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ASSESSING DROUGHT-PRONE AREAS IN NON-IRRIGATED AREAS USING WATER ACCOUNTING AND THE WEAP MODEL

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Abstract

The objectives of this study were to develop an annual water accounting framework and analyze drought-prone areas using the WEAP model under five different scenarios at the sub-district level for the Lam Chiang Krai River Basin. The study focused on the non-irrigated Lam Chiang Krai River Basin, Thailand, with analysis conducted at the sub-district level. Key research instruments included a Water Accounting Framework and the Water Evaluation and Planning (WEAP) model. Secondary data encompassing meteorological, hydrological, land use, crop calendar, and population figures were collected from relevant government agencies. Data analysis involved calculating water demands (agricultural using FAO Penman-Monteith, domestic, and environmental) and utilizing the WEAP model, integrated with water accounting principles, to simulate monthly water balance under five off-season rice cultivation scenarios. This identified drought-prone areas and assessed water shortage magnitudes, with model performance validated (R^2 = 0.74-0.88). Results revealed that expanding off-season rice cultivation significantly increased agricultural water demand by up to 30.63% compared to only wet-season cultivation. Crucially, under the 100% off-season rice scenario, total water demand surpassed effective rainfall, eliminating water outflow from the basin. While overall annual rainfall appeared sufficient, localized water scarcity emerged due to intensive agricultural water utilization patterns, particularly during the dry season months. The study confirmed the effectiveness of the integrated WEAP-water accounting approach for detailed drought vulnerability assessment in data-scarce, non-irrigated regions. Findings offered spatially and temporally explicit insights into water stress levels, directly informing local stakeholder decisions. This information was vital for developing targeted sub-district water management plans, optimizing existing resource allocation, and guiding the strategic placement and design of essential small-scale water infrastructure. The research strongly emphasized the critical need for carefully managing off-season rice cultivation to ensure sustainable water availability and enhance drought resilience within the Lam Chiang Krai River Basin.

Keywords: Water Accounting, Drought area, WEAP model, Non-irrigated areas

Introduction

Both management and sustainability of water resources were presented as a key role of water accounting at the river basin level. It prepared insights into water inflows/outflows and efficient water usage across various sectors, such as agriculture, industry, and household consumption (Pedro-Monzonís et al., 2016, p.182; Sawassi et al., 2024, p.3). This is particularly important in the context of Thailand, where issues of water scarcity and unequal distribution can significantly affect people's livelihoods and economic development. Water accounting also provided essential data for equitable water allocation, ensuring that different sectors would receive appropriate water resources while supporting sustainable water management (Sipayung et al., 2024, p.94).

Moreover, water accounting helped in monitoring environmental conditions, such as water quality and ecosystem situation, which were vital for preserving biodiversity in river systems. It also enhanced the ability to adapt to climate change by assessing the impacts of changing weather patterns on water availability, thus enabling better strategic adaptation planning (Dembélé et al., 2023; Hunink et al., 2019). In policymaking, water accounting played a critical role in supporting decisions related to infrastructure development, drought management, and water conservation. For transboundary river basins, water accounting promoted international cooperation for the sustainable use of shared water resources and helped reduce potential conflicts (Cravens et al., 2021; Vardon et al., 2025). In summary, water accounting was an important tool for ensuring water security, environmental protection, and enhancing social and economic sustainability at the basin level (Yao et al., 2021, p.217).

The WEAP model was a model for integrated water resource management, whose applications span geographies to address water-related challenges and to promote sustainable practices (Shahraki et al., 2016). The WEAP model became a globally accepted tool for addressing complex water resources challenges (Agarwal et al., 2018, p.38). Its ability to adapt to different geographical contexts and sectors made it valuable for planners and policymakers who focused on its application in water allocation and adapt to climate change in urban and agricultural management and cross-border cooperation (Rastegaripour et al., 2024; Hamdi et al., 2023).

Although previous studies explored water resource management and drought in Thailand using tools such as WEAP and water accounting (Kosa et al., 2024, p.24; Tingsa et al., 2024, p.15), detailed sub-district level assessments in non-irrigated basins like the Lam Chiang Krai remained limited, particularly regarding the quantitative impacts of expanding off-season rice cultivation. This study addressed this gap by applying an integrated Water Accounting and WEAP modeling framework to evaluate water balance scenarios at a high spatial resolution. By isolating the effects of off-season rice on local water scarcity risks, the research provided actionable insights for evidence-based water resource planning and management, offering critical support to local authorities operating in vulnerable, rainfed agricultural areas.

