159.2	156.2	−5.3	−7.7	−7.7	−9.5
Total	**3294.8**	**3294.8**	**3294.8**	**3294.8**	**3294.8**				

3.3. Assessment of Historical Agricultural Water Demand

Based on the analysis of cultivated areas in the Lam Takong River Basin, the historical agricultural water demand of major cash crops—rice, maize, sugarcane, and cassava—was assessed using the CROPWAT model during 2008–2018. Referring to Table 4, the results illustrate that the water requirement of cassava was the largest, at 271.8 million m^3/year (with the highest in months of May and June), and that of maize was the smallest, at 132.8 million m^3/year (with the highest in months of June and July). The rather high water demand of some field crops was noticed as it was driven by the continuation of cropland expansion (Provincial Office of Natural Resources and Environment Nakhon Ratchasima, 2020 [11]).

Table 4. Estimation of mean monthly agricultural water demand of major cash crops in the Lam Takong River Basin under historical conditions.

Crop Type	Agricultural Water Demand (Million m^3)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rice	0.0	0.0	0.0	0.0	40.1	62.2	62.6	59.4	45.2	0.0	0.0	0.0	269.5
Maize	0.0	0.0	0.0	6.8	25.4	45.8	42.9	11.8	0.0	0.0	0.0	0.0	132.8
Sugarcane	0.5	7.5	15.2	26.3	29.3	27.9	27.5	26.0	22.9	21.1	16.3	6.4	226.8
Cassava	0.0	0.0	21.6	40.8	52.6	50.2	49.5	38.1	19.1	0.0	0.0	0.0	271.8

3.4. Climate and Land Use Change Impacts on Future Agricultural Water Demand in the Lam Takong River Basin

Under the scenarios of changes in land use and climate, the effects on future agricultural water demand in the Lam Takong River Basin were analyzed. The downscaled future climate data from the three RCMs for RCPs 4.5 and 8.5 scenarios were employed as input into the CROPWAT model to estimate the future agricultural water demand for the four 20-year periods: near- (2020–2039), mid- (2040–2059), far- (2060–2079), and very far future (2080–2099) (hereafter termed NF, MF, FF, and VFF). As a consequence of both aforementioned impacts, the future annual agricultural water demand under RCP 4.5 was estimated to decrease from the baseline period (2008–2018) throughout the four 20-year periods, except the increase for sugarcane farming, which requires the highest amount of water, followed by cassava, rice, and maize (see Tables 4 and 5). The increased water demand for sugarcane cultivation was found to coincide with the evidence presented in Table 3, which illustrates the increase in planting area of sugarcane and vice versa for the other crops. Under RCP 8.5, the maximum water demand was expected for cassava, while increased water demand compared to the baseline was found for sugarcane and cassava

and the others were decreased. During 2020–2099, there was a slight increase in water demand by an average of 9.9%, 1.9%, 0.5%, and 0.4% for cassava, sugarcane, rice, and maize, respectively, under RCP 8.5 compared to RCP 4.5. The obtained findings under both RCPs related to the increase in future agricultural water demand of sugarcane coincide with the findings of Krittasudthacheewa, et al. (2012) [38], who revealed that the growing area of sugarcane in some parts of Northeast Thailand tends to increase in response to its higher market price. Finally, it is clear that the above overall results are reliable, as supported by the comparable results of the previous study performed by Boonpradub et al. (2009) [39], which found that the production of rice, maize, sugarcane, and cassava in Northeast Thailand would be most affected by the impact of climate change.

Table 5. Changes in agricultural water demand for future periods under RCP 8.5 relative to RCP 4.5.

