

INTEGRATED WATER ACCOUNTING AND WEAP MODELING FOR SUSTAINABLE WATER MANAGEMENT IN RAINFED AREAS: CASE STUDY IN NAKHON RATCHASIMA, THAILAND

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Abstract

Agricultural production in Thailand remains highly vulnerable to climatic variability, particularly drought, which recurrently disrupts rainfed systems in non-irrigated basins. This study integrates water accounting and the Water Evaluation and Planning (WEAP) model to assess water availability, agricultural demand, and drought vulnerability in four sub-basins of Nakhon Ratchasima Province in northeastern Thailand: Lam Takhong, Lam Phra Phloeng, Lam Chiang Krai, and Upper Mun. Monthly water accounts were constructed at subdistrict and basin scales, while WEAP simulations evaluated 24 scenarios that varied dry-season rice intensity and tested a crop-substitution strategy with sweet corn. Based on the results, dry-season rice cultivation was the principal driver of water deficits in Lam Chiang Krai and Upper Mun, with shortages concentrated during February–April. Substituting rice with sweet corn reduced deficits by 37–38%, highlighting the potential of crop diversification to strengthen drought resilience. Structured interviews with 879 farmers and a survey of parameters for 79 small reservoirs confirmed late dry-season water stress, limited groundwater potential, and strong community demand for small-scale storage and drought-tolerant crops. Methodologically, the integration of water accounting with dynamic modeling provided complementary insights into seasonal imbalances, spatial drought hotspots, and adaptation options. These findings underscore the need for adaptive, demand-focused water management strategies to enhance the resilience of rainfed agriculture in Southeast Asia.

Keywords: Water accounting; Water Evaluation and Planning (WEAP) model; Rainfed agriculture; Drought resilience; Crop diversification

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Introduction

Agricultural production in Thailand remains highly vulnerable to climatic variability, particularly drought, which recurrently affects large portions of non-irrigated areas. In provinces such as Nakhon Ratchasima in the northeastern region, recurrent droughts disrupt crop yields, threaten rural livelihoods, and exacerbate water insecurity despite the presence of large reservoirs. Often, non-irrigated farmlands, which depend predominantly on rainfall and small-scale water sources, face water shortages during the dry season and occasional flooding during the rainy season. This duality of extremes underscores the complexity of managing water resources under conditions of seasonal imbalance and spatial heterogeneity. Addressing drought in rainfed areas requires not only the expansion of water storage and distribution infrastructure but also the development of integrated tools that provide a transparent understanding of water availability and demand at multiple scales (Babel *et al.*, 2024; Khadka *et al.*, 2024; Ongsomwang & Sritarapipat, 2025).

Globally, rainfed agriculture has been identified as highly sensitive to drought, with yield gaps arising less from rainfall deficits per se and more from suboptimal management of soil moisture and “green water.” Research has called for a paradigm shift toward integrating rainwater harvesting, supplemental irrigation, and soil-plant-atmosphere management to enhance resilience (Rockström *et al.*, 2010). Furthermore, reviews have emphasized that crop water management must incorporate conservation tillage, mulching, and agronomic strategies aligned with climatic conditions to sustain productivity under water stress (Bodner *et al.*, 2015). Beyond agronomy, drought has cascading socio-economic consequences, exacerbating rural poverty and migration in rainfed regions (Wlostowski *et al.*, 2022). Syntheses of global evidence indicate that water scarcity stems from climate variability, land degradation, and governance failures, necessitating holistic responses involving crop diversification, innovation, and institutional reform (Ingrao *et al.*, 2023).

Methodological advances have strengthened drought risk assessments in non-irrigated systems. Probabilistic approaches quantify conditional risks of drought and flood (Yang *et al.*, 2023), while copula-based models capture non-stationary dynamics in hydrological and climatic variables (Das *et al.*, 2022). New irrigation-sensitive indices distinguish between irrigated and non-irrigated systems, improving drought monitoring in rainfed

areas (Tang *et al.*, 2023). In addition, conceptual perspectives have reframed drought resilience through the lens of “green water,” recognizing soil moisture management as fundamental to sustaining productivity in rainfed agriculture (Lankford and Agol, 2024).