Research Objectives

The objectives of this study were to develop an annual water accounting framework and analyze drought-prone areas using the WEAP model under five different scenarios at the sub-district level for the Lam Chiang Krai River Basin.

Research Methods

Methodology

For research design, this study adopted quantitative research design, primarily utilizing simulation modeling complemented by descriptive analysis to systematically assess drought vulnerability in the non-irrigated Lam Chiang Krai River Basin. The core of the methodology involved applying the Water Evaluation and Planning (WEAP) model to simulate monthly water balance, identify potential water shortages, and evaluate drought vulnerability across five distinct scenarios representing varying levels of off-season rice cultivation at the sub-district level. This simulation modeling approach was underpinned by a descriptive analysis using a detailed water accounting framework. This framework quantified crucial hydrological inputs, demands, and potential outflows (including effective rainfall, agricultural, domestic, and environmental water requirements) for each sub-district, providing essential data inputs for the WEAP model and enabling a comprehensive description of the basin's water status under different conditions. The integration of these quantitative methods provided a robust approach to understanding complex water resource dynamics and identifying drought-prone areas within the study's specific context.

This study consisted of two main processes which were water accounting analysis and drought scenario simulation using the WEAP model, as detailed below.

1. Water Accounting Analysis

This study conducted a surface water accounting analysis at the sub-district level, excluding groundwater due to data limitations. Total inflow (Gross Inflow, GI) was defined as effective rainfall (Ra), while net inflow (Net Inflow, NI) consisted solely of effective rainfall, as river discharge was excluded given the non-irrigated nature of the basin. Water depletion included agricultural evapotranspiration (ET) and domestic use (DU), classified as process consumption (P), with 10% of agricultural demand allocated for ecosystem maintenance as beneficial consumption (B). Outflow was represented by uncommitted outflow (UC), calculated as the surplus of rainfall after meeting all water demands.

Based on the principles of water accounting outlined above, the calculation and analysis of the relevant parameters were conducted through the following study procedures:

1.1 As for data collection and field survey, daily data collection and field surveys were conducted, including land use maps, meteorological data (maximum temperature, minimum temperature, maximum relative humidity, minimum relative humidity, wind speed, and sunshine hours), geographic locations of weather stations, crop calendars, reservoir and small pond data, streamflow data for the Lam Chiang Krai River, and effective rainfall data. These data were obtained from the Hydrology Division, Regional Irrigation Office 8, the Thai Meteorological Department, and the Land Development Department.

1.2 Effective rainfall referred to the portion of total rainfall that fell within an area and could be efficiently utilized for specific purposes. In the context of irrigation, effective rainfall signified the amount of rainfall that fell on cultivated land and was beneficial for crop growth, meaning that crops could utilize it effectively or that it could substitute for irrigation water that needed to be supplied to the cultivated areas. For the assessment of effective rainfall in this study, the effective rainfall data was collected from the Royal Irrigation Department.

1.3 Water usage for agriculture represented the highest demand within the hydrological cycle due to the predominant agricultural activities in most areas, as depicted in the land use maps for each watershed. The calculation of agricultural water usage involved the following steps:

1) Land use was classified using GIS data which was derived from land use maps. Initially, land use was categorized into agricultural areas (with specific crops identified, such as rice, cassava, corn, and various fruit and vegetable crops), forested areas, grasslands and scrublands, community and industrial areas, and water source areas. The study area primarily cultivated crops, including rice, sugarcane, and cassava presented in Figure 1.

