

EVOLUTION OF REMOTE SENSING APPLICATIONS IN THAILAND: FROM ENVIRONMENTAL MONITORING TO NATIONAL WATER ACCOUNTING AND WATER RESOURCES MANAGEMENT

ÉVOLUTION DES APPLICATIONS DE TÉLÉDÉTECTION EN THAÏLANDE : DU SURVEILLANCE ENVIRONNEMENTAL À LA COMPTABILITÉ NATIONALE DE L'EAU ET À LA GESTION DES RESSOURCES EN EAU

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ABSTRACT

Remote sensing has transformed water resources research by providing spatially continuous observations of environmental and hydrological processes across multiple spatial and temporal scales. This review synthesizes more than two decades of remote sensing research in Thailand and demonstrates how Earth observation technologies have progressively evolved from environmental monitoring tools into integral components of hydrological understanding, national water accounting, hydrological modelling, irrigation performance assessment, and operational water resources management.

The evolution began with environmental monitoring applications, including satellite-based assessment of water quality and watershed land-use dynamics. Early studies demonstrated the importance of atmospheric correction, field calibration, and optimized sampling strategies for improving the accuracy of water quality retrieval from satellite imagery. At the watershed scale, multi-temporal land-cover analyses revealed the influence of landscape change on runoff generation and flood response, establishing the methodological foundation for quantitative remote sensing applications in water resources management.

Subsequent research advanced toward hydrological process understanding through the development of the Normalized Difference Infrared Index (NDII) as a proxy for root-zone moisture storage. Strong relationships between NDII and model-simulated soil moisture enabled the integration of remotely sensed information into hydrological model structures, improving process representation and predictive capability. This transition marked an important shift from using remote sensing solely as an external source of information to employing it as a constraint on hydrological processes.

A major milestone was the implementation of a nationwide Water Accounting Plus (WA+) framework covering all 25 river basins and 254 sub-basins of Thailand. Satellite-derived precipitation, evapotranspiration, land-use information, and hydrological modelling were integrated to support water security assessment, resource allocation, and strategic water resources planning. Complementary evaluations of satellite evapotranspiration and precipitation products established reliable datasets for operational applications and highlighted the benefits of bias correction and ensemble approaches. More

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recently, the integration of NDVI, NDII, actual evapotranspiration, and gross primary productivity has enabled irrigation performance assessment and agricultural water management at regional and national scales.

Collectively, these developments demonstrate a clear progression from environmental observation to operational decision support, providing a transferable framework for strengthening water security and sustainable water resources management in tropical and data-scarce regions.

Keywords: Remote Sensing; Water Accounting; Hydrological Modeling; Satellite Precipitation; Evapotranspiration; NDII; Irrigation Performance; Water Resources Management.

RESUME

La télédétection a transformé la recherche menée sur les ressources en eau en fournissant des observations spatialement continues des processus environnementaux et hydrologiques à plusieurs échelles spatiales et temporelles. Cette revue synthétise une recherche menée sur la télédétection pour plus de deux décennies en Thaïlande et démontre comment les technologies d'observation de la Terre ont progressivement évolué des outils de surveillance environnementale vers des composantes intégrales de la compréhension hydrologique, de la comptabilité nationale de l'eau, de la modélisation hydrologique, de l'évaluation des performances d'irrigation et de la gestion opérationnelle des ressources en eau.

L'évolution a commencé avec les applications de surveillance environnementale, y compris l'évaluation par satellite de la qualité de l'eau et de la dynamique d'utilisation des terres dans les bassins versants. Les premières études ont démontré l'importance de la correction atmosphérique, de l'étalonnage sur le terrain et des stratégies d'échantillonnage optimisées pour améliorer la précision de l'extraction de la qualité de l'eau à partir d'images satellites. À l'échelle des bassins versants, les analyses multi-temporelles de la couverture terrestre ont révélé l'influence du changement de paysage sur la génération de ruissellement et la réponse aux inondations, établissant ainsi la base méthodologique des applications quantitatives de la télédétection dans la gestion des ressources en eau.

Les recherches ultérieures ont progressé vers la compréhension des processus hydrologiques grâce au développement de l'indice infrarouge à différence normalisée (NDII) comme indicateur indirect du stockage de l'humidité dans la zone racinaire. Les relations étroites entre le NDII et l'humidité du sol simulée par modèle ont permis l'intégration d'informations de télédétection dans des structures de modèles hydrologiques, améliorant ainsi la représentation des processus et la capacité prédictive. Cette transition a marqué un changement important, passant de l'utilisation de la télédétection uniquement comme source d'information externe à son emploi comme contrainte appliquée aux processus hydrologiques.

Un fait saillant était la mise en œuvre d'un cadre national de comptabilité de l'eau plus (WA+) couvrant les 25 bassins fluviaux et 254 sous-bassins de la Thaïlande. Les précipitations issues de satellites, l'évapotranspiration, les informations sur l'utilisation des terres et la modélisation hydrologique ont été intégrées pour soutenir l'évaluation de la sécurité de l'eau, l'allocation des ressources et la planification stratégique des ressources en eau. Des évaluations complémentaires de l'évapotranspiration satellite et des produits de précipitations ont établi des ensembles de données fiables pour des applications opérationnelles et ont mis en évidence les avantages de la correction du biais et des approches d'ensemble. Plus récemment, l'intégration du NDVI, de la NDII, de l'évapotranspiration réelle et de la productivité primaire brute a permis une évaluation des performances d'irrigation et une gestion de l'eau agricole aux échelles régionale et nationale.

Collectivement, ces développements démontrent une progression claire allant de l'observation environnementale vers l'aide à la décision opérationnelle, fournissant un cadre transmissible pour le renforcement de la sécurité de l'eau et la gestion durable des ressources en eau dans les régions tropicales et les régions où les données sont rares.

Mots-clés : Télédétection; Comptabilité de l'eau; Modélisation hydrologique; Précipitations par satellite; Évapotranspiration; NDII; Performance de l'irrigation; Gestion des ressources en eau.

1. INTRODUCTION

Water resources management is becoming increasingly challenging due to climate variability, population growth, agricultural intensification, urbanization, and environmental degradation. These pressures are particularly severe in tropical and monsoon-dominated regions where strong seasonal rainfall variability, recurrent floods and droughts, and limited monitoring infrastructure complicate water resources assessment and management. Consequently, reliable information on precipitation, evapotranspiration, soil moisture, vegetation dynamics, water storage, and water use is essential for achieving sustainable water security and climate-resilient development (Molden, 2007; McDonnell and Beven, 2014; UNESCO, 2023).