In Thailand, studies across multiple scales have confirmed the acute vulnerability of rainfed farming systems. For example, basin-level assessments in the Mun River Basin revealed that hazard - exposure - vulnerability frameworks effectively capture agricultural drought risks and document local adaptation measures (Babel *et al.*, 2024). Additionally, remote sensing analyses in the Thung Kula Ronghai region highlighted the severity of drought stress on Hom Mali rice (Varnakovida *et al.*, 2025), while national-level projections have indicated intensifying drought and precipitation extremes under climate change (de Oliveira-Júnior *et al.*, 2025). Crop-specific analyses, such as rainfed maize in the Upper Nan Basin, further illustrate the direct threats of climate-induced drought to food security and rural livelihoods (Bastola *et al.*, 2024). Comparative studies have confirmed that irrigated agriculture is markedly more resilient, maintaining yields during mild-to-moderate drought, whereas rainfed agriculture experiences sharp declines (Zhang *et al.*, 2023; Chen *et al.*, 2025).

Despite these insights, in Thailand, there remains limited integration of water accounting and dynamic modeling in rainfed contexts. Previous work has focused primarily on irrigated catchments, reservoir operations, or regional-scale hydrological studies, with insufficient empirical evidence for smallholder systems outside irrigation networks. Little is known about how integrated water accounting and the Water Evaluation and Planning (WEAP) model can be applied to identify drought-prone subdistricts, quantify the impacts of dry-season rice cultivation, and explore crop-switching strategies to mitigate water stress. This knowledge gap constrains the design of localized drought mitigation policies and weakens resilience planning for communities heavily dependent on rainfall and small-scale water sources.

Therefore, the current study aimed to address these gaps by integrating water accounting and WEAP modeling to evaluate water availability and agricultural demand in four river basins in Nakhon Ratchasima Province: Lam Takhong, Lam Phra Phloeng, Lam Chiang Krai, and Upper Mun. The objectives were: (1) to construct comprehensive water accounts at subdistrict and basin scales; (2) to

simulate current water management scenarios to assess spatial and temporal water deficits; and (3) to identify drought-prone areas, while evaluating alternative cropping strategies, including drought-tolerant crops. By combining quantitative analysis with field-based stakeholder insights, this research provides a holistic assessment of water scarcity in rainfed systems and proposes evidence-based strategies for sustainable water management and drought resilience in northeastern Thailand.

While this study provides a robust integration of water accounting, WEAP modeling, and stakeholder perspectives, several limitations must be acknowledged. First, the analysis did not incorporate future climate change projections, meaning that the results represent current and historical hydrological conditions rather than long-term climate scenarios. Second, groundwater dynamics were not modeled explicitly due to limited data availability, even though groundwater pumping is an important coping strategy for farmers. Third, the crop substitution analysis was limited to sweet corn as a representative drought-tolerant crop; future studies could broaden the scope to include additional crop alternatives. Addressing these limitations should enhance the predictive capacity of integrated water assessments and strengthen their application in long-term adaptation planning.

Description of study area

This study focused on four sub-basins of the Mun River Basin in Nakhon Ratchasima Province, northeastern Thailand: Lam Takhong, Lam Phra Phloeng, Lam Chiang Krai, and Upper Mun (Figure 1). These catchments are within the headwater zone of the Mun River (a major tributary of the Mekong River system) and are representative of non-irrigated agricultural landscapes where drought and seasonal water imbalances are recurrent challenges.

The climate of the study area is governed by a tropical monsoon regime, with annual rainfall in the range 1,000-1,300 mm. Rainfall is concentrated between May and October (wet season), while November to April constitutes the dry season, with extended low flows. This pronounced seasonality shapes both water availability and agricultural practices. Land use is dominated by rainfed paddy rice, cassava, and maize, supplemented by smaller areas of other upland crops.

