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Improving flood and drought management in agricultural river basins: an application to the Mun River Basin in Thailand

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ABSTRACT

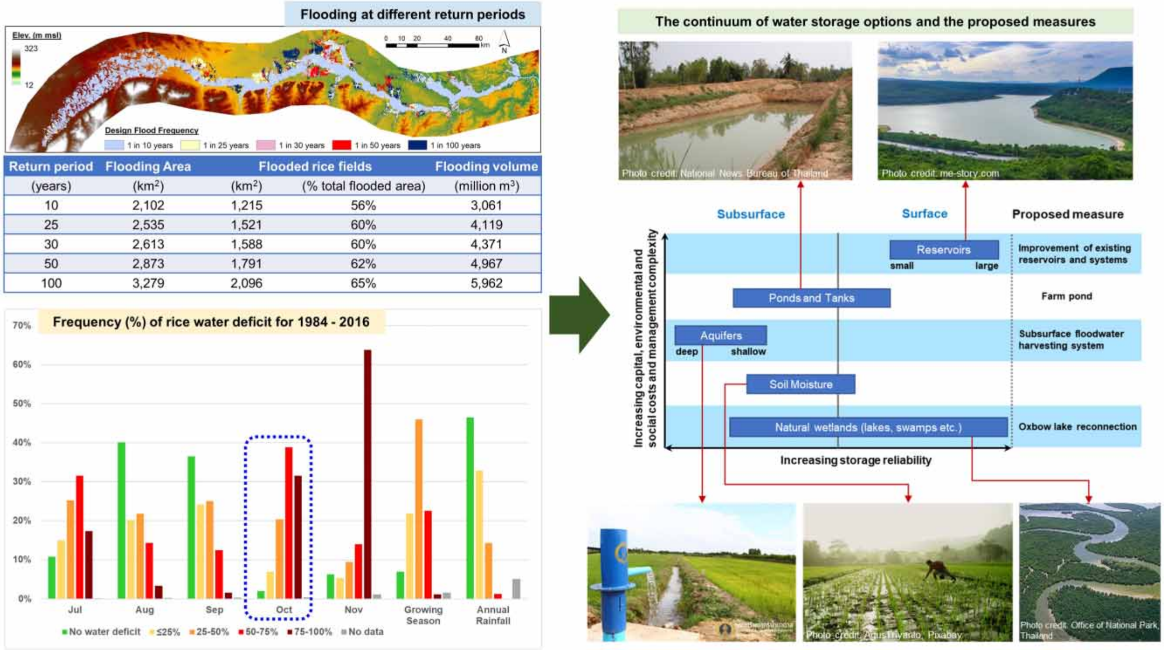
Agriculture productivity is regularly affected by floods and droughts, and the severity is likely to increase in the future. Even if significant efforts are spent on water development projects, ineffective project planning often means that they continue to occur or are only partly mitigated, for example, in the Mun River Basin, Thailand, where 1,000 s of water projects have been implemented. Despite this, the basin regularly experiences floods and droughts. In this study, an analysis of the adverse impacts of basin-scale floods and droughts on rice cultivation in the Mun River Basin is conducted, and an estimation of the coping capacity of existing measures. The results demonstrate that while the total storage capacity of in-situ and ongoing projects would be sufficient to tackle both hazards, it can only be achieved if the projects are effectively utilised. Based on this, proposed solutions for the region include small farm ponds, a subsurface floodwater harvesting system, and oxbow lake reconnections. The suggested measures are practicable, economical, environmentally low-impact, and their implementation (if executed with appropriate care) would reduce flood and drought problems in the basin. Notably, the measures and calculation methods proposed for this basin can also be applied to other crops and regions.

Key words: Farm pond, rice, Water demand, Water management, Water supply

HIGHLIGHTS

- The study aims at the solutions to mitigate flood and drought damage to agriculture.
- All dimensions associated with floods and droughts are considered at the basin scale.
- Feasible solutions to mitigate flood and drought damage are proposed.
- The equation to estimate the volume of the farm pond is proposed.
- The study area is the Mun River Basin in Thailand, where rice cultivation is dominated.

GRAPHICAL ABSTRACT



Return period	Flooding Area	Flooded rice fields		Flooding volume
(years)	(km^2)	(km^2)	(% total flooded area)	(million m^3)
10	2,102	1,215	56%	3,061
25	2,535	1,521	60%	4,119
30	2,613	1,588	60%	4,371
50	2,873	1,791	62%	4,967
100	3,279	2,096	65%	5,962

INTRODUCTION

Thailand suffers periodically from flooding during the wet season and drought during the dry season (Shannon, 2005; Pavelic *et al.*, 2012). Flooding is the most frequent natural disaster that has affected Thailand, with 66 floods throughout 1984–2014, causing a total of approximately US$ 44,885 million in damage. Riverine flooding is most common, usually induced by monsoonal and torrential rains and sometimes by tropical storms. At the same time, the country has regularly experienced droughts owing to the high seasonal variability of rainfall, which often leads to widespread crop failure. The cumulative damage from droughts from 1989 to 2014 is estimated at US$ 1,143 million (Department of Water Resources of Thailand, 2016).

Adverse impacts from floods and droughts in Thailand are on the rise as a result of climate change. The temperature tends to increase by 0.2–0.3 °C per decade in the warm and cold seasons (Johnston *et al.*, 2010). In the Mun River Basin in the northeast of the country, the minimum and maximum average monthly temperatures show upward trends with rates up to −0.1–0.65 °C and 0.8 °C per decade, respectively (Prabnakorn *et al.*, 2018). Further, a consistent rise in the number of consecutive dry days is observed, especially in the eastern part of the basin (Manomaiphiboon *et al.*, 2013). The dry season will, therefore, be dryer and longer (Snidvongs *et al.*, 2003) in the future. This will increase evapotranspiration and water demand for agriculture, making crops more vulnerable to yield reduction. Despite disagreement over rainfall variations and mixed trends, there is a common conclusion that heavy precipitation events will become more intense and more frequent (Snidvongs *et al.*, 2003; Johnston *et al.*, 2010; Manomaiphiboon *et al.*, 2013), increasing future flood damage.

Agriculture is the sector most often affected by these disasters, with rice being particularly vulnerable. Rice is the most important staple crop of Thailand, occupying almost half of the country's agricultural land, with approximately 60% of that located in the northeastern region. Most northeast rice fields use traditional farming methods, relying on local rainfall, and are thus highly susceptible to climate variations. The lack of irrigation support means that rice fields in the northeast have on average the lowest yield in the country: 2.3 ton/ha compared to 3.6, 3.9 and 3.0 ton/ha in the north, the central, and the south, respectively (Office of Agricultural Economics, 2018).