Remote sensing has transformed environmental and hydrological sciences by providing spatially continuous observations across multiple spatial and temporal scales. Since the launch of Earth observation satellites, remotely sensed data have been widely applied to environmental monitoring, land-use mapping, water quality assessment, vegetation monitoring, evapotranspiration estimation, flood mapping, and drought assessment (Tucker, 1979; Running et al., 2004; Anderson et al., 2012; Fisher et al., 2017). Compared with conventional ground-based monitoring systems, satellite observations provide consistent coverage over large geographical regions and are particularly valuable in tropical and data-scarce environments where observational networks are limited.

The role of remote sensing has evolved considerably over recent decades. Early applications focused primarily on environmental observation and resource inventory, whereas subsequent developments enabled quantitative estimation of hydrological variables such as precipitation, evapotranspiration, vegetation water content, and soil moisture. More recently, satellite observations have become increasingly integrated with hydrological models, water accounting frameworks, irrigation management systems, and operational decision-support platforms. This progression represents a paradigm shift in which remote sensing has evolved from a descriptive observation tool into a quantitative framework supporting hydrological understanding and water resources management.

Thailand provides an excellent case study for examining this scientific evolution. During the past two decades, remote sensing applications have progressed through a series of interconnected stages. Early studies demonstrated that satellite observations could be used to estimate water quality indicators such as Secchi Disk Transparency (SDT) and Suspended Sediment Concentration (SSC) in Bung Boraphet when supported by appropriate atmospheric correction and field calibration procedures (Sriwongsitanon et al., 2011). During the same period, multi-temporal Landsat imagery was integrated with hydrological observations in the Upper Ping River Basin to investigate the impacts of land-cover change on watershed hydrology and flood generation, revealing that watershed response is strongly influenced by antecedent hydrological conditions (Sriwongsitanon and Taesombat, 2011).

As remote sensing technologies matured, research expanded beyond environmental observation toward hydrological process understanding. A major advance was the development of the Normalized Difference Infrared Index (NDII) as a proxy for root-zone moisture storage (Sriwongsitanon et al., 2016). Strong relationships between NDII and root-zone storage simulated by the FLEXL rainfall–runoff model demonstrated that vegetation water content contains valuable information regarding catchment-scale hydrological states, establishing an important link between Earth observation and hydrological modelling. These advances subsequently enabled national-scale water resources assessments. The implementation of the Water Accounting Plus (WA+) framework across all 25 river basins and 254 sub-basins of Thailand integrated satellite-derived evapotranspiration, precipitation, land-use information, hydrological modelling, reservoir storage, and water demand assessments to provide the first spatially consistent evaluation of water availability, depletion, productivity, and water security at the national scale (Kasetsart University, 2016). The increasing reliance on satellite products also led to comprehensive evaluations of evapotranspiration and precipitation datasets. Studies by Sriwongsitanon et al. (2020)

and Kaprom et al. (2025) established suitable products for operational applications and highlighted the importance of validation, bias correction, and ensemble approaches.

More recently, remote sensing has become increasingly integrated into hydrological model structure and parameterization. The FLEX-SD semi-distributed rainfall–runoff model incorporated NDII-derived spatial information to constrain root-zone storage capacity, improving both model realism and predictive performance (Sriwongsitanon et al., 2023). In parallel, Earth observation technologies have expanded into operational water management through the integration of NDVI, NDII, Actual Evapotranspiration (AET), and Gross Primary Productivity (GPP) for irrigation performance assessment and agricultural water management (Williams et al., 2025; Kowsuvon and Williams, 2025).

Collectively, these developments reveal progressive evolution from environmental monitoring to hydrological understanding, national water accounting, satellite product evaluation, hydrological intelligence, and operational water management. Importantly, each stage provided the scientific foundation for the next, creating a coherent pathway through which Earth observation technologies evolved from research tools into integral components of water resources management systems.

Therefore, the objective of this review is to synthesize the evolution of remote sensing applications in Thailand and demonstrate how Earth observation technologies have progressively advanced from environmental observation to hydrological understanding, water accounting, predictive modelling, and operational decision support. By examining these developments within a single national context, this review provides insights into how remote sensing can contribute to sustainable water resources management and offers a transferable framework for other tropical and data-scarce regions seeking to strengthen water security through Earth observation technologies.

2. EVOLUTION OF REMOTE SENSING APPLICATIONS IN THAILAND

2.1 Phase I: Environmental Monitoring and Watershed Assessment (2008–2011)

The first phase of remote sensing research focused on establishing whether satellite observations could provide reliable quantitative information for water resources management. During this period, environmental monitoring in Thailand relied predominantly on field surveys and in-situ measurements, which were often costly, labor-intensive, and limited in spatial coverage. Consequently, a major research challenge was to determine whether remotely sensed data could be transformed into scientifically robust information capable of supporting environmental assessment across large and often inaccessible areas. One of the pioneering studies was conducted at Bung Boraphet (**Figure 1**), Thailand's largest freshwater lake and one of the country's most important wetland ecosystems. By integrating Landsat 5 Thematic Mapper (TM) imagery with extensive field measurements, the study developed empirical relationships for estimating Secchi Disk Transparency (SDT) and Suspended Sediment Concentration (SSC), two key indicators of aquatic ecosystem health. The results demonstrated that satellite imagery could successfully quantify water quality conditions when supported by appropriate atmospheric correction procedures and field calibration data.

More importantly, the study highlighted the critical influence of image preprocessing on the accuracy of water quality retrievals, emphasizing that atmospheric correction and calibration procedures are fundamental prerequisites for reliable environmental monitoring. The resulting spatial distribution maps of water clarity and suspended sediment concentration provided a synoptic view of lake conditions that would have been impractical, if not impossible, to obtain through conventional field surveys alone (**Figure 2**). This research represented one of the earliest demonstrations of operational remote sensing applications for water quality assessment in Thailand and established methodological foundations that would subsequently be adopted in numerous water resources studies.

Building upon these achievements, research efforts expanded from lake-scale environmental monitoring to watershed-scale hydrological investigations. Using nine Landsat 5 TM images acquired between 1988 and 2005, land-cover dynamics within the Upper Ping River Basin were quantified and linked to

observed hydrological responses derived from long-term rainfall and runoff records. The analysis revealed substantial landscape transformation during the study period, with forest cover declining from approximately 86% to 76%, accompanied by significant expansion of agricultural and urban areas.

To investigate the hydrological implications of these land-cover changes, remotely sensed land-cover information was integrated with hydrological observations from eleven sub-catchments distributed throughout the basin. The results demonstrated that relationships between land-cover change and flood generation are considerably more complex than commonly assumed. While conventional wisdom often suggests that increasing forest cover universally reduces flood risk, the analysis revealed that watershed response depends strongly on storm magnitude, antecedent soil moisture conditions, and catchment storage dynamics.

For relatively small rainfall events, forested catchments generally exhibited lower runoff coefficients due to higher evapotranspiration rates and greater soil-water storage capacity. However, during large and extreme rainfall events, forested catchments frequently produced higher runoff coefficients, because antecedent soil moisture conditions remained elevated prior to storm occurrence, thereby reducing available storage capacity. These findings challenged oversimplified assumptions regarding forest–flood relationships and demonstrated that flood generation is governed not only by land-cover characteristics but also by dynamic hydrological processes operating within the watershed.