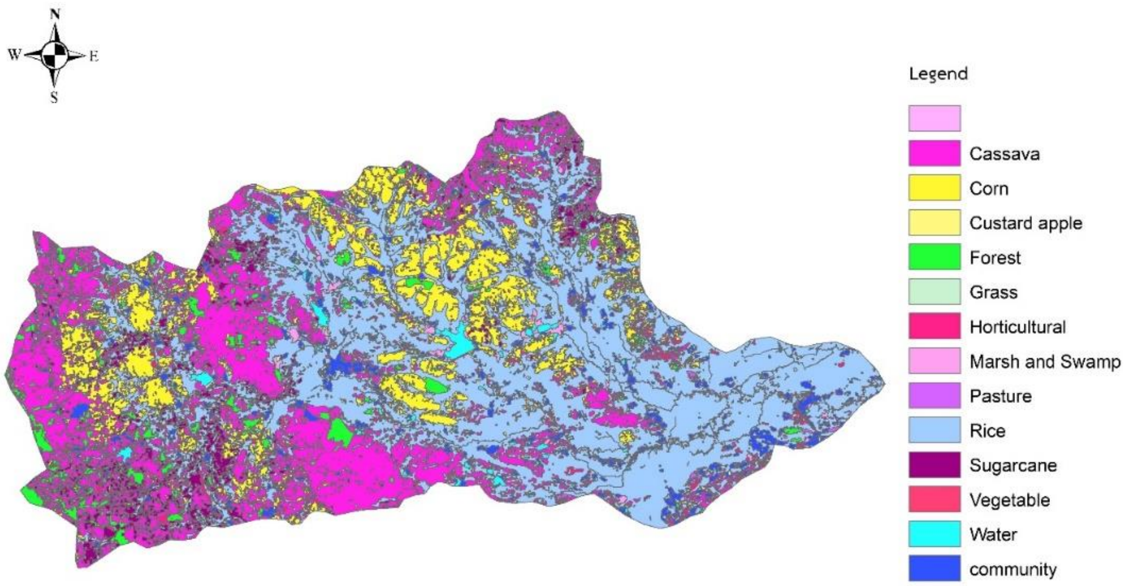


Figure 1 Land use map for the Lam Chiang Krai River Basin
in Nakhon Ratchasima Province, Thailand

2) Daily crop water use was calculated using the FAO Penman-Monteith equation (Allen et al., 1998) based on key meteorological variables—temperature, relative humidity, wind speed, sunshine hours, and station location—from Muang Nakhon Ratchasima, Pak Chong, and Chok Chai districts. Data spanning January 1, 1979, to September 30, 2010, were used to ensure representative meteorological and hydrological conditions, as severe flooding events after October 2010 could distort the climatic baseline. Daily reference evapotranspiration for each sub-district was computed accordingly, with agricultural calendars and field data coordinated through the Nakhon Ratchasima Provincial Agriculture Office.

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T_M + 273.2}u_2(e_s - e_a)}{\Delta + \gamma(1 - 0.34u_2)} \quad (1)$$

Where ET_o is reference crop evapotranspiration (mm d^{-1}), R_n is net radiation ($MJm^{-2}d^{-1}$), G is soil heat flux (MJ $m^{-2}d^{-1}$), T is air temperature (°C), e_s is saturation vapor pressure at air temperature (kPa), e_a is vapor pressure of air (kPa), u_2 is wind speed at a height of 2 meters (m s^{-1}), Δ is slope of saturation vapor pressure curve at air temperature (kPa C^{-1}) and γ is psychrometer constant (kPa C^{-1}).

Crop water use was calculated by applying fixed crop coefficients (Kc) of 1.49 for rice, 0.92 for sugarcane, and 0.80 for cassava, multiplied by the average monthly reference evapotranspiration derived from the FAO Penman-Monteith equation. Agricultural water demand was then assessed under five scenarios to capture the impact of expanding off-season (dry-season) rice cultivation: (1) baseline demand for various crops and wet-season rice; (2) addition of off-season rice covering 25% of rice areas; (3) 50% coverage; (4) 75% coverage; and (5) full (100%) coverage of off-season rice.

1.4 In calculating water usage for domestic purposes, the analysis was conducted at the sub-district level, considering the population of each sub-district for the year 2024. The water demand for municipal use was set at 120 liters per person per day. The total population in the Lam Chiang Krai River Basin is 671,693 individuals, which leads to the calculation of monthly water demand for domestic purposes.

1.5 Environmental water requirement was defined as 10% of the water allocated for agriculture. The calculated values of effective rainfall, water demand for agriculture and domestic use, and environmental water requirements, originally assessed at a daily time scale, were subsequently aggregated into monthly and annual values.