This shows the need for water development projects to safeguard rice agriculture from floods and droughts. Therefore, the government has spent billions of dollars increasing water storage capacity to mitigate flood problems and improve water availability in the dry season, particularly for agricultural purposes in northeast Thailand. However, the projects were done without assessing water demand at the basin scale and are operated by various government agencies mostly concerned with individual project implementation, meaning focus on overall river basin management is lacking (Floch *et al*., 2007). While thousands of water projects have been funded, they have not performed as intended, and flood and drought problems continue to occur in the Mun River Basin.

To help address this, this paper summarises the flood and drought conditions that affect rice growth and production, and from this the total excess rainwater supply and rice water demand are examined at the basin scale. Data is collected on current and ongoing water resources development projects, and the flaws and factors that influence the projects' achievements are discussed. Finally, practicable water management measures are proposed as well as corresponding responsible parties to cope with both problems and improve rice production. To ensure the proposed projects' feasibility, they are selected based on specific criteria emphasising flexible surface and subsurface storage options, cost, accessibility, and environmental impacts. The selected study area is the Mun River Basin in northeast Thailand, where both flood and drought problems are considerable. To our knowledge, this is the first time that a basin-scale dual floods and drought analysis has been performed in the region.

CASE STUDY AREA

General description

The Mun River Basin (Figure 1), the largest basin in Thailand with a total area of 7.1 million ha (71,060 km^2), located in the northeast of the country. It is bounded on the west and the south by mountain ranges, which are the headwaters of the Mun River and its tributaries. The 726 km river runs east and converges with the Chi River at Ubon Ratchathani Province before emptying into the Mekong River. The basin has five main landscapes consisting of river levees, flood plains, non-flood plains, undulating land, and hilly areas. Rice is cultivated on flood plains, non-flood plains, and lowlands of the undulating regions, occupying approximately 75% of the agricultural land and 55% of the basin's total area. About 90% of the rice fields are rain-fed (Prabnakorn *et al*., 2018). The Khao Dok Mali 105 (KDML 105) and Rice Department 6 (RD6) are the two major varieties of Jasmine rice being grown in the basin. They are both medium-maturing types with a growth duration of 120–140 days, roughly from July to November (Bureau of Rice Research and Development (BRRD), n.d.). The three growth phases are: vegetative (July–September) from sowing to panicle initiation, reproductive (October) from panicle initiation to flowering, and ripening (November) from flowering to full maturity (Brouwer *et al*., 1989).

The precipitation pattern in the basin is bi-modal, with distinct dry and wet seasons (Pinidluek *et al*., 2020). The precipitation concentrates in July to September (200 mm per month or more), while October and November are relatively dry. There are considerable spatial and temporal variations of precipitation across the basin with more precipitation in the eastern provinces because of the influence of tropical depressions, which occur annually in September and blow westward to the lower part of the region (The Meteorological Department of Thailand, n.d.)

Existing and future flood and drought mitigation projects

Thousands of water resources development projects have been implemented over the entire basin (Table 1). According to the Royal Irrigation Department (RID)'s classification, the projects are categorised into three groups: large, medium, and small-scale. The large-scale projects have a storage capacity of $\geq$100 million m^3, or

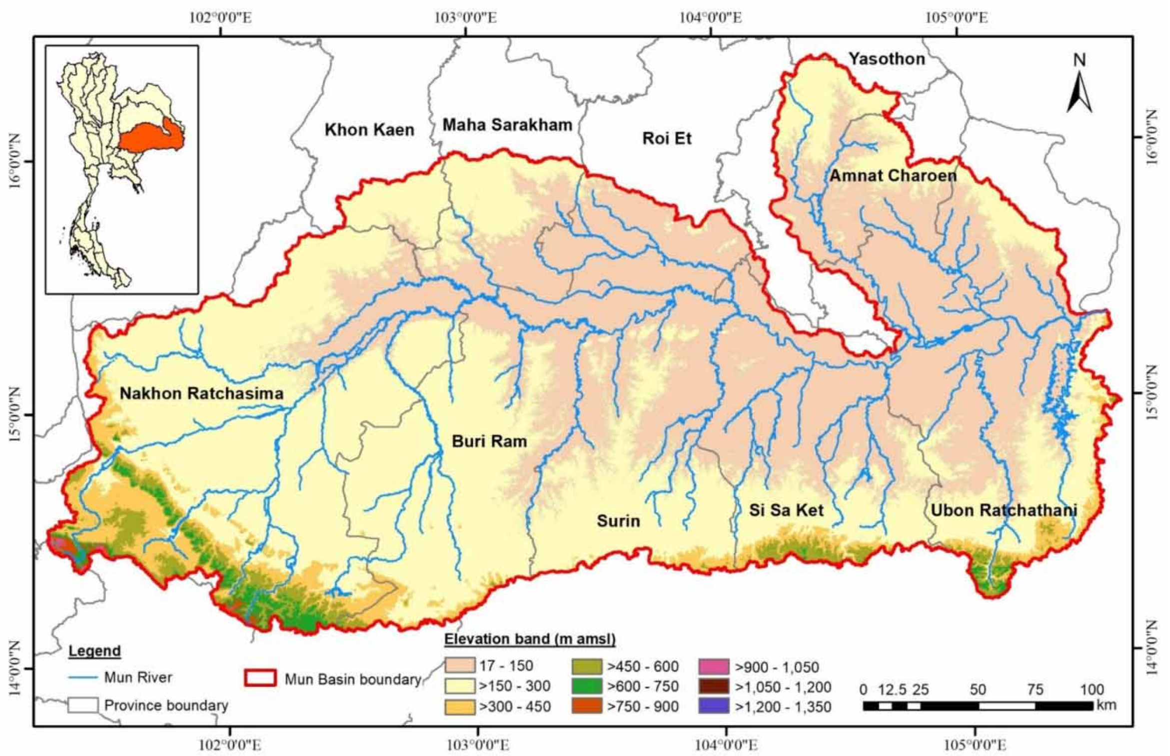


Fig. 1 | Location and topography of the Mun River Basin in northeast Thailand.

Table 1 | Summary of all water development projects in the Mun River Basin, 2016.