Taken together, these studies marked an important scientific transition in the application of remote sensing for water resources management in Thailand. Remote sensing evolved beyond its traditional role as a visual mapping tool and emerged as a quantitative environmental assessment framework capable of estimating water quality conditions, monitoring land-cover dynamics, and improving understanding of watershed hydrological behavior. This phase established the scientific and methodological foundation upon which subsequent advances in hydrological modeling, environmental monitoring, and integrated water resources management would be built.

Major Scientific Advancement

Remote sensing evolved from a predominantly observational technology into a quantitative environmental monitoring and watershed assessment tool. This transition enabled the estimation of water quality parameters, characterization of land-cover change, and improved understanding of hydrological processes across multiple spatial scales, thereby laying the foundation for future developments in remote sensing-based water resources management.

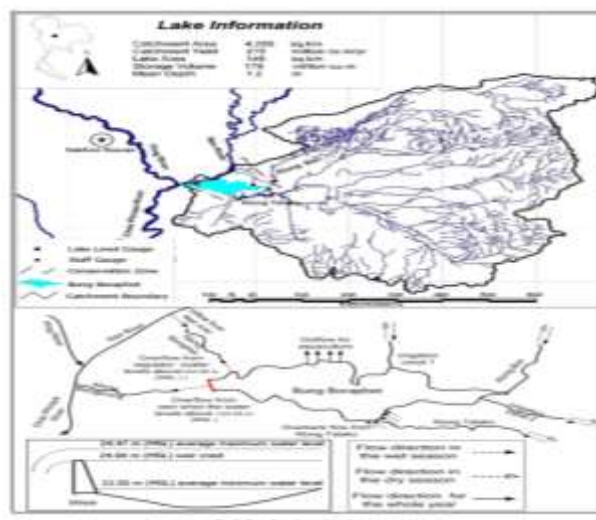


Figure 1. Location of Bung Boraphet and its contributing drainage basin in central Thailand, illustrating the study area used for satellite-based water quality assessment. (Sriwongsitanon et al., 2011)

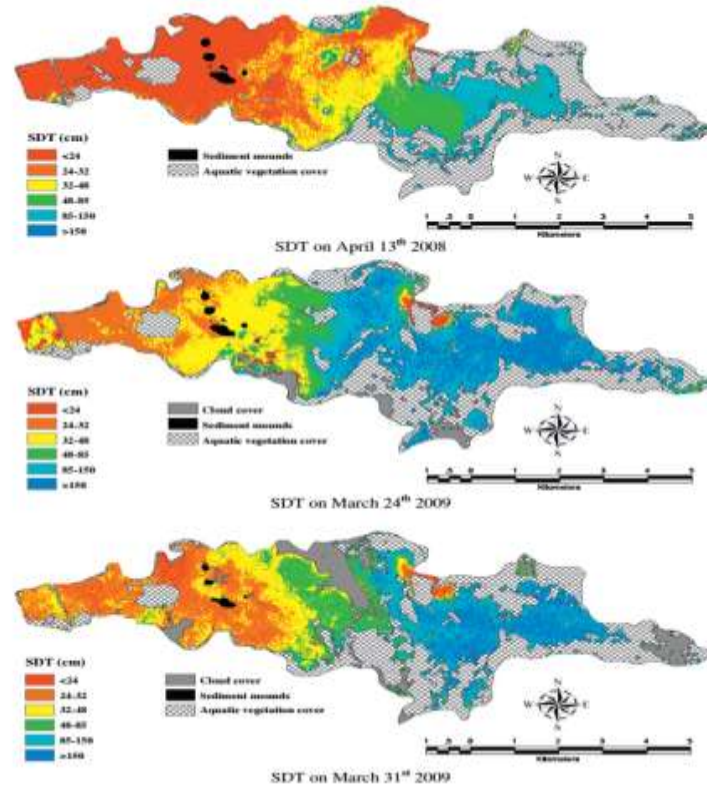


Figure 2. Spatial distribution of (a) Secchi Disk Transparency (SDT) and (b) Suspended Sediment Concentration (SSC) derived from Landsat 5 TM imagery, demonstrating the capability of remote sensing to quantify lake-wide water quality conditions. (Sriwongsitanon et al., 2011)

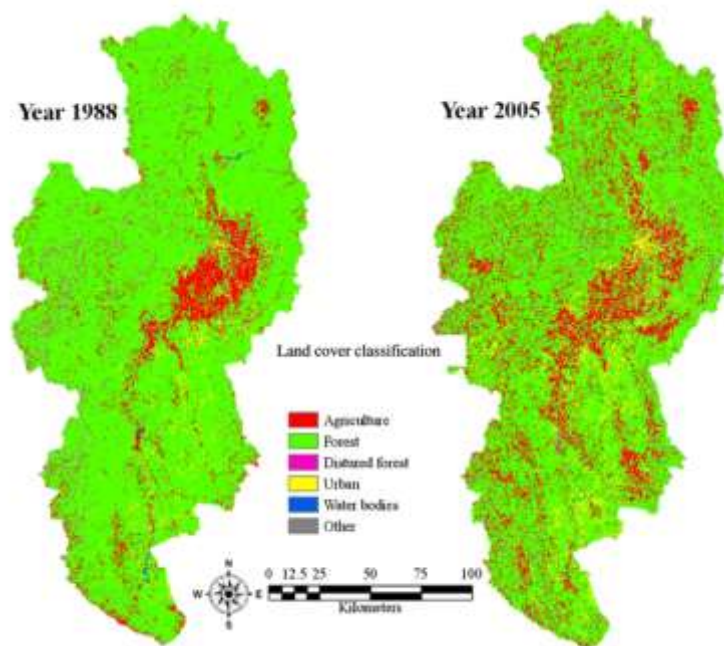


Figure 3. Land-cover change in the Upper Ping River Basin between 1988 and 2005 derived from Landsat imagery, showing the decline in forest cover and expansion of agricultural and urban areas. (Sriwongsitanon and Taesombat, 2011)

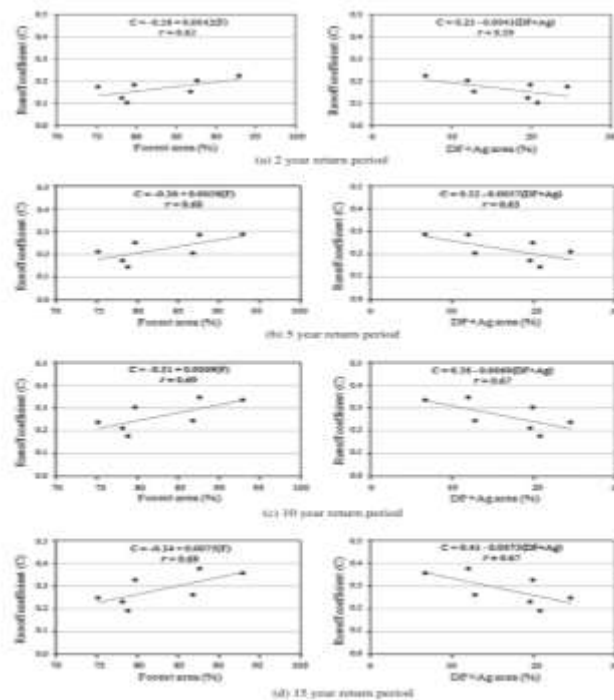


Fig. 4. Relationships between runoff coefficients and land cover for larger flood events for P.21 sub-catchment.