2. Drought Scenario Simulation Using the WEAP Model

The Water Evaluation and Planning (WEAP) model, developed by the Stockholm Environment Institute (SEI) since 1995, was a flexible and user-friendly tool for integrated water resource management. WEAP functioned both as a database and a forecasting and policy analysis tool, enabling the evaluation of water allocation scenarios among competing users (Siebe & Purkey, 2015, pp. 1-4). Based on water balance principles, WEAP could be applied to a range of systems, from municipal supply and agriculture to complex inter-basin transfers. It simulated hydrological and hydraulic processes— including runoff, baseflow, groundwater recharge, and reservoir operations— and supports water demand management, water quality analysis, ecological assessments, and financial evaluations of investment and project benefits.

The WEAP model study process consisted of four key steps, as outlined below:

1) The study began with defining the current water allocation system. Nodes for each sub-district were assigned based on their actual locations on the map. If a sub-district was traversed by the Lam Chiang Krai River, excess water would be transported downstream to the next sub-district. For sub-districts where the Lam Chiang Krai was absent, the only source of water inflow was effective rainfall.

A critical operational assumption configured within the WEAP model concerned water allocation priorities under conditions of limited supply. Consistent with standard water management practices prioritizing basic human needs, domestic water demand nodes were assigned the highest priority (Priority 1). This ensured that, in the simulation, domestic water requirements were met first whenever available water was insufficient to satisfy all demands. Agricultural water demand nodes were assigned the second priority (Priority 2). Consequently, agricultural water needs would only be fully met after domestic demands were satisfied. Environmental flow requirements, calculated as a percentage of agricultural demand in the water accounting phase, implicitly shared the priority level of agriculture in this setup. No other significant allocation priorities or complex operating rules were defined, focusing the simulation on the fundamental competition between domestic and agricultural sectors driven by varying off-season rice cultivation levels.

2) The current accounts represented the existing water allocation system, incorporating water demand, water supply sources, and pollution levels in water bodies. Monthly water balance data, derived from the water accounting analysis in the previous step, were integrated into the WEAP model. The spatial resolution of the model was at the sub-district level within the Lam Chiang Krai River Basin, while the temporal resolution was monthly.

Model validation was performed by comparing WEAP simulation results with manual calculations based on WEAP's computational framework and equations. The calibration process utilized monthly water balance data from 2005, while the validation process used data from 2008. The resulting coefficient of determination (R^2) values were 0.88 for calibration and 0.74 for validation, indicating that the WEAP model is reliable for use in this study.

3) Scenarios were designed to explore and formulate alternative water allocation strategies for the future. These included the five scenarios previously mentioned.

4) The evaluation phase involved analyzing water availability and its associated impacts. The WEAP model was employed to identify drought-prone areas, determine the volume and duration of water shortages, and calculate the percentage of available water relative to total demand. The spatial resolution remained at the sub-district level, while the temporal resolution was monthly.

Study Area Description

Nakhon Ratchasima Province, located upstream of the Mun River Basin—one of the major basins in Northeastern Thailand— has experienced rapid economic and social development, necessitating strategic water management amidst persistent annual droughts. Despite the presence of four large reservoirs (Lam Takhong, Lam Phra Phloeng, Mun Bon, and Lam Sae), water scarcity remains a challenge. The study area, the Lam Chiang Krai River Basin, originates from the watershed ridge between the Mun and Pasak Basins, covering approximately 2,958 km^2 with an average annual runoff of 263 million m^3. It spans several districts across Nakhon Ratchasima and Chaiyaphum Provinces. The basin includes two key reservoirs, Upper and Lower Lam Chiang Krai Reservoirs, the latter facing significant sedimentation and evaporation issues. In 2020, efforts to improve storage capacity raised the Lower Reservoir's capacity from 27.7 to 37.7 million m^3.

Research Results

The findings regarding the significant impact of off-season rice cultivation on increasing agricultural water demand and localized water scarcity in the Lam Chiang Krai Basin aligned consistently with recent research conducted in the neighboring Lam Takhong River Basin (Kosa et al., 2024, p.29). Both studies, utilizing similar methodologies (Water Accounting and WEAP model), identified agricultural water use, particularly during the dry season, as the primary driver of water stress in these non-irrigated areas of Nakhon Ratchasima province. This concordance underscored the widespread challenge posed by intensified agriculture on water resources in the region and reinforces the validity of the modeling approach for capturing these critical dynamics. While the specific magnitudes of water deficit and the precise sub-districts affected differed due to the unique characteristics of each basin, the underlying trend and major contributing factors identified in this study were corroborated by findings from the Lam Takhong, strengthening the overall conclusions presented here.

