Adaptation strategies for rainfed rice water management under climate change in Songkhram River Basin, Thailand
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ABSTRACT

This study investigates the potential impacts of climate change on water resources and evaluates adaptation strategies on rainfed rice water management under climate change scenarios in the Songkhram River Basin, Thailand. The Soil and Water Assessment Tool (SWAT) model was used to project the future water availability under climate change scenarios for the period of 2020–2044. Future annual water availability is expected to remain unchanged due to unchanged future rainfall but expected to reduce from June to November due to changes in seasonal rainfall. The effects of supplying irrigation water to reduce the impact of climate change and increase rainfed rice production were evaluated. To increase the rice production by 15%, it is proposed to construct a reservoir with a capacity of below 65 MCM in each of the 15 sub-basins to fulfill the irrigation water requirements during the rainfed rice season. Alternatively, adaptation at the farm scale can be implemented by constructing ponds with a capacity of 900 m³ to store water for 1 ha of rice field to meet the potential rice yield during the non-rainfed rice season. The results of this study are helpful to policymakers in understanding the potential impacts of climate change and the formulation of adaptation strategies for water and rice sectors in the basin.

Key words | adaptation, irrigation water requirement, SWAT model, water availability

HIGHLIGHTS

- Adaptation strategies for rainfed rice water management under climate change scenarios were evaluated at the farm and basin scale.
- The Soil and Water Assessment Tool model was used to forecast the future water availability for the rainfed cultivation.
- A pond with a capacity of 900 m³ is recommended to store water for 1 ha of rice to produce the potential rice yield.

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INTRODUCTION

Climate change has negative impacts on crop growth and production throughout the world, including many areas in Thailand. Temperature is expected to rise, and higher variability in rainfall is expected at both global and local scales (IPCC 2014). Changes in magnitude and patterns of temperature and rainfall could significantly reduce rice production (Babel et al. 2011; Shrestha et al. 2017; Boonwichai et al. 2018). Climate change can be defined as a trend in one or more climatic variables characterized by a fairly smooth continuous increase or decrease of the average value during the long period of record including higher surface temperature, floods, droughts, storms, and sea-level rise. The global mean surface temperature is expected to rise by 4.8 °C in the 21st century (IPCC 2014). Thailand’s temperature is expected to rise by approximately 2–3 °C during the middle of the century and continue increasing until the end (Chinvanno & Center 2009).

Climate is one of the most important factors in agricultural productivity and could directly influence it since it is linked to physiological processes (Deb et al. 2015). This issue could affect global food security, especially in developing countries (Babel et al. 2011). Climate change may have both positive and negative impacts on the quantity and quality of agricultural productions, depending on location, climate zone, and crops (Deb et al. 2015). Studies have established the interdependence between climate and agriculture, and generally agree that actions have to be taken to ensure future water security and food security (Corkal et al. 2011; Falkenmark 2013; Pradhan et al. 2015). Rice is one of the most important food crops in the world. Boonwichai et al. (2018, 2019) and Shrestha et al. (2017) studied the potential impact of climate change on rice production in Thailand and concluded that changes in the magnitude and patterns of temperature and rainfall could alter the crop growth period, water availability, and photosynthesis process. Temperatures above 35 °C affect the rice growth stage, significantly reducing the rice yield and quality (Tipparak & Aroonrungsikul 2011).

Water resources in Thailand are also affected by climate change. Such impacts include projections of increased inflow into the Ubonratana Dam (Shrestha 2014) and reduced annual runoff in the Upper Ping River Basin (Sharma & Babel 2015). Kosa & Sukwimolseree (2014) also found that relative humidity, evaporation, and infiltration are the main factors affecting runoff changes in the Mun River Basin.

Adaptation strategies can greatly reduce the magnitude of impacts on rice production under climate change conditions. Babel et al. (2011) suggested that planting date alteration and proper nutrient management can mitigate the effect of climate change on rice production in northeast Thailand. Changing planting date, reduction in fertility stress, and supplementary irrigation were evaluated in the lower Mekong basin (Mainuddin et al. 2013). Boonwichai et al. (2019) evaluated four adaptation strategies for rainfed rice in the Songkhram River Basin, Thailand. Supplying
irrigation water was found to be the most effective compared to changing planting date, fertilizer application date, and fertilizer application dose to increase rice production under climate change scenarios.

