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RESEARCH ARTICLE

Big Data-Driven Information System for Managing Recurrent Agricultural Drought in the Upper ING Watershed, Thailand: An Integrated Water Resources Management (IWRM) Approach

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ABSTRACT

Agricultural drought poses a recurring threat to the Upper Ing Watershed in Phayao Province, Thailand, particularly in the rainfed areas outside irrigation schemes. This study introduces an integrated big data-driven information system to support sustainable water management in community-based agro-ecological landscapes. Using spatial analysis, participatory mapping, and remote sensing technologies including UAV-based LiDAR and satellite imagery the study established a geospatial database and mobile application to monitor water sources, assess water balance, and guide decision-making. The system, developed collaboratively with local stakeholders, enabled real-time data collection, drought severity mapping, and optimized irrigation planning at the sub-watershed scale. Results demonstrate that integrating big data with localized decision-making processes enhances water governance and drought resilience in vulnerable agricultural regions.

INTRODUCTION

Agricultural drought is a recurrent and intensifying threat to water security and rural livelihoods in many regions of Southeast Asia, particularly in the Upper Ing Watershed of Phayao Province, northern Thailand. The area's complex topography, fragmented agricultural zones, and limited irrigation infrastructure have rendered it increasingly vulnerable to climate variability, especially prolonged dry spells. Over the past decade, local farmers have experienced repeated crop losses, particularly in rainfed areas that account for over 85% of the province's total agricultural land. The primary water source, the Ing River and its tributaries, no longer provide sufficient supply during critical growing periods, prompting an urgent need for a more adaptive and decentralized approach to water resource management. [Zhang et al., 2020; Feng et al., 2025].[1][2]

Despite the presence of various government agencies tasked with monitoring hydrology, agriculture, and meteorology, data remains siloed, non-integrated, and underutilized. Current water management systems are largely reactive, often relying on historical rainfall averages and generic cropping calendars that fail to capture local microclimates and seasonal drought variations. Moreover, existing treflectsr irrigation planning and drought preparedness rarely reflect the ecological and socio-economic contexts of smallholder farming communities. This results in low efficiency in water allocation, underutilization of reservoirs, and minimal community participation in water governance.

Integrated Water Resources Management (IWRM) offers a promising paradigm for addressing these systemic limitations. (Nagata et al., 2022; Jam et al., 2025)[3] By emphasizing cross-sectoral coordination, stakeholder inclusion, and data-driven planning, IWRM aligns well with the need for localized, adaptive management of water resources in complex agro-ecological systems. In recent years, the advancement of geospatial technology, remote sensing, and big data analytics has made it feasible to implement IWRM strategies even at sub-watershed or community scales. However, the challenge remains to translate these technologies into actionable decision-support systems that can be co-developed and sustained by local institutions. (Srivastava et al., 2022; Tanriverdi et al., 2025, Fatima et al., 2025) [4]

This study presents the design and deployment of a big data-driven information system to support integrated drought management in the Maesuk sub-watershed of the Upper Ing Basin. The system integrates spatial datasets, remote sensing indices, and participatory mapping into a real-time decision-support platform designed for farmers, local government units, and water user associations. Key innovations include the development of a mobile-based data collection tool, real-time drought monitoring using remote sensing, and the creation of irrigation zoning maps based on both hydrological and socio-economic parameters.

By embedding the principles of IWRM into the design and implementation process, the project aims to enhance institutional coordination, empower local stakeholders, and improve the efficiency and equity of water allocation. The findings from this research contribute to the growing body of literature on digital water governance and demonstrate how community-level innovation, supported by appropriate technology and policy frameworks, can advance sustainable water management under conditions of climate uncertainty.

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted in the Maesuk sub-watershed, a tributary of the Upper Ing River in Phayao Province, Thailand. The area covers 48.16 km^2 (30,103 rai), encompassing upland forest, mixed agriculture, and residential communities. It contains two primary reservoirs—Mae Suk and Mae Chua—serving as water sources for 2,900 rai of irrigated land and thousands of rai of rainfed fields (Figure 1).