Figure 4 Relationships between runoff coefficients and land cover for larger flood events for P.21 sub-catchment. (Sriwongsitanon and Taesombat, 2011)

2.2. Phase II: Remote Sensing for Hydrological Process Understanding and Model Integration (2012–2015)

Building upon the environmental monitoring and watershed assessment achievements of Phase I, the second phase of research focused on understanding the hydrological processes that govern watershed response. While previous studies demonstrated that remote sensing could successfully quantify environmental variables such as water quality and land-cover change, an important challenge remained: could satellite observations provide information on key hydrological state variables that are difficult to observe directly in the field?

One of the most important variables in hydrology is root-zone soil moisture storage, which controls the partitioning of rainfall into runoff, groundwater recharge, and evapotranspiration, while also regulating vegetation response to drought. However, direct measurement of root-zone soil moisture is extremely difficult because conventional observations are limited to a small number of monitoring locations and shallow soil depths. Consequently, understanding the spatial and temporal dynamics of soil moisture storage across large watersheds has long been a major challenge in hydrological science.

To address this issue, research was conducted in the Upper Ping River Basin (**Figure 5**) using MODIS satellite observations acquired between 2001 and 2013. The study investigated the potential of the Normalized Difference Infrared Index (NDII), derived from near-infrared and shortwave infrared reflectance, as an indicator of vegetation water stress and root-zone moisture storage. Unlike traditional remote sensing approaches that primarily focus on surface soil moisture, NDII reflects vegetation water content and therefore has the potential to provide indirect information on moisture conditions within the root zone. A key innovation of the study was the integration of satellite observations with the FLEXL conceptual rainfall–runoff model. Simulated root-zone moisture storage from the hydrological model was compared with NDII values derived from MODIS imagery across eight sub-catchments of the Upper Ping River Basin (**Figure 6**). The results revealed strong relationships between NDII and root-zone

moisture storage, particularly during the dry season when vegetation experienced water stress. These findings demonstrated that remotely sensed vegetation conditions could effectively represent subsurface hydrological storage dynamics that are otherwise difficult to monitor over large areas. Beyond drought monitoring, this research introduced an important conceptual shift in hydrological remote sensing. Traditionally, vegetation was often viewed as a source of uncertainty that complicated soil moisture retrieval from satellite observations. In contrast, this study demonstrated that vegetation itself can act as a natural sensor of moisture conditions within the root zone because leaf water content responds directly to water availability in the soil. Rather than being an obstacle, vegetation became a valuable source of information for understanding watershed storage dynamics and drought development.

The study also highlighted the potential for integrating remotely sensed information into hydrological modeling. By providing spatially distributed estimates of watershed moisture conditions, NDII offered a new opportunity to improve model realism, support calibration, and enhance hydrological prediction in data-scarce and ungauged basins. As a result, remote sensing evolved beyond environmental observation and became an important tool for investigating hydrological processes and supporting water resources management.

Together, these advances marked a significant progression in the application of remote sensing within water resources research. The focus shifted from observing environmental conditions at the Earth's surface toward understanding the internal functioning of watersheds and quantifying hydrological processes that control drought and runoff generation. This phase established a critical link between Earth observation and hydrological modeling, laying the foundation for subsequent developments in drought assessment, hydrological forecasting, and integrated water resources management.

Major Scientific Advancement

Remote sensing evolved from environmental monitoring to hydrological process assessment. By demonstrating that NDII could serve as a reliable proxy for root-zone moisture storage and drought conditions, this phase established a direct connection between satellite observations and hydrological modeling, providing new opportunities for process understanding and prediction in water resources management.

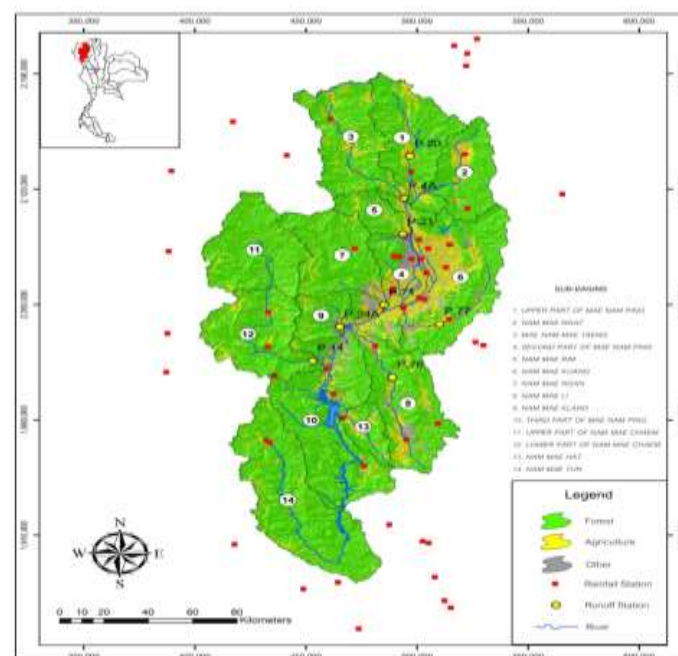


Figure 5. Location of the Upper Ping River Basin and the eight sub-catchments used for NDII-hydrological model integration. (Sriwongsitanon et al., 2016)