The key findings from the annual water accounting calculations and drought scenario simulations using the WEAP model were as follows:

1. Agricultural Water Demand

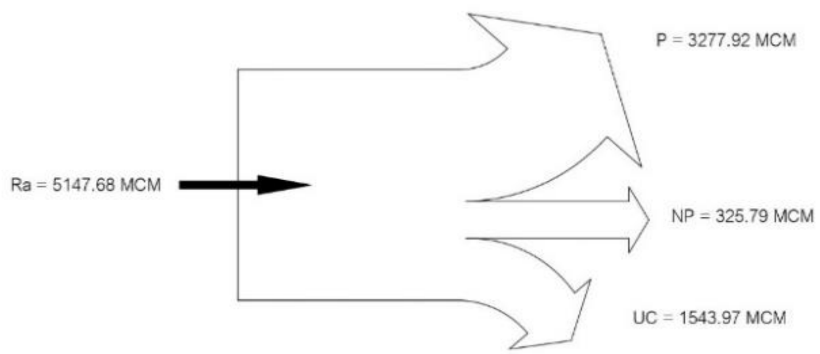
The results of the calculations for agricultural water demand across all five scenarios were summarized in Table 1, which revealed that the cultivation of off-season rice significantly increased the agricultural water demand. Specifically, the percentage increased in water demand when fully cultivating off-season rice (Scenario 5) compared to the exclusive cultivation of wet-season rice (Scenario 1) for the Lam Chiang Krai River Basin is 30.63%.

Table 1 Summary of Monthly Agricultural Water Demand for Scenarios 1-5 (Million Cubic Meters)

Month	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
January	169.54	238.63	307.73	376.83	445.93
February	155.18	218.42	281.66	344.91	408.15
March	181.14	254.96	328.79	402.61	476.44
April	167.53	235.81	304.10	372.38	440.66
May	403.53	403.53	403.53	403.53	403.53
June	388.45	388.45	388.45	388.45	388.45
July	413.82	413.82	413.82	413.82	413.82
August	391.53	391.53	391.53	391.53	391.53
September	324.52	324.52	324.52	324.52	324.52
October	346.06	346.06	346.06	346.06	346.06
November	150.41	211.71	273.01	334.31	395.61
December	166.21	233.95	301.69	369.42	437.16
Total	3257.90	3661.39	4064.87	4468.36	4871.85

2. Annual Water Accounting Analysis

The annual water accounting results for the Lam Chiang Krai Basin showed that total rainfall amounts to 5,147.68 million cubic meters. Water use across Scenarios 1 to 5 ranged from 3,603.71 to 5,379.05 million cubic meters, corresponding to 70.00% to 104.49% of total rainfall. Although agricultural water demand was the dominant use, it remained relatively low compared to total rainfall under Scenarios 1–4, allowing for outflows of 1,543.97 to 212.46 million cubic meters, respectively. Under Scenario 5, complete off-season rice cultivation resulted in a water deficit of 231.38 million cubic meters, eliminating outflow and exacerbating water scarcity. Thus, full off-season rice cultivation was not sustainable basin-wide; cultivation should be limited to no more than 75% of the agricultural area to maintain basin water balance. These findings were illustrated in Figure 2, focusing on non-irrigated areas of the Lam Chiang Krai Basin.