Crop Type	Mean Agricultural Water Demand (Million m^3/Year) and Relative Change (%)											
	2020–2039			2040–2059			2060–2079			2080–2099		
	RCP 4.5	RCP 8.5	% Change	RCP 4.5	RCP 8.5	% Change	RCP 4.5	RCP 8.5	% Change	RCP 4.5	RCP 8.5	% Change
Rice	203.1	203.5	0.2	163.3	164.6	0.8	135.6	136.3	0.5	118.7	119.5	0.7
Maize	120.5	121.0	0.4	116.5	117.2	0.6	112.8	113.8	0.9	109.0	108.8	−0.2
Sugarcane	284.4	293.9	3.3	268.1	272.0	1.5	255.3	257.5	0.9	247.5	251.8	1.8
Cassava	268.9	294.7	9.6	261.8	289.4	10.5	254.8	278.9	9.5	245.3	269.8	10.0

3.5. Daily Calibration and Validation Results of SWAT Model

To estimate the best hydrological parameter values used in the simulation processes, the calibration was manually undertaken so that the simulations can best represent the real physical circumstances. Thereafter, the validation was conducted using the parameters determined during the calibration in order to verify whether the calibrated model remains valid over other periods. The calibration was performed by adjusting seven parameters that were sensitive to discharges, i.e., parameters related to groundwater (ALPHA_BF, GWQMN, GW_DELAY), channel routing (CH_K2, CH_N1), evapotranspiration (ESCO), and transport and transmission processes in the main channels (TRNSRCH). Based on the daily time scale, the calibration was carried out from 1 January 2008 to 31 December 2012, and validation from 1 January 2013 to 31 December 2018. After that, the calculated daily discharge was estimated and then compared to the observed discharge (see Figure 3). The model results were assessed using visual inspection of both hydrographs and standard statistical measures (R^2 and NSE). Firstly, the visual inspection revealed that the discharges simulated by SWAT fit the observed ones well, even though the model tended to underestimate river discharge for some months during both calibration and validation periods. This might be because the study area has only eight rain gauge stations and half of them are located outside the study area, which probably affects the accuracy of spatial rainfall estimation and makes the response of SWAT model in simulating some river flows difficult (as mentioned by Pereira et al., 2016 [40]). When considering standard statistical measures, the R^2 and NSE values obtained during the calibration period were 0.75 and 0.74, respectively, whereas these values were found to be 0.69 and 0.63 during the validation period. It was noticeable that both performance measure values were within the range of acceptable model performance standards, as noted in Section 2.4, which indicated that the SWAT model is an effective tool in capturing the dynamics of flow across the Lam Takong River Basin.

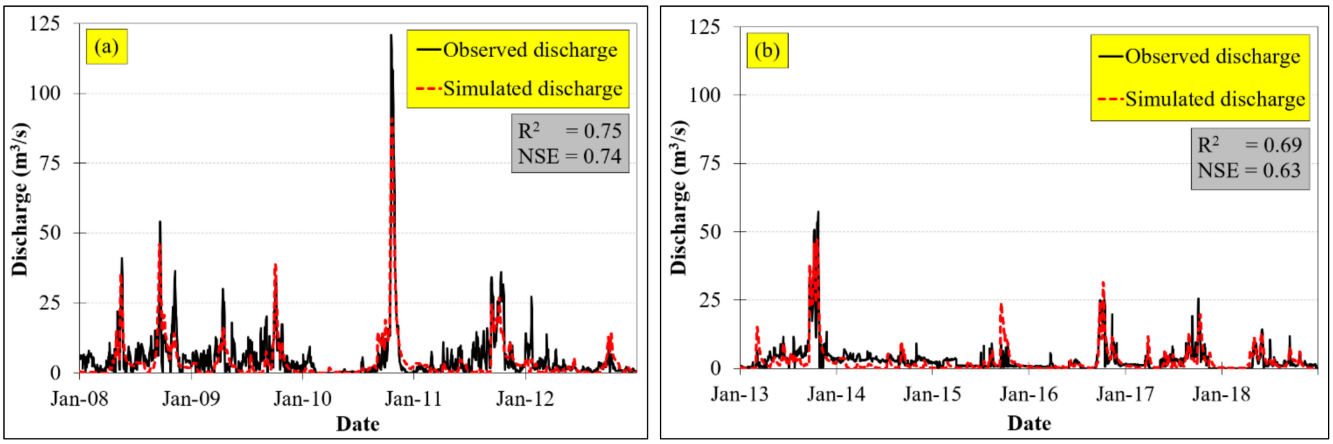

Figure 3. Comparison of observed and simulated daily flows at M.164 gauging station during (**a**) calibration (2008–2012) and (**b**) validation (2013–2018).