The basins differ greatly in their hydrological infrastructure. Lam Takhong (3,318 km²) and Lam Phra Phloeng (2,068 km²) are regulated by large multipurpose reservoirs, which provide relatively strong hydrological buffering against drought. In contrast, Lam Chiang Krai (1,987 km²) and Upper

Mun (2,296 km²) lack major irrigation structures and depend heavily on rainfall, small reservoirs, and farm ponds. These structural contrasts make them more vulnerable to seasonal drought and highly relevant for testing the impacts of alternative water management and crop substitution strategies.

Figure 1 illustrates the locations of the four study sub-basins and rainfall stations within Nakhon Ratchasima Province, northeastern Thailand: Lam Takhong, Lam Phra Phloeng, Lam Chiang Krai, and the Upper Mun. These sub-basins represent the headwater region of the Mun River, a major tributary of the Mekong River system. The basins vary in hydrological infrastructure, with Lam Takhong and Lam Phra Phloeng regulated by large multipurpose reservoirs, while Lam Chiang Krai and the Upper Mun rely primarily on rainfall and small-scale storage. This diversity provides a representative context for evaluating water accounting, WEAP-based scenario modeling, and adaptation strategies in non-irrigated agricultural systems.

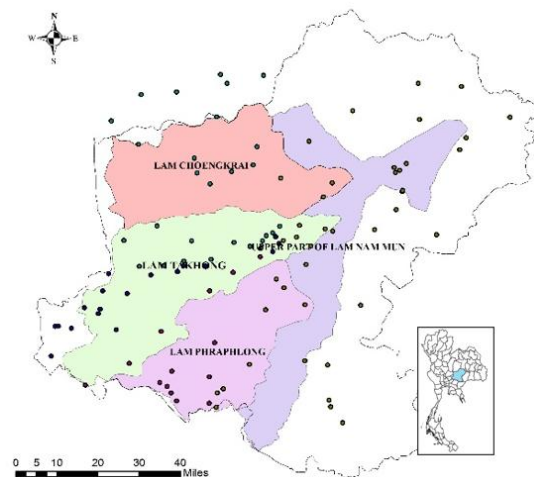


Figure 1. Study area and rainfall stations in Nakhon Ratchasima Province, northeastern Thailand

In addition, each sub-basin has distinct physical characteristics and land-use patterns, which substantially influence their respective water management strategies, as detailed below and in Table 1:

- Lam Takhong Sub-basin (LTK): the sub-basin has high land-use diversity, with 58.12% agricultural land and 24.35% forest cover. Notably, urban and built-up areas constitute 12.18% of the basin-the highest among the four studied areas, due to its coverage of major economic zones and the Nakhon Ratchasima metropolitan area.

Consequently, this basin faces substantial water demand for both domestic consumption and the service sector.

- Lam Phra Phloeng Sub-basin (LPP): this sub-basin is characterized by a relatively large area of forest cover (26.47%), mostly within the Khao Yai and Thap Lan National Parks. Agricultural land accounts for 65.26% of the area, with a predominance of field crops and orchards cultivated in the foothills and on the undulating plains.

- Lam Chiang Krai Sub-basin (LCK): this basin has the highest proportion of agricultural land (84.55%), primarily dedicated to paddy fields and field crops such as cassava and sugarcane. Conversely, forest cover accounts for only 5.84%. This land-use structure renders the basin highly vulnerable to severe water scarcity, particularly for agricultural activities.

- Upper Mun Sub-basin (UM): agricultural land occupies 72.44% of the basin, predominantly consisting of irrigated paddy fields. Forest cover represents 18.15% of the area. The basin's water resources are primarily managed through the Mun Bon and Lam Chae reservoirs, which serve as vital lifelines for supporting economic activities in the region.