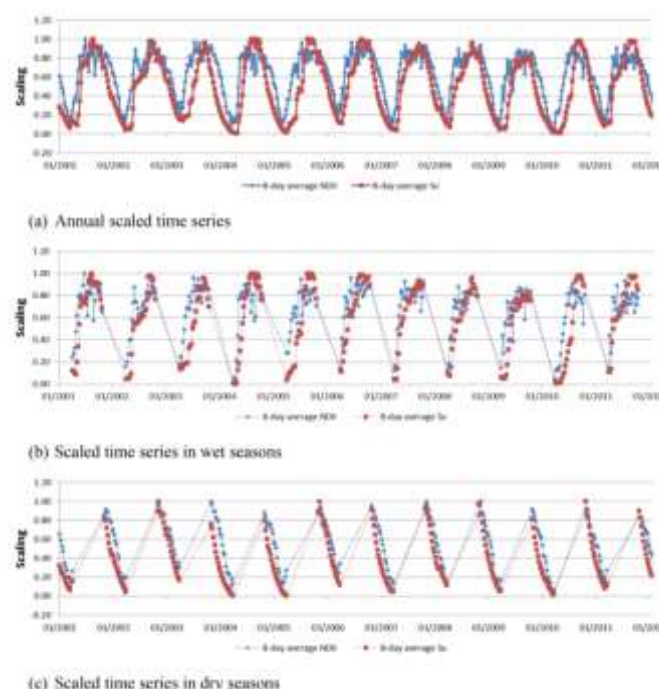


Figure 6. Relationship between NDII and simulated root-zone moisture storage (S_u) derived from the FLEXL hydrological model, demonstrating strong correlations during moisture-stress periods. (Sriwongsitanon et al., 2016)

2.3. Phase III: From Hydrological Understanding to National Water Accounting and Water Security (2015–2019)

The first two phases of research established that remote sensing could successfully quantify environmental conditions and reveal the hydrological processes controlling water availability across landscapes. However, a fundamental question remained unanswered: How much water does Thailand actually have, where is it being consumed, and is that consumption sustainable?

Answering this question required a conceptual shift from monitoring individual variables to accounting for the entire water cycle. This challenge led to the third phase of research, which focused on the development of a national-scale Water Accounting framework for Thailand. Rather than treating rainfall, evapotranspiration, runoff, groundwater, reservoirs, irrigation systems, and ecosystems as separate components, this phase integrated them into a single accounting system capable of tracking water from its arrival as precipitation to its final depletion through human and environmental uses.

At the time, water management in Thailand relied primarily on measurements of water supply, such as rainfall, reservoir storage, and river discharge. Yet water security is determined not only by how much water enters a basin but also by how much is consumed. To overcome this limitation, the study adopted the Water Accounting Plus (WA+) framework and implemented it across all 25 river basins and 254 sub-basins of Thailand. This represented one of the most comprehensive water accounting exercises ever undertaken in Southeast Asia and transformed Thailand into one of the first countries in the region to establish a spatially explicit national water accounting system.

A major scientific innovation was the integration of satellite-derived evapotranspiration products into national water accounting. While conventional hydrology focuses largely on runoff generation, water accounting recognizes evapotranspiration as the dominant pathway through which water leaves a basin. By combining six independent global evapotranspiration products, actual water consumption could be mapped continuously across the entire country at a spatial resolution of 250 m. More importantly, evapotranspiration was partitioned into Green ET, representing water derived directly from rainfall, and

Blue ET, representing water supplied through rivers, reservoirs, irrigation systems, and groundwater resources. This distinction provided, for the first time, a quantitative assessment of how Thailand's agricultural production depended on natural rainfall versus managed water resources.

The study subsequently demonstrated that satellite-derived evapotranspiration was remarkably consistent with conventional estimates of crop water requirements. Across all 254 sub-basins, strong relationships were observed between theoretical crop water demand and remotely sensed evapotranspiration, confirming that Earth observation data could serve not only as a monitoring tool but also as a direct indicator of agricultural water consumption and irrigation demand.

The resulting water accounts provided an unprecedented national picture of Thailand's water resources. The analyses revealed that annual net inflow ranged between approximately 644 and 761 billion cubic metres, while actual depleted water remained close to 480 billion cubic metres regardless of hydrological conditions. This finding challenged the common perception that water scarcity is solely a consequence of insufficient rainfall. Instead, the results demonstrated that large volumes of water continued to leave the country as downstream outflow, indicating that storage limitations, allocation inefficiencies, and spatial mismatches between water availability and demand were equally important determinants of water security.

Perhaps the most important contribution of this phase was the transformation of water accounting into a decision-support framework for national planning. A series of performance indicators was developed to evaluate ecosystem sustainability, water availability, beneficial water use, irrigation efficiency, and downstream water losses. These indicators enabled direct comparison among all 254 sub-basins and revealed previously hidden spatial inequalities in water security across the country. Areas vulnerable to ecological stress, irrigation inefficiency, flood-related losses, and water scarcity could be identified objectively using a common analytical framework.

Building upon this foundation, the study moved beyond assessment and into strategic planning. Multiple future scenarios were simulated, including environmental flow restoration, domestic and industrial water supply expansion, watershed rehabilitation, irrigation modernization, irrigation expansion, and major inter-basin transfer projects. Instead of evaluating projects individually, water accounting made it possible to assess their cumulative impacts on national water security, thereby creating a scientific bridge between hydrological analysis and policy formulation.

In retrospect, Phase III represented a fundamental change in the role of remote sensing within water resources management. During Phase I, satellites were used to observe environmental conditions. During Phase II, they were used to understand hydrological processes. In Phase III, remote sensing became the backbone of a national water accounting system capable of quantifying water availability, water consumption, ecosystem requirements, and water security simultaneously. This transformation elevated remote sensing from an observational technology to a strategic decision-support tool and established the scientific foundation for evidence-based water governance at the national scale.

The central achievement of Phase III was therefore not merely the construction of water accounts, but the creation of a framework that converted Earth observation data into actionable knowledge for sustainable water management. It demonstrated that water security can be measured, compared, and improved through a consistent accounting approach, providing a new paradigm for integrating science, policy, and resource management in Thailand and beyond.

2.4. Phase IV: Satellite Product Evaluation

Phase IV: Establishing Earth Observation as a Reliable Foundation for Water Resources Management (2020–Present) While the previous phase demonstrated the potential of remote sensing for national water accounting and water security assessment, a critical challenge remained unresolved. Water accounting, hydrological modelling, flood forecasting, and climate adaptation studies all depend on large-scale datasets of rainfall and evapotranspiration. However, the accuracy of satellite-derived

observations remains uncertain in many parts of the world, particularly in tropical regions where complex terrain, monsoon dynamics, and sparse monitoring networks introduce substantial uncertainties. Consequently, the fourth phase of research focused on answering a fundamental question: **Can Earth Observation products be trusted as operational data sources for water resources management?**

To address this challenge, a series of nationwide validation studies was conducted across Thailand, covering more than 500,000 km² and encompassing all major climatic, topographic, and hydrological environments. The first study evaluated seven globally available evapotranspiration products using water balance analysis, GRACE terrestrial water storage observations, and land-use information across 172 monitored sub-basins. Unlike traditional validations based on flux towers, the study employed an independent hydrological framework using rainfall, streamflow, and storage changes to assess actual evapotranspiration performance. Results demonstrated that all products performed remarkably well at annual scales (average NSE > 0.96) and satisfactorily at monthly scales (average NSE > 0.65), confirming the viability of satellite-derived evapotranspiration for large-scale water resources applications. Among the evaluated products, MOD16A2 emerged as the most suitable evapotranspiration dataset for Thailand because of its strong hydrological consistency, spatial resolution, and operational accessibility.