3.6. Potential Responses of Climate and Land Use Changes on Future Streamflow under Conditions of with and without Water Resources Management and Development Plan

To meet increased future water demand, the 2019 water resources management and development plan, which was mainly related to sediment dredging of the Lam Takong Reservoir, was proposed. The reservoir capacity was increased by 10 million m^3 to reach 324 million m^3 (Royal Irrigation Department, 2017 [25]). The hydrological response (i.e., mean annual discharge) to the aforementioned plan and different climate and land use change scenarios was simulated by SWAT. Under all combined scenarios compared to the baseline condition (2008–2018), the model results showed a slight increase in mean annual discharge at the M.164 gauging station. This is due to a relatively small increase in reservoir storage capacity by 3.2%, as well as in future rainfall (see Section 3.1.1). The results for both RCPs 4.5 and 8.5 showed a similar tendency with an increase in mean annual discharge for all future time horizons, in which the increase under RCP 8.5 was relatively higher than that of RCP 4.5. Correspondingly, the maximum increases of 1.2 million m^3 and 1.4 million m^3 were projected under RCPs 4.5 and 8.5 in the 2040–2059 and 2060–2079 periods, respectively, while the minimum increase was expected to be 0.1 million m^3 under RCP 4.5 during 2060–2079 (see Figure 4). These results are in line with the study of Singkran et al. (2015) [41], which stated that the influences of land use and climate changes on both projected yield and flow of water over the 56-year period (2010–2065) in the Lam Takong River Basin were noticeable compared to those obtained from the baseline hydrologic SWAT model (2001–2009). Moreover, Kosa and Sukwimolseree (2014) [42] depicted that based on the 2008 land use map and the daily weather data from 1979 to 2010, the climate change is a main parameter that affects surface runoff, as calculated by SWAT in the Upper Mun River Basin where the Lam Takong River Basin is located. Sukwimolseree and Kosa (2019) [43] also highlighted that the SWAT calculated average runoff in the Mun River Basin has a direct variation with rainfall from 1981 to 2010 and urban expansion on agricultural land within 5, 10, and 15 km from the urban agglomeration based on the 2008 land use data using GIS.

