ADVANCING FOOD SECURITY THROUGH THE DEVELOPMENT OF IOT BASED WATER ALLOCATION MODEL: THE CASE OF KLONG SUAN MAK RIVER BASIN IN THE NORTHERN THAILAND

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ABSTRACT

This paper presents a sustainable IoT-based water allocation model designed for the River Basin in Thailand, integrating Internet of Things (IoT) and remote sensing technology to monitor and forecast water usage in real time. The intelligent Water Allocation Scheduling and Monitoring (iWASAM) has been developed as a tool for water management designed for the Klong Suan Mak (KSM) river basin, a sub-basin of the Lower Ping River Basin in Northern Thailand, including an area of 1,213.4 square kilometers. The iWASAM model integrates hardware, software, and user interaction to import cultivation-related data, estimate irrigation water requirements, deliver water to irrigation areas, and evaluate irrigation efficiency and performance of water management practices. The model assists with precise water scheduling, distribution, and monitoring, leading to improved agricultural productivity and reduced resource wastage. The hardware devices consist of IoT-based weather stations and flow measuring stations. The weather data collected every 5 minutes includes temperature, relative humidity, wind speed, sun radiation, and rainfall. Flow rates are recorded every 15 minutes at canal head regulators and the reservoir outflow. The iWASAM system is accessible to users through a web application. Daily crop growth data (Kc) is obtained from the IrriSAT (satellite-based irrigation scheduling service), and daily weather forecasts for selected irrigation areas are sourced from the TMD Weather Forecast API of the Thai Methodological Department. Actual data regarding crop cultivation areas, yields, and prices are submitted manually for each season. All data were analyzed to estimate the daily irrigation water requirements and determine the target water delivery for the designated irrigation area. The efficiency of irrigation and the water productivity are evaluated and reported seasonally. Research findings show that iWASAM is able to assess real-time irrigation water requirements and estimate water demand up to 8 days in advance. This allows water users and irrigation officers to anticipate water requirements, strategize water consumption, and regulate water distribution to correspond with demands. It also demonstrates potential improvements in water-use efficiency and crop yield in the pilot areas. The research emphasizes the potential of modern technology in addressing water scarcity, ensuring food security, and promoting sustainable agricultural practices.

Keywords: Internet of Things (IoT); Irrigation system; River basin; Water allocation; Water management

1. Introduction

Food security is crucial for sustaining health and promoting economic stability. However, it is threatened by multiple factors, including conflicts and political instability, climate variability, economic downturns, and population growth (Prosekov and Ivanova, 2018, UNICEF, 2021). Addressing the issue of food security requires tackling the increasing food shortage, which is intensified by changes in water availability and demand from non-agricultural use (Hanjra and Qureshi, 2010). The impacts of climate change, including changes in the spatial and temporal distribution of precipitation, water availability, and other agricultural production parameters, pose substantial threats to global food security (Shayanmehr et al., 2022). In addition, the increasing frequency and intensity of these changes are exacerbated by poverty and high inequality. In Thailand, agricultural development policy in the past has focused on the country's food security (Isvilanonda and Bunyasiri, 2009). Although crop production is surplus at the macro level, food accessibility at the household level is still a problem, where high-income households were less likely to suffer from food insecurity (Jankhotkaew et al., 2022). This is due to the rising economic and population growth that is intensifying the food demand and prices. Producing enough food for a growing population is a primary

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challenge; small-scale farmers need boosting to enhance farm productivity through agricultural research and improve irrigation systems for the long-term solution (Isvilanonda and Bunyasiri, 2009).

There is no single solution for solving global food security; the reduction of food insecurity requires a commitment from various sectors at national and global levels (Mc Carthy et al., 2018). However, food policy must address the surging of water scarcity, as water is a key driver of agricultural production (Hanjra and Qureshi, 2010). The importance of irrigation for future food security has been highlighted by many studies (Domènech, 2015, Pereira, 2017, Kang et al., 2017, Kadiresan and Khanal, 2018, Li et al., 2024). As irrigation can help boost agricultural output in semi-arid and even arid environments and stabilize food production and prices (Hanjra and Qureshi, 2010). Water management is the key to ensuring future food security for the growing population (Kang et al., 2017). To address the water management challenges, there is a need for a multi-layered approach that boosts ecosystems and water productivity and promotes water conservation; maintains water quality across agriculture, fishery, and livestock; facilitates multiple water uses and their supply chains; and adopts a bottom-up participatory approach right from local to river basin level (Kadiresan and Khanal, 2018).

The increasing worldwide shortages of water and costs of irrigation are leading to an emphasis on developing methods of irrigation that maximize the water use efficiency (Jones, 2004). At present, most of the water resources management agencies in the world consider efficiency as the ultimate goal of water resources management and regulation (Niu et al., 2023). As the main objective of irrigation is to improve the crop yield, the term precision irrigation has emerged. Precision irrigation is an effective approach to distributing water that combines information, communication, and control technologies to make coordination of various irrigation factors better (Liang et al., 2020, Hossain et al., 2024, Abioye et al., 2020).

Irrigation is traditionally scheduled and allocated by considering a fixed period and overlooking the variability in the environment and plant properties. While these methods are generally straightforward and easy to implement, they have limitations in terms of flexibility, efficiency, and adaptability to changing conditions, especially problematic under shifting climate patterns or in areas with fluctuating water demand (Preite and Vignali, 2024). To address these challenges, researchers attempted to mitigate water consumption by improving irrigation equipment and techniques, adjusting cropping patterns, and optimizing irrigation systems to enhance water use efficiency (Domènech, 2015, Koech and Langat, 2018, Li et al., 2024). Modern approaches, such as sensor-based and automated systems, can build on these traditional foundations, improving responsiveness and efficiency.

