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REGULAR RESEARCH ARTICLE

Adaptive Water Management Strategies for Subsistence Rice Farming Under Projected Rainfall Variability in Drought-Risk Khon Kaen, Thailand

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ABSTRACT

This study offers new insights into adaptive water management for drought-prone subsistence rice farming in Ban Thum Sub-district, Khon Kaen Province, Thailand. By triangulating climate science, agronomy, and farmers' socio-economic conditions, we assess drought risk and identify feasible adaptation strategies. The analysis integrates 30 years of observed climate data (1994–2023), mid-century projections (2024–2053) under SSP 245 and SSP 585, as well as semi-structured interviews with farmers. Stage-specific effective rainfall, crop evapotranspiration, and supplemental water requirements were calculated. Although total rainfall is projected to rise slightly, severe and moderate droughts are expected to remain frequent, particularly during the heading and ripening stages. In drought years, sustaining yields of 200–300 kg rai^{-1} will require an additional 200–1,300 m^3 rai^{-1} of water. Groundwater wells and large farm ponds are technically effective but financially inaccessible to most smallholders; smaller ponds represent a more affordable alternative. The findings underscore the importance of targeted adaptation, including enhanced on-farm storage, optimized irrigation scheduling, and supportive policies such as low-interest loans and infrastructure subsidies. By linking climate projections to local capacities, this study provides a practical roadmap for strengthening rice-farming resilience and safeguarding food security in one of Thailand's most climate-vulnerable regions.

KEYWORDS
Adaptive Water Management; Climate Change Scenarios (SSP245, SSP585); Supplemental Irrigation; Crop Water Requirements; Northeastern Thailand.

1. INTRODUCTION

Rice is among the most important food crops worldwide, occupying roughly 46% of the total agricultural area in Thailand. The Northeast region contributes approximately 60.74% of the nation's rice-growing area (Office of Agricultural Economics, 2024), with the majority of this production primarily serving subsistence farming purposes (Suzuki et al., 1999). Notably, around three-quarters of this farmland relies heavily on rainfall rather than irrigation (Land Development Department, 2022). This rainfed cultivation system renders farmers particularly vulnerable to drought.

The rainy season in northeastern Thailand typically begins in March and follows a bimodal pattern (Fukai et al., 1998; Jongdee et al., 2006). Rainfall gradually increases from May to June, then declines briefly before intensifying again in July. Peak rainfall usually occurs in August and September, declining progressively in October (Fukai et al., 1998). According to the Thai Meteorological Department, between 1985 and 2015, the rainy season in Thailand generally lasted from May to October. In the northeast, the average annual rainfall is about 1,395 mm, with approximately 117 consecutive wet days (CWD) (Sujariya, 2018). Because this region often lacks irrigation, crop yield depends heavily on rainfall during the growing period (Fukui et al., 2000). Climate change may affect rice production by altering temperature and rainfall patterns, which in turn influence crop growth duration, water availability, and photosynthesis (IPCC, 2014; Boonwichai et al., 2021; Boonwichai et al., 2019). Notably, temperatures above 35°C can significantly reduce both the yield and quality of rice (Tipparak & Aroonrungsikul, 2011).

Drought is a significant challenge for rainfed rice production in northeastern Thailand, as it can occur at any point in the growing season. In the broader Mekong region, drought may develop at various stages of rainfed lowland rice growth (Fukai & Ouk, 2012). Kamoshita et al. (2008) classify drought based on its timing during the rice growth cycle into three types: early, intermittent, and late-season. Early-season drought, which occurs during the vegetative stage, may delay the transplanting of older seedlings or reduce the successful establishment of newly sown seeds (Fischer & Fukai, 2003; Babel et al., 2011). Among these types, late-season drought, occurring near the end of the growth cycle, is the most frequent and has a major impact on reducing yield (Jongdee et al., 1997; Fischer et al., 2012; Chhinh & Millington, 2015). In northeastern Thailand, terminal drought is the most common type. It commences during the reproductive stage and persists until maturity, often leading to severe yield losses or even total crop failure (Monkham et al., 2015).

In Khon Kaen Province, located in Northeastern Thailand, drought frequently disrupts subsistence rice production (Yang et. al., 2022). Ban Thum Subdistrict, the study area, is characterized by a high risk of drought, primarily due to its dependence on a single rainy season, limited irrigation infrastructure, and unpredictable rainfall patterns. These conditions pose significant challenges for farmers in achieving stable rice yields and sustaining food security. Furthermore, studies have projected that changes in rainfall magnitude and distribution are likely to intensify drought conditions in the region under future climate scenarios (Mainuddin et al., 2013; Boonwichai et al., 2021).

Previous studies have recommended broad adaptation measures, such as introducing drought-tolerant rice varieties, shifting planting schedules, and improving water management technologies, which have shown promise in mitigating climate-induced yield losses (Babel et al., 2011; Sarker et al., 2012; Mainuddin et al., 2013; Boonwichai et al., 2021). However, these recommendations are rarely connected to field-specific water deficits or to their practical feasibility for individual farmers. As a result, many smallholders are unable to adopt the proposed measures because the associated economic, technical, and policy requirements are not clearly articulated (Arimi, 2014; Pakeechay et al., 2020).

To address this gap, we employ a mixed-method approach that integrates (i) climate analysis based on historical observations and SSP 245/SSP 585 projections, (ii) growth-stage hydrological modelling, and (iii) farmers' socio-economic conditions. This integrated framework generates context-specific water-management strategies that are both practical and locally viable for Ban Thum's smallholders over the next three decades. The resulting roadmap links quantitative water targets to affordable infrastructure and policy instruments, thereby providing extension officers and planners with clear guidance for strengthening rice-farming resilience and food security in one of Thailand's most drought-vulnerable regions.

2. LITERATURE REVIEW

Drawing on a keyword-based literature review of climate-change impacts on rice production and farmers' adaptive responses, the principal findings can be grouped into the following thematic areas.

2.1 Climate-change impacts on rice production

Climate variability affects rice production through multiple interconnected pathways. Table 1 summarizes the main impact channels documented in the literature, illustrating how weather extremes translate into agronomic and economic losses across different regions.

Table 1. Synthesis of Documented Climate-Change Impacts on Rice Production

Impact sub-theme	Key points	Study location	Sources
Yield losses & crop failure	Floods, droughts, heat waves, and erratic rainfall cause empty grains, crop failure, or eliminate an entire season.	Rajshahi (Bangladesh) Northeast Thailand Savannakhet (Laos) Tarlac (Philippines)	Sarker et al., 2012; Penalba & Elazegui, 2013; Faisal et al., 2014; Polthanee et al., 2014; Thampanishvong et al., 2015; Laikasikam, 2020; Pakeechay et al., 2020; Arifah et al., 2023; Souksomphan et al., 2023.
Pest & disease outbreaks	Warmer, humid, and variable climates accelerate brown planthoppers, caterpillars, rice blast, and leaf spot, causing higher pesticide costs.	Indonesia Napal Chiang Mai (Thailand) Huaphan (Laos)	Kamaluddin et al., 2012; Gahatraj et al., 2018; Singsin et al., 2019; Souksomphan et al., 2023; Arifah et al., 2023
Soil & water degradation	• Intense downpours trigger erosion (30–70 % yield loss on slopes) • Low-lying paddies suffer prolonged waterlogging	Philippine hill paddies poorly drained plains in Thailand	Penalba & Elazegui, 2013; Thampanishvong et al., 2015; Kim et al., 2017
Escalating Production Costs & Income Volatility	• Extra fertilizer, pesticides, and pumping cause higher production costs • Crop losses lead to substantial income reductions.	Phatthalung (Thailand) Chiang Mai (Thailand) Northeast Thailand	Faisal et al., 2014; Polthanee et al., 2014; Singsin et al., 2019; Laikasikam, 2020

2.2 Farmers' adaptation strategies

Rice growers respond to climate stress through a spectrum of on-farm adjustments, livelihood diversification, collective action, and technology adoption. Table 2 details the principal strategies reported across the region.