No.	Project	Number of projects	Storage (million m^3)	Irrigated Area (ha)
1	Large	12	3,367.54	156,756
2	Medium	194	1,270.33	172,986
3	Small	2,476	460.34	213,515
4	Electric pump	274	0.00	59,634
	Total	2,956	5,098.21	602,891

a water surface area of $\geq$15 km^2, or a command area of $>$12,800 ha (Hydro and Agro Informatics Institute, 2012). All large-scale projects are multi-purpose; 10 out of the total 12 projects are under the RID administration. The other two are hydroelectric dams: Pak Mun Dam is under the Electricity Generating Authority of Thailand (EGAT), and Sirindhorn Dam is under the RID and EGAT.

Medium-scale projects complement the large-scale schemes and have storage capacities between 2 and 100 million m^3, or water surface areas $<$15 km^2, or command areas between 480 and 12,800 ha. The small-scale projects require a construction period of less than one year, and no land compensation schemes are embedded into development plans. Both medium and small-scale projects are single-purpose, primarily for domestic water use or irrigation with very few forest conservation projects. The vast majority of medium-scale projects are under the

RID's responsibility. The rest are under the Department of Water Resources (Hydro and Agro Informatics Institute, 2012), while about 16 government agencies are involved in small-scale projects (Patamatamkul, 2001).

Electric pumping stations (without storage) have been installed adjacent to the main river and its major tributaries throughout the basin. The pump operation and maintenance are under the Subdistrict Administration Organization (SAO) (Hydro and Agro Informatics Institute, 2012). Besides the stations, the RID provides mobile pumping units, which are requested by farmers through the SAO for a minimum area of 48 ha in the time of droughts, where possible and needed (Floch *et al*., 2007).

The government has continuously invested in other development schemes. The RID proposes and is undertaking 3 large-scale, 148 medium-scale, and 1,209 small-scale projects, as well as 196 pumping stations with a total capacity of 2,635 million m^3, covering 143,158 ha of irrigable area.

MATERIALS AND METHODS

The overall process of this study is presented in Figure 2. The process starts with flood and drought hazard assessment. The findings are then compared with the total coping capacity of all existing and ongoing water projects to identify if a further study on potential water management solutions is needed or not. If either the total coping capacity is insufficient to tackle both hazards, or the calamities persist in the area, a study on possible solutions is conducted, based on a literature review. At this stage, the criteria for the selection of the possible measures are proposed. After obtaining the potential measures, a detailed study on the selected measure is performed.

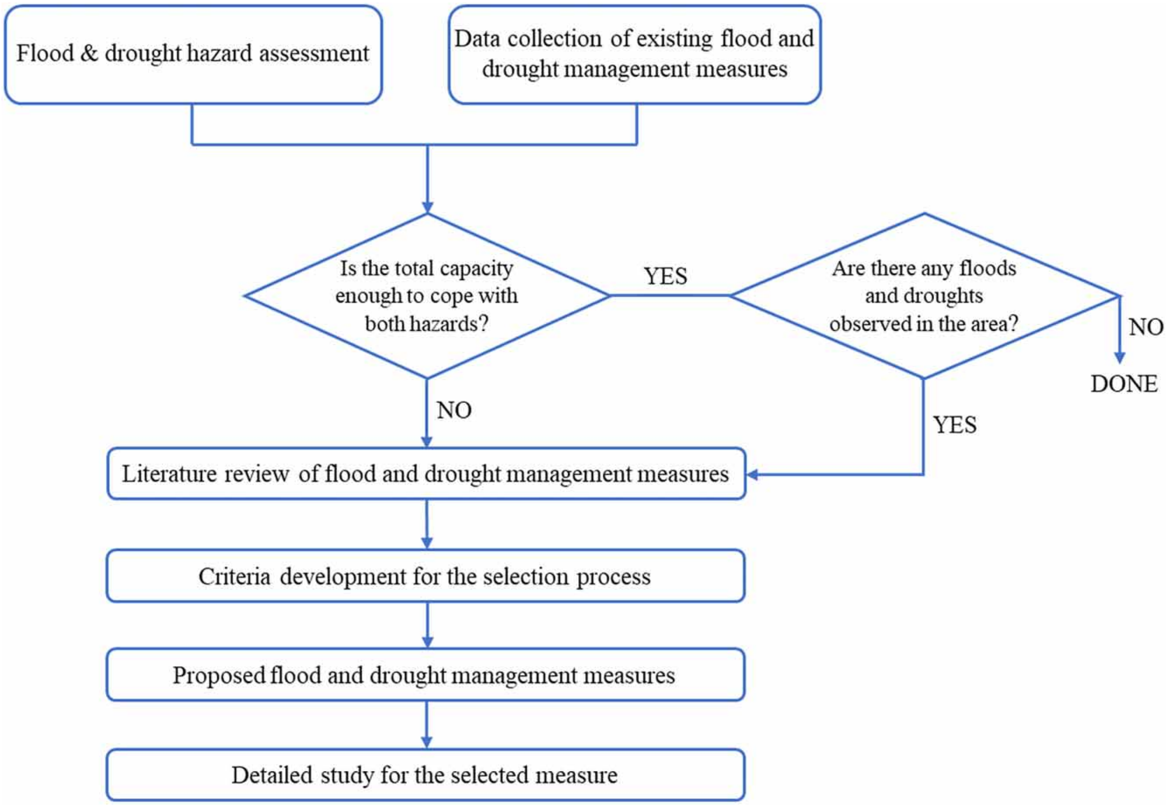


Fig. 2 | Summarised process of the study.

The flood hazard at different recurrence periods in the Mun River Basin were assessed using the integrated hydrologic (SWAT) and hydraulic (HEC-RAS) models. Complete model development and parameter calibration and validation can be found in Prabnakorn *et al.* (2019). Recurrence periods of 10, 25, 30, 50, and 100 years derived from rainfall frequency analysis were used, as they are usually adopted in the design of structural measures in Thailand. The datasets used in the study consist of precipitation (1985–2015), temperature (1985–2015), land use, soil type, water level (2005–2014), and discharge (2005–2014). These were obtained from different ministerial departments in Thailand, namely, the Royal Irrigation Department (RID), the Meteorological Department, and the Land Development Department.