Several studies used a modeling approach to evaluate the adaptation options using hydrological models such as the Soil and Water Assessment Tool (SWAT). The model has been extensively used to simulate basin hydrology under different climate change scenarios around the globe and evaluate the adaptation options to offset the negative impacts of climate change (Mishra et al. 2013; Shrestha et al. 2018a, 2018b).

The study aims to investigate the impact of climate change on water availability and evaluate adaptation strategies for water management on rice fields at the sub-basin and farm scales for the period of 2020–2044 under RCP4.5 and RCP8.5 scenarios in the Songkhram River Basin of Thailand. The results of this study will provide technical and policy insights to support decision makers for the better understanding and implementation of Thailand’s water resources management strategies under the 20-year master plan (2018–2037).

**METHODOLOGY**

The study was conducted following the methodological framework in Figure 1. The SWAT model was used to simulate water availability in the basin under future climate conditions (projected by Boonwichai et al. 2019), with calibration and validation being based on two discharge gauge stations (KH.55 and KH.74). The observed discharge periods of 1995–1999 were used for calibration for both stations, and periods of 2000–2014 and 2000–2005 were used for validation for KH.55 and KH.74 discharge gauge stations, respectively. The model outputs were used to estimate the future water availability under future climate change scenarios for the period of 2020–2044. The Decision Support System for Agrotechnology Transfer (DSSAT) crop simulation model was used to simulate the future crop water requirement (CWR) and irrigation water requirement (IWR) under climate change scenarios. Based on the results, adaptation strategies were evaluated for water resource management for the rainfed rice season at both the river basin and farm scales.

**Study area**

The Songkhram River Basin is a sub-basin of the Mekong River Basin and the second-largest in Northeast Thailand (Figure 2). It has a catchment area of approximately 13,215 km², covering five provinces: Sakon Nakhon, Nakhon Phanom, Bung Kan, Nong Khai, and Udon Thani. The Songkhram River draining the basin is approximately 420 km long and originates at the Phu Phan Mountains in the Song Dao District of Sakon Nakhon Province and the Nong Han District in Udon Thani Province. The Songkhram River meets the Mekong River at the Chai Buri sub-district and Tha Uthen District in Nakhon Phanom.

The basin has a tropical, semiarid climate with three seasons: summer (March–May), rainy (June–October), and winter (November–February), and receives more annual rainfall than other parts of Thailand (Satrawaha & Wongpakam 2022). The Thai Meteorological Department (TMD) reported variations in the annual rainfall between 1,200 and 2,000 mm, peaking during the months of July and August. The average mean temperature varies from 21 to 34 °C, with the minimum temperature falling below 10 °C in the winter season during the months of December and January and rising to over 40 °C during April in the summer season.

The Songkhram River Basin is a floodplain, making it suitable for paddy fields. The Land Development Department (LDD) reports that the majority of land use in the
basin is agriculture, covering approximately 68% of the land area. There are two main rice-growing seasons: major – from June–November and secondary – from January–May. Rice yield in the basin depends mainly on rainfall, and the Office of Agricultural Economics in Thailand reported that the average major rice yield in the basin is 2.16 t/ha.

Data collection

Meteorological data

Observed meteorological data (six temperature and eight rain gauge stations) were obtained from the TMD. The historical weather data from 1980 to 2004 in the Songkhram River Basin show an average annual maximum temperature of 31.7 °C, an average annual minimum temperature of 21.5 °C, and an average annual rainfall of 1,391 mm. Missing temperature data were filled by a linear interpolation technique, and missing rainfall data were filled based on APHRODITE’s daily gridded precipitation dataset (http://www.chikyu.ac.jp/precip/). The four RCMs were selected in this study to project future climate: ACCESS1-CSIRO-CCAM, CNRM-CM5-CSIRO-CCAM, ICHEC-EC-EARTH-SMHI-RCA4, and MPI-ESM-LR-CSIRO-CCAM with spatial resolutions of 0.5° latitude × 0.5° longitude (http://cordex.org/). The future climate was projected based on observed data for the period 1980–2004. The hydrological model calibration and validation are based on the period of 1993–2014 to project the future water availability under climate change scenarios in the period of 2020–2044.
Discharge data

The daily discharge of two discharge gauge stations (Figure 2) obtained from the Royal Irrigation Department, Thailand was used for the hydrological model calibration and validation. The KH.55 and KH.74 discharge gauge stations located at the downstream and upstream of the basin, respectively, have discharge data available from 1993 to 2014 and 1993 to 2005.