Table 2. Synthesis of Documented Farmers' Climate-Adaptation Strategies

Adaptation Strategy Category	Typical actions	Study location	Sources
Production-level changes	• Stress-tolerant /short duration varieties • Adjust sowing dates • Direct seeding	Central Thailand Northeast Thailand	Ajetomobi et al., 2011; Penalba & Elazegui, 2013;

Adaptation Strategy Category	Typical actions	Study location	Sources
	• Zero-tillage & rotations • Small farm reservoirs, groundwater wells, water pumps • Alternate wetting and drying (AWD) irrigation system	Laos Philippines Nigeria	Polthanee et al., 2014; Singsin et al., 2019; Pakeechay et al., 2020.
Livelihood diversification & risk reduction	• Intercrop/rotate with a low water demand crop • Diversify activity (e.g., livestock) • Supplemental income (non-farm work) • Reduce rice area to improve production efficiency • Seasonal and permanent migration to urban areas to find non-farm jobs	Indonesia Nigeria Thailand	Kamaluddin et al., 2012; Faisal et al., 2014; Kim et al., 2017; Singsin et al., 2019; Saediman et al., 2021; Pakeechay et al., 2020.
Community & network action	• Collective organizations • Participatory water planning • Shared/invest in water infrastructure (e.g., embankments, weirs, drainage canals) • Coordinated irrigation scheduling • Farmer associations for information and finance	Thailand Philippines Bangladesh	Sarker et al., 2012; Penalba & Elazegui, 2013; Singsin et al., 2019; Pakeechay et al., 2020
Technological & information use	• Climate-informed planning • Precision land preparation • Water-saving irrigation • Farm management records	Thailand Philippine Nigeria	Ajetomobi et al., 2011; Thampanishvong et al., 2015; Pakeechay et al., 2020

2.3 Factors shaping adaptive capacity

Adaptive capacity differs among farming households and is shaped by their assets, institutional support, and access to knowledge. Table 3 summarizes the principal factors that enable or hinder adaptation as reported in the literature.

Table 3. Synthesis of Documented Factors Shaping Adaptive Capacity

Factors	Role in Shaping Adaptation	Study location	Sources
Financial & technological capital	Wealthier households can more readily invest in high-cost adaptation measures such as wells, pumps, and improved seeds, allowing them to	Thailand	Sinnarong et al., 2016; Pakeechay et al., 2020

Factors	Role in Shaping Adaptation	Study location	Sources
	adopt these innovations sooner.		
Education & climate-risk awareness	Higher educational attainment and heightened risk awareness accelerate the adoption of new practices.	Nigeria Kenya	Ajetomobi et al., 2011; Arimi, 2014
Extension services	The presence of engaged extension personnel and local agricultural agencies is instrumental in delivering technical assistance and facilitating knowledge transfer.	Philippines Indonesia	Penalba & Elazegui, 2013; Arifah et al., 2023
Government programmes	Policies such as the promotion of climate-resilient rice varieties, agricultural insurance programs, and risk reduction initiatives enhance farmers' adaptation capacity.	Thailand Philippine	Thampanishvong et al., 2015; Pakeechay et al., 2020
Farmer networks & peer learning	Collaborative learning and farmer networks strengthen adaptation by facilitating knowledge sharing and collective action.	Thailand	Thampanishvong et al., 2015

2.4 Policy & local-level measures to strengthen resilience

The reviewed literature identifies a set of actionable measures for governments and development partners to take. Table 4 summarises the interventions most frequently recommended, along with illustrative examples.

Table 4. Synthesis of Documented Policy and Local-level Measures to Strengthen Resilience

Measure	Core actions	Study location	Sources
Supporting Small-Scale Irrigation and Water Storage Systems	Encourage farmers to develop small-scale irrigation infrastructure, water pumps, and community-based water reservoirs to mitigate drought impacts.	Thailand Nepal Philippine	Penalba & Elazegui, 2013; Gahatraj et al., 2018; Pakeechay et al., 2020
Developing Climate-Resilient Rice Varieties	Promote research and the breeding of rice varieties resistant to climate extremes, pests, and diseases, along with risk-mitigation tools such as agricultural insurance.	Bangladesh Thailand	Sarker et al., 2012; Thampanishvong et al., 2015; Pakeechay et al., 2020; Ali et al., 2021

Measure	Core actions	Study location	Sources
Improving Weather Forecasting Systems	Enhance the accuracy of climate predictions and ensure effective communication of weather forecasts to farmers to support decision-making.	Thailand	Pakeechay et al., 2020
Providing Technical and Financial Support	In some regions, governments implement policies such as tax reductions, technical assistance, low-interest credit, and crop insurance programs to aid farmers.	Philippine	Penalba & Elazegui, 2013; Arifah et al., 2023
Promoting Climate Awareness and Training	Encourage climate risk literacy and provide training on modern rice cultivation techniques to help farmers adapt effectively.	Bangladesh Lao PDR	Sarker et al., 2012; Kim et al., 2017
Enhancing Financial Instruments	Policymakers should consider expanding financial tools such as crop insurance, post-disaster tax reductions, and low-interest loans to support farmers during recovery periods.	Philippine Indonesia	Penalba & Elazegui, 2013; Arifah et al., 2023

3. METHODOLOGY

3.1 Study area selection

Based on the Climate Risk and Vulnerability Assessment (CRVA) for Khon Kaen province, Ban Thum subdistrict was identified as the area with the highest drought risk, with a drought risk score of 0.57. It is also the only one subdistrict in Mueang Khon Kaen district classified as a high drought-risk area (see Figure 1). Consequently, this research selected Ban Thum subdistrict, Mueang district, Khon Kaen province, as the study area.

Ban Thum subdistrict (Figure 2) covers a total area of 61.97 km^2, located west of Mueang Khon Kaen district and approximately 14 km away. The topography is characterized primarily by a plateau outside the irrigation zone, with sandy and saline soil. Land use in Ban Thum subdistrict is divided into five categories: agricultural area (32,812.5 rai[1]: 84.7%), community areas and buildings (4,431.25 rai: 11.44%), water sources (275 rai: 0.71%), and public utilities (1,212.5 rai: 3.13%). Agriculture is the primary occupation for 52.79% of the population, with an average landholding of 11.52 rai per household^{-1}. Key economic crops include rice, mango, flowers, and vegetables. Additionally, the local economy provides employment in the public sector, private agencies, agriculture, and industrial factories. The average income per person is 96,103.34 THB[2] yr^{-1} (Data obtained from Ban Thum Municipality).

[1] One rai is equivalent to 0.16 hectares (ha)

[2] According to the exchange rate on April 26, 2025, 1 Thai Baht (THB) was equivalent to approximately 0.027 US Dollar (USD).