The rise of IoT and cloud-based data storage aims to enhance the efficiency and sustainability of integrated infrastructure that allows for real-time data collection, monitoring, analysis, water management, and allocation (Gloria et al., 2020, Et-taibi et al., 2024). Several wireless communication technologies are utilized in the wireless sensor network to effectively communicate data for improving irrigation systems, such as Wi-Fi, ZigBee, and Bluetooth. Recently, research in the field of water management technology has been exploring the use of remote sensing and machine learning technology, which intends to improve the way we manage and monitor the water consumption. For example, Pernapati (2018) proposed an IoT-based low-cost smart irrigation system using smart wireless sensors. Puengsungwan (2020) presented a soil moisture sensor based on IoT technology with real-time data collection. Devan et al. (2021) developed an IoT-based solar-powered smart irrigation system using an embedded method that is supervised using a Wi-Fi module.

Thailand, as an agricultural country, acquires large amounts of water for its agricultural sector. Economic development and market pressures have caused diversification and input-driven innovations in agriculture, creating new challenges for water resource management in Thailand (Bastakoti and Chalermphol, 2021). Thailand is working to improve water management as it is facing uncertainties regarding the lack of a long-term water planning strategy (Apipattanavis et al., 2018). However, there is a gap between the supply of various advanced models and the application by the irrigation and drainage community. Given the complexity of future irrigation management, the likelihood of adaptation by a broader model user community will increase if the models become more user- and data-friendly. Therefore, in this paper, we presented a user-friendly web-based application combining IoT and remote sensing technology, which aims to optimize water allocation, improve scheduling precision, and advance water monitoring techniques for sustainable development of agricultural productivity and food security. Additionally, the system focuses on optimizing water delivery into canals to enhance irrigation efficiency.

2. Materials and methods

2.1 Study area

The Klong Suan Mak (KSM) is a sub-basin of the Ping River basin, identified under basin code 0630. It spans an area of approximately 1213.4 square kilometers (758,395 rai). KSM is located in Kamphaeng Phet Province, Thailand. The climate of KSM is categorized into three seasons. Summer is from March to May, with April being particularly hot and humid. The rainy season starts mid-May and continues until mid-October, with humid weather and substantial precipitation that gradually diminishes by October. Winter is marked by cooler weather, which begins around mid-October and continues until February.

The physical geography of KSM is abundant in forest cover (58.9%), including deciduous forests, mixed deciduous forests under restoration, and fully regenerated forest plantations. The upper forest areas are primarily situated within the Klong Wang Chao National Park (**Figure 1**). The KSM sub-basin receives an average annual rainfall of 1,259 mm, resulting in a total precipitation volume of 1,528 million cubic meters (m^3) annually. The total water demand across all activities in the sub-basin is 389 million m^3 per year, with 385 million m^3 required for agriculture alone. To address the water scarcity, the Klong Suan Mak Reservoir has been proposed to have a usable capacity of 56.54 million m^3 (maximum storage of 66.84 million m^3 and minimum of 10.30 million m^3). The reservoir is expected to decrease the water-scarce area by 70% of the total irrigated area and enhance agricultural and water resource management.