Building upon this foundation, attention shifted toward precipitation estimation, which remains the most important input for hydrological modelling. A nationwide database comprising 1,779 rainfall stations was subjected to rigorous quality control using Double Mass Curve (DMC) analysis before being used to evaluate five satellite-based precipitation products. The study demonstrated that even the quality of conventional rainfall observations can significantly influence the perceived performance of satellite products. By combining DMC quality assurance with multiple bias-correction approaches, substantial improvements were achieved for all satellite precipitation estimates. The final ensemble product, generated from the best-performing corrected datasets, achieved NSE values approaching 0.90 and demonstrated that the integration of multiple satellite products can outperform any single product alone. The most recent study further expanded the scope by evaluating fifteen satellite precipitation products from the TRMM, GPM IMERG, CHIRPS, CMORPH, and PERSIANN families. Using one of the densest rainfall monitoring networks in Southeast Asia, the research assessed product performance across varying elevations, rainfall frequencies, climatic regions, and levels of data scarcity.

The results revealed that CMORPH-BLD, CHIRPS-Preliminary, TRMM-3B42, and GPM IMERG-Final consistently ranked among the most accurate products. Importantly, the study demonstrated that bias correction remained effective even when the number of available rain gauges was progressively reduced, highlighting the robustness of satellite observations in data-scarce environments. Furthermore, the development of an ensemble precipitation product showed that combining multiple satellite products substantially reduced individual product uncertainties and generated more reliable rainfall estimates than any standalone dataset.

Collectively, these studies established a comprehensive framework for evaluating and improving Earth Observation products before their integration into operational hydrological applications. The research demonstrated that remote sensing products should not be treated as fixed datasets but rather as information sources whose reliability can be systematically quantified, corrected, and enhanced. This represented a major conceptual advance because it transformed remote sensing from a passive provider of environmental observations into an actively calibrated component of water resources management systems.

More importantly, Phase IV provided the scientific foundation required for the next generation of water management tools. Accurate evapotranspiration products support water accounting and irrigation assessment. Reliable satellite rainfall estimates support hydrological modelling, flood forecasting, drought monitoring, and climate adaptation studies. By rigorously validating both components of the water cycle, this phase established the confidence necessary for operational implementation of Earth Observation technologies at national scales.

In retrospect, the significance of Phase IV extends beyond the evaluation of individual satellite products. The phase demonstrated that satellite observations can be transformed into scientifically defensible and operationally reliable datasets capable of supporting real-world decision making. Whereas Phase I focused on observing environmental conditions, Phase II sought to understand hydrological processes, and Phase III quantified national water availability and consumption, Phase IV addressed the critical issue of data trustworthiness. It provided the evidence required for Earth Observation to become a primary source of information for water resources planning, modelling, and management.

The central achievement of Phase IV was therefore the establishment of a rigorous scientific framework for validating, correcting, and integrating Earth Observation products into operational water resources management. This transformed satellite observations from experimental datasets into trusted information systems capable of supporting national-scale decision making under conditions of increasing climatic and hydrological uncertainty.

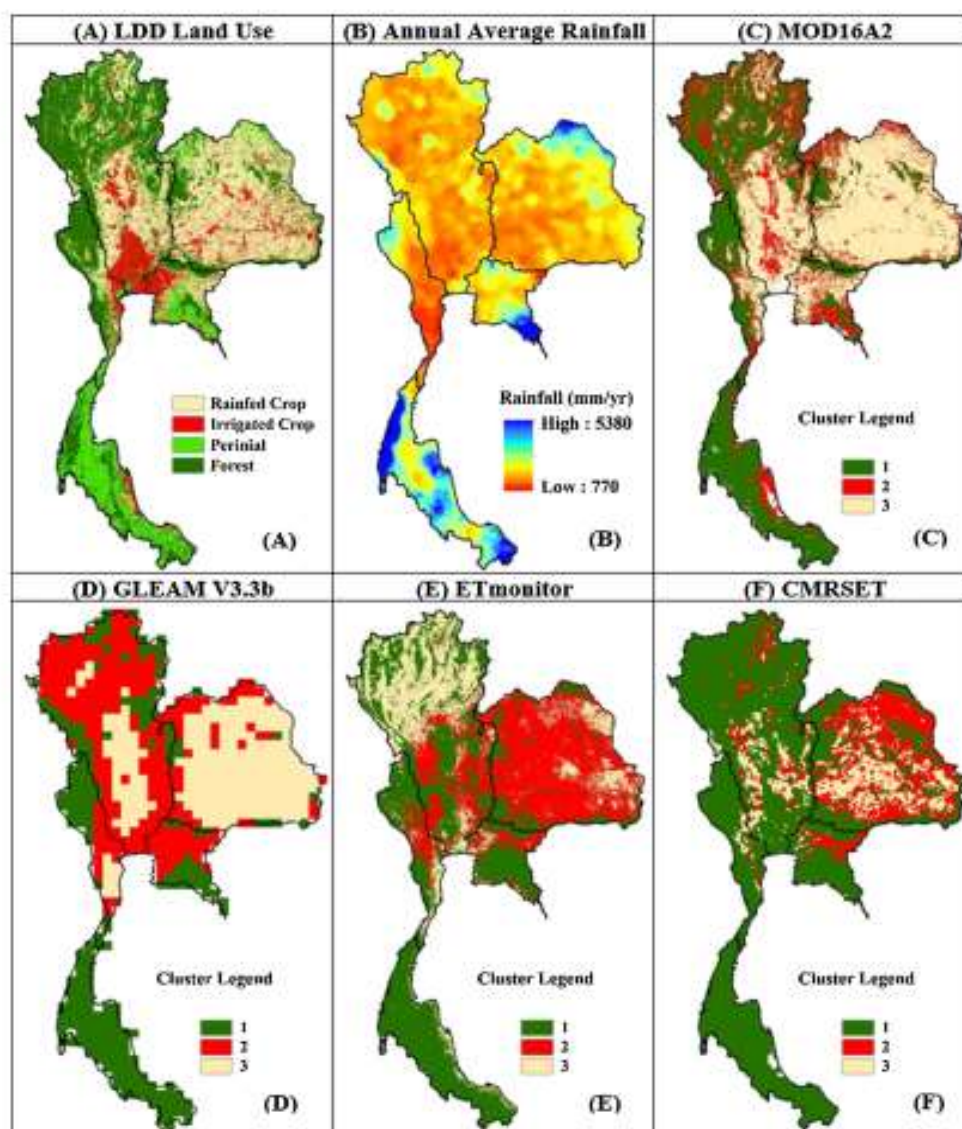


Figure 7. The revised classification of ETRS pixels into three clusters by four ET products (C–F), with reference to the LDD land use classification (A) and the spatial variation of annual average rainfall (B). (Sriwongsitanon et al., 2020)

2.5. Phase V: Integrating Earth Observation into Hydrological Intelligence (2021–Present)

Following the successful validation of Earth Observation products during Phase IV, the next challenge was to move beyond the use of satellite observations as external data sources and explore whether remote sensing could directly improve the representation of hydrological processes within models. Traditional rainfall–runoff models are often calibrated using streamflow observations alone, resulting in parameter sets that reproduce observed discharge but may not accurately represent the underlying hydrological processes. This issue becomes particularly important in ungauged and data-scarce catchments where internal catchment behaviour cannot be directly observed.