Table 1. Comparison by sub-basin of land use proportions and total areas

Sub-basin	LTK	LPP	LCK	UM
Agriculture (%)	58.12	65.26	84.55	72.44
Forest (%)	24.35	26.47	5.84	18.15
Urban (%)	12.18	4.82	4.27	5.63
Others (%)	5.35	3.45	5.34	3.78

Materials and Methods

Water Accounting Framework

A water accounting framework was applied to establish transparent balances at both the subdistrict and basin levels, following the IWMI conceptualization of water bookkeeping (Molden *et al.*, 2003; Hoekstra *et al.*, 2012). The governing mass-balance equation is:

$$I - O = \Delta S \quad (1)$$

where I is the gross inflow (effective rainfall and surface runoff), O is the outflow (uncommitted water leaving the basin), and ΔS is the change in surface water storage. Effective rainfall was estimated using Thiessen polygon interpolation of 28 rainfall stations, a method applied widely in agricultural hydrology (Rockström *et al.*, 2010).

Runoff contributions were derived from the Royal Irrigation Department (RID) rainfall-runoff coefficient relations, consistent with empirical drought risk studies in Thailand.

Water depletion was disaggregated into: (i) process consumption, consisting of crop evapotranspiration (ET_c) and domestic use, and (ii) non-process consumption, represented by environmental flows set at 10% of agricultural demand (Poff *et al.*, 2010; Arthington *et al.*, 2018). Reference evapotranspiration (ET_o) was computed using the FAO Penman-Monteith equation, while ET_c was calculated as the product of ET_o and crop coefficients (K_c), following FAO-56 guidelines (Allen *et al.*, 1998).

This accounting framework enabled monthly balances at the subdistrict level, which subsequently were aggregated to basin and annual scales, thereby supporting both spatially disaggregated and basin-wide analyses of water availability.

Agricultural Demand Scenarios

The sensitivity of water scarcity to cultivation intensity was captured based on defining six agricultural scenarios. Scenarios 1-5 progressively increased the proportion of dry-season rice, ranging from none (Case 1) to full-scale cultivation (Case 5). Case 6 introduced crop substitution, replacing dry-season rice with sweet corn across all paddy fields, as shown in Table 2.

Table 2. Summary of six scenarios used

Case	Cultivation Pattern	Description
1	Rainy-season rice + other crops	No dry-season rice
2	Rainy-season rice + 25% dry-season rice	Partial dry-season rice
3	Rainy-season rice + 50% dry-season rice	Moderate dry-season rice
4	Rainy-season rice + 75% dry-season rice	High-intensity dry-season rice
5	Rainy-season rice + 100% dry-season rice	Full dry-season rice
6	Rainy-season rice + sweet corn (substitution)	Crop diversification with sweet corn

Crop Substitution Scenario (Case 6)

Case 6 was designed to evaluate the potential of crop diversification as a demand-side adaptation strategy. Sweet corn was selected due to its shorter growing season, lower crop water requirement, and higher drought and salinity tolerance compared to rice.

- Crop coefficients (K_c): Sweet corn K_c values were obtained from FAO-56 (Allen *et al.*, 1998) and validated with Thai agronomic data from field trials and extension guidelines. Stage-specific K_c values

(initial, mid-season, late season) were applied to compute ET_c.

- Agronomic parameters: Local planting calendars and growing season lengths for sweet corn in Nakhon Ratchasima were used to ensure accurate representation of cropping cycles.

- Integration in accounting and WEAP: ET_c for sweet corn was incorporated directly into the water accounting framework and demand nodes in the WEAP model, replacing dry-season rice water requirements.

This scenario allowed a direct comparison between rice-dominated and diversified systems, quantifying reductions in deficits at both subdistrict and basin scales.