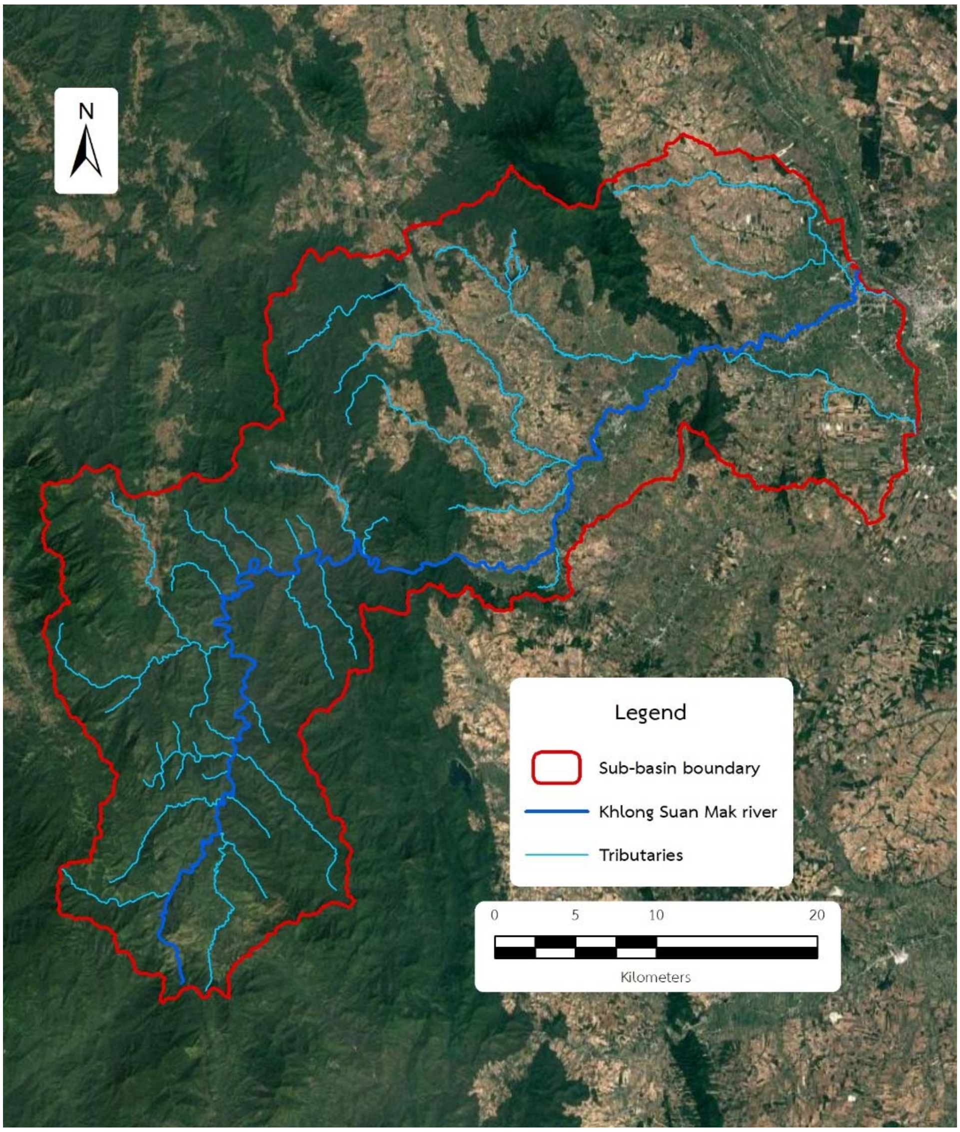

Figure 1 Map of the Klong Suan Mak sub-basin (KSM) boundary, main river, and its tributaries within the study area. The sub-basin boundary defines the watershed, while the river network illustrates the main river course and its tributaries.

2.2 The issue faced in the region

The Klong Suan Mak sub-basin faces three main water management challenges, including soil erosion and sedimentation in rivers and water bodies, water scarcity (shortage), and risk of flooding (**Figure 2**). These three challenges are interconnected and significantly impact the agricultural productivity, food security, and livelihood of the people within the basin area. For example, soil erosion worsens flooding by reducing the land's ability to retain rainwater, and flooding contributes to water scarcity by contaminating and wasting valuable water resources. The combined effects of these challenges significantly reduce agricultural productivity, leading to crop failures, yield reductions, lower food availability, and decreased income for farming households, ultimately threatening food security in the region.

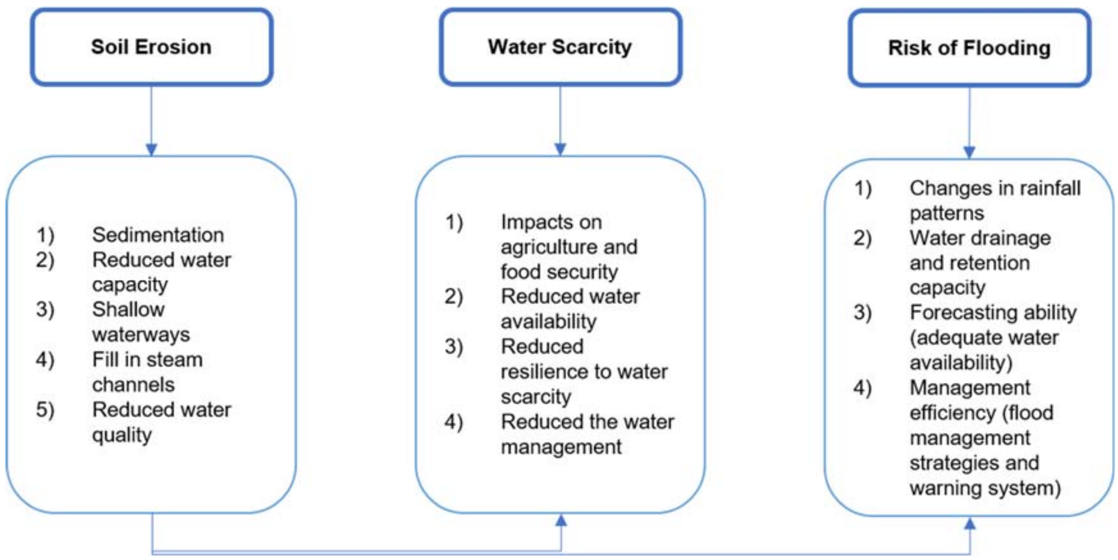

Figure 2 Challenges in the Klong Suan Mak sub-basin area.

Addressing these challenges is critical to promoting sustainable agriculture and food security in the KSM sub-basin. Therefore, there is a need for a cohesive and sustainable strategy in water management (Pansak et al., 2024). The main goal of this study is to optimize water delivery into irrigation canals to enhance irrigation efficiency and address agricultural water shortages. This is achieved by assessing soil erosion severity, evaluating flood-prone areas, and assessing the effectiveness of water distribution.

This study also establishes a participatory water allocation and real-time water monitoring mechanism involving local stakeholders, government officers, and relevant parties to enhance water management efficiency and productivity.

2.2.1 Soil erosion and sedimentation in rivers and water bodies

Soil erosion and sedimentation refer to the erosion of topsoil and the deposition of sediment in rivers and water bodies. The erosion occurs as a result of insufficient soil protection, changes in rainfall patterns, deteriorated forest conditions, and agricultural practices on terrain that is lacking appropriate soil conservation and management (Morgan, 2009, Sirikaew et al., 2020). Sedimentation happens due to the transportation of eroded soil from agricultural and forest areas by water into rivers and reservoirs (Dutta, 2016). Sediment depositions lead to the shallowing of reservoirs, reducing the water capacity and increasing water scarcity (Schleiss et al., 2016).

The evaluation of soil erosion in the KSM sub-basin found an annual erosion rate of approximately 2,922,055 tons/year, equating to 3.94 tons/rai/year or 1.5 mm/year, which complies with the standard set by the Land Development Department (LDD). The SWAT model simulation of precipitation, runoff, and sediment indicated that the average annual sediment load ranged around 246,129–380,053 tons/year. This corresponds with suspended sediment measurement at Tha Kradan Weir, where about 281.815 tons of sediment passed through from August 1, 2021, to February 28, 2022.