Land-use and land-cover data

Land-use and land-cover data for year 2013 were collected from the LDD (Figure 3(a)). The majority of land use in

Figure 3 | (a) Land use and land cover, (b) soil, and (c) DEM in the Songkhram River Basin, Thailand.
the basin is agriculture, covering about 8,800 km² or 68% of the total land area (Supplementary Material, Table S1). Most of the area consists of paddy fields, rubber, and eucalyptus trees, taking up almost 93% of the agricultural land area in 2013. Water availability is the main issue in the basin due to water storage, as water body covers about only 4% of the basin area.

Soil data

Soil data for the SWAT model were obtained from the Harvard World Map website (https://worldmap.harvard.edu/data/geonode:DSMW_RdY, accessed March 2019). Seven major classes, according to FAO (Food and Agriculture Organization of United Nations) soil classification, including Af60-1-2a-4260, Ag16-2a-4264, Ag17-1-2a-4264, Ao90-2-3c-4284, Ge56-3a-4325, Af59-1-2a-4452, and Gd29-3a-4499, of soil are found in the Songkhram River Basin (Figure 3(b)). The acronyms represent the following soil classes: Ferric Acrisols (Af), Gleyic Acrisols (Ag), Orthic Acrisols (Ao), Eutric Gleysols (Ge), and Dystric Gleysols (Gd).

Digital elevation model data

The digital elevation model (DEM) with a 30-m spatial resolution was collected from Open Topography (http://www.opentopography.org/, accessed March 2019) (Figure 3(c)). The elevation ranges between 54 and 676 m above mean sea level, and with the Phu Phan National Park has the highest elevation in the basin.

Hydrological model

The SWAT model was used to evaluate the future water availability under climate change scenarios in the Songkhram River Basin. The model is a public domain model activity supported by the United States Department of Agriculture (USDA), Agricultural Research Service at the Blackland Research and Extension Center in Temple, TX, USA (Neitsch et al. 2011). The SWAT is a semi-distributed river basin model which can be separated into two major divisions: the land phase and the water or routing phase of the hydrological cycle. The minimum data required for the model inputs include climate data, land use, soil, and DEM (Arnold et al. 2015). The hydrological cycle is simulated based on the water balance equation (Neitsch et al. 2011), as shown in the following equation:

\[
SW_t = SW_0 + \sum_{i=1}^{t} \left( R_{\text{day}} - Q_{\text{surf}} - E_a - w_{\text{seep}} - Q_{\text{gw}} \right)
\]

where \(SW_t\) is the final soil water content (mm), \(SW_0\) is the initial soil water content on day \(i\) (mm), \(t\) is the time (days), \(R_{\text{day}}\) is the amount of precipitation on day \(i\) (mm), \(Q_{\text{surf}}\) is the amount of surface runoff on day \(i\) (mm), \(E_a\) is the amount of evapotranspiration on day \(i\) (mm), \(w_{\text{seep}}\) is the amount of water entering the vadose zone on day \(i\) (mm), and \(Q_{\text{gw}}\) is the amount of return flow on day \(i\) (mm).

For the Songkhram River Basin, the model was set up using the observed daily precipitation and daily maximum and minimum temperature from 1980 to 2004. The DEM data of 30×30 m resolution, land-use data, and soil data were used as the input for the model. After setup of the model, the watersheds were divided into HRUs (hydrologic response unit) with different categories of slope which define the varieties of surface.

The sensitivity analysis, calibration, and validation process were carried out automatically in the SWAT-CUP using the SUFI-2 algorithm (Sequential Uncertainty Fitting (Version 2)). The study used hydrological data from 1993 to 1999 for calibration and 2000 to 2004 for validation of model from two discharge gauge stations (KH.55 and KH.74). Four statistical indicators including coefficient of determination (\(R^2\)), Nash–Sutcliffe efficiency (NSE), percent bias (PBIAS), and root mean square error (RMSE) observations of the standard division ratio (RSR) were used to evaluate the performance of the SWAT model. The model performance rating was in accordance to Moriasi et al. (2007) (Supplementary Material, Table S2).

RESULTS AND DISCUSSION

Climate change scenarios

Boonwichai et al. (2019) projected future climate in the Songkhram River Basin, Thailand based on four regional circulation models (RCMs), namely ACCESS1.0-CSIRO-CCAM, CNRM-CM5-CSIRO-CCAM, ICHEC-EC-EARTH-
SMHI-RCA4, and MPI-ESM-LR-CSIRO-CCAM under RCP4.5 and RCP8.5 scenarios. This study used the same projection results to investigate the impact of climate change on future water availability.