Scenario 1

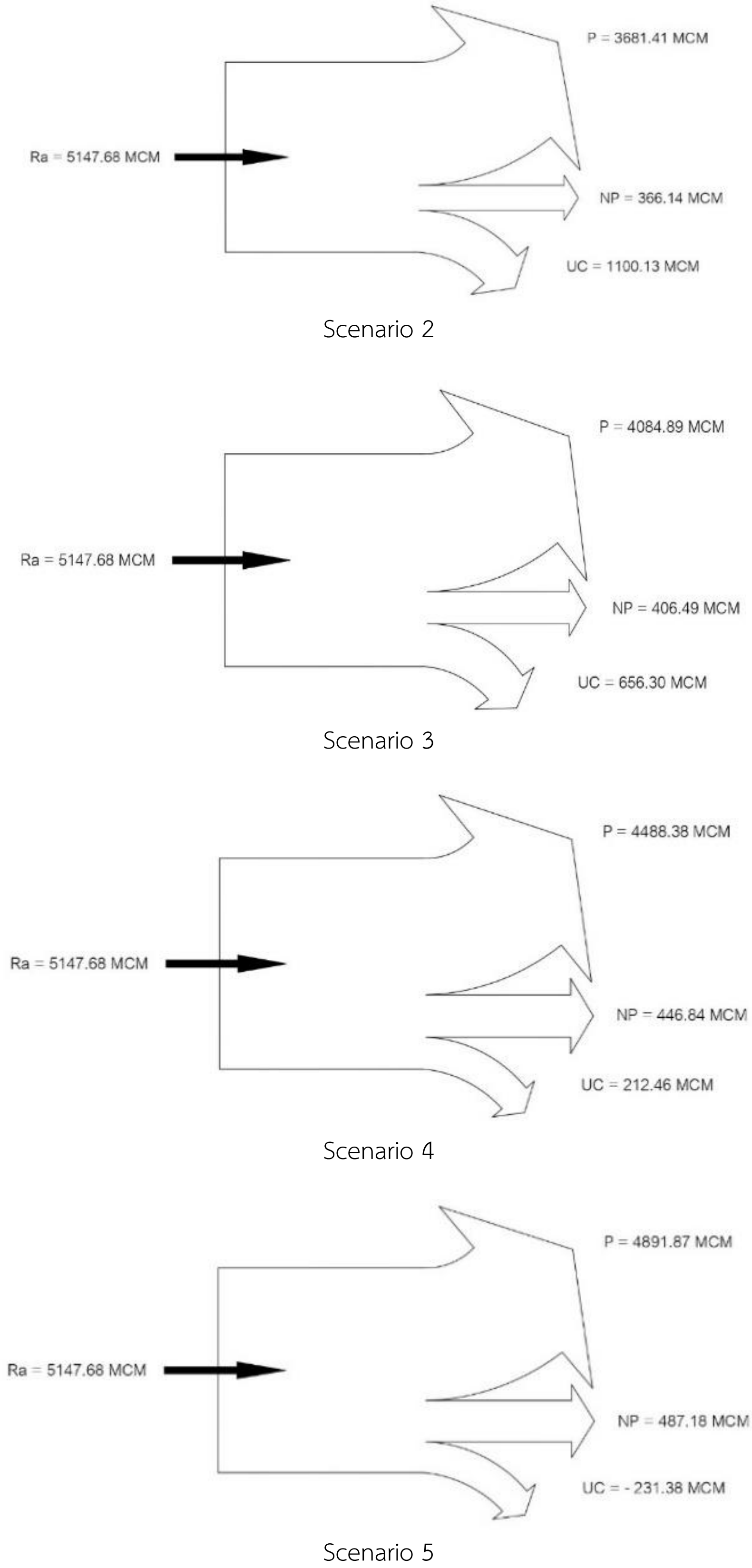


Figure 2 Annual water accounting for areas outside the irrigation zone scenario 1 to 5

3. Analysis of Water Scarcity using WEAP Modelling

The WEAP-based water balance analysis assessed the adequacy of water supply under five scenarios and identified sub-districts experiencing water scarcity, defined as months with a water deficit exceeding 20% of demand (Charoensawat & Marjang, 2021, p.246). Across all scenarios, 24 sub-districts in the Lam Chiang Krai Basin were classified as water scarce. Notably, Ban Prang Sub-district (Khong District) consistently faced deficits exceeding 100 MCM annually, while Non Muang Sub-district (Kham Sakae Saeng District), Don Muang, Nong Bua Noi, and Nong Ya Khai Sub-districts (Sikhiu District) exceeded 50 MCM. Sema Sub-district (Sung Noen District) and Samrong Sub-district (Non-Thai District) recorded deficits above 40 MCM annually.