To address this challenge, research during the fifth phase focused on integrating satellite-derived information on vegetation water stress and soil moisture dynamics into hydrological modelling frameworks. The cornerstone of this phase was the development of the FLEX-SD (Semi-Distributed FLEX) model, a parsimonious rainfall–runoff modelling framework that combines physically meaningful hydrological processes with spatially distributed catchment characteristics. Building upon the widely applied FLEXL conceptual model, the Upper Ping River Basin in northern Thailand was subdivided into 32 sub-catchments, allowing runoff generation, routing, and moisture storage processes to be represented in a semi-distributed manner.

A key innovation was the use of the Normalized Difference Infrared Index (NDII), derived from MODIS satellite observations, as a proxy for root-zone moisture storage capacity. Previous studies had shown that NDII is strongly related to vegetation water content and moisture stress. In this study, NDII information was incorporated directly into the model structure to constrain the spatial distribution of the root-zone storage parameter (Sumax), one of the most important controls on runoff generation and evapotranspiration. Two alternative model formulations were developed, FLEX-SD-NDIIMaxMin and FLEX-SD-NDIIAvg, which used seasonal NDII dynamics and long-term average NDII conditions, respectively, to estimate spatial variability in catchment storage capacity.

The results demonstrated that incorporating NDII-derived information significantly improved both model performance and hydrological realism. Compared with the traditional lumped FLEXL model and the established semi-distributed URBS model, the FLEX-SD framework achieved similar or higher predictive accuracy, particularly during independent validation periods. More importantly, the NDII-constrained models produced spatial patterns of root-zone storage capacity that corresponded closely with ecological characteristics of the landscape. The FLEX-SD-NDIIAvg model showed a strong relationship between estimated storage capacity and evergreen forest cover ($R^2 = 0.69$), indicating that the model was capturing physically meaningful variations in catchment behaviour rather than merely fitting observed streamflow.

An additional breakthrough was the use of independent Earth Observation products for model evaluation. Simulated root-zone moisture storage was compared with both NDII observations and the Soil Water Index (SWI) derived from ASCAT satellite measurements. The strong agreement between simulated and observed moisture dynamics demonstrated that the model could successfully reproduce not only streamflow but also internal hydrological states that are rarely observable at catchment scales. This represented an important shift from traditional calibration approaches based solely on discharge toward multi-source, process-based model evaluation.

The significance of Phase V extends well beyond the development of a single hydrological model. The research established a new paradigm in which Earth Observation products are used not only to monitor environmental conditions but also to constrain, validate, and improve hydrological process representation. By integrating satellite observations directly into model structure and parameter estimation, the study reduced parameter uncertainty, improved model transferability, and strengthened predictive capability in ungauged and partially gauged basins. This approach provides an important pathway for hydrological prediction in regions where conventional monitoring networks remain sparse or incomplete.

In retrospect, Phase V represents the emergence of what may be termed **Hydrological Intelligence**, where Earth Observation, hydrological theory, and process-based modelling are merged into a unified framework. Whereas Phase I focused on observing environmental conditions, Phase II on understanding hydrological processes, Phase III on quantifying water resources, and Phase IV on establishing trust in Earth Observation datasets, Phase V demonstrates how satellite observations can actively shape model behaviour and improve our understanding of hydrological systems.

The central achievement of Phase V was therefore the integration of Earth Observation into hydrological model development, transforming remote sensing from a source of environmental information into an active component of hydrological intelligence and predictive water resources management.

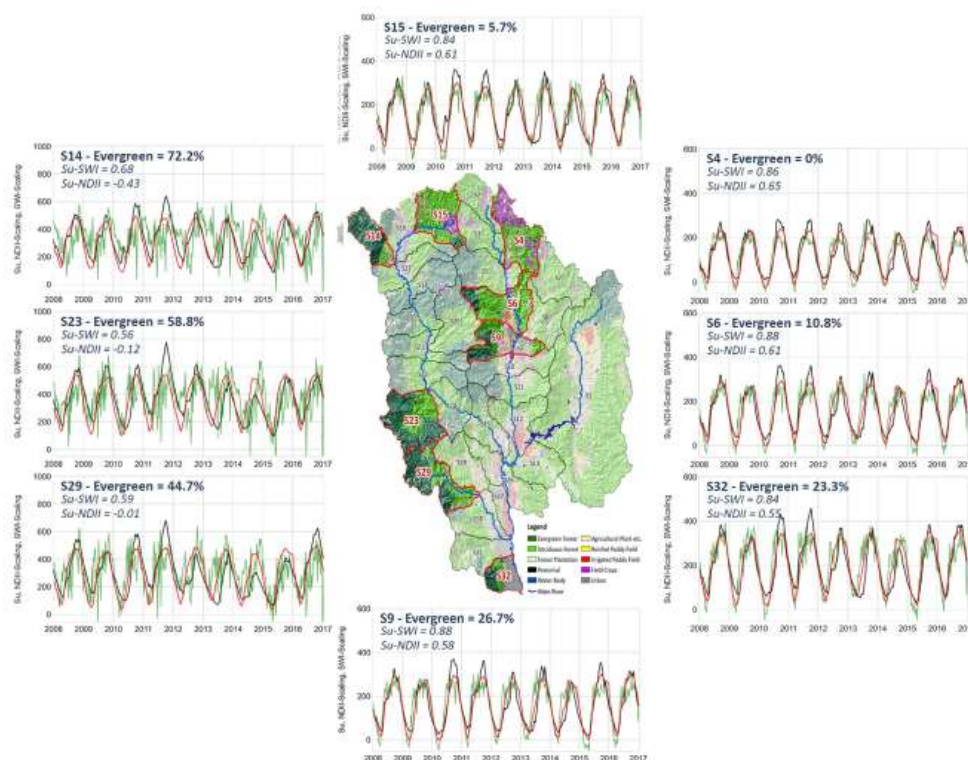


Figure 8. Comparison between simulated root zone moisture storage (Su; in black), NDII (in green), and SWI (in red) for eight sample sub-catchments with different percentages of evergreen forest. (Sriwongsitanon et al., 2023)

2.6. Phase VI: From Hydrological Intelligence to Smart Irrigation and Agricultural Water Management (2023–Present)

The previous phase demonstrated that Earth Observation could improve hydrological model structure and process representation. However, a major challenge remained: how can this information be translated into practical tools for improving agricultural water management and irrigation performance? Given that agriculture accounts for the largest share of water consumption in Thailand, the ability to monitor crop conditions, water stress, and irrigation effectiveness in near real time became increasingly important for ensuring food security and sustainable water use.