The maximum and minimum temperatures are expected to rise under both scenarios during 2020–2044. The maximum temperature is expected to increase which varies between 0.8 and 1.2°C and between 0.5 and 1.2°C under RCP4.5 and RCP8.5 scenarios, respectively (Figure 4(a); Table 2). The minimum temperature is also expected to rise which varies between 0.6 and 1.4°C and between 0.6 and 1.6°C under RCP4.5 and RCP8.5 scenarios, respectively (Figure 4(b); Table 2). In contrast, future rainfall might increase or decrease depending on the location which varies between −0.5 and 14.5% and between 0% and 26.6% under RCP4.5 and RCP8.5 scenarios, respectively (Figure 4(c); Table 1).

Impacts of climate change on rainfed rice IWR

Temperature rise would increase both the CWR and IWR. The IWR for KDML105 rice variety is projected to increase under climate change scenarios causing a significant decrease in rice yield (Boonwichai et al. 2018). According to Boonwichai et al. (2019), under RCP4.5 and RCP8.5 scenarios, respectively, for 2020–2044, future rice yield could increase by 15% when supplying 60 and 70 mm of water, and water deficit is expected to be 349 and 408 MCM (Figure 5). The water deficit in each sub-basin for rainfed rice field might hit 64 MCM per season under climate change scenarios (Figure 5; Table 5).

Hydrological model

Sensitivity analysis

Sensitivity analysis focuses on the most influential parameters for reducing model uncertainty (Brouziyne et al. 2017). Sensitivity analysis was carried out on 27 different SWAT input parameters based on previous studies (Abbaspour et al. 2015; Meaurio et al. 2015; Brouziyne et al. 2017). Therefore, eight parameters, including SOL_AWC.sol, REVAPMN.gw, ESCO.hru, SHALLST.gw, RCHRG_DP.gw, OV_N.hru, GW_DELAY.gw, and CN2.mgt, which are highly significant ($p < 0.05$), were used to calibrate the model in this study (Supplementary Material, Figure S1 and Table S3).

Calibration, validation, and model performance evaluation

Model calibration is the process for estimating the values of model parameters to reduce errors between observed and simulated values (Brouziyne et al. 2017). Calibration was performed manually and automatically using the SWAT-CUP program (Abbaspour 2013). Table 2 shows the parameters that were adjusted from the model default values during calibration. The observed discharge data for the period of 1993–1999 were used for model calibration for both discharge gauge stations. The validation periods are selected based on data availability: 2000–2005 for the KH.74 discharge gauge station at the upstream (Figure 6(a)) and 2000–2014 for the KH.55 discharge gauge station at the downstream (Figure 6(b)).

The $R^2$, RSR, NSE, and PBIAS were analyzed for the model performance evaluation. The model performance evaluation indicates satisfactory performance (Table 3). The $R^2$ values ranged from 0.73 to 0.82 during the calibration and validation periods, with $R^2$ values greater than 0.5 considered acceptable (Moriasi et al. 2007). The RSR values ranged from 0.43 to 0.60 during the calibration and validation periods for both stations. The model performance for streamflow ranged from good to very good, and the NSE values ranged from 0.67 to 0.82 for calibration and from 0.64 to 0.76 for validation at both stations. The average magnitude (PBIAS) fell within the good and very good range during both calibration and validation periods. However, the simulated peaks did not meet the observed very well. Since this study mainly focused on water availability than flooding, the performance is satisfactory.

Climate change impacts on water resources

The average annual discharge was approximately 12,631 MCM for the baseline period (1990–2014). The projected future annual discharge varied between 10,756 and 13,396 MCM and between 10,961 and 15,541 MCM under RCP4.5 and RCP8.5 scenarios, respectively, as shown in Table 5. Blake & Pitakthesombut (2006) reported that the
Figure 4 | Projected change in (a) maximum temperature, (b) minimum temperature, and (c) rainfall in the Songkhram River Basin under four RCMs for RCP4.5 and RCP8.5 scenarios for the period of 2020–2044. (continued.)
peak discharge usually occurs in August or September, with minimum flows during February and April. This study found that the peak may occur in August and September, although the future water availability pattern may change. The average annual water availability could be both increased and decreased. The future water availability might decrease under ACCESS1.0-CSIRO-CCAM, CNRM-CM5-CSIRO-CCAM, and MPI-ESM-LR-CSIRO-CCAM climate models.