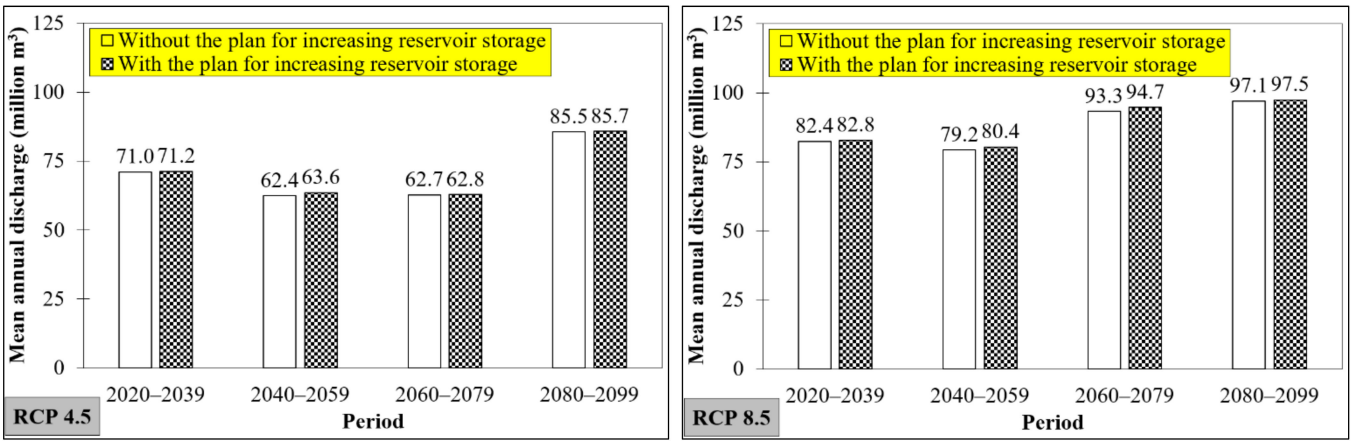

Figure 4. The comparison of mean annual discharge under scenarios with and without the water resources management and development plan, and both climate and land use changes.

3.7. Assessment of Water Sufficiency for Agriculture

It is believed that the Lam Takong River Basin, whose inhabitants depend largely on farming for their livelihood, is likely to be exacerbated by climate and land use changes. Both variations would place increasing pressure on limited water resources for agriculture. Therefore, in this study, more attention was given to the assessment of both future impacts on water sufficiency or unmet demand with a focus on the monthly water balance between water availability and use, as calculated through Equation (2).

$$\text{Water sufficiency} = \text{Water supply} - \text{Water demand} \quad (2)$$

From Table 6, under historical (baseline) conditions, the results revealed that the average water sufficiency for agriculture was threatened since the average water availability was found to be inadequate to meet the average agricultural water demand, with a difference of 162.22 million m^3. The average water sufficiency in June was determined to be the lowest at 39.55 million m^3 due to the highest water demand of 46.52 million m^3 and a rather low water availability of 6.96 million m^3. The same situation was also found for July, and this is due to a dry spell around the end of June to July, which caused a water scarcity problem in some areas of Northeast Thailand, as also addressed by Mongkolsawat et al. (2001) [44].

Table 6. Water sufficiency for agriculture in the Lam Takong River Basin under the baseline scenario.

Parameter	Average Monthly Streamflow (Million m^3/Month)												Total (Million m^3/Year)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Water supply	6.24	4.08	5.17	6.30	9.88	6.96	8.91	9.09	19.54	37.26	11.59	4.38	129.40
Water demand	0.49	7.54	36.81	18.47	36.84	46.52	45.64	33.79	21.81	21.07	16.28	6.35	291.61
Water sufficiency	5.75	−3.46	−31.63	−12.17	−26.97	−39.55	−36.73	−24.71	−2.27	16.19	−4.69	−1.98	−162.22

When comparing the baseline and both RCPs 4.5 and 8.5 conditions, the annual water insufficiency/annual unmet water demand was found to increase for all time horizons (see Tables 6–8). Under RCP 4.5, as shown in Table 7, the anticipated annual water insufficiency was found to decline from about 228.15 million m^3 (2020–2039) to 166.04 million m^3 (2080–2099). Likewise, under RCP 8.5, a decreasing trend was basically the same as that of RCP 4.5, from 227.18 million m^3 (2020–2039) to 166.28 million m^3 (2080–2099) (see Table 8). A very limited increase in annual unmet water demand under RCP 8.5 for a very far future period (2080–2099) compared with RCP 4.5 was found to be approximately 0.24 million m^3. For both RCPs 4.5 and 8.5, in the near future period (2020–2039), the agricultural sector would expect to face the highest unmet water demand in the June dry spell period, while the other future periods (2040–2099) would be in the dry period of March.

Table 7. Water sufficiency for agriculture in the Lam Takong River Basin under RCP 4.5.

Water Sufficiency during	Average Monthly Streamflow (Million m^3/Month)												Total (Million m^3/Year)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2020–2039	0.04	−9.32	−40.61	−20.38	−34.88	−41.93	−38.04	−19.13	10.78	−10.82	−17.35	−6.51	−228.15
2040–2059	0.01	−8.85	−38.88	−19.00	−32.33	−38.81	−36.07	−16.41	7.78	−11.43	−16.02	−6.25	−216.24
2060–2079	−0.16	−8.54	−37.47	−18.42	−30.70	−35.67	−32.02	−8.62	11.23	−17.28	−16.82	−6.37	−200.85
2080–2099	−0.13	−8.22	−35.46	−16.64	−28.93	−34.03	−26.51	7.26	16.26	−17.07	−16.25	−6.30	−166.04

Table 8. Water sufficiency for agriculture in the Lam Takong River Basin under RCP 8.5.

