

UNDERSTANDING the ROLE of REMOTE SENSING and WATER ACCOUNTING in supporting AGRICULTURAL WATER MANAGEMENT in VIET NAM





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Suggested citation: Souter R, Ha Thanh L, Lillicrap A, Do Thi Thuy H, Nguyen Quynh P, Dinh Xuan H, Le Bich N, Ndehedehe C. (2026). 'Understanding The Role Of Remote Sensing And Water Accounting In Supporting Agricultural Water Management In Viet Nam'



Australian Centre
for International
Agricultural Research



This project was funded by ACIAR Australian Centre for International Agricultural Research, Australian Government.

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EXECUTIVE SUMMARY

Viet Nam is facing increasing pressure to strengthen agricultural water governance under conditions of climate variability, groundwater stress, and decentralized water management responsibilities. Reliable, timely and spatially explicit water data is essential to support planning, allocation, monitoring and compliance functions at basin and subbasin levels. This report represents the second of three outputs from the small research activity: *Understanding the Role of Remote Sensing (RS) in Supporting Agricultural Water Management in South East Asia*. It describes the further development through pilot application of water accounting using remotely sensed data, to a case study basin and its subbasins in Viet Nam.

This case study research explored the potential application and scaling-up of remote sensing and water accounting to support agricultural water management in Viet Nam using an approach that integrated two key strategies:

- Explore the technical feasibility to downscale water accounting, supported by remotely sensed data, in subbasin pilots.
- Engage with stakeholders throughout to maximise the potential usefulness of such tools and data outputs, as well as the usability, interest, and accessibility and feasibility to implement such tools.

The case study research involved development and pilot application of water accounting, supported by remote sensing and GIS analyses, in 3 sub-basins of the Srepok basin in Viet Nam: Ban don sub-basin, Krong Buk sub-basin and an irrigation cluster (Figure 1.1).