### Table 1 - Projected future climate of four RCMs under two climate change scenarios for the period of 2020–2044 for the Songkhram River Basin, Thailand

| Scenarios     | ACCESS1.0-CSIRO-CCAM | CNRM-CM5-CSIRO-CCAM | ICHEC-EC-EARTH-SMHI-RCA4 | MPI-ESM-LR-CSIRO-CCAM |
|---------------|----------------------|----------------------|---------------------------|------------------------|
| **Maximum temperature (°C)** |                       |                       |                           |                        |
| Observation   | 31.7 ± 0.4           | 32.8 ± 0.6           | 32.6 ± 0.4                | 32.6 ± 0.7             |
| RCP4.5        | 32.8 ± 0.6           | 32.5 ± 0.5           | 32.6 ± 0.4                | 32.6 ± 0.7             |
| RCP8.5        | 32.8 ± 0.6           | 32.3 ± 0.5           | 32.8 ± 0.4                | 32.8 ± 0.7             |
| **Minimum temperature (°C)** |                       |                       |                           |                        |
| Observation   | 21.5 ± 0.3           | 22.3 ± 0.4           | 22.8 ± 0.3                | 22.2 ± 0.5             |
| RCP4.5        | 22.3 ± 0.4           | 22.1 ± 0.4           | 23 ± 0.5                  | 22.6 ± 0.6             |
| RCP8.5        | 22.6 ± 0.3           | 22.1 ± 0.4           | 23 ± 0.5                  | 22.6 ± 0.6             |
| **Rainfall (mm)** |                       |                       |                           |                        |
| Observation   | 1,391 ± 179          | 1,409 ± 225          | 1,490 ± 297               | 1,349 ± 243            |
| RCP4.5        | 1,409 ± 225          | 1,327 ± 216          | 1,490 ± 297               | 1,349 ± 243            |
| RCP8.5        | 1,452 ± 274          | 1,402 ± 164          | 1,592 ± 254               | 1,386 ± 184            |
and increase under the ICHEC-EC-EARTH-SMHI-RCA4 climate model under both scenarios (Figure 7; Table 4). Reduced future water availability during the cropping season, especially the rice season, may affect crop growth and yield. Boonwichai et al. (2018) reported that the water deficit has a significant impact on rice production.

![Figure 5](image-url) Projected IWR under RCP4.5 and RCP8.5 scenarios for the period of 2020–2044.

| Change type | Parameter name | Description | Value | Default range | Initial | Calibrated |
|-------------|----------------|-------------|-------|---------------|---------|------------|
| V           | GW_DELAY.gw   | Groundwater delay (days) | 0–500 | 31            | 1.63    |            |
| R           | CN2.mgt       | Number of SCS runoff curves | 35–98 | 77–87         | 76–86   |            |
| V           | SHALLST.gw    | Initial depth of water in the shallow aquifer (mm) | 0–50,000 | 1,000 | 11,102 |            |
| V           | ESCO.hru      | Soil evaporation compensation factor | 0–1 | 1 | 0.44 |            |
| V           | RCHRG_DP.gw   | Deep aquifer percolation factor | 0–1 | 0.05 | 0.013 |            |
| R           | SOL_AWC(..).sol | Available water capacity of the soil layer | 0–1 | 0.06–0.17 | 0.05–0.14 |            |
| V           | OV_N.hru     | Manning’s ‘n’ value for overland flow | 0.01–30 | 0.14 | 28.48 |            |
| V           | REVAPMN.gw   | Threshold depth of water in the shallow aquifer for ‘revap’ to occur (mm) | 0–500 | 750 | 486 |            |

V, the existing parameter value is to be replaced by a given value; R, an existing parameter value is multiplied by (1 + a given value).
Figure 6 | Observed and simulated discharge and precipitation at (a) KH.74 (upstream) and (b) KH.55 (downstream) during SWAT calibration and validation.
Table 3 | Hydrological model (SWAT) performance evaluation for KH.74 and KH.55 stations

| Stations   | Calibration | Validation | Calibration | Validation | Calibration | Validation | Calibration | Validation | Calibration | Validation |
|------------|-------------|------------|-------------|------------|-------------|------------|-------------|------------|-------------|------------|
| KH.74      | 0.79        | 0.73       | 0.57        | 0.60       | 0.67        | 0.64       |             |            | –12.52      | –14.36     |
| (upstream) | (good)      | (good)     | (good)      | (good)     | (good)      | (satisfactory) |             |            | (good)      | (good)     |
| KH.55      | 0.82        | 0.77       | 0.43        | 0.57       | 0.82        | 0.76       |             |            | 10.80       | –5.18      |
| (downstream) | (very good) | (good)     | (very good) | (good)     | (very good) | (very good) |             |            | (good)      | (very good) |