Water Sufficiency during	Average Monthly Streamflow (Million m^3/Month)												Total (Million m^3/Year)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2020–2039	−0.01	−9.08	−42.88	−21.48	−36.23	−45.86	−36.00	−19.30	16.67	−9.17	−17.25	−6.61	−227.18
2040–2059	−0.17	−8.99	−41.61	−20.62	−34.60	−39.53	−29.71	−8.20	14.40	−17.64	−17.71	−6.74	−211.12
2060–2079	−0.18	−8.52	−40.18	−18.96	−31.53	−35.11	−19.54	2.02	14.00	−18.95	−17.06	−6.61	−180.61
2080–2099	−0.21	−8.69	−37.66	−16.79	−30.91	−32.86	−16.68	8.71	12.07	−19.45	−17.07	−6.74	−166.28

It can also be noticed that due to the future increase in temperature (Figure 2a,b) and crop water requirement (Tables 4 and 5) and the absence of an increasing trend in rainfall under RCP 4.5 (Figure 2c), the Lam Takong River Basin could have a profound impact on agricultural water stress in the coming decades. This result was supported by Boonwichai et al. (2018) [45], who found that changes in rainfall in the upper northeast region of Thailand would possibly increase crop water stress in the future. Singkran et al. (2015) [41] also noted that as the land use and climate changes might affect the decrease in projected annual water yield and flow during 2010–2065, water scarcity will then tend to take place across the Lam Takong River Basin in the near future. In contrary, the results also indicated that the potential increase in rainfall under RCP 8.5 would decrease the unmet water demand by the maximum of 20.24 million m^3 during 2060–2079 as compared to RCP 4.5 (see Tables 7 and 8).

4. Conclusions

It seems undeniable that climate and land use changes will affect the balance between water availability and agricultural water demand in the Lam Takong River Basin, Thailand. Therefore, we investigated the balance between both aspects and possible consequences. In this context, the possible impacts of climate change on the availability and demand of water for the Lam Takong River Basin were evaluated using three climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5), namely, IPSL-CM5-MR, NorESM1-M, and CanESM2, for four future periods (2020–2039, 2040–2059, 2060–2079, and 2080–2099). The representative scenarios were the combinations of the three selected climate models run with RCPs 4.5 and 8.5. From the analysis of trends and future projections of climate variables over the Lam Takong River Basin, the future minimum and maximum temperature were predicted to have a statistically significant ascending trend until 2099 under RCPs 4.5 and 8.5. The 80-year average maximum temperature was expected to increase by 0.018 °C/year and 0.038 °C/year under RCPs 4.5 and 8.5, respectively. The future minimum temperature was also found to increase by the rate of 0.022 °C/year and 0.045 °C/year under both RCPs 4.5 and 8.5, respectively. Above the present condition (2019), the 1.76 °C and 1.45 °C increases in future minimum and maximum temperatures, respectively, were estimated to appear in 2099 under RCP 4.5, while the increases of 3.59 °C and 3.02 °C, respectively, were projected for RCP 8.5. The small increase in future rainfall of about 0.34 mm/year was predicted under RCP 4.5, while the projected increase of 1.06 mm/year was determined under RCP 8.5. Comparing to the present year (2019), the increases in future rainfall were observed to be 26.94 mm and 84.54 mm under RCPs 4.5 and 8.5, respectively.