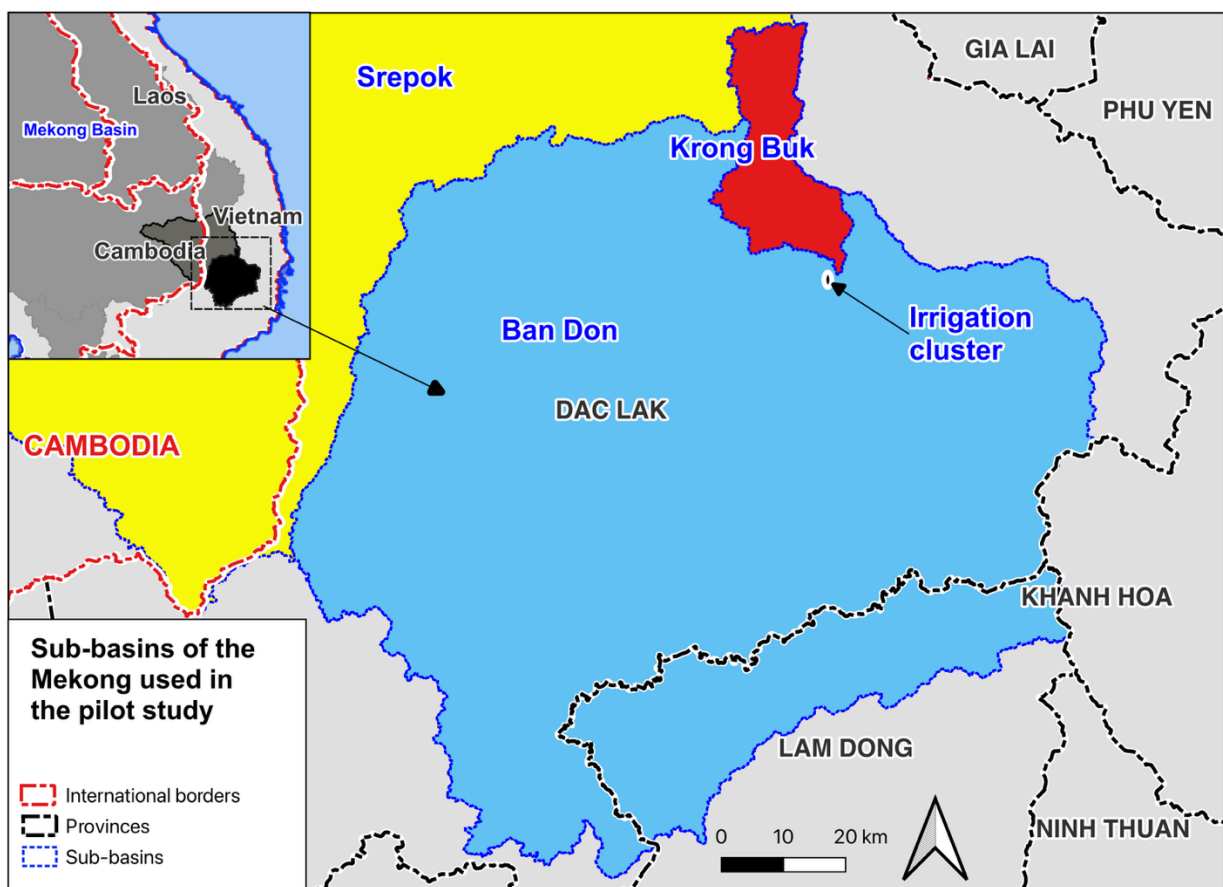


FIGURE 1.1 STUDY AREAS FOR THE PILOT PROJECT

This study demonstrated that integrating remote sensing-based information with water accounting approaches and validating through local decision-making realities can produce practical and meaningful inputs into subbasin water management in Viet Nam. In contexts where in-situ hydrological and biophysical measurements are absent—inaccessible or scattered—for example, groundwater abstraction, crop yield, drought conditions, publicly available remote sensing products offer a viable primary source of data for water management decisions.

The project took an intentional research-to-impact strategy by integrating structured qualitative social research and policy engagement from the outset. For many participants, the opportunity to shape technical outputs according to their operational needs was novel and highly valued, strengthening ownership and relevance of the result.

The application of a localised water resources management maturity framework was useful (i) in identifying existing strengths and weaknesses of data-informed water resources management, and (ii) as a structured, participatory process for stakeholder self-assessment of current WRM practices and data availability.

This user-centred approach clarified existing water management tasks, data gaps and institutional constraints. The research confirmed that many core water resources management tasks are already being undertaken across planning, management, and operations of water resources infrastructure. However, the extent to which these tasks are systematically informed by water data varies considerably, with stronger application in surface water operation and management, including flood and drought, and weaker application in groundwater management, monitoring of allocation, water-use efficiency and productivity and water accounting. The qualitative research revealed that limitations in data use are not only driven by a mismatch in the technical complexity of the tools and existing technical GIS and water accounting skills of staff but also relate to institutional fragmentation and limited accessibility of data products.

Pilot testing of down-scaled water accounting, supported by remote sensing, applied to basin, subbasin and irrigation cluster levels, indicates strong potential to enhance robust information of water availability and use, support seasonal and annual planning, and improve transparency in allocation and compliance discussions. The research demonstrated there are many water accounting and related parameters that can be produced by drawing upon remotely sensed data, and which are useful to water resources management in Viet Nam, including at subbasin scales. Examples include:

- Evapotranspiration
- Change in storage
- Rainfall deficit
- Net primary production
- Yield
- Water productivity
- Basin water balance (Precipitation – evapotranspiration +/- change in storage)
- System outflows

Depending upon the spatial scale, and methodology involved for each parameter, there are varying levels of complexity in acquiring and computing these datasets. Generally, lower resolution applications required a higher skill level to acquire and process data.

The study also indicated that such tools are most effective when they are tailored to the spatial and temporal scales at which decisions are made in the local context, embedded with existing management protocols, and accompanied with targeted capacity development.

The user-centred research process, involving stakeholders in Lam Dong and Dak Lak provinces, indicated:

- **Demand and interest in water data is high**, as it is seen as a necessary and appropriate advancement to meet legal requirements, support operational activities, and provide independent data that can validate efficiency and performance of operations.
- Through engagement in this project, awareness about the potential usefulness and availability of remote sensing data was improved and created stronger demand and interest for new technologies to improve water data.
- Although stakeholders have a high interest, there is currently **insufficient technical capacity** and practical experience, for both remote sensing and water accounting, especially at provincial and commune levels. This makes the existing tools **less usable by all interested staff in their current forms**.
- Demand for **simplified tools** was expressed, however, a complimentary approach discussed was an internal **service-provider model**, in which mandated units / teams within The Ministry of Agriculture and Environment (MAE) and Irrigation Management Company (IMC), nationally or in provincial offices (where the base level of skills exists), act as 'data producers' - acquiring and processing data, operating GIS and water accounting tools, and distributing data outputs to data users in local level government and IMC offices. This could increase the usability of tools, although some simplification to user interfaces is still required.
- Demand for training is strong: Stakeholders stressed the need for **hands-on, tiered training** (differing levels of complexity, potentially relating to the service-delivery model described above), **practical guidelines, and reliable, user-friendly software tools** to help decision-makers at all levels. Regardless of who produces water accounting outputs, there was widespread demand for training all data users to be able to interpret, verify and apply the outputs.
- Certain organisations have more autonomy and resources than others, making it easier for them to develop capacities and update procedures and systems, to adopt new technologies. Future projects to scale-up remote sensing and water accounting need to accommodate different levels of resourcing and autonomy.
- **Accessibility** is also hampered by **limited access to no cost but high resolution** (spatial and temporal) datasets. Some datasets, particularly larger, lower resolution datasets are easy and inexpensive to access, while datasets at smaller scales often require a higher skill level to access and process the data. Access to computing equipment is moderate, although much monitoring and data management is currently manual; better access and skills in computing would assist with efficiency of accessing data. Feasibility to implement requires development of capacities of data producers and data users, and systems to enable the requesting/sharing of data outputs for WRM use.
- There is a desire for automated, continuously updated data systems linking remote sensing, hydrology, and water accounting to improve the timeliness of application of data to operations and reduce workload.
- Policies and data systems are fragmented: Current overlapping regulations from different ministries and fragmented data sources hinder efficient water resource planning and operations.
- **An emphasis on collaboration:** There is strong interest in continued pilot testing, feedback loops, and joint problem-solving amongst practitioners, and between researchers and practitioners, to ensure solutions are practical and scalable. Practitioners identified the benefits of participating in workshops alongside practitioners from other areas, in particular learning from each other's experiences with agricultural water management, remote sensing and potential application of water accounting.

A further important conclusion relates to the contribution of qualitative research and the inclusive user engagement and participatory approach, which presented a novel approach of working with technical research projects. Rather than being positioned only as end-users of predefined technical works, stakeholders were co-developers, actively engaged in shaping the direction of the research, articulating decision-making needs, and guiding the designing and presentation of remote sensing and water accounting outputs. Throughout the process, participants particularly valued the opportunity to communicate the specific types of water data, indicators, spatial units, and temporal frequencies required to support their operational and management opportunities.

Aligning data availability, complexity and capacity

Larger basins had freely available remote sensing data available, smaller basins such as Ban Don (~10,000 km²), had freely available precipitation and evapotranspiration data but changes in storage, using GRACE needed to be downscaled and calculated. With even smaller basins such as Krong Buk (~ 250 km²), and irrigation clusters, finer scale remote sensing data is not always available, so required data had to be computed using algorithms like ETLook, which required higher skill levels not available amongst the stakeholders managing those smaller scales (Figure 1.2).

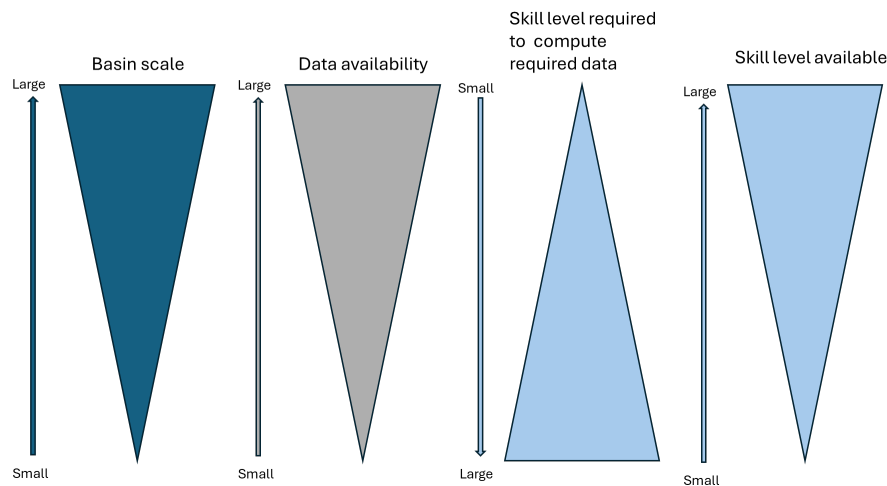


FIGURE 1.2 SUMMARY OF LINKS BETWEEN BASIN SIZE, DATA AVAILABILITY, COMPLEXITY TO COMPUTE DATA, AND CAPACITY AVAILABLE. LARGE BASINS HAVE HIGH DATA AVAILABILITY WITH LOWER SKILL LEVELS NEEDED TO CALCULATE WATER BALANCES, THOUGH WITH HIGH SKILL LEVELS AVAILABLE. CONVERSELY, SMALL BASINS HAD LIMITED DATA AVAILABILITY AND REQUIRED ADVANCED SKILL LEVELS TO COMPUTE THE REQUIRED DATA TO DERIVE WATER BALANCES BUT HAD LIMITED CAPACITY.