2.2.2 Water scarcity (shortage)

Water scarcity, especially during the dry season, is another pressing issue. Inconsistent rainfall patterns, compounded by climate change, result in insufficient water for agricultural activities. The KSM sub-basin receives an annual rainfall of approximately 1,502 million m^3 (rainy season 87% and dry season 13%). The rainfall generates an annual runoff of 575 million m^3 and contributed 96 million m^3 to groundwater recharge. The combined storage capacity of surface water reservoirs, including dams, weirs, and pounds, is about 33.81 million m^3 which accounts for only 6% of the average annual runoff. Groundwater has become a key alternative for agricultural irrigation as the extraction rates in this area are about 10-30 m^3/hour. The agricultural area is approximately 267,515 rai (42,802.4 hectares), which can be divided into irrigation area, irrigation within the sub-basin area, and rain-fed agriculture. The high water demand for irrigating crops creates intense competition for limited resources with the total water requirement of 203.96 million m^3/year or 2,774 m^3/year per rai. As a result, certain areas are often left without adequate water, which directly impacts crop health and yields, ultimately threatening the livelihoods of farmers and the food supply chain.

2.2.3 Risk of flooding

Flooding during the rainy season disrupts farming operations, damages crops, and contaminates water sources with pollutants and sediments. The flood risk assessment of the KSM sub-basin utilized the MIKE Flood model.

The MIKE 11 was calibrated using GISTDA flood data from 2005 to 2017 and field surveys to identify flood-prone areas within the sub-basin. The result indicated around 19,690 rai of flood-prone areas, particularly in Tha Khun Ram and Nakhon Chum sub-districts. Flooding in the KSM sub-basin is usually lasting only a couple of days (short-lived). However, floods can destroy any infrastructure in their flow path. Therefore, numerous studies recommend focusing on improvements of programs such as early warning systems and community disaster management training to prevent damage, save lives, and enhance society's resilience (Cools et al., 2016, Pal et al., 2018, Liu et al., 2018, Chaithong, 2022).

3. Implementation and pilot study (KSM)

3.1 Model overview

The iWASAM is an intelligent water allocation scheduling and monitoring system developed as a water management tool, which operates through hardware, software, and user interaction. The system integrates hardware designed to assist in data collection of both water resource management and meteorological data, which is acquired from various automatic monitoring stations, as illustrated in **Figure 3**. This system is capable of calculating real-time water usage and displaying results every 5 minutes using data obtained from IrriSAT (accessible via the IrriSAT website) and the developed weather and water stations. Additionally, iWASAM can monitor the available water volume in reservoirs and weirs, as well as measure the volume of water delivered into the canals in real-time. Data obtained from the automatic water measuring stations are recorded and displayed in the system every 15 minutes. The iWASAM system also provides daily summaries and forecasts of water demand and water delivery targets up to 8 days in advance. This enables irrigation officers to make more accurate decisions regarding water contribution, allocation, and scheduling.

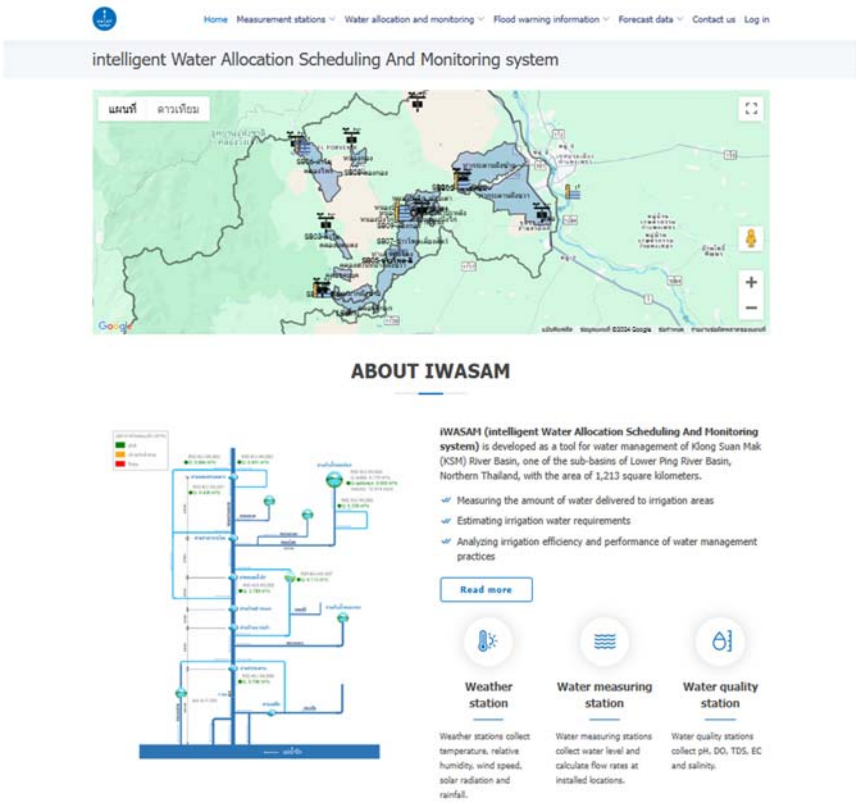

Figure 3 The iWASAM web-based application user interface, featuring an interactive map of the KSM sub-basin and key features such as weather and water monitoring stations.