WEAP Model Application

The model inputs encompassed multiple hydrological and socio-economic datasets. Rainfall-runoff series were derived from Thiessen polygon interpolation combined with rainfall-runoff coefficients provided by the RID. Crop water requirements (ET_c) were estimated for both rice and sweet corn using the FAO-56 methodology (Allen *et al.*, 1998), supplemented with locally validated agronomic parameters for Thailand. Domestic water demand was obtained from national census records to reflect current population-driven consumption patterns. In addition, reservoir storage capacities and operating rules were incorporated based on RID documentation, ensuring that the modeled dynamics reflected actual system management practices. (Sieber & Purkey, 2015)

Calibration of the WEAP model was performed using observed streamflow and reservoir storage data, with model performance evaluated through the Nash-Sutcliffe Efficiency (NSE) and coefficient of determination (R^2) values (Legates & McCabe, 1999). Cross-validation against independently compiled water accounts confirmed the consistency of mass balances at both the subdistrict and basin levels. The calibrated model reproduced baseline hydrological conditions with high fidelity, achieving NSE values exceeding 0.80 and R^2 values greater than 0.80. These metrics demonstrated strong predictive capability and reliability in simulating flow dynamics and reservoir behavior under current management conditions. Such performance levels are regarded widely as robust for basin-scale hydrological modeling and provide confidence in the validity of subsequent scenario analyses.

The model was executed for 24 cases (4 basins $\times$ 6 cultivation scenarios), with the major outputs being unmet demand, coverage, and reliability-standard performance indicators in drought risk and allocation studies. These scenarios represented

progressively higher levels of dry-season rice cultivation, thereby enabling assessment of system sensitivity to cultivation intensity (Table 2). Simulations were conducted at a monthly timestep for all subdistricts and subsequently aggregated to the basin and annual scales, following established protocols in water resources research.

The sixth scenario specifically examined the substitution of dry-season rice with sweet corn, a crop widely cultivated in northeastern Thailand and recognized for its tolerance to drought and salinity. This substitution was analyzed within the same integrated water accounting and WEAP modeling framework, with sweet corn crop water requirements (ET_c) estimated using FAO-56 crop coefficients (K_c) and complemented by local agronomic studies.

For clarity, the term baseline scenario in this study denoted the prevailing water management and land-use conditions against which all alternatives were evaluated. It encompassed existing cultivation patterns (rainy-season rice with the current extent of off-season cropping), agricultural and domestic water demands, and hydrological inputs such as historical rainfall, runoff, and reservoir operations. Thus, this baseline reflects the status quo of cultivation and water use in the study area, serving as the reference point for assessing the effects of alternative drought-mitigation strategies.

Model Configuration and Calibration

The WEAP model was configured to simulate hydrological processes and water balance across the four sub-basins. The analysis period for the model simulation was established based on a 30-year historical dataset from 1991 to 2020 to ensure a robust representation of long-term climatic variability.

The accuracy of the model was investigated using calibration and validation based on comparing the simulated streamflow with the observed data from key hydrological stations. The specific stations used for model calibration in each sub-basin were:

- Lam Takhong Sub-basin: Station M.38C (Lam Takhong in Ban Khao Noi, Pak Chong District).

- Lam Phra Phloeng Sub-basin: Station M.145 (Lam Phra Phloeng in Ban Wang Bon, Pak Thong Chai District).

- Lam Chiang Krai Sub-basin: Station M.173 (Lam Chiang Krai in Ban Non Kum, Non Thai District).

- Upper Mun Sub-basin: Station M.164 (Mun River in Ban Bak Ruea, Khon Buri District).

The calibration process involved adjusting the soil moisture capacity and runoff resistance factor to achieve a high correlation between the observed

and simulated discharges, thus ensuring the model's reliability for drought scenario analysis.

Stakeholder Interviews and Small Reservoir Survey

The quantitative modeling was completed using a stakeholder survey undertaken with 879 respondents, involving farmers and community leaders across 47 subdistricts. The structured interviews elicited perceptions regarding water availability, critical stress periods, coping strategies, and openness to adopting alternative crops such as sweet corn. In parallel, a field inventory was conducted of 79 small reservoirs, ponds, and check dams that collectively provided 119.32 million m³ of storage. These assets were geocoded and integrated into a spatial database to evaluate their role in buffering local shortages and to spatially contextualize water management capacity.

A purposive sampling strategy was applied to ensure coverage of drought-prone communities. Subdistricts were deliberately selected from non-irrigated agricultural areas, representing diverse geographic and drought-risk conditions. This approach (as opposed to random sampling) strengthened the representativeness of the findings for drought-mitigation planning and enhanced the practical relevance of the insights generated.