3.2 Data collection

The data used in this paper were obtained from two sources: secondary data and primary data. The details are described below.

3.2.1 Secondary data

Observed climatic data were obtained from the Thai Meteorological Department (TMD) at gauge station 381201, the closest station to the study area. Historical climatic data from 1994 to 2023 (the past 30 years) served as baseline data. Two scenarios, SSP245 and SSP585, were selected to project future rainfall for the period from 2024 to 2053 (the next 30 years). The SSP245 scenario represents a moderate emissions pathway, which is a highly plausible future projection, while the SSP585 scenario represents a high-emissions pathway, reflecting a worst-case future forecast. The projected climatic data were obtained from the Hydro–Informatic Institute (Public Organization) (HII) at gauge station 381201. Future projections are divided into three intervals: 2024–2033, 2034–2043, and 2044–2053. These climatic data are utilized to assess effective rainfall, determine crop water requirements for rice cultivation, and evaluate the supplemental water needs for rice farming.

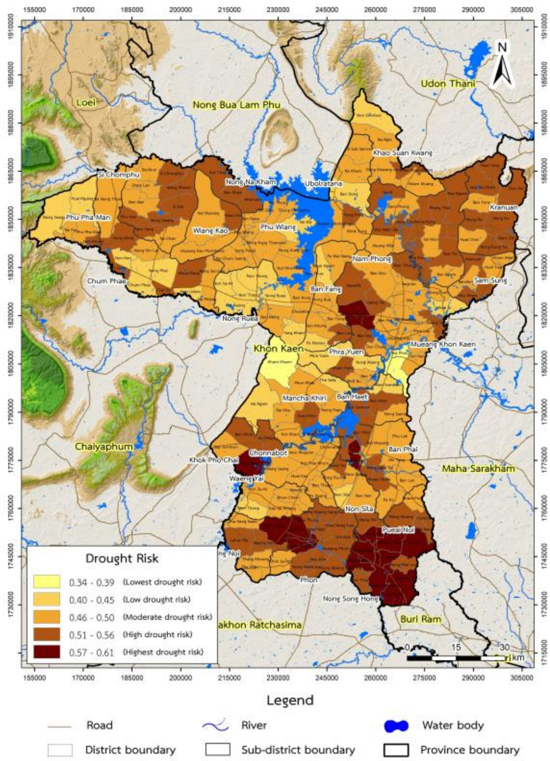

Figure 1. Drought risk areas, Khon Kaen University

3.2.2 Primary data

The rice-production calendar was obtained through semi-structured interviews with three farmers nominated by the sub-district head. These farmers consistently achieve above-average yields and are viewed locally as innovative farmers. A short questionnaire was then administered to all 59 members of the Ban Thum Community Rice Production Center, a farmer group that coordinates seed, inputs, and training. The survey recorded rice yields for (i) the most recent season, (ii) the most severe drought year, and (iii) the best-yielding year, and asked about perceived climate impacts and adaptation measures.

Because the sample comes from a single community, the results are context-specific rather than statistically generalizable to the wider Northeast. Nonetheless, the data provide an empirical basis for designing and piloting drought-adaptation strategies in comparable rain-fed rice systems.

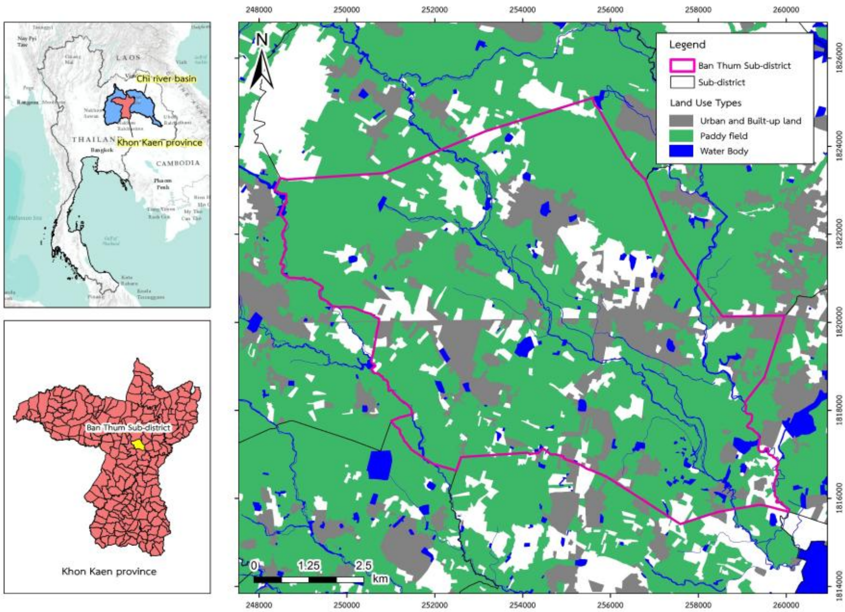

Figure 2. Location and land use map of Ban Thum subdistrict in Khon Kaen province

3.3 Data analysis

3.3.1 Effective rainfall (Peff)

Peff calculations for rice paddy were conducted by analyzing the average monthly rainfall in the study area, using both historical data and projected future data. The monthly rainfall amounts were then evaluated according to the values specified in Table 5. For example, in May 2023, the average rainfall was 166 mm, which falls within the range of 101–200 mm for Weighted Rainfall (WRFL). Therefore, the Peff used for calculation is determined by applying the WRFL multiplier of 0.70. Consequently, the Peff for May 2023 is 116.20 mm (Royal Irrigation Department, 2011).

Table 5. Values for Weighted Rainfall (WRFL) and Effective Rainfall based on monthly rainfall data to calculate ER for rice paddy fields (Royal Irrigation Department, 2011)

Weighted Rainfall (WRFL) (mm)	Effective Rainfall (mm)
0–10	WRFL x 0
11–100	WRFL x 0.8
101–200	WRFL x 0.7
201–250	WRFL x 0.6
251–300	WRFL x 0.55
>300	WRFL x 0.5

3.3.2 Crop water requirement for rice cultivation

In this study, crop water requirements were estimated using climate data through the Reference Crop Evapotranspiration (ETo) calculation, specifically utilizing the Penman-Monteith method (Allen et al., 1998). This method is widely used and accepted in irrigation and agricultural water management studies. The data for these calculations are generally divided into two main categories: geographical coordinates: latitude, longitude, altitude (MSL), and climatic data: average maximum, minimum, and mean temperatures; average relative humidity; average wind speed at 2.00 m above ground (km day⁻¹); and average sunshine hours or cloudiness (0-10). The ETo can be calculated using the following equation:

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \qquad (1)$$

Where:

- ETo = Reference Evapotranspiration (mm day⁻)
- Rn = Net radiation at the crop surface (MJ m^{-2} day^{-1})
- G = Soil heat flux density (MJ m^{-2} day^{-1})
- T = Mean daily air temperature at 2m height (°C)
- Δ = Vapor pressure curve (kPa $°C^{-1}$)
- γ = Psychrometric constant (kPa $°C^{-1}$)
- U_2 = Wind speed at 2m height (m/s)
- (es - ea) = Saturation vapor pressure deficit (kPa)

3.3.3 Supplemental water requirement for rice cultivation (SWR)

The supplemental water requirement for rice is calculated based on two main factors: The Peff and crop water use or crop evapotranspiration (ETc) (Royal Irrigation Department, 2011). The equation for determining crop irrigation demand is as follows:

$$SWR = ETc - Peff \qquad (2)$$

Where:

- SWR = crop irrigation demand (mm $month^{-1}$)
- ETc = crop evapotranspiration rate (mm $month^{-1}$)
- Peff = effective rainfall (mm $month^{-1}$)

ETc is the actual water required by the crop, which includes the amount lost from the field through transpiration and evaporation. In this study, crop water use (ETc) is calculated by comparing it with reference crop evapotranspiration (ETo) and using the crop coefficient (Kc) provided by the Royal Irrigation Department. The crop coefficient used is categorized according to the growth stages of rice, as shown in Table 6. The equation for calculating ETc is as follows:

$$ETc = Kc \times Eto \qquad (3)$$

Where:

- ETc = the crop evapotranspiration rate (mm $month^{-1}$)
- Kc = the crop coefficient
- ETo = crop evapotranspiration (mm $month^{-1}$)

Table 6. The growth stages of rice and rice crop coefficient (Kc) (Royal Irrigation Department, 2012)

Growth stage	Germi-nation	Vegetative		Flowering	Grain Formation		Ripening
		Seedling Stage	Stem Elongation	Panicle Initiation	Booting	panicle exertion	
Days per Stage	16	53		16	47		22
Time period	Jun 15–30	Jul 1-31	Aug 1-22	Aug 23 – Sep 7	Sep 8-30	Oct 1-24	Oct 25 – Nov 15
Crop Coefficient (Kc)	1.0	1.1	1.2	1.3	1.4	1.19	0.9

3.3.4 Projection of drought risk for rice cultivation in Ban Thum sub-district, Khon

Kaen Province

The prediction of drought risk for rice cultivation in Ban Thum sub-district begins with the establishment of criteria to categorize effective rainfall levels for rice production. These criteria are defined based on rice yield. According to data from the 2016/17 growing season, the average rice yield in Northeastern Thailand was 350 kg rai^{-1} (Agricultural Information Center, Office of Agricultural Economics, Ministry of Agriculture and Cooperatives). Using this benchmark, the effective rainfall levels for rice yields were classified into three distinct categories as follows.

a) Critical Drought: Corresponds roughly to a rice yield of 100 kg rai^{-1}
b) Moderate Drought: Corresponds roughly to a rice yield of 200 kg rai^{-1}
c) Adequate Rainfall: Corresponds roughly to a rice yield of 300 kg rai^{-1}

This classification provides a framework for assessing the relationship between rainfall availability and its impact on rice yields, enabling a more precise evaluation of drought risk in the region. Rice yield data from farmers in Ban Thum subdistrict were analyzed for both years with adequate rainfall and years characterized by low or drought conditions. This analysis was conducted in conjunction with effective rainfall specific to the rice-growing season. A trendline was plotted to determine the relationship between effective rainfall levels and rice yields in the area (Figure 3).

The equation derived from the graph is $y = 1.1552x - 485.76$, with a coefficient of determination ($R^2 = 0.6131$). This indicates that approximately 61.31% of the variance in rice yield is explained by effective rainfall in the model.

At the points where the trendline intersects the rice yield axis, effective rainfall conditions can be classified into four categories, as shown in Table 7.

Table 7. Classification of Effective Rainfall Conditions and Corresponding Rice Yields

Classifications	Effective rainfall (mm yr^{-1})	Rice yields (kg rai^{-1})
Severe drought	≤ 500	approximately 100
Moderate drought	> 500 but < 690	approximately 200
Adequate rainfall	≥ 690 but full water requirement for rice	approximately 300
Ample rainfall	≥ full water requirement for rice	exceeding 300

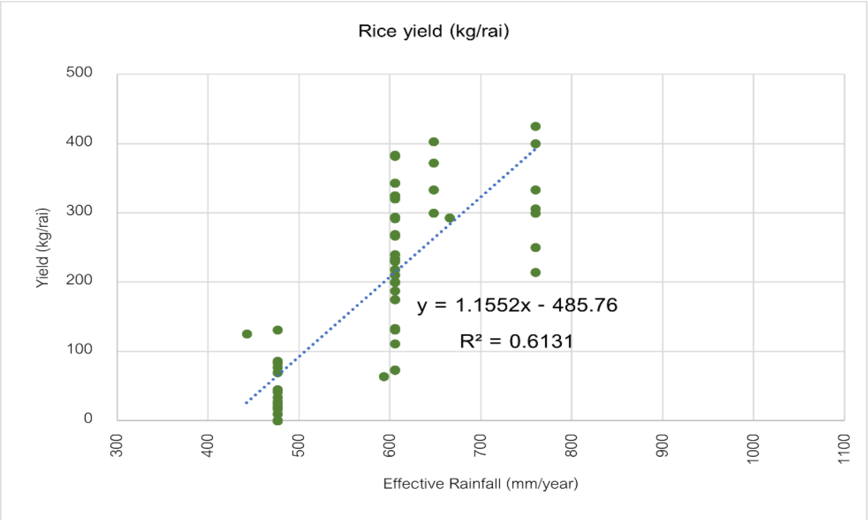

Figure 3. A graph illustrating the relationship between rice yield and effective rainfall during the rice-growing season (June to November) in Ban Thum Sub-district.

These thresholds were then applied to predict future rice cultivation scenarios. The effective rainfall levels were overlaid onto projections of effective rainfall during the rice-growing season for the next 30 years (2024–2053) under two climate scenarios, SSP245 and SSP585. This analysis aimed to forecast future rice cultivation conditions in Ban Thum Sub-district.

4. RESULTS AND DISCUSSION

4.1 Rice cultivation

Rice cultivation in Ban Thum Subdistrict is primarily oriented towards self-consumption, with any surplus sold. Approximately 70% of the harvest is retained for household consumption, while 30% is marketed. People in Northeast Thailand prefer to consume glutinous rice. The main variety grown is RD 6 (glutinous rice), with a smaller amount of KDML 105 (non-glutinous rice).

The rice production calendar is shown in Figure 4. Soil preparation begins with primary plowing between April and May. The duration of soil preparation depends on the availability of machinery or tractors, as most farmers do not own their own tractors and are unable to plow by themselves—primarily because many are elderly. Consequently, they must hire tractors with drivers for this work. When a large number of farmers hire tractors in areas with limited availability, tractor owners are forced to schedule services to accommodate everyone, meaning that farmers cannot choose their preferred timing. As one farmer stated, "*The plowing schedule depends on the tractor; if it comes, we can plow; if it doesn't, we have to wait.*"

Rice planting begins in May or June. Most farmers opt for broadcasting and mechanized dibbling for direct-seeded rice because these methods require lower capital and labor. The cost for broadcasting is 700 THB rai^{-1}, while mechanized dibbling for direct-seeded rice costs 900 THB rai^{-1}. A limitation of the seed-dropping method is that the soil must be dry at the time of seeding. However, since farmers must hire machinery for soil preparation, the timing for preparing the soil and for seeding or seed-dropping cannot be precisely controlled; farmers must wait in line.

Weeds are the primary pest in rice fields. Therefore, once the farmers in Ban Thum subdistrict have broadcast or seed-dropped the rice, they spray chemicals to control the weeds, ensuring that the application occurs within 10 days after seeding. Following this, fertilizer is applied to nourish the rice plants. Most farmers in Ban Thum apply fertilizer twice during the growing season. The first application occurs from the seedling stage to the tillering and panicle elongation stage (or from early July to late August), and the second application is made at the panicle initiation stage (or in September). However, the timing depends on the water availability in the fields, as fertilizer cannot be applied when the fields lack water.