3.2 Technological framework

Hardware devices comprise IoT-based weather stations and water monitoring stations. iWASAM is available through a web application and incorporates crop growth data from the IrriSAT API (weather-based irrigation scheduling service) and spatial weather forecast data from the TMD weather forecast API supplied by the Thai Meteorological Department (TMD). The iWASAM Server, accessible at https://iwasam.eng.kps.ku.ac.th/, serves as the central repository for data collected from all automatic monitoring stations. This centralized data collection supports iWASAM's functionalities, including real-time monitoring, data analysis, and decision-making tools for effective water resource management.

3.2.1 Satellite imagery

IrriSAT is a weather-based irrigation management and benchmarking technology that uses remote sensing to provide site-specific crop water management information across large spatial scales (Montgomery et al., 2015). IrriSAT combined satellite imagery and weather data to estimate crop coefficients (Kc) at a 30-meter resolution. Kc is calculated from a linear relationship with a satellite-derived Normalized Difference Vegetation Index (NDVI) and reference evapotranspiration (ET_o from on-ground weather stations).

3.2.2 RID KU weather station

The RID-KU automatic weather station measured temperature, relative humidity, wind speed and direction, solar radiation, and rainfall every 5 minutes (**Figure 4 A**). The on-site weather station offers real-time weather conditions that help to retrieve accurate crop coefficients.

3.2.3 Water monitoring station

The water monitoring station includes water level, quality, and visual monitoring through the CCTV station as shown in **Figures 4 B, C, and D**. The water level monitoring station uses an ultrasonic sensor to monitor the level of water and gate lift height (in the case where structures have water gates) every 15 minutes to calculate the water volume flowing through the structures. This station is installed at the weir in KSM to measure water flow through weirs and water dates to determine water availability at headworks for irrigation and water distribution planning in irrigated areas. The current meter is also installed to measure water velocity. Then the flow velocity measured by the current meter is used to calculate the discharge rate using the formula Q = A x V. The flow rate data obtained using the current meter is used to verify the accuracy of the flow rate measured by the automated water monitoring station.

A water quality station was installed to monitor the quality of water in the KSM, including pH, dissolved oxygen (DO), electrical conductivity (EC), total dissolved solids (TDS), salinity, and temperature. Real-time data from the station allows water users and officers to assess water quality and implement timely solutions to prevent damages caused by water quality concerns.

CCTV (closed-circuit television) station is to provide water users and officers with live visual updates of water conditions at various points. Images are updated every 15 minutes to support decision-making on necessary adjustments to water usage based on actual conditions. This station enables efficient and timely responses to changing water conditions and enhances the overall management and sustainability of the water system.

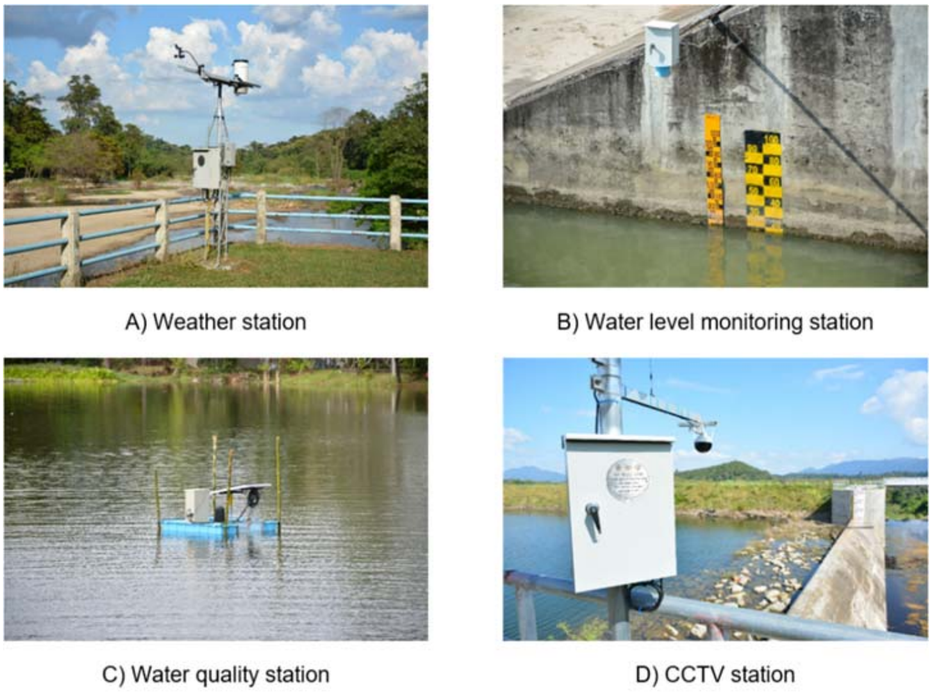

Figure 4 Example of a weather station, water level monitoring station, water quality station, and CCTV systems.

3.3 Data integration and processing

The development of an efficient and sustainable water management system for the KSM sub-basin relies on the integration of multiple data sources and their processing. The core elements of this system include crop growth data from the IrriSAT API (weather-based irrigation scheduling service) and daily weather forecast data for selected areas from the TMD (Thai Meteorological Department) weather forecast API, which were retrieved into the system daily (https://data.tmd.go.th/api/index1.php). The actual crop cultivated area data, crop yields, and prices in each season were input by the staff of Water Master (Kamphaeng Phet Irrigation Project). All the data were processed to get the estimation of daily irrigation water requirements and target water delivery of the selected area. Finally, irrigation efficiency and performance of water management were evaluated and reported seasonally.

3.3.1 Key data and utilization

IrriSAT provides daily crop coefficient (Kc) values for the cultivated area. This data is retrieved daily via the IrriSAT API. The collected weather data from TMD is then used to calculate the daily reference crop evapotranspiration (ET_o), which is then applied to determine the crop water requirement using the formula $ET_c = Kc * ET_o$.