Results and Discussion

Comprehensive Water Accounts at Subdistrict and Basin Scales

The water accounts constructed for the four sub-basins revealed significant heterogeneity in water availability. The annual analyses showed that the Lam Phra Phloeng and Lam Takhong basins consistently exhibited water surpluses, with effective rainfall surpassing agricultural requirements. In contrast, the Lam Chiang Krai and

Upper Mun basins were more vulnerable. Lam Chiang Krai maintained adequate supply under Cases 1-4 but shifted to a clear deficit under Case 5 (representing full-scale dry-season rice cultivation). Similarly, Upper Mun shifted from surplus in Cases 1-2 to deficits in Cases 3-5 (Table 3).

At the monthly scale, the subdistrict accounts demonstrated concentrated shortages between February and April, indicating that aggregate annual surpluses masked critical seasonal imbalances. This reinforces the conceptual understanding that drought in rainfed systems is not solely determined by total rainfall but is strongly influenced by timing and water management practices.

WEAP Model Simulation of Current Management Scenarios

The WEAP simulations validated the accounting analysis, producing dynamic insights into unmet demand and system reliability. Lam Phra Phloeng and Lam Takhong had negligible unmet demand (<5%) with reliability above 95%, confirming their hydrological resilience. In contrast, Lam Chiang Krai and Upper Mun recorded unmet agricultural water demands of 20-30% during dry-season scenarios, with coverage ratios declining to 65-75%. These deficits were concentrated consistently in February-April, reinforcing the late dry-season vulnerability highlighted in global probabilistic drought models and irrigation-sensitive drought indices (Tang *et al.*, 2023), as shown in Table 4.

In addition, spatial heterogeneity was apparent. Even in surplus basins, such as Lam Phra Phloeng, some subdistricts reported localized shortages, consistent with remote-sensing evidence of heterogeneous drought impacts. This pattern aligned with hazard-exposure-vulnerability frameworks previously applied in the Mun River Basin (Babel *et al.*, 2024).

Table 3. Annual water balance results under five cultivation cases and one crop substitution scenario (sweet corn) across four basins

Basin	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
LTK	Surplus	Surplus	Surplus	Surplus	Surplus	Surplus
LPP	Surplus	Surplus	Surplus	Surplus	Surplus	Surplus
LCK	Surplus	Surplus	Surplus	Surplus	Deficit: 45 MCM	Deficit: 28 MCM (~38% reduction)
UM	Surplus	Surplus	Deficit: 18 MCM	Deficit: 25 MCM	Deficit: 32 MCM	Deficit: 20 MCM (~37% reduction)

Table 4. Summary of WEAP simulation results under baseline scenario

Basin	Annual Unmet Demand (% of total requirement)	Reliability (coverage ratio)	Months of Critical Shortage
LTK	< 5%	> 95%	None
LPP	< 5%	> 95%	None
LCK	20–30% (dry season)	65–75%	Feb–Apr
UM	15–25% (dry season)	70–80%	Feb–Apr

Identification of Drought-Prone Areas and Evaluation of Crop Alternatives

Hotspot analysis identified persistently drought prone areas as the central and lower Lam Chiang Krai Basin and the upper tributaries of the Upper Mun. These areas rely heavily on rainfall and small reservoirs, with limited groundwater potential due to salinity.

The introduction of Case 6 (sweet corn substitution) provided an important comparative perspective. Replacing dry-season rice with sweet corn reduced deficits substantially: in the Lam Chiang Krai Basin, where shortages fell from 45 MCM in Case 5 to 28 MCM in Case 6 (~38% reduction), while in the Upper Mun Basin deficits declined from 32 MCM to 20 MCM (~37% reduction), as shown in Table 5. These reductions occurred primarily during the critical February–April period, highlighting the lower water demand of sweet corn relative to rice. Although localized hotspots, such as Ban Prang and Nong Hua Rat, continued to experience shortages, both the severity and spatial extent of the deficits decreased markedly.