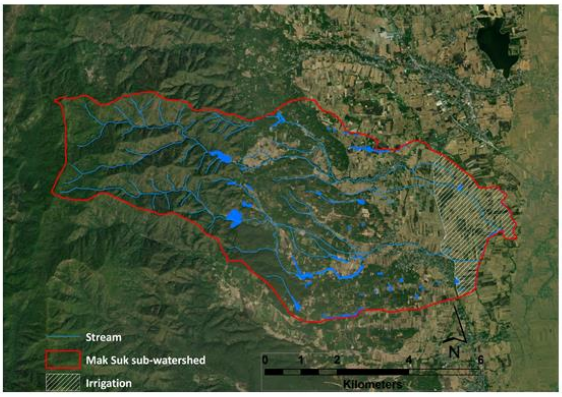

Figure 1. Spatial Distribution of Reservoirs, Streams, and Water Distribution Networks in the Mae Suk Sub-Watershed, Upper ING Basin, Phayao Province, Thailand

2.2 System Development Framework

The project involved a three-pronged methodology: (1) stakeholder coordination and participatory design, (2) development of a geospatial big data system, and (3) application of remote sensing for monitoring and validation. A customized mobile application was developed using AppSheet for field data collection on water bodies, including physical dimensions, usage, water availability, and user ownership. Data were structured as spatial (GIS) and attribute layers and integrated into a PostgreSQL database (Figure2).

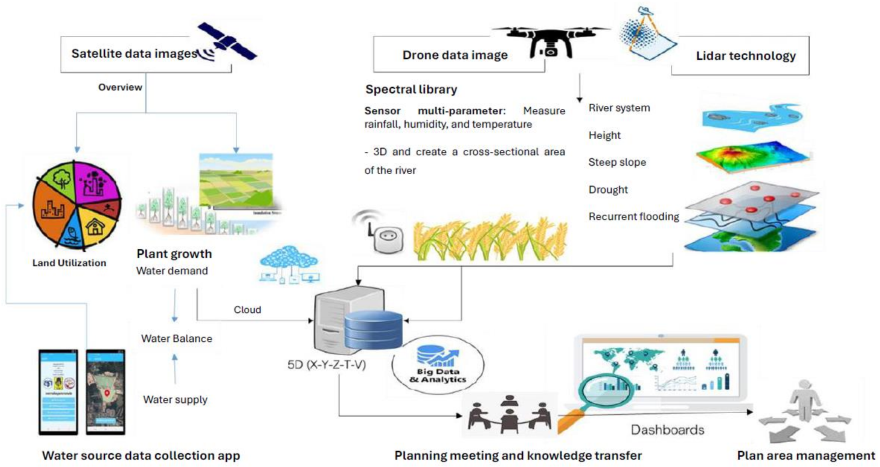

Figure 2. Methodological Framework of the Big Data-Driven Water Management System, Outlining Stakeholder Engagement, Mobile-Based Data Collection, Geospatial Database Development, and Integration of Remote Sensing Indices

2.3 Remote Sensing and Water Balance Monitoring

Satellite imagery from Sentinel-2 and Landsat-8, combined with UAV surveys, was used to map water surface area, land use, and soil moisture. Moisture Stress Index (MSI) and NDWI were calculated to assess drought severity. Ground-truth soil moisture data were collected at 10 cm and 30 cm depths across 30 sampling points. These data validated the remote sensing outputs and informed seasonal drought forecasting (**Figure 3)**.

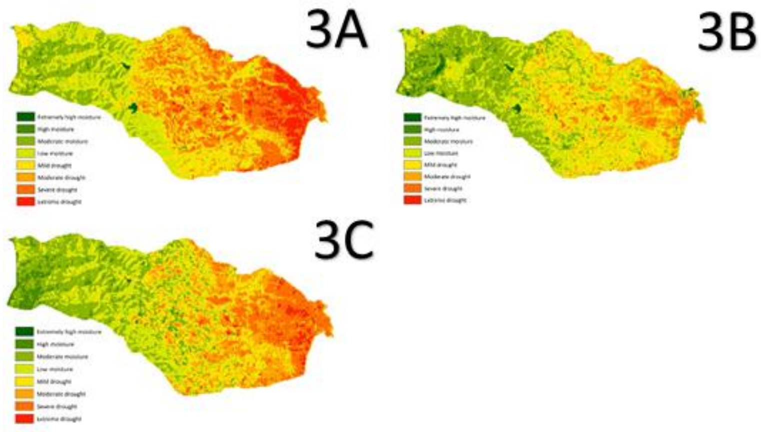

Figure 3. MSI Index across Three Temporal Periods in the Mae Suk Watershed (3A-17 Mar 1998, 3B-25 Mar 2001 and 3C 16 Mar 2015X

2.4 Community Training and Data Application

Field training workshops were held to enable local farmers and municipal staff to collect data and interpret maps. Resulting outputs included water resource inventory maps, crop water demand profiles, and irrigation zoning plans. Final datasets and dashboards were transferred to local authorities for ongoing use and integration into water planning and governance.