From the booting stage to the heading stage—that is, from mid-September to late October—farmers must pay the utmost attention to monitoring the water levels in their rice fields. This period is critical because rice requires the highest amount of water for grain development in order to produce fully formed, high-weight grains (Deng et al., 2022). Interviews with farmers revealed that during the booting-to-heading phase, effective rainfall is insufficient to meet the crop's water requirements; consequently, farmers must secure supplemental water. One farmer remarked, *"Without water during this period, the rice will die, and there will be no yield." Another added, "Water is the most important factor in rice cultivation. If you had to choose between flooding and drought, flooding is preferable because at least there is water. In Ban Thum, flooding is neither severe nor prolonged, and while it may necessitate some replanting, a yield is assured if water is available. In contrast, drought creates numerous problems for rice cultivation, such as the rapid growth of weeds, pest infestations, and even rodents feeding on the rice plants."* A further comment was, *"Water is the most essential element in rice farming; as long as there is water, farmers can work with peace of mind and achieve high yields."*

Farmers must be diligent in maintaining their rice fields by inspecting the crops, assessing weed density, and monitoring water levels on a daily basis. For instance, if weeds are observed in the field, they must be removed; if a bund is leaking, it should be promptly repaired to retain water. If the soil is dry but there is still water available in a pond or stream, it must be pumped into the field; however, if there is no water, no remedial action can be taken. Moreover, if yellowing or wilting of rice plants is noticed, farmers must immediately determine whether the cause is disease, insect infestation, or rodent damage. In cases of disease or insect problems, appropriate chemicals should be applied; if rodents are the issue, the grass along the bund should be cut to eliminate their habitat; and if the yellowing is due to a nutrient deficiency, farmers will purchase and apply fertilizer. As one farmer explained, *"I observe the rice plants; if I feel they are not growing well (if the rice does not look healthy), I go home and try to gather money to buy fertilizer for the field, but if I have no money, there is nothing I can do."*

Farmers in Ban Thum subdistrict harvest their rice between early and mid-November by hiring local combine harvesters as well as external contractors, both of which charge a uniform rate of 1,000 THB rai^{-1}. The harvesting schedule is determined by the availability of combined harvesters, which typically operate on a zonal basis, allowing farmers with fields in proximity to be harvested simultaneously. Rice yields among farmers in Ban Thum subdistrict fall into two scenarios: under normal rainfall conditions, the average yield is 343 kg rai^{-1}, while under severe drought conditions, the average yield drops to 84 kg rai^{-1}.

Interviews with farmers revealed several major impacts of climate change on rice production. The most commonly mentioned issues were a noticeable drop in yields (90%), water shortages or long dry spells during the growing season (80%), unpredictable rainfall—especially rain falling during the rice drying period (80%), and stunted rice growth due to lack of water (76.67%).

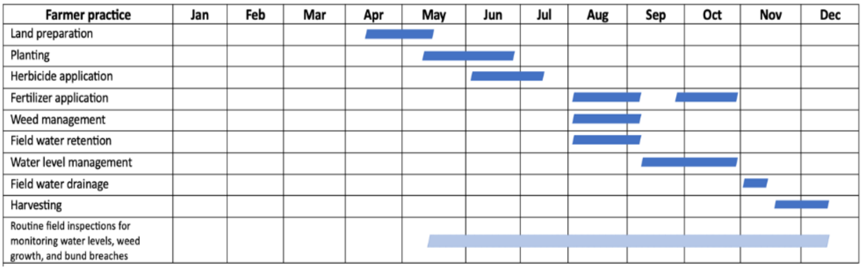

Figure 4. Farmers' agricultural practices in rice production.

For adaptation, the primary strategy adopted is to enhance water security, particularly through the construction of on-farm ponds (61.63%). Among these, 56.6% have a storage capacity of less than 1,500 m^3. However, the majority of ponds (58.49%) can only supply water during the rice production season. A smaller proportion (37.74%) is usable year-round, while the remaining 3.85% is insufficient even for a single growing season due to water shortages. Additionally, groundwater extraction through well drilling accounts for 20.3% of the adaptation practices.

4.2 Projected and effective rainfall

4.2.1 Rainfall

Figure 5 presents projected future rainfall patterns under two greenhouse gas emission scenarios: SSP245 and SSP585. The projections indicate an overall increase in rainfall, with a pronounced rise in September. Notably, the SSP585 scenario anticipates a more substantial increase compared to SSP245, suggesting that higher emission trajectories may exacerbate climate change impacts. Furthermore, under SSP585, the onset of increased rainfall is projected to occur earlier in the year, potentially affecting agricultural practices and water resource management strategies.

Table 8 presents a comparison of rainfall changes over different future time periods (2024-2053) compared to the baseline period (1994-2023) under two greenhouse gas emission scenarios. Rainfall is projected to increase in the first period (2024-2033) under both scenarios. However, during the second period (2034-2043), rainfall decreases under SSP585 (-2.96%), while it increases slightly under SSP245. By 2044-2053, rainfall shows significant increases under both scenarios, with a higher increase in SSP245 (16.35%) than in SSP585 (14.77%).

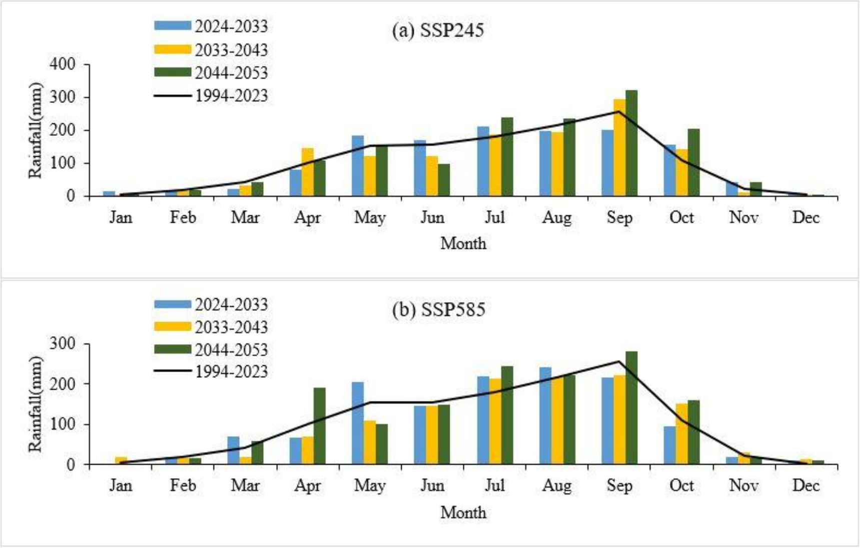

Figure 5. Graphs comparing future rainfall projections under two different greenhouse gas emission scenarios: SSP245 and SSP585

Table 8. Scenarios of future changing rainfall for the study area

Baseline (1994-2023)	Future timescales	SSP245 scenario	Change	SSP585 scenario	change
Rainfall 1264.24 mm	2024-2033	1,310.22 mm	3.64%	1,313.67 mm	3.91%
	2034-2043	1,277.30 mm	1.03%	1,226.80 mm	-2.96%
	2044-2053	1,470.92 mm	16.35%	1,450.97 mm	14.77%

4.2.2 Effective rainfall (Peff)

Figure 6 illustrates the variability of Peff across three conditions: historical data (1994-2023) and future projections under the SSP245 and SSP585 scenarios. The box plot for historical data (1994-2023) indicates that Re ranged between 449.00 mm and 890.30 mm, with an average of 632.12 mm.