In this study, drought is defined based on the agronomist's view, representing a condition of water stress that affects crop growth and yield (Pereira *et al.*, 2002). The drought was assessed based on an imbalance between water supply and water demand. Droughts occur when the demand is higher than the supply. The water supply is defined as mean areal precipitation representing the rainfall volume falling over the entire basin. It is computed for each rice-growing month and over the growing season using the monthly rainfall for 1985 to 2015 from all 53 rainfall-gauging stations. The basin average is computed based on the Thiessen Polygons method. Water demand refers to the water required for rice growth. The calculation of water demand is carried out based on Brouwer *et al.* (1989), which includes the water needs for soil saturation, evapotranspiration, percolation and seepage losses, and the establishment of a water layer. The calculation utilises specific data from the field (study area) and rice cultivars in the area and is of the form:

$$\mathrm{WD} = \mathrm{SAT} + \mathrm{ET}_{\mathrm{rice}} + \mathrm{PS} + \mathrm{WL}, \tag{1}$$

where WD (mm) is a water requirement for rice at each growing month, SAT is the amount of water needed for soil saturation at the beginning of the growing season. An SAT value of 200–250 mm is obtained from field observations (Kirdpitugsa & Kayankarnnavy, 2009). The rice water need (ET_{rice}) is equal to $ET_0 \times K_c$; where ET_0 (mm) is the reference evapotranspiration rate, and the K_c is the crop factor for the KDML105 and RD6 obtained from the studies and experiments by the RID. PS (mm) is the percolation and seepage losses obtained from field observations, approximately 1–3 mm/day (Kirdpitugsa & Kayankarnnavy, 2009). For the SAT and PS, the average values are used in the calculation. Lastly, WL (mm) is the amount of water needed to establish a water layer, which was obtained from Brouwer *et al.* (1989).

The total rice areas' net water requirement, 38,565 million m^2, is determined as the difference between mean areal precipitation and water needs for rice cultivation over all growing months (July–November) and the growing season. Equal land areas are assumed for the KDML105 and RD6. Additionally, the data of existing mitigation measures implemented in the area, i.e., the number of large, medium, and small-scale projects, electric pumping stations, storage capacity, and actual irrigated areas, are obtained from the RID.

RESULTS AND DISCUSSION

Flood hazard

The flood map for the 30-year return period is presented, as an example, in Figure 3. The extent of flooding is larger on the western part of the riverbank, and the flood depths mostly vary between 0 and 4 m. Approximately 60% of floodplain inundation is less than 1 m, mainly at the upstream part of the Mun River, where a vast majority of areas are paddy rice fields. The extent of flooding is not as large as upstream at the river downstream, but the flood depth is deeper. This creates adverse impacts on people living in the flood-prone Mueang district of Ubon Ratchathani province. Affected cities (from upstream) include Sateuk district in Buri Ram province, Rattanaburi, Tha Tum, and Chumphon Buri districts in Surin province, Rasi Salai district in Si Sa Ket province, and Phibun

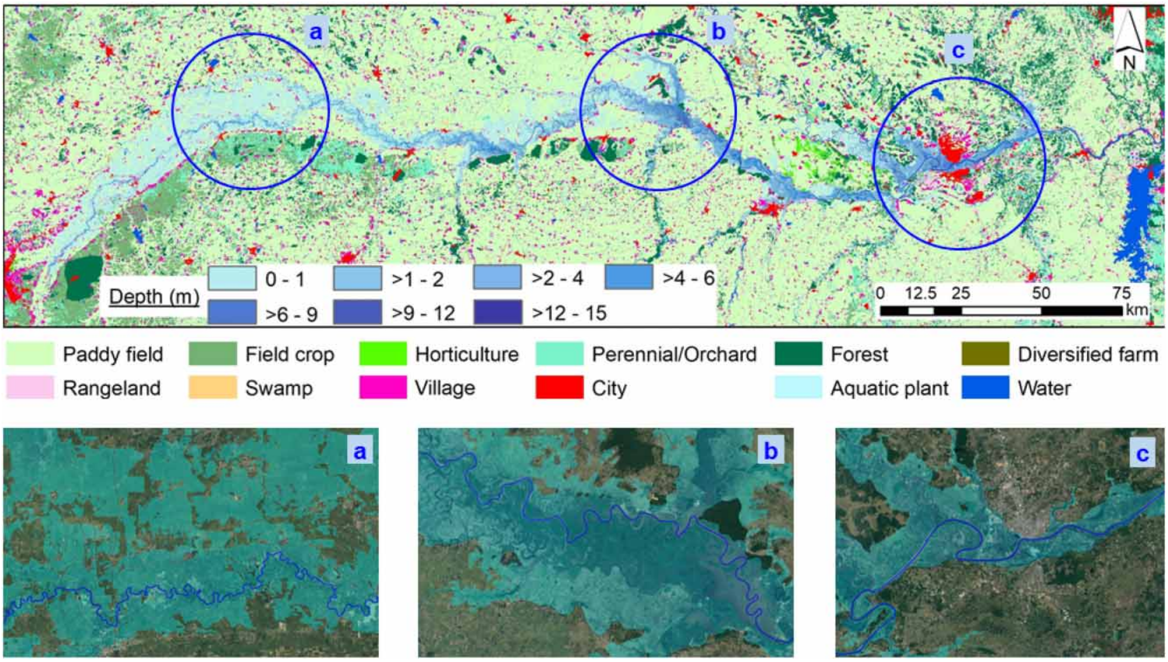


Fig. 3 | The flood map for the 30-year return period: (a) shows the inundated area upstream at Muang Yang and partly in Lamtaman Chai and Chum Phuang districts in Nakhon Ratchasima province; (b) presents the inundated wetland area in the central part of the basin; (c) presents the inundated area at Mueang district in Ubon Ratchathani province, one of the largest cities in northeast Thailand.

Mangsahan, Warin Chamrap districts in Ubon Ratchathani province. Moreover, due to the flat terrain – a bed slope roughly between 0.00007 and 0.00014, the duration of flooding is long, which can cause damage to crop growth and yields, as well as the cities located in flood-prone areas.

Figure 4 compares inundated areas of different scenarios, with information about affected areas and flooding volumes given in Table 2. For more extreme events, the increase of flooded areas is mostly observed in the central part of the basin (Boong Taam) due to the mild slopes. Boong Taam is a seasonally flooded freshwater swamp forest and is the most important wetland in the northeast region. Some parts of Boong Taam are used for rice

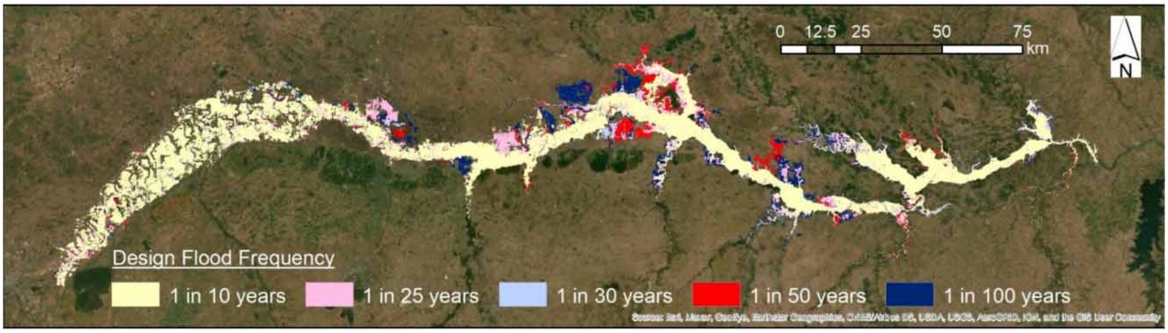


Fig. 4 | Comparison of inundated areas at 10, 25, 30, 50, and 100-year return periods in the Mun River Basin, Thailand.