In summary, this project demonstrated:

- the maturity of water resources management and governance is good but opportunities to strengthen data-informed WRM exists.
- the potential for remote sensing and water accounting to provide useful and usable data to support water resources management in Viet Nam at subbasin scales.
- however, at the smallest scales, such as irrigation clusters/schemes, models are required to fill spatial data gaps.
- there is strong stakeholder interest for Vietnamese WRM to be strengthened with greater data-informed management systems and practices.

- however, further attention to accessibility is required, primarily relating to the capability of staff, at differing levels of government and irrigation management, to access the data outputs from remote sensing and water accounting.

RECOMMENDATIONS

The following recommendations reflect the opportunities remote sensing and water accounting offer, and seek to address the accessibility challenges, to progress the scaling-up of remote sensing and water accounting in Viet Nam.

REMOTE SENSING – TECHNICAL DEVELOPMENT OF DOWNSCALED TOOLS

Remote sensing tools should continue to be refined and tested at the subbasin and irrigation scheme scales, where operational decisions are made. Priority should be given to:

- Include scaling out to new geographical zones which have different climates, terrains and crops to improve the robustness and applicability of the tools
- Translating geospatial into easy-to-understand outputs such as bulletins and maps, so they are accessible and comprehensible for local authorities in their routine planning and operational decisions
- Coupling remote sensing with hydrologic models to (i) improve spatial resolution of data, which remote sensing alone cannot achieve across all useful hydrological parameters and (ii) improve projection capabilities, such as to enable scenario testing.

WATER ACCOUNTING TOOLS

With existing / emerging capacities and interests, water accounting outputs are most likely to be generated at provincial government and Irrigation Management Company (IMC) management levels, with less interest and capacity in commune and local IMC operators to prepare their own water accounting analyses. It is therefore recommended that:

- Continuing the user-centred approach by guiding tool development with practical use cases such as seasonal/monthly water balance assessments, drought hotspot identification and management, irrigation performance assessment. Water accounting applications should be established and defined, based on clear decision use cases at each level:
 - Provincial government: to support annual/seasonal allocation planning, drought mapping and response, groundwater abstraction licensing and control, including compliance.
 - Commune government: water accounting as a tool to support hotspot detection (declining groundwater, dry wells, abnormal water use efficiency), scheduling of demand management, substitution for statistics and in-situ measurements such as accounting for yield, resources, rainfall etc.
 - Irrigation management companies: water accounting as a tool for irrigation scheme/cluster scheduling and performance tracking (i.e., ET, biomass production, water productivity, irrigation efficiency, equity), benchmarking between upstream/downstream, irrigation clusters.
- A “service delivery model” be considered to increase the usability of water accounting, whereby mandated units / teams within The Ministry of Agriculture and Environment (MAE) and IMC, nationally or in provincial offices, act as ‘data producers’ - acquiring and processing data, operating GIS and water accounting tools, and distributing data outputs to data users in local level government and IMC operations offices

- Water accounting output visualization should be done in two practical formats: (i) standardized sheets summarizing key metrics and maps for spatial display; (ii) simple interactive dashboards/webs that allow users to filter by the level of details and administrative boundaries.
- Capabilities to generate water accounting outputs should include hydrological modelling, which has the capability to assess the impact of seasonal and longer climate projections on water resources.

IMPROVED DATA QUALITY AND INTEGRATION

- Enhance the accuracy of remote sensing data by integrating it with ground-based monitoring systems.
- Invest in automatic monitoring devices and software with real-time linking and updating functions to support forecasting, drought management, and water allocation.
- Promote research to improve remote sensing and water accounting methodologies and their adaptation to Viet Nam's hydrological and agricultural conditions.
- Ensure algorithm transparency and data verification to build user trust in system outputs.