Monthly analysis revealed Prang Sub-district (Khong District) as the area with the highest water scarcity from May to November and overall annually across all scenarios. Other sub-districts with critical shortages included Hoi Long, Nong Krad, and Krisana, varying by month and scenario. Furthermore, several sub-districts demonstrated water shortages throughout all 12 months, with 0% demand site reliability, including Nong Ngua Lueam (Chaloem Phra Kiat District), Pho Klang, Cho Ho, Si Moom (Mueang Nakhon Ratchasima District), Samrong (Non Thai District), Nong Suang (Khamsakaesang District), and multiple sub-districts in Sikhiu District.

The heightened water scarcity observed in certain sub-districts, notably Ban Prang (Khong District) and Samrong (Non-Thai District), could be attributed to a confluence of factors evident from the input data and simulation results. Ban Prang exhibited a particularly high proportion of agricultural land, especially areas potentially suitable for rice cultivation, leading to substantial water demand that escalated sharply under off-season scenarios. Compounding this, its location potentially received less effective rainfall compared to upstream areas (if applicable or mention other factors like soil type if known). Samrong Sub-district, while perhaps having slightly lower agricultural intensity than Ban Prang, faced persistent deficits likely due to a combination of moderate agricultural demand, significant domestic water requirements driven by population density, and potentially limited local surface water availability (as it might lack direct access to the main river channel or sufficient storage ponds), making it highly sensitive even to moderate increases in water stress, especially during dry months. These examples illustrated how the interplay between land use intensity, population pressure, and localized hydrological conditions drove the varying levels of drought vulnerability across the basin.

Discussion

This study, which integrated the WEAP model with water accounting to assess drought vulnerability in non-irrigated areas of the Lam Chiang Krai River Basin, found that the expansion of off-season rice cultivation had significant impacts on the water balance, resulting in localized water shortages—particularly during the dry season. These findings aligned with the study by Kosa et al. (2024, p.29) in the nearby Lam Takhong Basin, which employed a similar methodology. Comparisons could also be drawn with the work of Kimala and Kositsakulchai (2013, p.74) in the Sedone River Basin in Lao PDR, which, while using the SWAT model, focused on water accounting and the impacts of varying irrigation scenarios. Both cases indicated a regional trend whereby changes in agricultural water use exerted considerable pressure on water resources.

Furthermore, the study by Lolupiman (2021, p.1), which developed a drought monitoring system using a drought risk index for Thailand based on factors such as rainfall and historical drought-prone areas, reinforced the importance of assessing vulnerability at multiple spatial scales for effective water resource management. A key contribution of the present study lied in its finer-scale assessment—conducted at the sub-district level and using monthly water balance analysis—providing a more localized and specific understanding than the daily provincial-level assessments by Ticha et al. or the annual HRU-based averages used by Kimala and Kositsakulchai (2013, p.77). This enabled more targeted micro-level water management and drought adaptation strategies tailored to each sub-district within the Lam Chiang Krai Basin.

The finding that off-season rice cultivation (a dry-season crop) increased water demand and led to water scarcity was consistent with general water management principles. It also resonated with the research of Noichaisin (2019), who assessed water shortage areas in Sa Kaeo Province by considering climate variability impacts (El Niño/La Niña), which also affected water availability for dry-season agriculture. Although Likhit's study primarily used GIS and expert weighting methods, its results similarly highlighted the vulnerability of agricultural zones to water fluctuations. In contrast, the use of WEAP and water accounting in this study offered a robust quantitative tool to analyze the effects of dry season cropping on water balance at the sub-district level.

This differed from the work of Sukkasem et al. (2020, p.3), who applied the Temperature Vegetation Dryness Index (TVDI) using MODIS satellite data to assess soil moisture and agricultural drought in the Phetchaburi Basin. While their approach provided spatial information on drought conditions, it did not directly simulate water balance dynamics. In contrast, the present study made a novel contribution through scenario-based analysis of off-season rice cultivation expansion, ranging from 0% to 100% of the suitable area. This level of detail was not commonly addressed in previous studies and enabled the identification of a "tipping point" or sustainable cultivation threshold for the basin (e.g., not exceeding 75% of agricultural land). This information was particularly valuable for policymakers and agricultural extension agencies in advising farmers to reduce water shortage risks and enhance the resilience of rainfed agricultural systems.