Where ET_c is the volume of water required by a crop to maintain maximum rates of crop evapotranspiration. This approach ensures that the crop water requirements are accurately estimated based on both real-time weather data and growth-specific crop coefficients.

3.3.2 Irrigation estimation

The data is processed to calculate daily irrigation water requirements and establish the target water delivery for each selected area by integrating weather forecasts, crop growth data, and real-time field inputs. Seasonal evaluation of irrigation efficiency and water management performance is also conducted. These evaluations provide insights into the adequacy and effectiveness of the water delivery system to optimize water allocation to match crop requirements, enhance efficiency in water use and improve irrigation performance, and assist in decision-making for future planning. This data-driven approach ensures that the irrigation system is adjustable to various climate and crop conditions, therefore improving agricultural activity, productivity, and sustainability.

3.4 The implementation

By combining all the above features, the implementation of iWASAM for the KSM sub-basin began with the deployment of an automatic water monitoring station at a key location within the KSM sub-basin as described in section 2.2. The main page displays a map with the boundaries of irrigated areas, benefit areas, and a system workflow diagram (**Figure 3**). To facilitate decision-making, iWASAM was implemented as a web-based platform with five key components. (1) Irrigation water demand estimation, which predicts future water requirements for five irrigation areas within the KSM sub-basin. (2) Irrigation efficiency assessment, which analyzes water use efficiency by comparing scheduling versus actual water delivery. (3) Water delivery monitoring, offering real-time updates on water distribution and flow rates at control gates and canals. (4) Weather forecasting module, which integrates meteorological and hydrological predictions to anticipate water shortages or excess flows. (5) Automated monitoring stations, equipped with IoT-based sensors and solar-powered cameras to monitor water levels and enable timely interventions. The most important part is the irrigation water demand section, which is divided into three main parts. The first part is the irrigation water demand summary page, which presents a 7-day forecast of irrigation water demand for five irrigated areas. This allows users to plan their water usage effectively. The second part is the specific area water demand page, which shows the area of interest and detailed data necessary to calculate water demand for the selected location. The third part is the previous day summary page, which provide a summary of the net irrigation water demand, required irrigation water delivery, and water measurement at the canal headworks. The web application was built with a user-friendly interface, which offers easy access through smartphones, provides straightforward information, and supports the download of historical data for further analysis.

3.5 System functionality

The system functionality of the irrigation model is designed to evaluate the efficiency and performance of water management through multiple components to ensure effective distribution, monitoring, and optimization. Irrigation efficiency and performance of water management were evaluated and reported seasonally on the iWASAM system. Key functionalities include real-time monitoring, integration of weather and crop-specific requirements for precise water delivery, and automated reports on system performance. The water quantity data, including both water demand and water delivery, serve as an assessment of the efficiency of the irrigation system in the study area. One of the key metrics for evaluating the efficiency of the system is the Deliver Performance Ratio (DPR). DPR is the indicator that reflects the efficiency of water delivery with a value close to 1 indicates high efficiency.

$$DPR = \frac{Q_t \text{ (actual water delivery)}}{Q_m \text{ (target water delivery)}}$$

The system also evaluated crop yield, water use efficiency, and economic returns to assess overall productivity. These metrics are analyzed seasonally to determine the effectiveness of the implemented solutions.

4. Result and discussion

4.1 Key finding

The Klong Suan Mak River Basin spans a total area of 758,395 rai, covering 14 subdistricts across four districts in Kamphaeng Phet Province. Approximately 267,515 rai within the basin is dedicated to agricultural activities. Major crops grown in the area include cassava (134,549 rai or 49.2%), sugarcane (63,181 rai or 23.1%), rice (40,899 rai or15%), maize (9,251 rai or 3.4%), and other crops. Furthermore, the irrigation areas, benefiting zones, and pump-operated areas comprise 27% of the total agricultural land (**Table 1**). The data presented in **Table 1** includes water demand, which is calculated from IrriSAT.

Table 1 Water demand across different agricultural areas, measured in rai (a Thai unit of area, where 1 rai = 1,600 m^2).

Area types	**Area (rai)**	**Water demand**	
		Million m^3/year	**m^3/rai**
Irrigated area	73,528	203.96	2,773.9
Rain-fed agriculture area	193,987	181.37	935.0
Total agriculture area	**267,515**	358.33	1,440.4

When rainfall and runoff data were used to calculate the 10-day average rainfall and runoff over a 30-year period (1995-2024) (**Figure 5**). Rainfall has a significant influence on runoff at Ban Pong Nam Ron station (P.47) and Ban Mai station (P.26A). Although, on average, there is continuous water flow in the KSM canal throughout the year, the runoff volume from December to April is very low. The graph also illustrates that rainfall in the KSM is heaviest at the beginning of the rainy season (May) and toward the end (September–October), while there is a noticeable decrease in rainfall during the mid-season (late June to early July). Once the rainy season begins (late April to early May), runoff in the Klong Suan Mak Canal starts to increase in early May. After this initial rise, the runoff slightly decreases before increasing again in September, reaching its highest level in late October. Once the rainy season ends, runoff in the Klong Suan Mak Canal declines rapidly and remains very low throughout the dry season.