In relation to the historical land use trend, a decrease in agricultural land was observed, while an increase in residential and built-up land and water bodies was detected. When the validation of changes in 2017 was performed with high relative validity (acceptable Overall Accuracy of 86.60% and acceptable Kappa Hat coefficient of 0.78), the CA-Markov model was considered worthy to predict future land use during 2020–2099. By comparing to the 2017 baseline, the uses of land for rice, maize, and cassava cultivation were projected to decline during 2020–2099, while the sugarcane cultivation area showed a growth trend of increasing until 2079 and then declining afterwards. In 2099, the largest increase in land use within the Lam Takong River Basin was found on the use of land for residential and built-up land, while water body area was ranked as the second largest increase in 2099, followed by other agricultural land in 2059. The largest decrease was noted in paddy fields in 2099, while the second largest decrease occurred in the forest category in 2099, followed by the orchard category during 2059–2079.

To ascertain water sufficiency, the linkage between water supply (availability) and water demand was explored. The SWAT model was applied for water supply estimation, and its performance was found satisfactory at both calibration and validation stages with values of R^2 and NSE higher than 0.6. This indicates that SWAT can accurately simulate hydrological processes in the Lam Takong River Basin under different climate conditions and topography. If implemented with the planned expansion of reservoir storage capacity of 10 million m^3, the mean annual discharge as influenced by future climate and land use changes was projected to increase under RCPs 4.5 and 8.5 above the baseline. The biggest mean annual discharge changes were found with increases of 1.2 million m^3 and 1.4 million m^3 under RCPs 4.5 and 8.5 in the 2040–2059 and 2060–2079 periods, respectively, while the minimum increase was noted as 0.1 million m^3 during 2060–2079 under RCP 4.5. Then, the CROPWAT model developed by the FAO was used to analyze the historical agricultural water demand trends in order to confidently determine the future water demand. It was found that cassava would require the highest amount of water, followed by rice, sugarcane, and maize. Under both climate and land use change scenarios, only the future water demand of sugarcane (the highest water demanding crop) under RCP 4.5 was seen to increase from the baseline, while others were not and maize had the lowest water demand among other selected major cash crops. Under RCP 8.5, the water demand of sugarcane and cassava was estimated to increase from the baseline and the rest were projected to decrease, with cassava presenting by far the highest water demand, followed by sugarcane, rice, and maize. Of course, the water demand of all selected cash crops under RCP 4.5 was lower than the RCP 8.5 scenario. It was found that there is a robust signal of water insufficiency or unmet water demand for agriculture during baseline and future periods. When considering baseline conditions, the water availability was found to be limited compared to the needs, especially during June and July, and the deficit was estimated to reach 162.22 million m^3/year, varying across the Lam Takong River Basin. Under both RCPs 4.5 and 8.5, the annual water insufficiency was predicted to increase from the baseline in all future scenarios, and the annual unmet water demand was expected to decrease continuously for every 20-year period from 2020 to 2099. Additionally, the minimum future unmet water demand under both RCPs was also observed during 2080–2099, whereas the maximum potential was found during 2020–2039. Clearly, the increase in unmet water demand was observed to be higher under RCP 8.5 compared with RCP 4.5 due to a lesser increase in future rainfall and a lower agricultural water demand of the lower emission scenario of climate change to 2099 (RCP 4.5). However, as the water demand in agriculture and the unmet water demand would expect to increase in all scenarios, a further intensification of pressure on water resources and agriculture would lead to water scarcity in some areas within the Lam Takong River Basin in the near future and onwards.

To confirm the reliability and validity of obtained results of this study, various diagnostic tests were conducted through a comparison between results from the literature, simulations, and theory. Some attained results related to either historical or future changes

in rainfall, land use, streamflow, and agricultural water demand and sufficiency were validated with the literature. Moreover, the results gained from the land use prediction model and hydrological process simulations were also validated with the theory of classification accuracy assessment and observed data, respectively, in which the acceptable accuracy criteria were set according to guidelines reported in the literature. The obtained findings under both future climate and land use changes provided insights into the variations in water availability and agricultural water demand, which could lead to more frequent water shortage conditions. Thus, the identification of potential future threats gained from this study could foster better decisions, precise mitigation, and applicable adaptation and resiliency strategies for ensuring water sustainability and security in the Lam Takong River Basin.

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