Finally, the integration of water balance modeling and satellite-based drought indices could complement each other in confirming high-risk areas and periods of drought induced by agricultural practices, especially during the dry season. Such comparisons reinforced the validity of the findings and demonstrate the study's contribution to providing actionable insights for water management in non-irrigated, rainfed regions.

Conclusion and Suggestions

This study evaluated drought vulnerability in the non-irrigated areas of the Lam Chiang Krai River Basin using water accounting and the WEAP model. Results highlighted that off-season rice cultivation significantly increased agricultural water demand, leading to localized water scarcity despite adequate rainfall overall. Inefficient water use and a lack of interconnected infrastructure further exacerbated drought risks, particularly in specific sub-districts. The findings underscored that unregulated expansion of off-season rice cultivation pushes water demand beyond sustainable levels, impacting both agriculture and domestic use. Sustainable water management must therefore integrate regional water availability with localized water use practices.

Building on the findings, this study recommended targeted actions for stakeholders. That is, Local Administrative Organizations should utilize the vulnerability assessment for drought planning and prioritizing small-scale water infrastructure in high-risk areas like Ban Prang and Samrong. Additionally, regional agencies could use the data for optimizing allocation and long-term planning. While farmer support should be focused on promoting water-saving practices and drought-tolerant crop alternatives to off-season rice, particularly during critical dry season months (January-April). Furthermore, the research underscored the need for aligning agricultural policies with water availability and suggested future research priorities, including integrating groundwater analysis, assessing socio-economic impacts, and evaluating climate change effects using the established WEAP framework, to foster sustainable water management and long-term resilience in the Lam Chiang Krai River Basin.

Recommendation for using to benefit

To address drought vulnerability and improve water management in the Lam Chiang Krai River Basin, the following strategies were recommended:

1. Targeted Water Allocation: Apply WEAP-based, spatially focused water allocation, prioritizing high-risk sub-districts such as Ban Prang, and optimize reservoir releases in alignment with localized water balances.

2. Agricultural Diversification and Efficiency: Promote crop diversification and the adoption of water-saving technologies, such as drip irrigation and rainwater harvesting, through targeted policies and incentives.

3. Interconnected Water Infrastructure: Invest in expanding and upgrading storage, canal, and pipeline systems to enable efficient basin-wide water transfers.

4. Strengthened Water User Associations (WUAs): Establish and empower sub-district-level WUAs to manage allocation, monitor usage, resolve conflicts, and lead conservation efforts, supported by regular stakeholder engagement.

5. Enhanced Drought Monitoring and Early Warning: Develop an integrated real-time system combining rainfall, streamflow, groundwater, and demand data to enable proactive drought mitigation.

Recommendation for future research

To advance sustainable water management in the Lam Chiang Krai River Basin, future research should focus on:

1. Groundwater Assessment: Conduct comprehensive hydrogeological surveys, monitor groundwater dynamics, and develop robust groundwater models to define sustainable extraction limits.

2. Climate Change Modeling: Develop climate models to project changes in rainfall, temperature, and evapotranspiration; integrate projections into WEAP to assess water system sensitivity and adaptation strategy effectiveness.

3. Economic Valuation: Undertake a comprehensive economic valuation of water resources, encompassing agricultural, domestic, industrial, and ecosystem service values to inform allocation and pricing policies.

4. Social-Ecological Resilience: Investigate the interplay between human communities and the environment to identify key social, economic, and ecological factors contributing to resilience against drought.

5. Governance Analysis: Critically assess the existing water governance framework to identify institutional barriers and foster enhanced stakeholder collaboration.

General Applicability and Future Directions

The analytical framework integrating water accounting principles and the WEAP model, as demonstrated in this study, had broad applicability beyond the Lam Chiang Krai River Basin, particularly for assessing drought vulnerability and water management in non-irrigated or data-scarce regions with agricultural water stress. To adapt this framework to new areas, key steps include: (1) compiling site-specific data, (2) reconfiguring the WEAP model to fit the new basin, (3) recalibrating and validating the model with historical data, and (4) developing relevant water management scenarios. The approach could serve as a basis for comparative drought studies, assist policymakers in integrated river basin planning, and aid local drought preparedness. Future research could expand by incorporating groundwater interactions, water quality, or economic analyses for more comprehensive assessments.

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