In the SSP245 scenario, the average Peff in the 2033s and 2043s is quite similar, at 655.11 mm and 638.65 mm respectively, reflecting only a slight decline between these periods. However, by the 2053s, the average Peff increases notably to 735.46 mm. The 2053s presents the broadest range, between 592.74 mm and 949.83 mm, suggesting a wetter and more extreme climate compared to the historical baseline.

For the SSP585 scenario, the average Peff in the 2033s is 656.83 mm, which decreases slightly to 613.40 mm in the 2043s. However, by 2053, the average increases to 725.49 mm. The 2033s shows the highest variability, with a wide range from 339.66 mm to 1,036.34 mm. In contrast, the 2053s presents a narrower range, from 502.77 mm to 980.10 mm.

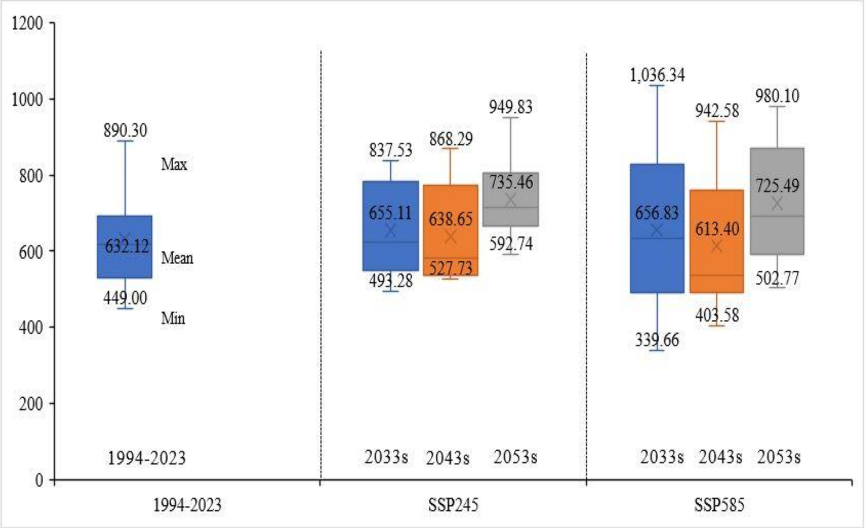

Figure 6. The variability of Peff under three different conditions: historical data (1994-2023) and future projections under two scenarios, SSP245 and SSP585.

4.3 Projection of drought risk for rice

As shown in Figure 7, under Scenario SSP245, there are a total of 8 years characterized by Severe drought conditions (red bars), defined as years in which the annual Peff is less than or equal to 500 mm. During these years, farmers can produce rice only 100 kg rai-1. In addition, there are 10 years of experience with Moderate drought conditions (green bars), defined as years with an annual Peff greater than 500 mm but less than 690 mm; during these years, the rice yield is limited to 200 kg rai-1. Finally, there are 12 years with Adequate rainfall conditions (blue bars), years in which the annual Peff exceeds 690 mm but is less than the full water requirement for rice, allowing farmers to produce rice 300 kg rai-1, which is sufficient for household consumption. Under Scenario SSP585, the pattern differs slightly. There are also 8 years with Severe drought conditions. However, there are 14 years with Moderate drought conditions. In contrast, there are 8 years with Adequate rainfall conditions.

4.4 Adaptive water management strategies under projected rainfall variability on rice farming in Ban Thum sub-district, Khon Kaen Province

4.4.1 Implementing irrigation scheduling for rice based on the crop's actual water demands

As shown in Table 9, which details the water requirements for rice cultivation across various growth stages under the future climate scenarios SSP245 and SSP585 between 2024 and 2053 (subdivided into three periods: 2024–2033, 2034–2043, and 2044–2053), several notable trends emerge. Historically, water demands more than 180 m^3 rai^{-1} yr^{-1} were observed during the emergence, panicle initiation, panicle exertion, and ripening stages, with the highest demand of 269.88 m^3 rai^{-1} yr^{-1} recorded at the onset of the ripening stage.

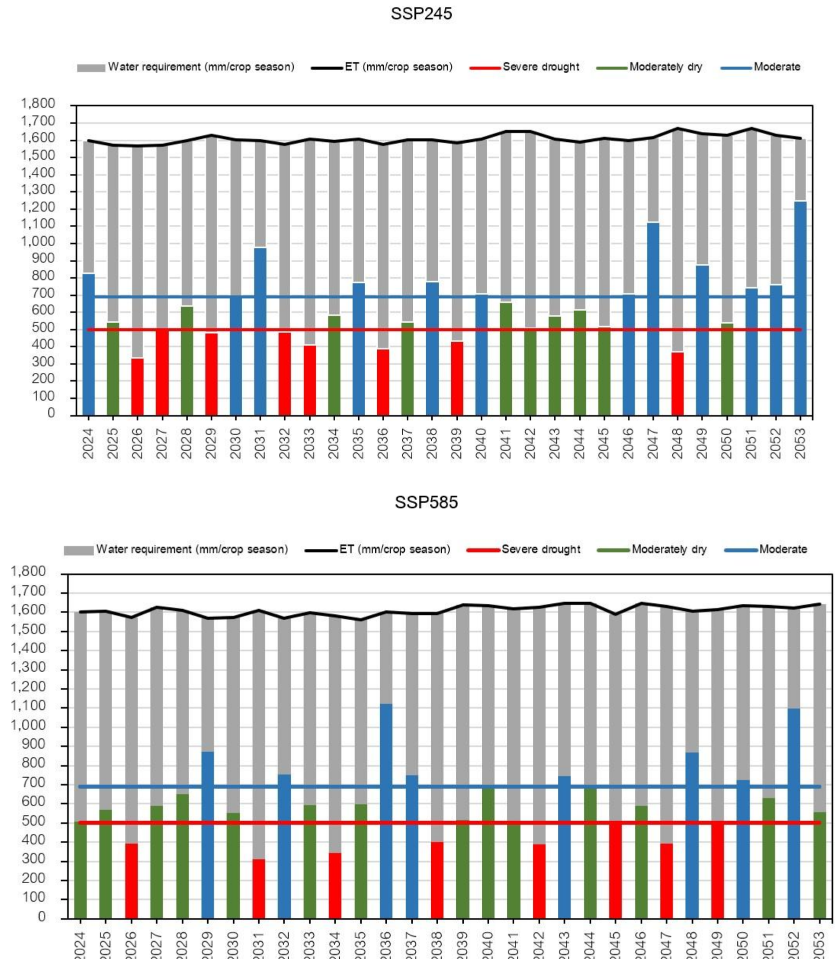

Figure 7. Projected drought risk for rice cultivation in Ban Thum subdistrict, under two future scenarios (SSP245 and SSP585) during the period 2025 -2053).

Under the SSP245 scenario, between 2024 and 2043, rice cultivation is projected to require more than 180 m^3 rai^{-1} yr^{-1} during emergence, stem elongation, and ripening. Notably, the water demand peaks at 281.01 m^3 rai^{-1} yr^{-1} during the initial ripening stage in the 2024s and rises further to 281.89 m^3 rai^{-1} yr^{-1} in the 2034s.