3. RESULTS

The implementation of the big data-driven water management system in the Maesuk sub-watershed yielded significant advancements in spatial analysis, participatory water governance, and drought monitoring. Results are organized into four core dimensions: (1) water resource mapping and inventory, (2) drought monitoring and moisture assessment, (3) irrigation zoning and water demand profiling, and (4) system usability and stakeholder response.

3.1 Water Resource Mapping and Spatial Database

The research team successfully developed a comprehensive geospatial database integrating base maps, topography, land use, and hydrological infrastructure across the 48.16 km^2 watershed area. A total of 2 major reservoirs, 11 weirs, and 7 gated irrigation structures were identified and mapped. In addition, 29 groundwater wells were recorded—27 within irrigation zones and 2 outside—based on survey and Department of Groundwater Resources data. The resulting base maps were digitized from the L7018 topographic series, refined using drone surveys and GPS-verified field data. The digital elevation model revealed terrain gradients critical to water flow modeling and micro-zone planning. Stakeholder discussions facilitated the delineation of water user zones, which were classified into four zones based on canal distribution, crop type, and relative elevation **(Figure 4)**.

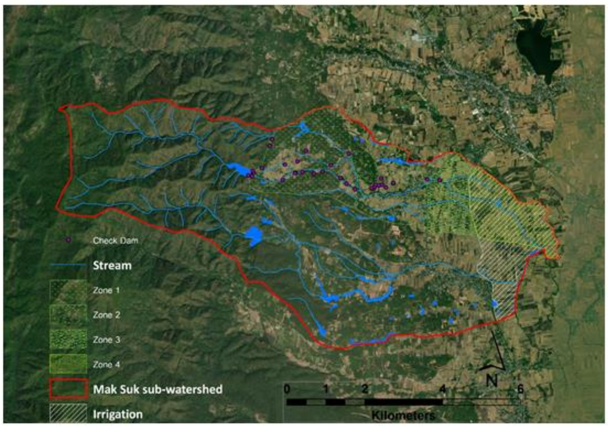

Figure 4: Irrigation Zoning Map Check Dam and Stream Network in Mae Suk Sub-watershed

3.2 Drought Monitoring and Soil Moisture Validation

Satellite imagery from Sentinel-2 and Landsat 8, combined with UAV observations, allowed for detailed monitoring of seasonal water availability. The NDWI and MSI indices were calculated to assess surface water extent and soil moisture stress. Ground-truthing through soil sampling (30 plots across 10 locations) at 10 cm and 30 cm depths validated the satellite-derived moisture stress indices. Correlation coefficients ranged from 0.68 to 0.94 depending on depth and date, confirming the reliability of the MSI values. These indices were used to classify drought severity into eight MSI levels. During the 2022 dry season, over 2,000 rai were classified as experiencing severe drought, primarily in upland paddy zones. The MSI-based zoning maps were delivered to local authorities to assist in drought contingency planning **(Figure 5)**.

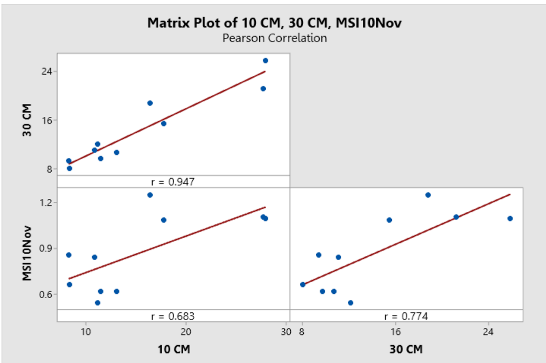

Figure 5. Seasonal Drought Risk and Water Availability Classification Based on MSI and NDWI Indices, Illustrating Dry Versus wet Season Conditions. Maps were Validated with in-Situ Soil Moisture Measurements at 10 cm and 30 cm Depths

3.3 Irrigation Zoning and Crop Suitability Mapping

The team integrated land use data, crop distribution, and irrigation infrastructure to develop zoning maps for water distribution. Areas were categorized based on elevation, canal accessibility, and crop type—namely paddy rice, maize, and fruit trees. Irrigation scheduling recommendations were developed for each zone. Survey data indicated that 99% of rice fields (totaling 9,029 rai) were within highly suitable zones for cultivation, as determined by soil type and NDVI growth stage monitoring. However, only 29% of these fields were within formal irrigation zones, highlighting the reliance on rainfall and informal water sources. The system further provided estimates of crop water requirements and matched them to supply forecasts to aid water release planning from the two major reservoirs (Figure 6).