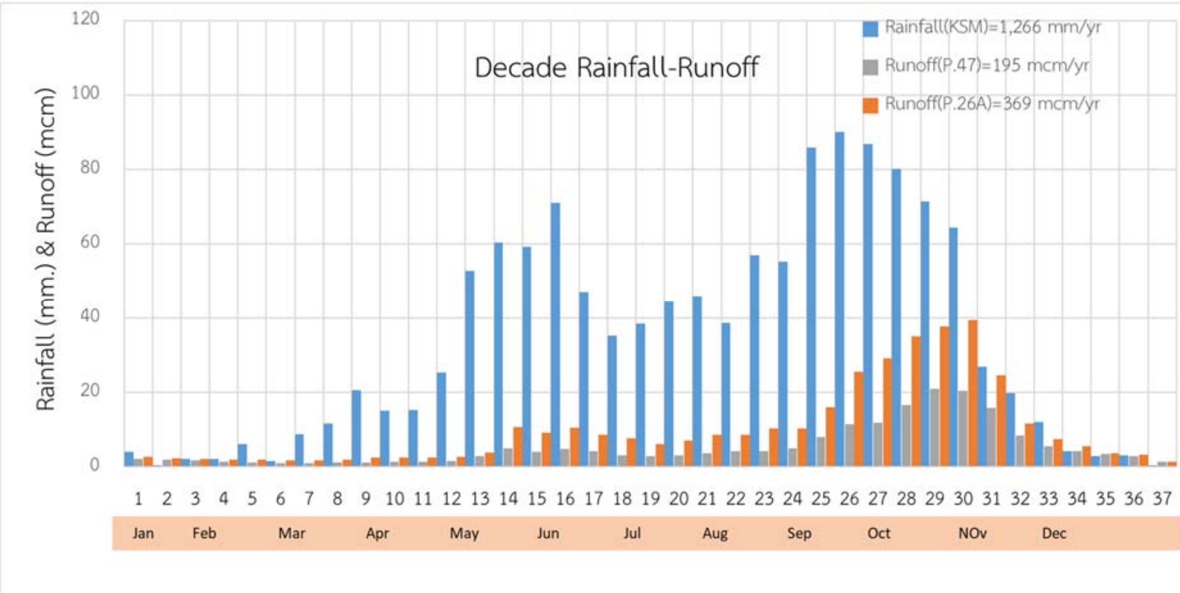

Figure 5 the annual rainfall and runoff volume at water monitoring stations P.47 (Ban Pong Nam Ron) and P.26A (Ban Mai), as recorded by the Royal Irrigation Department from 1991 to 2018.

The rainfall in the KSM sub-basin reaches 1,266 mm per year, which is approximately 3.5 times the total agricultural water demand across the area. However, water shortages remain a persistent issue in several locations. The approach addressing water scarcity in the KSM sub-basin in this study consists of non-structural (implementing iWASAM) and structural approaches that analyze the potential impact of constructing a KSM reservoir. From this study, the implementation of iWASAM significantly improves drought mitigation by enabling real-time irrigation demand assessment and providing a 7-day water demand forecast. Analysis using the SWAT-Mike Hydro Basin simulation model from 2011 to 2020 revealed that the KSM reservoir's effectiveness in addressing the issue faced in the area was conducted using the and found that the reservoir can alleviate water shortages in the KSM area by covering approximately 51,470 rai (about 70% of the irrigated agricultural area). Furthermore, it can help mitigate flooding by reducing the peak flow rate at the Klong Suan Mak Weir by 70%.

4.2 Water delivery performance

Key performance indicators to assess irrigation water delivery include adequacy, efficiency, dependability, and equality (Nam et al., 2016, Zema et al., 2019). Regarding actual water delivery and planned water delivery, most of the study areas delivered more water than planned, exceeding the net water demand in all seasons. During the 2021 rainy season, the DPR ranged from 0.88 to 4.39, with the left bank of Klong Suan Mak having the value closest to 1 at 0.88. In the 2022 rainy season, the DPR ranged from 1.54 to 5.05, with the right bank of Klong Suan Mak having the closest value to 1 at 1.54, while the left bank of Klong Suan Mak had a value of 5.05. During the 2023 rainy season, the DPR ranged from 1.33 to 4.15. For the 2024–2025 dry season, the DPR ranged from 0.97 to 3.14, with the right bank of Klong Suan Mak having the closest values to 1, at 1.04. The left bank of Klong Suan Mak had values far from 1, at 3.14.

From the delivery performance, we recommend that the system operates in two dynamic modes. (1) Storage Mode, activated during the late rainy season and early dry season when flow rates at the Tha Kradan Weir drop below 15 m^3/s, allowing controlled water storage to meet agricultural demand; and (2) Full Release Mode, triggered at the start of the rainy season to rapidly discharge excess water into the Ping River, preventing flooding and minimizing sediment buildup. By limited flow in irrigation canal systems can significantly affect water distribution (Mai et al., 2024). Along with the use of iWASAM, which acts as a decision support system for water management planning, ensuring that water usage is optimized for each specific area. The water delivery performance for the pilot area indicates that the water delivery was sufficient to meet the water demand. However, the excessive water delivery in some areas may require further planning to match water delivery more appropriately with water demand. Nevertheless, the implementation of the water delivery tracking system, which covers the entire irrigation and cultivation cycle from production to distribution, has significantly supported the study area. Although it may not yet be possible to directly compare seasonal performance across different years since the system's installation, it has provided valuable insights into the context of the study area. Continuous monitoring up to the present (2025) allows for more accurate seasonal performance comparisons.