CAPACITY DEVELOPMENT AND TRAINING

- Implement an ongoing system of tailored, hands-on training programs on the use of remote sensing, GIS, modelling and water accounting for water management in Viet Nam. These programs should include step-by-step user manuals, online tutorials, and periodic refresher courses to support continuous capacity building. Training of Trainers can also be considered as a good approach to ensure sustained capabilities.
- Integrate technology transfer into future remote sensing, model and water accounting development to enhance the autonomy of agencies in applying advanced tools. Efforts should prioritize the needs of water resource managers and operators at the local level, particularly at commune and provincial scales.
- Consider "scaling out" opportunities with other Southeast Asian countries, sharing amongst practitioners from different geographic locations, with different cultures and context, which is especially relevant in term of transboundary water management (e.g., Mekong region).
- Establish a regional community of practice to sustain learning and integration. This can be done in technical cooperation framework such as ASEAN, ASEAN-6 (six advanced countries in ASEAN comprising Singapore, Indonesia, Malaysia, Philippines, Thailand and Viet Nam). A practical mechanism, such as periodic regional diagnostic exchanges, joint case studies, and shared technical guidelines, would welcome continuous exchange on WRM challenges and solutions, including those relevant to transboundary basins and broader ASEAN cooperation.

PILOT PROGRAMS AND SECTORAL APPLICATIONS

- To complement capacity development and training, launch pilot projects integrating remote sensing, modelling and water accounting data in priority areas such as agriculture water allocation (e.g., for coffee plantations), reservoir regulation, and urban water supply planning. These will:
 - Enhance capacity development through hands-on action learning
 - Identify and support development of internal systems for data management and data product systems
 - demonstrate cost savings, efficiency gains, and sustainability improvements
 - build trust and motivate adoption by stakeholders.

CENTRALIZED AND INTEGRATED DATA SYSTEM

- Establish a national, standardized, and centralized database that integrates RS, modelled and WA+ data with other water-related datasets to enable seamless data sharing among sectors—irrigation, agriculture, urban water supply, and disaster management—to avoid fragmentation. The database and the related software should be user-friendly and be able to provide outputs in practical formats (maps, charts, dashboards, automated reports).
- Prioritize the development of open-source or low-cost software tools and RS-based applications.

LEGAL AND POLICY FRAMEWORK

- Develop clear legal definitions and policy frameworks to promote the application of WA and RS in water management.
- Facilitate dialogue between the water resource and irrigation sectors to streamline policies and develop a unified water data and accounting framework.

ONGOING RESEARCH AND COLLABORATIVE SUPPORT

- Continue research to improve data accuracy, especially for remote sensing-based estimates of evapotranspiration, groundwater, and crop water use.
- Create a feedback mechanism for end-users to report practical challenges to research teams for responsive improvement.
- Promote technology transfer and co-development with local agencies to strengthen long-term autonomy.

Next steps to progress the above recommendations

It is recommended that a multi-year research and capacity development project be designed and delivered in Viet Nam to establish and pilot a water accounting & remote sensing (WA+RS) service delivery model that is used by water managers for basin and sub-basin agricultural water management of surface and groundwater resources. Specifically, the project would aim to:

- promote the use of water accounting and remote sensing for water-related decision-making (1-2 years)
- strengthen the technical robustness of the remote sensing and water accounting tools, with additional landcover and crop types, and hydrogeological situations (1-3 years)
- expand the technical capabilities of national and provincial government staff and support them to establish a service delivery model, delivering basin and sub-basin water accounting reports for use by other provincial, commune and irrigation management company water managers (2-3 years)
- develop the capabilities of provincial, commune and IMC staff intending to use water accounting and remote sensing 'reports' (2-3 years)
- institutional integration and long-term systems development (3-4 years)

This would entail:

- (a) Agreeing with MAE a model and program to **develop WA+RS service delivery teams at provincial government levels** (and if appropriate, provincial IMC departments), which will be supported by IWRP (MAE). As shown in Figure 7.2, these teams would function as specialised “data producers”, responsible for:
 - Acquiring and processing remote sensing and modelled datasets
 - Operating GIS, modelling and water accounting workflows

- Generating standardised maps, reports, dashboards and seasonal bulletins on state of surface and groundwater resources
- Distributing these outputs to operational water managers and planners

This model recognises that the technical complexity of generating WA+RS outputs currently exceeds the operating capacity available at commune and local irrigation management levels, while local actors still require timely and accessible information to support decision-making.