Table 2 | Different scenarios flooded area, flooded rice field, and flooding volume considered in this study.

Return period (years)	Flooding area (km^2)	Flooded rice fields (km^2)	Flooded rice fields (% total flooded area)	Flooding volume (million m^3)
10	2,102	1,215	56%	3,061
25	2,535	1,521	60%	4,119
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cultivation (Chusakun, 2013), where the rice is severely affected by flooding. The flooding volume represents the total excess water over the floodplain at different severities. The value is essential for effective planning and design of flood mitigation measures such as reservoirs or retention storage.

Drought hazard

Table 3 shows the water supply, water needs for rice, and net water requirements of the wet-season rice for all growing months (July-November) and over the growing season overall. The annual precipitation is sufficient for the rice water needs for both KDML105 and RD6 varieties, but the rainfall over the growing season is not. The maximum amount of water demand occurs in July to saturate the soil for land preparation. Thus, droughts in this month do not harm rice but delay the onset of the growing season. The most severe water shortage appears in October during the rice flowering, and grain-filling stages occur, which are the most vulnerable stages for rice production. Both stages need a significant amount of water to maintain moisture throughout the month. The deficiency of water supply to the rice field could result in considerable yield reduction (Fukai *et al.*, 2000; Bouman *et al.*, 2007).

In contrast, surplus water and reduced water scarcity are observed in August and September due to the high precipitation and moderate water requirements in these two months. In November, the observed water deficit only has a small effect on maturation and harvesting (Wopereis *et al.*, 2008).

Table 3 | Water supply, water needs, and net water requirements for the KDML105, RD6 over the entire basin.

	Jul	Aug	Sep	Oct	Nov	Total (growing season)	Annual
Water supply to rice (mm)							
Mean areal precipitation	200	230	254	120	24	828	1,292
Water needs for rice (mm)							
KDML105	329	212	273	328	90	1,232	
RD6	329	235	266	300	85	1,215	
Average	329	223	270	314	87	1,224	
Net water requirements (million m^3)							
KDML105	−2,485	358	−367	−4,022	−1,271	−7,787	1,166
RD6	−2,485	−94	−243	−3,479	−1,168	−7,469	1,483
Total	−4,970	264	−610	−7,501	−2,439	−15,256	2,649

Institutional framework

In October 2017, the Thai government established the Office of the National Water Resources (ONWR), a neutral agency responsible for integrating information, plans, projects, budgets, and administration associated with water resources development in Thailand. It is mandated to facilitate, advise, monitor, and evaluate the implementation of all 38 water-related agencies country-wide. In December 2018, the first National Water Resource Act, B.E. 2561, was enacted, upon which the 20-year water resources management master plan (2018–2037) drafted by the ONWR and other related agencies, was approved by the government in June 2019 (National News Bureau of Thailand, 2019). It is hoped that this reform and policy formulation will bring about unity in water resources management in Thailand and can effectively and sustainably tackle chronic flood, drought, and wastewater problems in the country.

Issues with existing flood and drought mitigation projects

Although the Thai government has implemented a tremendous number of water-related projects across the basin, the achievement is still far from their stated goals. The total storage capacity of all existing and ongoing projects (7,733 million m^3) is anticipated to deal with the flooding volume at a 100-year return period (5,962 million m^3), and the most considerable water deficit for rice (October: $-7{,}501$ million m^3). Under ideal conditions, the basin should be resistant to flood and drought damage due to the projects. However, in reality, both events have regularly occurred, e.g., in the 2014–2016 period (Department of Disaster Prevention and Mitigation, 2016). The main reasons the expected benefits from the projects have not materialised are geography, insufficient planning, lack of maintenance, low river flows, institutional leadership and reservoir control. Each of these reasons are explained in more detail below.

The basin's geological and physical characteristics are the dominant constraints on water resources development and achievement. The undulating topography and sandy soil with a low water-holding capacity limit viable sites for storage construction. Therefore, the projects required extensive local resettlement, making them difficult and costly. Moreover, as is common in the region, the basin lies over a rock salt formation; thus, the salinity in both soils and water is high. Evaporation rates due to high temperatures in the dry season (above 30 °C) mean that irrigation water is highly saline, nullifying irrigation benefits. The use of irrigation water on the infertile and saline soil is commonly found in the area, significantly reduces rice yields and adds greatly to the land's salt burden (Kamkongsak & Law, 2001; Shannon, 2005; Floch *et al*., 2007).

The justification for most water development projects in northeast Thailand is mainly political rather than technical or economic. Thus, the development projects were often approved and built without sufficient research. For example, Rasi Salai Dam was constructed without assessments on environmental impacts, the suitability of soil or water demand (Shannon, 2005; Matthews, 2011). It caused social and environmental devastation (Matthews, 2011; Kiguchi & Watch, 2016), finally leading to a large compensation agreement (US$0.08 billion/2.5 billion Baht, from 1997 to 2019) (The Nation, 2019), which was almost triple the cost of construction (US$27.8 million/872 million Baht) (Chusakun, 2013). Besides, many local people feel that flooding is more frequent and more severe than in the past (Shannon, 2005; Siegel, 2021). According to National Hydroinformatics Data Center (2021), in the last 10 years, flooding events were observed in Sri Sa Ket in 2011, 2014, 2015, 2017, 2018, 2019, and 2020 (7 out of 10 years). Moreover, for drought mitigation, the water of the Rasi Salai reservoir has a high salinity level, making it less suitable for irrigation. As a result, only about 1,600 ha of farmland is irrigated instead of the promised 5,500 ha as in the plan (Matthews, 2011; Kerdviboon, 2021). Further. The same troubles are also found at the Hua Na Dam, the largest cement dam located 95 km downstream of the Rasi Salai Dam (Shannon, 2005).