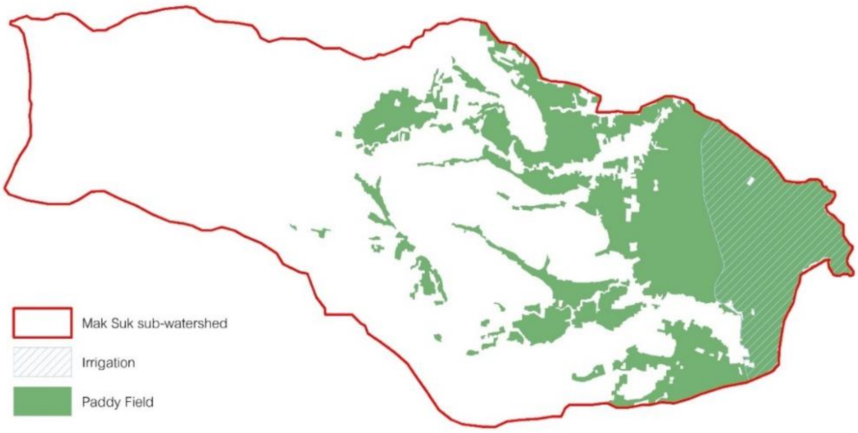

Figure 6. Crop Suitability Zoning for Paddy Fields in the Mae Suk Sub-Watershed, Integrating Land Use, Soil Characteristics, and Canal Access. Irrigation Scheduling Recommendations are Aligned with NDVI Growth Stage Monitoring

3.4 System Utilization and Community Engagement

Through participatory mapping workshops and field training, local users—including farmers, municipal officers, and reservoir managers—were introduced to the SmartWater@Phayao platform and trained in the use of the mobile app. Stakeholder feedback indicated high satisfaction with the system's real-time capability and ease of use. The mobile application developed using AppSheet allowed for decentralized data collection on water resources, irrigation structures, and soil moisture. Over 300 records were collected in two months and synchronized with the central database. The visual dashboards displaying NDWI, rainfall trends, and reservoir storage levels were especially useful for decision-making during the late 2022 drought period. Community water user groups adopted the zoning maps as a reference for rotational water sharing and were involved in verifying canal paths, gate positions, and informal water storage areas. The integration of satellite data with participatory inputs enhanced trust and local ownership, laying the foundation for sustained data updating and governance.

Together, these results highlight the technical and institutional viability of localized, big data-enabled IWRM systems in semi-arid agricultural contexts. The project not only improved situational awareness of drought conditions but also supported participatory planning and adaptive water allocation

4. DISCUSSION

The implementation of a big data-driven information system in the Upper Ing Watershed represents a significant shift in localized water governance, particularly in regions where drought has become a chronic hazard. This project demonstrated how technological tools, when properly adapted to local context and accompanied by stakeholder engagement, can support the operationalization of Integrated Water Resources Management (IWRM) at the sub-watershed level. The following discussion highlights the implications of the results in four key areas: (1) practical application of

IWRM principles, (2) integration of remote sensing with local knowledge, (3) institutional capacity and stakeholder trust, and (4) scalability and future applicability.

4.1 Translating IWRM into Local Practice

IWRM is often perceived as a high-level policy framework, but this study shows how it can be effectively grounded in the realities of smallholder farming systems. Through participatory zoning, decentralized data collection, and cross-sectoral coordination, the project offered a real-time mechanism for managing competing water demands under drought conditions. The zoning maps and reservoir-linked irrigation scheduling represent tangible outputs of IWRM that directly address equity and efficiency—two core IWRM goals. Furthermore, the clear spatial delineation of water user zones enabled more transparent and accountable water sharing during peak demand periods. In areas like the Upper Ing Watershed, where traditional water governance is fragmented, the study offers a replicable model for making IWRM actionable at the village scale.

4.2 Blending Technological and Indigenous Intelligence

One of the project's most valuable contributions was the seamless integration of high-resolution satellite data with ground-level observations and local knowledge. Validation of soil moisture indices (MSI) with field samples proved essential in building trust among farmers, who were initially skeptical of remote sensing data. The co-creation of digital water resource maps with community members reinforced the legitimacy of the system and encouraged adoption. This hybrid approach also helped correct discrepancies between official irrigation maps and informal water-sharing arrangements. It aligns with emerging global water management literature that emphasizes the importance of co-produced data for enhancing decision-making in complex socio-ecological systems.