For Lam Phra Phloeng and Lam Takhong, which maintained surpluses in all rice-based scenarios, the sweet corn substitution produced negligible changes, as these basins were already suffering due to storage and rainfall conditions.

Table 5. Impact of crop substitution (dry-season rice → sweet corn) on water deficits

Basin	Deficit Volume (MCM) before	Deficit Volume (MCM) after	% Reduction in Deficit
LTK	Negligible	Negligible	–
LPP	Negligible	Negligible	–
LCK	45	28	~38%
UM	32	20	~37%

These results were consistent with global evidence, emphasizing diversification and “green

water” management as key strategies for resilience in rainfed agriculture (Rockström *et al.*, 2010; Ingrao *et al.*, 2023; Lankford and Agol, 2024). Regionally, the findings paralleled studies on rainfed maize in northern Thailand, which documented similar vulnerabilities to climate-induced drought (Bastola *et al.*, 2024).

Stakeholder Perceptions and Small Reservoir Survey

The stakeholder survey provided strong qualitative support for the quantitative analyses. Across the 879 interviews in 47 subdistricts, 65% of farmers identified March as the month of peak water stress, corroborating the modeled deficits concentrated in the late dry season (Feb–Apr).

Water quality issues were also prominent: 40% reported salinity problems, particularly in Lam Chiang Krai and Upper Mun, while 27% mentioned turbidity and 18% highlighted agrochemical contamination. These findings underscored that water scarcity in non-irrigated systems was a compound issue of both quantity and quality.

Coping strategies varied, with 54% of respondents using on-farm ponds or small reservoirs, 32% pumped groundwater despite salinity risks, 29% reduced dry-season cultivated areas, and 21% shifted toward drought-tolerant crops such as sweet corn. Notably, 72% supported institutional measures for small-reservoir rehabilitation and community water-sharing mechanisms, reinforcing the role of governance in enhancing resilience.

The field survey of the 79 small reservoirs, ponds, and check dams (total capacity: 119.32 million m³) confirmed their importance as drought buffers. However, many were silted and poorly maintained, reducing effectiveness—an issue repeatedly raised by community leaders during interviews.

Synthesis and Comparative Perspective

The integration of water accounting, WEAP simulations, and stakeholder insights produced a comprehensive and internally consistent picture of drought vulnerability in the study basins. Key findings were: (i) dry-season rice cultivation was the principal driver of water deficits in Lam Chiang Krai and Upper Mun, whereas Lam Phra Phloeng and Lam Takhong remain buffered by infrastructure; (ii) seasonal shortages were clustered in February–April, consistent with both model outputs and farmer perceptions; (iii) spatial drought hotspots persisted, even within surplus basins, reflecting localized heterogeneity documented in both satellite evidence (Varnakovida *et al.*, 2025)

and farmer surveys; (iv) crop substitution with sweet corn reduced deficits by ~37-38%, with farmers already beginning to adopt such practices as adaptive responses; and (v) small reservoirs play a critical but underutilized role, with rehabilitation and expansion emerging as clear community priorities.

Together, these findings demonstrate that integrated modeling and stakeholder perspectives converge on the same message that water insecurity in non-irrigated systems arises not only from rainfall variability but also from cultivation choices, storage limitations, and governance gaps. Addressing these shortcomings requires combining technical solutions (diversification, reservoir rehabilitation) with participatory and policy-driven strategies.

Discussion

This study highlighted the central role of dry-season rice cultivation as the principal driver of water deficits in non-irrigated basins of Nakhon Ratchasima Province, northeastern Thailand, particularly Lam Chiang Krai and Upper Mun. These findings reinforce global arguments that water scarcity in rainfed systems emerges not solely from rainfall deficiency but from mismatches between demand and seasonal availability (Rockström *et al.*, 2010; Bodner *et al.*, 2015). In contrast, Lam Takhong and Lam Phra Phloeng had stable surpluses, reflecting the buffering effect of storage infrastructure, consistent with comparative studies showing greater drought resilience in irrigated systems (Zhang *et al.*, 2023; Chen *et al.*, 2025).