Figure 7 | Projected monthly water availability under (a) RCP4.5 and (b) RCP8.5 scenarios for the period of 2020–2044.
Table 4 | Projected monthly water availability under both climate change scenarios for four RCMs for the period 2020–2044

| Month      | Observation (MCM) | ACCESS1.0-CSIRO-CCAM | CNRM-CMS-CSIRO-CCAM | ICHEC-EC-EARTH-SMHI-RCA4 | MPI-ESM-LR-CSIRO-CCAM |
|------------|-------------------|----------------------|---------------------|--------------------------|------------------------|
|            | RCP4.5            | RCP8.5               | RCP4.5              | RCP8.5                   | RCP4.5                 |
| January    | 74                | 53                   | 42                  | 53                       | 69                     |
|            |                   |                      |                     |                          | 68                     |
|            |                   |                      |                     |                          | 43                     |
| February   | 36                | 38                   | 24                  | 78                       | 110                    |
|            |                   |                      |                     |                          | 10                     |
|            |                   |                      |                     |                          | 8                      |
| March      | 33                | 26                   | 14                  | 42                       | 175                    |
|            |                   |                      |                     |                          | 11                     |
|            |                   |                      |                     |                          | 7                      |
| April      | 33                | 69                   | 17                  | 73                       | 736                    |
|            |                   |                      |                     |                          | 43                     |
|            |                   |                      |                     |                          | 581                    |
| May        | 653               | 678                  | 763                 | 1,113                    | 963                    |
|            |                   |                      |                     |                          | 737                    |
|            |                   |                      |                     |                          | 1,109                  |
| June       | 7,230             | 6,773                | 7,264               | 9,739                    | 5,815                  |
|            |                   |                      |                     |                          | 6,715                  |
|            |                   |                      |                     |                          | 7,147                  |
| July       | 24,112            | 21,995               | 20,257              | 21,500                   | 22,318                 |
|            |                   |                      |                     |                          | 27,721                 |
|            |                   |                      |                     |                          | 19,391                 |
| August     | 50,599            | 56,495               | 45,201              | 46,494                   | 55,586                 |
|            |                   |                      |                     |                          | 69,603                 |
|            |                   |                      |                     |                          | 45,845                 |
| September  | 49,845            | 41,946               | 39,987              | 38,038                   | 53,859                 |
|            |                   |                      |                     |                          | 60,645                 |
| October    | 16,378            | 13,011               | 13,034              | 12,871                   | 18,514                 |
|            |                   |                      |                     |                          | 18,300                 |
|            |                   |                      |                     |                          | 12,779                 |
| November   | 2,285             | 2,066                | 1,757               | 1,773                    | 2,328                  |
|            |                   |                      |                     |                          | 2,323                  |
|            |                   |                      |                     |                          | 1,884                  |
| December   | 289               | 259                  | 204                 | 204                      | 276                    |
|            |                   |                      |                     |                          | 299                    |
|            |                   |                      |                     |                          | 210                    |
| Mean       | 12,631            | 11,951               | 10,756              | 10,998                   | 13,396                 |
|            |                   |                      |                     |                          | 15,541                 |
|            |                   |                      |                     |                          | 10,832                 |
|            |                   |                      |                     |                          | 10,961                 |

Table 5 | Projected average annual IWR for rice and water availability of each sub-basin under both different climate change scenarios for four RCMs for the period of 2020–2044