The construction of storage is not done in parallel with an expansion of irrigation service areas and regular inspection and maintenance programs, resulting in most of the schemes not functioning properly. For example, the Lam Se Bai Weir – only one distribution system of a total of 3 – was completed 9 years behind schedule. Moreover, many parts of the distribution systems (i.e., electric pumps, distributed canals, gates, etc.) fell into disrepair because of lack of maintenance (State Audit Office of the Kingdom of Thailand, 2016).

The electric pumping schemes have had limited success because of insufficient river flows in the dry season (Floch *et al*., 2007). The actual irrigated area served by one pump has been only 33.6 ha, on average, despite the Department of Energy Development and Promotion (DEDP) claim that each electric pump project could irrigate an average of 240 ha (Kamkongsak & Law, 2001; Shannon, 2005).

There is a lack of a single-commanding authority and integrated approach in the region, as the institutional framework is highly fragmented. There are 38 water-related agencies involved in water resources development in Thailand (Office of the National Water Resources, 2018). Most of them are primarily concerned with individual project implementation, lacking unity and coordination. This frequently leads to overlapped or overlooked service areas, inconsistent strategies, and other impediments to efficient water management and project achievement (Netherlands Embassy in Bangkok, 2016).

Reservoir operation and management in the area are challenging due to conflicts over the operation. For flood control, water levels in the reservoirs need to be lowered as much as possible, whereas to handle drought, they need to retain water to the greatest extent possible. Reservoir operation is thus a key factor in exacerbating or mitigating floods and droughts. It, therefore, remains a major undertaking in the basin.

POTENTIAL WATER MANAGEMENT SOLUTIONS

Water storage has a vital role in tackling floods and droughts in the Mun River Basin because the rainfall pattern is very complicated. Rainfall shows considerable variability ranging from 0 mm/month to more than 200 mm/month. This leads to a large number of surface water storages in the basin.

However, due to the uncertainty associated with rainfall variability, planners need to focus on flexibility in storage systems. Combining a variety of water storage types (Figure 5) will provide a crucial mechanism for adaptation to the coming climate extremes (International Water Management Institute (IWMI), 2009). The concept is promoted in Mediterranean countries and Africa (Johnston & McCartney, 2010; Iglesias & Garrote, 2017). Therefore, we proposed a diverse storage infrastructure system based on all IWMI options, apart from soil moisture. This is because soil moisture conservation techniques (e.g. bunding and terracing) are commonly used in rice cultivation.

The following criteria were developed for the proposed measures in the region:

1. They address both floods and droughts.
2. They are simple and affordable, building on existing initiatives (as they need to be implemented by local stakeholders, rather than waiting on the central government to act).
3. They have proven to be effective in previous studies or pilot projects.
4. They apply nature-based solutions where appropriate.

These criteria allow feasible flood and drought mitigation measures to be selected whilst minimising environmental impacts. They need to be executed with careful consideration and cooperation among the responsible parties, as presented in Table 4.

Improvement of existing measures

Despite investment in new water development projects, the government focus would perhaps be better spent on existing measures' (in)effectiveness. Some recommendations to improve the performance and efficiency of in-situ measures are given below.

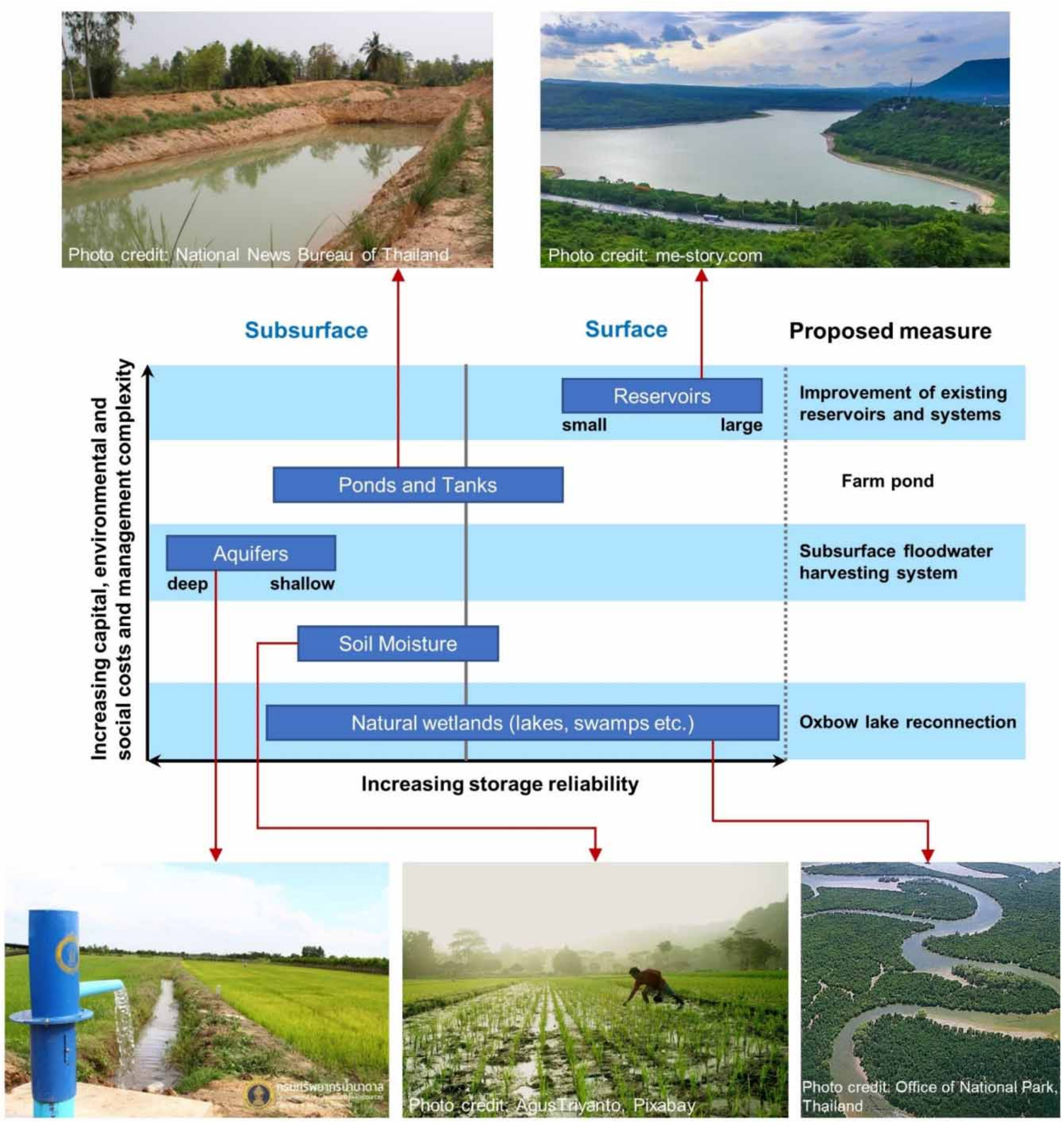

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Fig. 5 | The continuum of water storage options (International Water Management Institute (IWMI), 2009), and our proposed measures (the last column) for mitigating floods and droughts at the Mun River Basin, Thailand.