The temporal clustering of shortages in February-April underscored the structural vulnerability of late dry-season cultivation, echoing evidence from probabilistic drought models and irrigation-sensitive indices that emphasize this period as a critical risk window (Yang *et al.*, 2023; Tang *et al.*, 2023). Spatial heterogeneity further complicates basin-level assessments: even within surplus basins, certain subdistricts reported persistent shortages, consistent with remote sensing findings from Thung Kula Ronghai (Varnakovida *et al.*, 2025) and hazard-exposure-vulnerability frameworks in the Mun River Basin (Babel *et al.*, 2024).

Based on the Case 6 analysis (involving the substitution of dry-season rice with sweet corn), there was a reduction in deficits by approximately 37–38% in Lam Chiang Krai and Upper Mun. This outcome underscored the potential of crop diversification as a viable adaptation strategy.

Stakeholder interviews reinforced this perspective, with farmers expressing openness to drought-tolerant crops if institutional and market support were secured. These results aligned with broader calls for integrating “green water” management, crop diversification, and adaptive demand-side strategies into rainfed agriculture (Ingrao *et al.*, 2023; Bastola *et al.*, 2024; Lankford and Agol, 2024).

Methodologically, the integration of water accounting and WEAP proved effective in capturing both static balances and dynamic allocation patterns. By combining quantitative modeling with stakeholder and reservoir data, the study offers a holistic perspective that addresses technical, social, and institutional dimensions of drought vulnerability. This reinforces the relevance of integrating such tools into basin-level governance frameworks for scenario-based planning and policy design in Thailand’s non-irrigated contexts.

Conclusions

This study integrated water accounting and WEAP modeling with stakeholder insights to evaluate water availability, agricultural demand, and drought vulnerability in four non-irrigated basins of Nakhon Ratchasima Province. The findings confirmed that dry-season rice cultivation was the principal driver of deficits, particularly in Lam Chiang Krai and Upper Mun, whereas Lam Takhong and Lam Phra Phloeng maintained water surpluses due to stronger hydrological buffering. Seasonal shortages were concentrated in February-April, highlighting the structural vulnerability of rainfed farming during the late dry season. Notably, spatial drought hotspots persisted even within surplus basins, underscoring the necessity of subdistrict-scale planning. Crop diversification proved effective in mitigating water stress, with sweet corn substitution reducing deficits by approximately 37-38%, thereby demonstrating the potential of demand-side adaptation strategies. Stakeholder perspectives further reinforced these findings, emphasizing the critical role of small-scale reservoirs, water-sharing mechanisms, and institutional support. From a policy standpoint, the findings call for a strategic shift toward adaptive and demand-focused interventions, discouraging full-scale dry-season rice in deficit-prone basins, prioritizing measures during the late dry season, investing in hotspot subdistricts through rainwater harvesting and small-scale storage, and promoting crop diversification via market incentives and extension services. Embedding integrated accounting and modeling frameworks into basin-level governance offers

a pathway to strengthen the resilience of Thailand's rainfed agricultural systems, reduce vulnerability to climate-induced drought, and safeguard rural livelihoods under growing climatic uncertainty.

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Author Contributions

Conceptualization: T.S., P.K.; Methodology: T.S., P.K.; Investigation: T.S., P.K.; Data Curation: T.S.; Writing – Original Draft: T.S.; Writing – Review & Editing: T.S., P.K.; Supervision: P.K. All authors have read and agreed to the published version of the manuscript.

Ethics Statement

Ethical approval was not required for this study because it did not involve human participants, animals, identifiable personal data, or materials requiring institutional ethical review.

Declaration of Generative AI Use

During the preparation of this manuscript, the authors used ChatGPT to assist with language editing and proofreading to improve clarity and readability. All AI-assisted outputs were critically reviewed, verified, and revised by the authors, who accept full responsibility for the content of this manuscript.

Conflict of Interest

The authors declare that they have no conflicts of interest related to this work.

Data Availability Statement

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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