In the future, under the SSP585 scenario, rice cultivation is projected to require more than 180 m^3 rai^{-1} yr^{-1} during the emergence and ripening stages in all three periods. Notably, water demand peaks at over 270 m^3 rai^{-1} yr^{-1} during the early ripening stage in the 2034s, reaching 284.27 m^3 rai^{-1} yr^{-1} in the 2024s and further increasing to 290.72 m^3 rai^{-1} yr^{-1} in the 2044s.

Across all time periods, the early ripening stage remains the period of highest water demand. Both climate pathways indicate a consistent rise above the 180 m^3 rai^{-1} threshold during the emergence stage, suggesting that early-season rainfall uncertainty becomes a second critical factor necessitating supplemental irrigation. This trend highlights the importance of pre-planting water storage or timely refilling of farm ponds to secure adequate water supplies. Furthermore, the high-emissions pathway (SSP585) is projected to increase peak water demand by approximately 5–8% compared to SSP245, corresponding to an additional 10–20 m^3 rai^{-1}.

Table 9. Seasonal Water Requirements for Rice Growth Stages under Historical and Projected Climate Scenarios SSP245 and SSP585 (m^3 rai^{-1} yr^{-1}, 1994–2053)

Growth stage		Period	1994-2023	SSP245			SSP585		
				2024-2033	2034-2043	2044-2053	2024-2033	2034-2043	2044-2053
Establishment	Emergence	15-30 Jun	214.73	196.48	243.50	242.64	227.51	244.90	259.55
Vegetative stage	Seedling	Jul	117.72	81.10	105.63	48.19	84.03	77.29	57.16
	Stem elongation stage	1-22 Aug	125.89	191.63	209.05	162.99	123.95	172.24	188.56
Flowering	Panicle initiation	23-31 Aug	200.00	165.19	177.18	164.53	195.77	167.12	144.20
		1-7 Sep	164.56	170.60	158.25	140.41	145.51	174.12	124.91
Grain formation	Booting	8-30 Sep	99.92	172.12	65.34	48.66	171.04	131.86	123.47
	Panicle exertion	1-24Oct	188.65	123.51	138.81	76.22	185.63	137.23	117.17
Mature stage	Ripening stage	24-31Oct	269.88	281.01	281.89	291.49	284.27	277.57	290.72
		1-15 Nov	231.58	222.76	240.94	217.73	238.81	224.33	258.88

The findings of this study highlight the importance of incorporating temporal variability in water supply into irrigation scheduling for rice-growing areas, particularly during the flowering and maturity stages, when the crop is most sensitive to moisture stress. Mainuddin (2013) demonstrated that the application of an additional 190–380 m^3 rai^{-1} of water during the reproductive stage can effectively prevent significant yield losses. This result underscores the critical need for targeted water management during key developmental phases to safeguard rice productivity. Furthermore, the results are consistent with those of Zhu et al. (2025), reinforcing the conclusion that integrating effective rainfall data into irrigation practices can substantially enhance water management efficiency. When natural rainfall meets approximately 27–35% of the crop's total water requirements during specific growth phases, the reliance on supplemental irrigation is markedly reduced. Implementing such an approach not only optimizes water-use efficiency but also reduces production costs and alleviates pressure on scarce water resources. The integration of real-time effective rainfall data into irrigation management strategies is therefore essential for strengthening the resilience of rice production systems in the face of increasing climate variability. Access to timely and localized rainfall information enables farmers to adjust their irrigation practices with greater precision and responsiveness, thereby supporting both yield stability and water conservation efforts.

4.4.2 Planning for supplemental water requirements for rice cultivation

The amount of water required for rice cultivation in the Ban Thum subdistrict under future projection scenarios is shown in Figure 8. Under the SSP245 scenario, during the period 2025 to 2053, the supplemental water required to achieve a target rice yield of over 300 kg rai-1, indicative of ample rainfall conditions, is projected. The annual supplemental water demand fluctuates, with the highest requirement reaching 1,298.5 m^3 rai^{-1} in 2048. Therefore, to ensure yield stability, farmers should prepare for up to 1,300 m^3 rai^{-1} of supplemental water annually. However, projections indicate that in 7 of the 30 years, farmers will face severe drought conditions. During these years, to attain a moderate yield of approximately 200 kg rai-1, farmers should secure at least 200 m^3 rai^{-1} of supplemental water annually. Additionally, in 18 of the projected years, rainfall will be insufficient to achieve optimal yields, though not classified as a severe drought. Farmers will require at least 400 m^3 rai^{-1} of supplemental water to attain yields of around 300 kg rai-1.

Under the SSP585 scenario, projections suggest that farmers will face severe drought conditions in only one year throughout the 2025–2054 period. To cope with this condition, securing at least 120 m^3 rai^{-1} of supplemental water will be necessary. However, in 11 out of the 30 years, farmers are expected to encounter moderate drought conditions. During these years, achieving a rice yield of approximately 300 kg rai-1 will require at least 400 m^3 rai^{-1} of supplemental water annually. In general, the supplemental water needed to achieve yields exceeding 300 kg rai-1 is projected to fluctuate throughout the period. The highest estimated requirement is 1,297 m^3 rai^{-1} in 2031. Therefore, to maintain yield stability and minimize risk, farmers should plan to have up to 1,300 m^3 rai^{-1} of supplemental water available annually.

These projections highlight the comparatively lower drought risk under the SSP585 scenario compared to SSP245. However, variability in water needs still emphasizes the importance of adaptive water management strategies and improved on-farm storage capacity to ensure consistent rice production under changing climatic conditions.

In summary, farmers require at least 200 m^3 rai^{-1} of supplemental water to produce a minimum rice yield of 200 kg rai-1. To achieve a yield of 300 kg rai-1, at least 400 m^3 rai^{-1} of water is needed. For yields exceeding 300 kg rai-1, approximately 1,300 m^3 rai^{-1} of water is required.

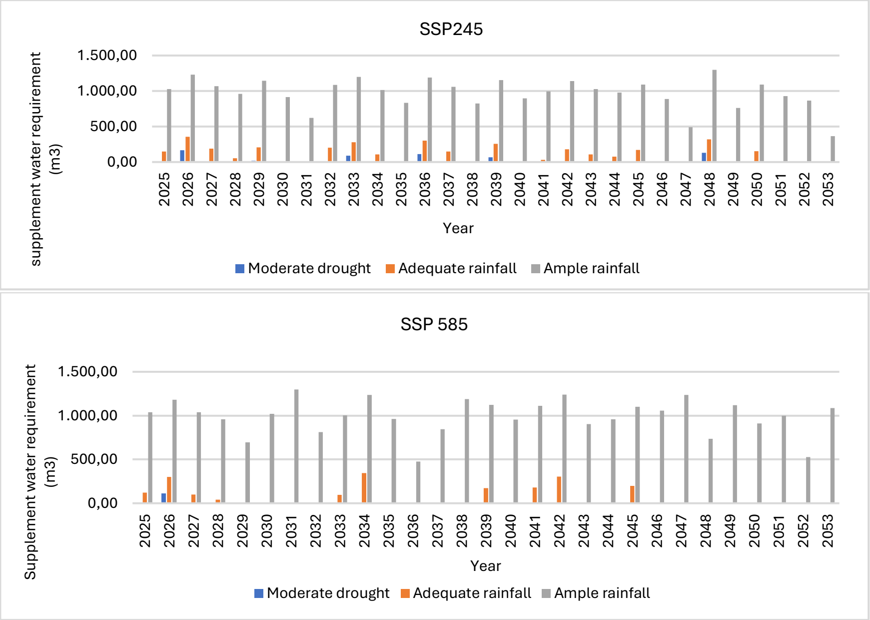

Figure 8. Projected supplemental water requirements for rice cultivation in Ban Thum subdistrict, under two future scenarios (SSP245 and SSP585) during the period 2025 -2053.