| Sub-basin | IWR (MCM) | ACCESS1.0-CSIRO-CCAM | CNRM-CMS-CSIRO-CCAM | ICHEC-EC-EARTH-SMHI-RCA4 | MPI-ESM-LR-CSIRO-CCAM |
|-----------|-----------|----------------------|---------------------|--------------------------|------------------------|
|           | RCP4.5    | RCP8.5              | RCP4.5              | RCP8.5                   | RCP4.5                 |
| 1         | 15        | 18                   | 798                 | 818                      | 939                    |
| 2         | 8         | 9                    | 316                 | 322                      | 371                    |
| 3         | 13        | 16                   | 388                 | 412                      | 500                    |
| 4         | 28        | 32                   | 1,061               | 1,086                    | 1,249                  |
| 5         | 14        | 17                   | 377                 | 401                      | 480                    |
| 6         | 32        | 37                   | 1,491               | 1,466                    | 1,746                  |
| 7         | 22        | 26                   | 1,160               | 1,142                    | 1,355                  |
| 8         | 1         | 1                    | 52                  | 52                       | 64                     |
| 9         | 4         | 4                    | 166                 | 167                      | 205                    |
| 10        | 13        | 16                   | 638                 | 645                      | 788                    |
| 11        | 50        | 58                   | 1,263               | 1,341                    | 1,608                  |
| 12        | 28        | 33                   | 520                 | 523                      | 459                    |
| 13        | 55        | 64                   | 1,021               | 1,023                    | 1,333                  |
| 14        | 53        | 61                   | 915                 | 985                      | 1,282                  |
| 15        | 13        | 16                   | 712                 | 709                      | 914                    |
| Total     | 349       | 408                  | 10,817              | 11,063                   | 13,471                 |
|           |           |                      |                     |                          | 15,659                 |
|           |           |                      |                     |                          | 10,894                 |
|           |           |                      |                     |                          | 10,961                 |
Adaptation strategies for rainfed rice water management

Adaptation strategies are necessary to cushion the impacts of climate change and increase crop production. The following subsections suggest adaptation strategies at both the river basin and farm scales.

Adaptation strategies for water management at the river basin scale

Temperature rise could increase the CWR which results in increasing water stress and decreasing crop production. Boonwichai et al. (2019) suggested that supplying 60 and 70 mm of irrigation water under RCP4.5 and RCP8.5 scenarios, respectively, could increase the rice production by 15%. The total future IWR of the Songkhram River Basin is 349 and 408 MCM for RCP4.5 and RCP8.5 scenarios, respectively. The future IWR of all 15 sub-basins could vary between 1 and 55 MCM and between 1 and 64 MCM under RCP4.5 and RCP8.5 scenarios, respectively, as shown in Table 5.

The future water availability could be enough to fulfill the IWR. The average annual future water availability is 11,805 and 12,445 MCM under RCP4.5 and RCP8.5 scenarios, respectively, for the period of 2020–2044. The future water availability of all 15 sub-basins could vary between 51 and 1,746 MCM and between 51 and 1,953 MCM under RCP4.5 and RCP8.5 scenarios, respectively, as shown in Table 5 and Figure 8. Proper water storage solutions, such as constructing a reservoir or a pond, are required for water management in the basin. However, a feasibility study should be conducted to determine the optimal location of the reservoir. According to Rufin et al. (2018), water storage structures should be decentralized for allocation efficiency. To increase the rice production by 15%, it is proposed to construct a reservoir in each sub-basin to fulfill the IWRs.
Adaptation strategies for water management at the paddy farm scale

A possible option for storing water for paddy fields is to construct or enlarge ponds (De Loë et al. 2001). Farmers should have their own ponds to store water for one rice season. The assumption is that farmers would have 1 ha (10,000 m²) of paddy field and grow only in the rainfed season. The farmers would have to store about 60–70 mm per season under RCP4.5 and RCP8.5 scenarios, respectively, of extra water plus 20% to allow for losses from evaporation and infiltration. The pond would be required to store between 720 and 840 m³ of water for 1 ha of rice field per season under RCP4.5 and RCP8.5 scenarios, respectively. Therefore, the pond should measure 20 m in length, 15 m in width, and 3 m in depth to store 900 m³ of water (Figure 9) for addressing both scenarios. In addition, the location of the pond should be selected according to the monkey’s cheek technique. Furthermore, the construction materials, such as biocrete, polythene, clay, and chicken litter, should be selected to avoid water loss from the seepage. The monkey’s cheek (called ‘Kaem Ling’ in Thai) is a project based on the suggestion of the HM King Bhumibol Adulyadej (Rama IX). The concept involves storing excess water to use and for flood control. HM King Bhumibol Adulyadej (Rama IX) guided the self-sufficiency model (known as the ‘sufficiency economy’). His Majesty introduced an unprecedented approach to managing farmland (The Chaipattana Foundation 2017). The land is divided into four parts with a ratio of 30% allocated for a pond to store rainwater, 30% for rice cultivation during the rainy season, 30% for fruit, vegetables, field crops, and herbs, and 10% for accommodation and other structures. This approach will be useful for reducing the impact of climate change in the future given cooperation from farmers and local stakeholders.