4.3 Strengthening Institutional Capacity and Adaptive Planning

The introduction of SmartWater@Phayao, with its user-friendly mobile interface and real-time dashboards, significantly improved institutional capacity for adaptive water planning. Municipal staff, which previously lacked access to spatial data or seasonal drought forecasts, now have tools for scenario analysis and early warning. The participatory approach not only transferred technical capacity but also fostered a culture of shared responsibility among water users. The transparent data flows and interactive dashboards facilitated rapid responses during the 2022 drought period and enabled rotation-based irrigation practices grounded in empirical data. This reinforces the argument that digital governance tools, when coupled with local ownership, enhance institutional resilience to climate extremes.

4.4 Pathways for Scaling and Policy Integration

While the project focused on a single sub-watershed, its methodologies and tools are designed for replication in other drought-prone areas. The modularity of the mobile data collection app and GIS dashboard allows for adaptation to diverse landscapes and user needs. Moreover, the engagement with provincial water authorities and integration of government datasets laid the foundation for vertical policy alignment. With modest investment, the system could be expanded to cover the broader Upper Ing Basin or linked to national drought monitoring networks. Future efforts should explore coupling the system with groundwater data, economic models, and water quality monitoring to support more holistic planning. In doing so, the approach aligns not only with IWRM but also with SDG 6 (Clean Water and Sanitation), SDG 13 (Climate Action), and Thailand's national climate adaptation strategies.

In summary, the project contributes to bridging the persistent gap between water policy and implementation, demonstrating how community-based innovation, enabled by digital technology and anchored in participatory governance, can drive transformative change in the face of climate uncertainty.

4. DISCUSSION

4.1 Localization of IWRM through Big Data and Stakeholder Engagement

This study demonstrates that the practical application of Integrated Water Resources Management (IWRM) can effectively be localized at the sub-watershed level by integrating big data technologies with participatory stakeholder engagement. Similar approaches have been implemented successfully in other regional initiatives, such as the WISDOM Project in the Lower Mekong Delta, where integrated spatial databases have supported policy-making in water management)Kuenzer et al.,2016). The delineation of irrigation zones and resource allocation maps in this study addresses key IWRM principles—equity and efficiency—highlighting tangible improvements in local water governance.

4.2 Integration of Remote Sensing and Local Validation

The validation of remotely sensed moisture indices, such as MSI and NDWI, through ground-truthing significantly enhanced local trust and acceptance of the technology. These findings align closely with studies that have validated satellite-based vegetation indices as reliable indicators for drought assessment across Southeast Asia. Specifically, the validation methods in this study echo approaches from recent research utilizing bias-corrected satellite data for SPI and SPEI analyses at the sub-basin level in South Asia, emphasizing the robustness and applicability of remote sensing in regional drought monitoring and planning. [Ali et al., 2024; Senapati et al., 2025; Gayanthika et al.,2025]

4.3 Decision Support Systems for Effective Water Governance

The development and deployment of SmartWater@Phayao as a comprehensive DSS demonstrated the critical role of decision-support technologies in contemporary water management. This aligns with research emphasizing that the participatory process of DSS development is often as important as the technical design itself. Comparable systems, such as Thailand's AWARD project, which integrated ANN and fuzzy logic for efficient water gate management, highlight the growing recognition of intelligent decision-support platforms in reducing water losses and enhancing allocation efficiency, particularly under drought conditions. [Khairudin et al., 2022; Sahib et al., 2022].

4.4 Enhancing Institutional Capacity and Adaptive Management

Institutional strengthening through the real-time application of spatial data and participatory processes was a significant achievement of this project. Local municipal officers and community stakeholders received critical training, enabling informed decision-making during drought episodes. These findings reflect broader adaptive management strategies, emphasizing that continuous stakeholder feedback loops and iterative system improvements are essential for sustainable resource governance, particularly given the inherent uncertainties in climate change impacts.

4.5 Scalability, Policy Linkages, and Future Directions

While focused primarily on the Maesuk sub-watershed, the modular structure of the developed system allows for scalability to other vulnerable regions. Parallel examples, such as WFP's PRISM platform, demonstrate how successful pilot interventions can effectively scale across broader geographic and socio-economic contexts. The potential integration of groundwater data, economic modeling, and water quality assessments within the existing DSS framework further aligns with comprehensive regional and national water management policies, supporting global sustainability goals such as SDG 6 (Clean Water and Sanitation) and SDG 13 (Climate Action). (Nandi and Swain 2024)

In summary, this research contributes significantly to narrowing the gap between theoretical water resource management frameworks and practical localized implementation. By leveraging big data, stakeholder engagement, and advanced remote sensing, it provides a replicable model for effective drought management and resilient water governance in agricultural communities facing climate variability.

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