In practice, the most Peff management option is to use groundwater because it provides an unlimited supply. However, drilling a groundwater well is expensive, with a single well costing between 40,000 THB and 50,000 THB, depending on land characteristics. This expense may be unaffordable for some farmers. An alternative approach is to construct farm ponds for water storage. For example, a pond with a capacity of 1,300 m^3 rai^{-1} may cost between 32,500 THB and 52,000 THB (approximately 25–40 THB per m^3), depending on land characteristics, which is comparable to the cost of drilling a groundwater well. Nevertheless, building such a large pond may also be prohibitive for certain farmers. Therefore, constructing smaller ponds may be a more accessible option. For instance, a pond with a capacity of 400 m^3 might cost between 10,000 THB and 16,000 THB, while a pond with a capacity of 200 m^3 may cost between 5,000 THB and 8,000 THB. These smaller ponds are likely to be affordable for most farmers. Therefore, most farmers may not be able to meet the full water requirements for rice cultivation; however, ensuring an adequate water supply during the most critical periods could serve as a viable alternative.

Groundwater serves as a reliable supplemental water source for rice cultivation but requires careful management to prevent ecological impacts and resource depletion. Groundwater extraction for rice irrigation should remain within sustainable safe-yield limits, as indicated by the Groundwater Potential Maps published by the Department of Groundwater Resources. These maps help mitigate risks such as declining water tables, land subsidence, and degradation of aquatic ecosystems. Supporting this approach, Arlai et al. (2018) developed sustainable extraction thresholds using groundwater flow models in northern Thailand, while Kaewdum & Chotpantarat (2021) and Kaewdum & Surinkum (2022) employed GIS analyses to map groundwater potential and recharge zones, highlighting the importance of aligning extraction with local recharge capabilities.

Farm ponds have emerged as a cost-effective and practical solution for enhancing water security in rice farming in the context of climate change. Boonwichai et al. (2021) recommended constructing farm ponds of approximately 900 $m^3\ ha^{-1}$ (≈144 $m^3\ rai^{-1}$) to stabilize rice yields during dry spells, highlighting their accessibility for smallholders. Similarly, Kabir et al. (2025) demonstrated that pond-deepening offers positive economic returns, reinforcing the financial viability of investing in pond infrastructure to address water scarcity. Additionally, Arunrat & Sereenonchai (2022) showed that farm ponds support not only irrigation but also income diversification through rice–fish co-culture systems, offering higher economic returns and improved ecosystem services. Together, these studies confirm that farm ponds are a sustainable, economically sound adaptation strategy for small-scale rice farmers facing increasing climatic risks.

5. CONCLUSION

Based on an integration of historical (1994–2023) and future (2024–2053) climate data under SSP245 and SSP585 scenarios, this study confirms a growing threat of moderate to severe drought in Ban Thum Subdistrict, Khon Kaen Province. These events can drive effective rainfall well below thresholds needed for healthy rice growth, particularly at heading and ripening. If no adaptive measures are implemented, rice yields may fall to as low as 100 kg rai-1.

Findings indicate that farmers may require 200–1,300 m^3 of supplemental water per rai to sustain acceptable yields. Smaller on-farm ponds or occasional groundwater pumping can offset severe-moderate drought conditions, but wells or larger reservoirs become essential for consistently higher yields. However, drilling costs, pond construction, and the technical demands of scheduling irrigation reveal disparities in farmers' adaptive capacity.

On-farm ponds and groundwater wells emerge as promising strategies to meet these water demands. Nonetheless, high installation costs often exceed farmers' budgets, pointing to a need for policy intervention in the form of affordable financing, technical assistance, and expanded community-based irrigation infrastructure. Taken together, the findings stress that building resilience to climate change in this region depends on both engineering solutions, such as appropriately sized farm ponds, and supportive policies that enable smallholders to adopt water-saving innovations.

Overall, this research highlights the importance of forward-looking water management. By quantifying future drought risks, aligning them with practical adaptation strategies, and underscoring the importance of policy support, the study provides a clear roadmap for safeguarding rice yields, sustaining local livelihoods, and enhancing food security in one of Thailand's most drought regions.

6. POLICY IMPLICATIONS AND FUTURE RESEARCH DIRECTIONS

6.1 Policy implications

The recommended policy measures for both scenarios are outlined below.

1) The Land Development Department's on-farm pond construction program currently provides fixed-size designs that often do not align with individual farm areas or water requirements. To enhance storage efficiency and cost-effectiveness, policy should: (i) Permit flexible pond sizing through modular design options or scaled subsidies tailored to each farm's area and projected water demand; (ii) Integrate the guidelines developed in this study into extension services to guide farmers in pond planning and management, and (iii) Pond excavation guidelines should require anti-seepage measures (e.g., pond wall lining, soil compaction, and sufficient pond depth) to ensure reliable, year-round water storage.
2) The Department of Groundwater should deliver training on sustainable groundwater use and promote drilling practices that minimize environmental impacts.
3) Subdistrict administrative organizations should establish year-round public reservoirs to provide supplemental irrigation in dry seasons. Under Thailand's decentralization framework, local governments are responsible for securing water for both domestic and agricultural needs. Policies should also enable the integration of large public reservoirs or irrigation canals with on-farm ponds to ensure continuous water distribution.
4) On-farm ponds and other storage structures help, but they cannot meet irrigation needs in dry years when rainfall is too low to refill them. Farmers must therefore receive clear, timely climate information each season so they can adjust cropping area, variety choice, and irrigation schedules to the water that is likely to be available. To support this, governments should: (i) Improve the accuracy of seasonal rainfall forecasts. (ii) Create user-friendly channels such as mobile alerts, community radio, or extension bulletins, that translate forecasts into simple planting and water-management guidelines. (iii) Incorporate climate-risk awareness and forecast use into routine extension programmes.
5) Farmers should organize water-user groups or cooperatives to manage agricultural water collectively and to advocate for local government budget allocations for irrigation infrastructure. Policymakers ought to facilitate the formation of these farmer-led associations, provide technical and financial support for community-managed irrigation systems, and integrate them into existing extension services. By pooling resources and coordinating water management, these groups can buffer against rainfall variability and enhance smallholder resilience to climate change.

6.2 Future research directions:

1) Future research should focus on making climate forecasts more accurate for the medium term (3–6 months) and long term (over one year). Currently, reliable forecasts extend only 7–14 days, which is too short for farm planning. Better seasonal and yearly forecasts would guide farmers in selecting crops, setting

planting dates, and managing irrigation, thereby helping agriculture cope with climate change.

2) Future research should investigate farmers' adaptive capacity to climate change. This work can (i) classify distinct farmer types, (ii) pinpoint the key factors that influence adaptation, and (iii) identify which areas merit priority support. Such insights would allow planners to target scarce resources more effectively, especially when budgets are constrained.

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