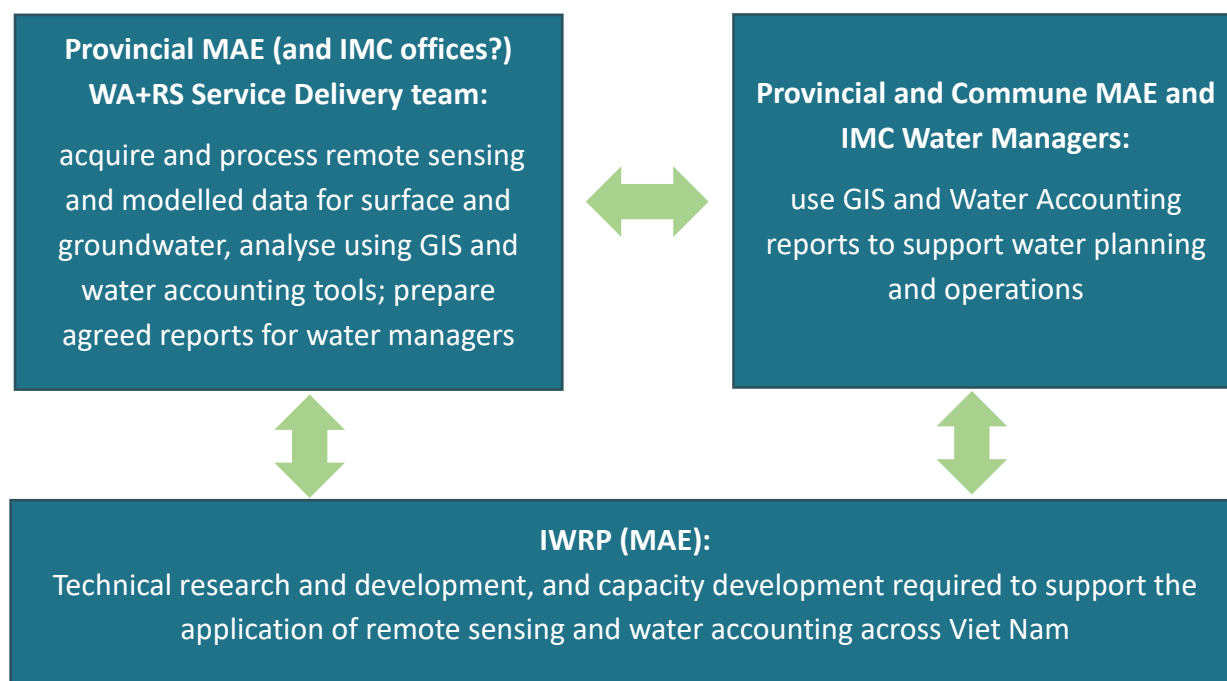


FIGURE 1.3: SERVICE DELIVERY MODEL TO ACHIEVE THE APPLICATION OF REMOTE SENSING AND WATER ACCOUNTING TO AGRICULTURAL WATER MANAGEMENT IN VIET NAM

- We recommend this commence with the Central Highlands provinces of Lam Dong and Dak Lak, building on the work of the existing ACIAR SRA project, developing a suitable approach to establishing these service teams, before expanding to additional provinces. Appropriate **governance arrangements** will need to be agreed between stakeholders, including arrangements for basins and sub-basins that span provincial boundaries. This includes addressing data management and policy and regulatory frameworks to ensure cohesive basin/sub-basin management is possible.
- Delivering **capacity development programs for the provincial service delivery teams** that combines structured training in foundational skills and knowledge, with practical real-world use of remote sensing and water accounting tools, and development of outputs for basin and sub-basin water managers in their provinces. A key focus will be on defining (with water managers), specific applications of water accounting and/or remote sensing data (beyond those identified herein). Skills developed will include: GIS data sourcing, processing, analysis and reporting; hydrological modelling of surface and groundwater for water accounting; water accounting calculations and water accounting reporting for water managers; validating reports with on-ground data and insights from water managers.

- (d) Delivering **capacity development programs for provincial, commune and IMC water managers** in the use of the reports / outputs of water accounting and remote sensing for agricultural water management of surface and groundwater resources. This capacity Development will similarly apply a mix of structured training in foundational water accounting and GIS concepts, and hands-on application of real-world water accounting and GIS outputs produced by the service delivery team in their province.

Joint training workshops, bringing together the WA+RS teams with water managers in a given province, will strengthen the mutual knowledge of the strengths and limitations of applying the data and tools to real management decisions, and, establish a practice of ongoing two-way feedback so as to avoid one-way communication from data providers to data users (this can lead to data reports that do not meet the needs to water managers).

- (e) Identifying additional sub-basins across Viet Nam with different land cover, crops and hydrogeology to **expand the technical validity of the remote sensing and water accounting tools**. These sub-basins will align with the agreed program of expansion of WA+RS across Viet Nam, to ensure technical tools are available for those provinces in which WA+RS will be piloted and expanded

Additional next steps

Two additional key findings warrant further progress:

1. Managing groundwater (over) extraction in Viet Nam

The finding of overextraction of groundwater in some locations in the Central Highlands should be further pursued in two ways:

- A groundwater study to establish the scale of groundwater over extraction across selected priority regions (where pressure on groundwater is high) to better understand groundwater dependence, groundwater abstraction pressures, seasonal storage dynamics, and implications for water security, including interactions with climate change. This will inform the need for improved ongoing monitoring and management of groundwater, in which areas, of Vietnam.
- Review current groundwater monitoring and management practices to assess how Water Accounting Plus and remote sensing can augment these practices to strengthen groundwater management across Viet Nam.