The construction of designed distributed canals and systems should be completed, as well as the repair or rehabilitation of existing deteriorated elements. Moreover, the distribution canals in some areas need to be reconsidered because of the salinity problem outlined above. A routine inspection and maintenance plan, in which the division of duties between the two stakeholders is clearly described, is also needed. The plan should be developed by the local government agencies in collaboration with farmers. The involvement of farmers is

Table 4 | Summary of proposed measures and strategies, along with responsible parties.

Proposed measures and strategies	Responsibility Central government	 Local government	 Farmers
Improvement of existing measures			
– Completion of designed distribution systems, and repair of the deteriorated schemes	✓	✓	✓
– Planning and execution of regular inspection and maintenance practices		✓	✓
– Post-implementation reviews of the controversial projects	✓	✓	✓
– Reservoir operation and early warning systems	✓	✓	✓
Individual farm pond		✓	✓
Subsurface floodwater harvesting system		✓	✓
Oxbow lake reconnection		✓	✓

essential for maximising returns from irrigation projects (Jurriëns & Jain, 1993). Since farmers' livelihood depends on that common property, they, therefore, have the greatest incentive to maintain it over time (Meinzen-Dick *et al.*, 2002). To increase the effectiveness of farmers' involvement, legislative backing and financial incentives will be required, especially in the initial years (Jurriëns & Jain, 1993).

If the government wishes to continue controversial projects such as Rasi Salai, Hua Na, etc., monitoring and reviews should be conducted for at least 5 years after implementation. The large projects affect local people's livelihoods and are connected to ecosystem degradation and various health issues, e.g., snail-borne diseases such as schistosomiasis or opisthorchiasis, and mosquito-borne diseases such as malaria and filariasis (Service, 1991; Shannon, 2005). These undesirable side effects usually receive little attention because other priorities (e.g., increasing agricultural production and economics) are considered more important (Service, 1991). The reviews should include all environmental, social, health, economic aspects, and require greater intersectoral and interdisciplinary stakeholder collaboration. The knowledge of local communities should not be undervalued as they are the ones directly impacted by the projects.

The government should implement daily and seasonal operational rules for reservoir management, utilising real-time measurements and forecasts of weather and flow conditions. These rules should be based on multi-purpose optimisation, with model predictive control to support real-time reservoir operating decisions. In addition, the results from reservoir operation and forecasts can also be used for flood early warning downstream of the reservoir.

Individual farm ponds

Historically, one of the main justifications for promoting investment in water-related projects in northeastern Thailand was to promote dry-season rice agriculture. However, large-scale adoption of dry-season rice farming never succeeded, being employed in less than 5% across the basin (Floch *et al.*, 2007). From our point of view, it is difficult for large-scale dry-season rice cultivation to be possible if other factors, i.e., cropping pattern, field irrigation practices, etc., remain unchanged. This is because the average annual precipitation over the past 30 years (1985–2015) is not sufficient for dry-season rice agriculture. In some areas (the west part of the basin), it is even not enough for wet-season rice cultivation. As precipitation is still the primary source for rice cultivation, the only objective in the region should be ensuring sufficient water for wet-season rice cultivation. This would be possible if rainwater is efficiently caught and stored. If there is surplus of water, farmers can benefit from other less water-consuming crops such as soybeans, watermelons, and vegetables suitable for the dry season.

According to the 'New theory' agriculture developed by King Bhumibol Adulyadej of Thailand, after the large, medium, and small reservoirs, distribution canals, and systems were constructed, villagers should build small farm ponds and connect to those reservoirs to be able to efficiently manage the water and their farmland (The Chaipattana Foundation, n.d.). The pilot project was conducted at Ban Limthong, a village with 108 households in Buri Ram province in the study area. The pilot has been hugely successful, as the flood and drought problems that plagued the community for decades have been significantly reduced, and it also creates a stable buffer for the village (Steenbergen *et al.*, 2011).

The reservoirs have already been constructed over the entire basin; we propose to build individual farm ponds to complete the system. Estimating pond size is necessary to ensure water availability on a probability basis for irrigation (Palmer *et al.*, 1982). Thus, in this study, we develop and propose Equation (2) to estimate the volume of the farm pond:

$$P_v = \left[\frac{(WR - P) \times A_I}{E_f} + PS \times A_w + E \times A_s\right] \times (1 + S) \tag{2}$$

where P_v (m^3) is the total pond volume, WR (m) is the total crop water requirement, P (m) is average precipitation, A_I (m^2) is the total irrigation area, and E_f (%) is on-farm irrigation efficiency (80% for open channel flow (Kirdpitugsa & Kayankarnnavy, 2009). PS (m) is total percolation and seepage losses (the average value of 2 mm/day from observation is adopted (Kirdpitugsa & Kayankarnnavy, 2009), A_w (m^2) is the wetted area of the pond, E (m) is total pan evaporation obtained from Hydro and Agro Informatics Institute (2012), A_s (m^2) is the surface area, and S is the surplus storage (at least 10% of the full storage) (Clark *et al.*, 2002). It is important to note that PS and E account for the water's total duration to be stored in the pond before irrigation.

Due to the high water deficit observed in October, we estimate the farm pond size that would be required for this month per hectare of rice cultivation. The precipitation is assumed to start in mid-May and reach its maximum in August or September when some areas are flooding. The proposed farm pond would keep this excess runoff, then utilise it in October when precipitation declines. Therefore, besides reserving water for rice cultivation, another advantage is increasing the total water storage capacity, reducing or perhaps preventing flood damage.

The estimated required pond sizes are 3,100 m^3 per 1 ha (500 m^3 per 1 rai) (rai is the local Thai measurement of areas = 1,600 m^2) if only the KDML105 is planted; 2,670 m^3 per 1 ha (435 m^3 per 1 rai) if only the RD6 is planted; and 2,880 m^3 per 1 ha (470 m^3 per 1 rai) if both the KDML105 and RD6 are equally planted. The pond sizes are estimated relative to the average precipitation over the entire basin; thus, water deficits in some areas or some years may arise if rainfall is less than the average. However, if the farm ponds are connected with the reservoirs, the reservoirs can help replenish the ponds and ensure water availability.