4.3 Challenges and limitations

From the issues faced in the region and the impact on agricultural productivity and food security, which are deeply interconnected. For farmers in the KSM sub-basin, this means unreliable irrigation, reduced soil fertility, and lower crop yields. Moreover, sedimentation increases maintenance costs for irrigation canals and drainage systems, further straining local resources. Water scarcity, especially during the dry season, is another pressing issue. Inconsistent rainfall patterns, compounded by climate change, result in insufficient water for agricultural activities. The high water demand for irrigating crops like rice and vegetables intensifies competition for limited resources, often leaving certain areas without adequate water. This directly impacts crop health and yields, ultimately threatening the livelihoods of farmers and the food supply chain. Flooding during the rainy season disrupts farming operations, damages crops, and contaminates water sources with pollutants and sediments. The unpredictability and intensity of floods in recent years have made traditional water management practices less effective. Flooding not only leads to immediate losses in agricultural productivity but also long-term degradation of soil quality and infrastructure. These issues are not isolated. For example, soil erosion exacerbates flooding by reducing the land's ability to absorb rainwater, and flooding contributes to water scarcity by contaminating and wasting valuable water resources. Together, these challenges create a volatile agricultural environment, making it difficult for farmers to plan and adapt effectively. The combined effects of these water management challenges significantly reduce agricultural productivity in the KSM sub-basin. Crop failures and yield reductions lower food availability and income for farming households, directly threatening food security in the region. Furthermore, increased costs for water management and disaster recovery divert resources away from sustainable agricultural development.

Despite its potential, iWASAM has not yet fully achieved the expected improvements in drought mitigation or water productivity. The efficiency and productivity indicators still fluctuate, making it difficult to confirm with certainty that iWASAM has successfully enhanced water management efficiency. However, the feedback from water users, farmers, and local authorities provided valuable insights into the challenges faced. These interactions allowed the research team to better understand the practical issues and user requirements, leading to key improvements in the iWASAM system. Farmers emphasized the need for more localized water demand predictions, improved accessibility to real-time data, and a simplified interface for mobile users. Irrigation officials pointed out the importance of better coordination between water release schedules and actual field conditions, as well as the need for more accurate flood warnings in vulnerable areas.

The result from this study is similar to the study from Zema et al. (2019) and Seyed Hoshiyar et al. (2021) that the analysis detected poor adequacy and reliability of water delivery with low user satisfaction. A key challenge lies in changing long-established behaviours in water use and management. To maximize iWASAM's effectiveness, irrigation projects must prioritize efficiency and effectiveness in water management, actively monitor and review the system's daily reports, and integrate its insights into decision-making processes. If irrigation officers consistently track and respond to iWASAM's reports, it is likely that officials and water users will recognize the importance of efficient water use and adopt improved practices. Given these challenges, this issue will be a central focus of the next research phase, aiming to demonstrate that iWASAM can be a key tool for improving water use efficiency and effectiveness. Future research will explore strategies for enhancing user engagement, refining system accuracy, and ensuring that iWASAM can fully support sustainable water resource management.

4.4 Implications for agricultural sustainability and food security

The frequency and severity of extreme weather events have increased and made the prediction of weather extremely challenging. Extreme weather impacts agricultural activity and food security. Therefore, the implications for agricultural sustainability and food security highlight the interconnected challenges and opportunities in managing resources, adopting innovative technologies, and supporting resilient agricultural systems.

The existing literature suggests that the scope of saving consumptive use of water through advanced irrigation technologies is often limited as these improvements raise water prices and require (Perry et al., 2009, Levidow et al., 2014). Toward resilient agriculture and food security, traditional irrigation management includes water distribution systems with less capacity than the peak demand, irregular delivery rates, and low irrigation efficiency. It is necessary to strategically compare the estimated irrigation demands with the actual water supplies for decision-making in order to maintain the water supply according to the demand (Nam et al., 2016). Through the integration of technology and stakeholder engagement, this study lays the foundation for resilient agricultural practices and sustainable food security in the KSM sub-basin area. Sustainable water management as implemented in the KSM sub-basin demonstrates how resource efficiency and resilience can be improved in the face of extreme weather events. This approach not only mitigates the adverse impacts of unpredictable weather patterns on agricultural activity but also promotes long-term food security by optimizing water usage and ensuring its equitable allocation. The iWASAM model is replicable and can be adapted to other regions facing similar water management issues.

The system highlights the strengths and weaknesses of each region, enabling targeted analysis and improvements in water management practices. Over time, as the system operates at full efficiency, it will contribute to the sustainability of agriculture and irrigation systems in the Klong Suan Mak area. Moreover, this model can be applied to other study areas, enhancing overall water management efficiency and promoting sustainable agricultural practices in diverse regions.

5. Conclusion

The iWASAM model has been developed to tackle significant water management issues in agricultural contexts. It serves as a comprehensive tool for improving water management efficiency through the integration of IoT-based sensors, real-time meteorological and flow data. iWASAM optimizes water distribution corresponding with actual irrigation requirements. Moreover, this model can forecast water consumption with advanced forecasting capabilities, the model predicts irrigation water requirements up to 8 days in advance. This allows irrigation officers and water users to monitor real-time water demand for proactive water planning, allocation, scheduling, and management. This can help promote optimal crop growth and development, resulting in increased agricultural output and improved resource efficiency. From the Klong Suan Mak sub-basin site, we analyzed six seasons of data over three years, and at the end of the season, iWASAM summarizes the water delivery performance, providing essential data for the Kamphaeng Phet Irrigation Project and the water user group at the KSM area to support decision-making in crop planning and water allocation for the next season and future irrigation operation. These attributes establish iWASAM as an effective instrument for attaining sustainable water management and tackling global issues, including water shortage and food security. As we can see, the proposed model works effectively in the study area. This approach has the potential to scale up and update the model to use in other regions. Future direction for research will require the use of blockchain technology for data transparency and explore strategies for enhancing user engagement, refining system accuracy, and ensuring that iWASAM can fully support sustainable water resource management.

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