Future work should consider the strong interaction between groundwater, surface water, evapotranspiration and land use change observed in the Central Highlands or areas with expanding perennial crop systems and increasing irrigation demand.

2. Water Accounting sub-basin technical underpinnings.

To address the lack of existing formulas and models to accurately estimate groundwater and surface water flows, using remote sensing data, and which are suitable for sub-basin scales, it is recommended:

A multi-institution, technical project, be established, collaborating across key Water Accounting developers, such as IHE Delft and IWMI. This project would focus on developing and assessing suitable formulas, and models as needed, for use at sub-basin scales, in a range of settings, including and beyond Viet Nam.

PROJECT OVERVIEW

2.1 PROJECT BACKGROUND

Strong governance of agricultural water use is needed to support agri-food system sustainability, through increasing volatile and unpredictable water resource scenarios, and to support broader water security needs. Agriculture often consumes vast amounts of water and achieving sustainable withdrawals without detriment to the environment and other societal benefits, is a key aim of water accounting, smart water monitoring and water regulation. Water users and managers must have awareness of water resources conditions, especially in circumstances where climate change may reduce stream flow and groundwater stocks. Water users must make decisions accordingly, to allocate water to balance the competing social welfare, economic benefits and ecosystem functions.

In the SE Asian region much of the agricultural activity occurs on small scale farms, and indeed globally small-hold farms occupy between 70 and 80 per cent of the world's farmland. The presence of many small holder farmers, and/or irrigation scheme managers, making individual decisions about water extraction and use of shared water resources, requires good management and regulation at basin and subbasin levels to ensure sustainable water resources management. However, in many areas of Asia, current water management and irrigation practices are leading to water consumption and water quality issues such as salinisation and agricultural contaminants (pesticides and nutrients) that do not appear to be sustainable in the long term (ADB, 2020).

Additionally, in many regions water is treated as a public good, often free, that performs invaluable social and cultural welfare roles. In the absence of appropriate water data and tools, management to protect such public good services of water can come at the cost of limiting water supplies for other environmental, domestic and industrial purposes. The adoption of water balance, or water accounting, approaches, to support water allocation and regulations, is a useful governance tool that allows for trade-offs to be identified and deliberated and informed water allocation decisions to be made. However, water accounting is viewed with suspicion by some stakeholders as a method of introducing a pricing mechanism that will create further burden on poorer communities. Consequently, the adoption of water accounting methodologies to improve efficiency, livelihood outcomes and environmental benefits requires engagement and capacity building with stakeholders to address social and political concerns about changing water tenure arrangements, especially for less resilient communities.

The ways in which water data and water accounting can practically be used to guide the types of allocation and management decisions described above, is tightly linked to the existing and planned governance and management instruments of a particular place. This enabling system can vary in technical complexity, regulatory sophistication, decentralisation, and stakeholder engagement, between countries, as well as within countries at different provincial and/or basin scales. Agricultural water governance and management systems can span, broadly, from no regulatory oversight with no or minimal water data use to guide decision-making, to mature water resources governance systems using high currency water data to inform and enforce allocations, and with varying levels of decentralisation to subbasin levels or communities (e.g. Dell'Angello et al., 2014; Waalewijn, et al., 2020). Understanding the governance and management regime of a particular basin/subbasin helps to identify the current water data needs and specify the application of data and tools. Additionally, gaining access to enhanced water data and accounting tools that underpin water allocation regulations can help drive advances further along the spectrum of governance and management regimes.

In Viet Nam, there is recognition from water management research institutes in government of the urgent need to integrate the management of groundwater and surface water, to improve irrigation management, and to use water data and accounting to support this advancement. Water use and allocation decisions are

necessarily being made by irrigation scheme managers and other subbasin water management stakeholders; there is keen interest to identify ways that these water managers can access and use RS data and water accounting/balance tools to improve water management decisions. A particular case study suggested to explore subbasin water management decision-making processes – both existing and potential decisions that could be made with improved RS and water accounting – is the Vietnamese Central Highlands, where coffee production is highly dependent on groundwater and where current canal water distributions are limited.