Figure 9 | Possibility of a pond occupying 1 ha of a rice field for the rainfed rice season under RCP4.5 and RCP8.5 scenarios for the period of 2020–2044.

Implications and perspectives

In June 2019, the cabinet of Thailand approved a 20-year master plan (2018–2037) on water resource management. The master plan comprises six areas of strategic planning, including managing water for human consumption, building water security in the production sector, inundation control, managing water quality, restoring watershed and degraded forests, and management and administration. The plan includes constructing over 541,000 small dams, restoring 5,600 km² of watershed areas, supplying safe water to 75,032 villages by 2030, and finding solutions to the country’s chronic droughts in 66 different areas (ONWR 2019).

The production sector is very important to Thailand’s economy. Thus, the second strategy of the 20-year master plan on water resource management strives for water security in the production sector with aims to increase water storage capacity and agricultural production. The LDD of Thailand also encouraged farmers to construct 45,000 ponds for paddy fields in non-irrigated areas to mitigate the impact of droughts in the year 2018. However, the implementation of measures, such as the development of small community-level reservoirs and farm ponds to adapt against the climate change impact on the agriculture sector, needs effective water governance and management including investment focused on equitable access to all farmers.

The role of local institutions, such as Sub-district Administrative Organization, is very crucial to transform the farmers’ coping capacity into adaptive capacity to offset the negative impact of climate change on the production sector. Agrawal (2008) provides a clear review of adaptation to climate change, highlighting the role of local institutions. The review suggests that adaptation to climate change is inevitably local and that institutions influence adaptation and climate vulnerability in three critical ways: (a) they structure impacts and vulnerability, (b) they mediate between individual and collective responses to climate impacts and thereby shape outcomes of adaptation, and (c) they act as the means of delivery of external resources to facilitate adaptation and thus govern access to such resources. Huntjens et al. (2010) propose a theoretically improved institutional design, and Groves et al. (2008a, 2008b) identify concrete actions for water management.
institutions. Their study suggested the importance of several regime elements in adaptive and integrated water management: agency, awareness-raising and education, type of governance and cooperation structures, information management – exchange, policy development – implementation, risk management, and finances and cost recovery.

The adaptation to climate change must be factored in as part of the ongoing technological development in agriculture, including plant breeding, irrigation management, and application of information and communication technology. However, such technologies should maintain and possibly improve soil quality and water resources, which are essential for improving resilience to climate change and climate variability in cropping systems (Olesen et al. 2011).

It is recommended that the relevant authorities in Thailand should develop suitable policies, strategies, and action plans to combat the negative impacts of climate change on the agricultural production sector which will help people who rely on farming activities for livelihood, especially in North East of Thailand wherein a large agricultural area is under rainfed and hence heavily depends on rainfall. The provision of storage facilities at the farm level will improve the availability of water to meet the crop water demand as well as encourage farmers to adapt to integrated farming.

**CONCLUSIONS**

In this study, the impact of climate change on water resources in the Songkhram River Basin was investigated using the SWAT model, and the effects of supplying irrigation water to reduce the impacts and increase rainfed rice production were evaluated at the river basin and farm scale. Results suggest that the uncertainty in future seasonal water availability would pose challenges for future water management. At the basin scale, the total future water availability is projected to be over 10,000 MCM under both RCP4.5 and RCP8.5 scenarios, enough to fulfill the IWR for all 15 sub-basins with proper water management techniques. Although the Government of Thailand just approved a 20-year (2018–2037) master plan for managing water resources, including a specific goal to achieve water security in the production sector, it is necessary to conduct location-specific studies to devise proper budget plans and strategies. Moreover, at the farm scale, adaptation strategies for water management during the rainfed rice season were proposed following government policies. In line with the government’s efforts to enhance water security, the study suggests constructing reservoirs to store irrigation water as an adaptation strategy for water management at the farm scale. The ponds should measure 20 m in width, 15 m in length, and 3 m in depth to store 900 m$^3$ of water for each hectare of rice to overcome the water deficit and achieve the potential rice yield. Concerns such as maintenance, locations of pond constructions, and water network management to prevent and mitigate flood and drought issues, however, must be addressed with the participation of all stakeholders prior to implementation. This study thus serves as a preliminary step leading to the suitable policies, strategies, and actual action plan to ensure sustainability in the face of climate change.

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**DATA AVAILABILITY STATEMENT**

Data cannot be made publicly available; readers should contact the corresponding author for details.

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