To address this challenge, the sixth phase of research focused on integrating multiple satellite-derived indicators into an operational framework for crop monitoring and irrigation performance assessment. Rather than relying solely on conventional measures such as irrigated area, water delivery records, or crop statistics, this phase explored how vegetation condition, plant water status, evapotranspiration, and productivity could be simultaneously monitored using Earth Observation technologies.

A central innovation was the combined use of the **Normalized Difference Vegetation Index (NDVI)** and the **Normalized Difference Infrared Index (NDII)**. While NDVI measures vegetation vigor and crop growth, NDII provides information on plant water content and moisture stress. Together, these indices enable direct assessment of the relationship between crop development and water availability. Long-term analyses using MODIS imagery from 2010 onward demonstrated that NDVI and NDII could successfully characterize crop dynamics across diverse irrigation environments in Thailand, including paddy fields, field crops, orchards, and perennial plantations.

A significant methodological advancement was the development of a satellite-based crop classification framework using multi-temporal NDVI and NDII signatures combined with K-means clustering and a refinement procedure developed by SENSAT. The methodology was tested in four major irrigation projects representing contrasting hydro-climatic conditions. Results showed that crop classification accuracy exceeded 98% in several projects and improved substantially even in more complex agricultural landscapes. Satellite-derived crop areas exhibited excellent agreement with official records, with coefficients of determination ranging from 0.90 to 1.00. Importantly, NDII frequently outperformed NDVI in identifying irrigated agricultural areas because of its greater sensitivity to vegetation water content.

Beyond crop identification, the research introduced a new concept for evaluating irrigation performance based on the relationship between crop growth and water availability. By analysing long-term correlations between NDVI and NDII, it became possible to determine whether crop development was synchronized with available water resources. Irrigation schemes exhibiting strong NDVI–NDII relationships demonstrated efficient water management, whereas weaker relationships indicated either excessive water supply, inadequate water delivery, or rainfall-dominated conditions. The Kraseaw Irrigation Project emerged as an example of highly effective water management, exhibiting consistently strong relationships between vegetation growth and plant water status throughout the year. In contrast, weaker relationships observed in Northern Rangsit reflected conditions where abundant water availability reduced the sensitivity of vegetation growth to moisture variations.

Building upon these findings, the framework was expanded to a nationwide scale covering all 17 Regional Irrigation Offices of the Royal Irrigation Department and approximately 4.07 million hectares of irrigated land. This represented one of the largest operational applications of agricultural remote sensing in Southeast Asia. The system integrated NDII with three complementary indicators: NDVI, Actual Evapotranspiration (AET), and Gross Primary Productivity (GPP). Together, these variables provided a comprehensive description of agricultural water use, vegetation health, crop productivity, and irrigation effectiveness.

The nationwide assessment revealed distinct regional patterns in irrigation performance. Central Thailand exhibited the strongest relationships among NDII, NDVI, AET, and GPP, indicating highly effective synchronization between water supply and crop requirements. Conversely, Southern Thailand displayed weaker correlations, largely due to abundant rainfall that reduced the dependence of crop growth on irrigation water. These findings demonstrated that remote sensing could distinguish differences in irrigation effectiveness across climatic regions and provide objective performance indicators at national scales.

Perhaps the most important contribution of this phase was the development of a remote sensing-based irrigation performance assessment system capable of continuous, near-real-time monitoring. Unlike traditional performance indicators that depend on field surveys and administrative records, the proposed approach provides spatially explicit information on crop conditions, water stress, productivity, and irrigation effectiveness across millions of hectares. This creates opportunities for adaptive water allocation, drought preparedness, irrigation scheduling, and precision agriculture under increasingly variable climatic conditions.

In retrospect, Phase VI represents the transition from understanding and modelling water systems to actively managing agricultural water use through Earth Observation. While Phase I focused on environmental monitoring, Phase II on hydrological processes, Phase III on water accounting, Phase IV on validating Earth Observation products, and Phase V on hydrological intelligence, Phase VI demonstrates how these advances can be translated into operational tools for managing water in the agricultural sector.

The central achievement of Phase VI was therefore the creation of a remote sensing-based framework for nationwide irrigation performance assessment, transforming Earth Observation from a monitoring and modelling technology into an operational decision-support system for precision agriculture and smart irrigation management.

3. DISCUSSION, FUTURE PERSPECTIVES, AND CONCLUSIONS

The evolution of remote sensing applications in Thailand reflects a progressive transition from environmental observation toward operational water resources management. Rather than occurring as isolated studies, each phase addressed limitations of the previous phase and provided the scientific foundation for subsequent advances.

The first phase established the capability of remote sensing to quantify environmental variables such as water quality and land-cover dynamics. The second phase extended these applications to hydrological process understanding through the use of NDII as a proxy for root-zone moisture storage. Building upon this understanding, the third phase expanded remote sensing applications to national-scale water accounting and water security assessment through the implementation of the Water Accounting Plus (WA+) framework. The fourth phase focused on the evaluation and improvement of satellite-derived precipitation and evapotranspiration products, establishing the confidence required for operational applications. Subsequently, the fifth phase integrated Earth observation directly into hydrological model structure and parameterization, improving process representation and predictive capability. Finally, the sixth phase translated these scientific advances into practical water management applications through irrigation performance assessment and agricultural water monitoring.

Collectively, these developments demonstrate a clear scientific progression:

Observe → Understand → Account → Trust → Predict → Manage

This progression highlights the growing role of Earth observation as a bridge between environmental monitoring, hydrological science, and operational water resources management. A key finding is that the value of remote sensing extends far beyond data collection. Its greatest strength lies in integrating environmental observations with hydrological theory, modelling frameworks, and management objectives to support informed decision making.

Future developments are expected to focus on the integration of remote sensing with artificial intelligence, digital twins, and real-time forecasting systems. These technologies will enable more accurate monitoring, prediction, and management of water resources under increasingly uncertain climatic conditions. In particular, the integration of Earth observation with machine learning offers significant opportunities for drought forecasting, flood prediction, irrigation scheduling, and reservoir operation. The experience gained in Thailand demonstrates that remote sensing can evolve from a research tool into an operational framework for water resources management. This provides a transferable pathway for other tropical and data-scarce regions seeking to strengthen water security and climate resilience through Earth observation technologies.

Key Message

Remote sensing in Thailand has evolved from a tool for observing water resources into a framework for understanding, accounting for, predicting, and managing water systems, establishing Earth observation as a cornerstone of modern water resources management.

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