Assuming a depth of 3 m, the ponds would occupy about 10% of the farm area. In other words, farmers have to sacrifice about 10% of their land to ensure water availability in October, which will significantly enhance rice yields. It is thus a trade-off between agricultural land and water security for rice cultivation. If farmers want to be assured of no water deficits for rice (i.e. also accounting for periods with less than average rainfall), about 15% of the area is required to excavate the ponds. The pond sizes can be redesigned to be more cost-effective and suitable for each farm by using the above equations along with specific climatic conditions, cropping patterns, and soil properties in each area.

Farmers themselves are the key driver for farm pond development. However, due to their low income, they will need financial support to carry out the relevant activities. Cooperation with local government agencies to construct irrigation canal systems, data support and consulting (Steenbergen *et al.*, 2011) is therefore needed.

Subsurface floodwater harvesting system

Flood and drought mitigation measures in Thailand have previously revolved around surface water storage. Recently, however, the concept of subsurface floodwater harvesting systems (also known as Managed Aquifer Recharge – MAR) Pavelic *et al.* (2012) has been used to transform floodwater to groundwater recharge. The groundwater can later be drawn up for agriculture practices during the dry season. A pilot trial is being conducted in the Lower Yom River Basin, a sub-basin of the Chao Phraya River Basin. The findings reveal that the groundwater recharge reduced the magnitude of flooding and generated approximately USD 250 M/year in farm earnings from dry season production of irrigated rice.

This approach is an element of water storage that should not be neglected (International Water Management Institute (IWMI), 2009). It can be adopted to mitigate flood and drought problems in the Mun River Basin. However, some parts of the basin, especially the Mun River and its tributaries in the upper part of the basin, have salinity problems. It is not worth the investment to conduct MAR in those areas because although it can reduce flood peaks, the groundwater cannot be drawn back up in the dry season for productive use. This is because the groundwater is not suitable for irrigation, and it may cause severe yield reduction. Therefore, we propose implementing the MAR at the upstream tributaries of the lower and the eastern parts of the basin where there are fewer or no salinity problems. This will result in fewer flood impacts downstream, will supplement surface water utilisation and will ensure ongoing groundwater is available for the 75% of villages over northeast Thailand (Srisuk *et al.*, 2001) that depend on it for agriculture and consumption.

Though MAR has the advantage of a smaller footprint on the landscape, the total cost of the whole system establishment, operation, and maintenance is too high for the farmers alone. The local government agencies' support is necessary in terms of budget availability and technical and administrative work. A thorough study regarding MAR implementation in the basin is necessary to ensure that only floodwater is captured without significantly impacting the supply-demand balance downstream. This requires a close partnership between the local government and farmers. The farmers also play an important role in the ongoing operational performance and maintenance of the flood harvesting structure. Financial incentives may be needed to solicit their efforts and continuing participation and contribute to reducing the magnitude of flooding downstream (Pavelic *et al.*, 2012).

Oxbow lake reconnection

Reconnection of oxbow lakes is a Nature-Based Solutions measure that can help slow runoff (thus reducing flood peaks) and store excess water in the lake to use during dry spells. Additionally, the oxbow lakes accommodate habitat diversity as spawning places for fish and other aquatic groups (Obolewski & Glińska-Lewczuk, 2011). There is substantial evidence of fruitful implementation of oxbow reconnection in many areas. The oxbow lake reconnections help increase flood protection capacity, restore hydrological connectivity and significantly benefit ecological status.

The Mun River's physical characteristics are meandering and anabranching. As a result of the hydrological and geomorphological process, numerous oxbow lakes have been cut off from the main river, causing a reduction in the river's storage capacity. Thus, reconnecting the oxbow lakes is an effective method of flood and drought mitigation. The approach uses the river's natural characteristics; therefore, the required work is not as vast as entirely new projects and could likely be achieved through the cooperation of villagers and local government agencies.

Local people also should have a major role in operation and maintenance with financial and technical assistance from the local water agencies.

Besides the proposed measures mentioned above, non-structural measures such as field management practices, land use planning and policies should be considered. Field management techniques for rice cultivation include furrow irrigation, alternate wetting and drying irrigation (AWD), rice ratooning, diminishing water demand for rice cultivation and increasing water productivity. Successful implementation of these practices has been documented in various studies. Land-use planning minimises development in flood-prone areas and conserve floodplains and wetlands as natural water storage. This will reduce flood and drought damage and is essential for ecosystems.

CONCLUSIONS

The study assesses flood and drought problems for rice cultivation in the Mun River Basin in Thailand, as well as current water development projects used to address these problems. The impacts of both flood and drought hazards are considered at the basin scale, including affected areas, flooding volumes, water supply, water demand and water deficit. The coping capacity of the current and ongoing projects is then evaluated, and the flaws and factors influencing their performance are discussed. We then propose potential measures and corresponding responsible parties to cope with both problems and enhance rice yields. The measures proposed meet criteria developed for the region to ensure successful implementation.

The results show that the total storage capacity of all existing measures is sufficient to tackle floods and droughts. However, floods and droughts continue to occur periodically and more frequently. The major causes of this failure include geological and physical characteristic constraints, developments based on political rather than technical and economic motivations, incomplete construction of irrigation distribution systems, lack of regular inspection and maintenance, reservoir operation challenges, and a fragmented institutional framework. The expected improved performance of our proposed solutions is in line with the aims of a recent national plan from the Thai government. The launch of the first National Water Resource Act and the 20-year master plan are expected to unite various government sectors and improve water resources management consistency in Thailand.

We propose potential measures that provide flexibility by combining a wide range of water storage options. The proposed measures are improvement of existing projects, farm ponds, subsurface floodwater harvesting systems, and oxbow lake reconnections. These measures are selected based on four criteria: addressing both floods and droughts, simplicity and cost, proven effectiveness in previous studies, and applying nature-based solutions where appropriate.

For rice cultivation at the basin scale, this paper provides an analysis of the impacts, coping capacity and in-situ mitigation projects related to floods and droughts. This information is vital for stakeholders so that proper solutions can be developed based on current conditions. If the proposed measures are carefully executed with appropriate pre- and post-project studies and reviews, the flood and drought problems in the area can be reduced or solved sustainably. Moreover, the study provides a method to directly calculate the required size of one proposed solution (farm ponds), which can be adjusted for other basins, single- or multi-crops, or different levels of water use.

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DATA AVAILABILITY STATEMENT

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

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