2.2 PROJECT PURPOSE & OBJECTIVES

Typically, in low/middle income countries, *in situ* monitoring of water resources such as river flows, groundwater levels, and water consumption by irrigated agriculture, is limited. The investment required for *in situ* monitoring infrastructure and capacity, particularly for groundwater, can be prohibitive. Consequently, there is often a paucity of detailed and robust data upon which to generate water balances and in particular to conduct water accounting exercises. On basin and larger scales, inroads are being made to address this gap by harnessing the latest in big data and applying remote sensing (RS) and earth observation (EO) data products. However, the potential for such data and associated products to assist with subbasin scale water management is not known.

This SRA aimed to address this knowledge gap by exploring, describing and demonstrating the roles and utility of remote sensing (RS) data products to fill hydrological data gaps and support subbasin agricultural water management; this included determining their applicability at the spatial and temporal scales relevant to the range of decisions being made (i.e., local, subbasin).

The research had four key objectives.

1. Determine and describe what can be inferred from remote sensing data products about water availability and use as relevant to subbasin water management, and describe the accessibility in terms of technical capacity, cost to produce/access and computer resourcing required.
2. Characterise the nature of agricultural water decision-making at subbasin scales as relates to small scale farming (i.e. describe the existing and emergent governance and management regime applying to small-scale agricultural water use): who, how, when and what water decisions are, or could be, made, using Viet Nam as a case study for SE Asia. Situate the case study management regime including the use of data, and types of actors using water data, in a generalised schema/typology of maturity of data-informed water resources management, and a typology of actors (water data users) by drawing on broader (regional) literature.
3. Pilot the application of a localised water accounting or water balance tool and identified remote sensing products for use by water managers in relation to subbasin-scale agricultural water use in rural Viet Nam, with a focus on the usability and accessibility of these products, and usefulness (relevance to existing and developing management requirements, and the changed decision-making practices that could be enabled by the adoption of remote sensing with water accounting at this scale). This activity also aims to test a process to localise an existing water accounting tool that incorporates remote sensing data.
4. Identify the opportunities and strategies to apply such RS and associated water accounting products to subbasin water management within, and beyond Viet Nam.

This report focuses on the Viet Nam Pilot study, which specifically aimed to:

1. Assess remotely-sensed information relevant to subbasin water management in Viet Nam.
2. Characterise Vietnamese water resources decision-making processes at subbasin levels in agricultural contexts. This includes describing governance and management structures, identifying key stakeholders, and testing a framework for the Maturity of data-informed water resources management & governance
3. Pilot a localised water accounting tool that incorporates selected remote sensing products for subbasin water managers in rural Viet Nam. The pilot will test the tool's usability, accessibility, and potential to support improved decision-making within current and emerging management frameworks.
4. Identify interest and opportunities in scaling up the application of RS-based water accounting tools in Viet Nam.

2.3 RESEARCH PARTNERSHIP

This research was undertaken by a multidisciplinary team of local and international researchers, combining expertise from ground and surface water remote sensing, agricultural management, water accounting, water governance, and stakeholder research-application research.

The research was led by a partnership of International Water Centre at Griffith University, Australia, and Institute of Water Resources Planning, Ministry of Agriculture and Environment, Viet Nam, and involved frequent engagement with government agencies, irrigation companies and academia.

Funding and support are being provided by the Australian Government's Australian Centre for International Agricultural Research (ACIAR).

Additional information, and access to project outputs, is available from the project website: WATERCENTRE.ORG/AGRICULTURAL-WATER-MANAGEMENT-IN-SE-ASIA/

THE ROLE OF STAKEHOLDERS IN THE RESEARCH

This project adopted a user-centred approach, prioritising the needs and perspectives of subbasin water managers, addressing key gaps in how they access and utilize remote sensing products to support sustainable agricultural water management, particularly in contexts where field-based data is limited and cost-prohibitive.

The research will assess the applicability and relevance of remote sensing products and tools across various spatial and temporal scales, examine the relationships between national and regional water management agencies and local subbasin operators, and recognize the limitations of RS data— while identifying practical products and strategic investments that can improve decision-making at subbasin levels.

To understand the needs of subbasin water management, interviews were undertaken with stakeholders. These stakeholders were identified because of their current professional role in water management – groundwater or irrigation/surface water. These stakeholders in irrigation operators, irrigation/surface water managers in any level of government, and groundwater managers in any level of government.

2.4 RESEARCH APPROACH

The R&D approach proposed in this research project combines a technically focused activities with user-centred qualitative research activities. In this case, the user is defined as subbasin water managers – these may be provincial or local governments, irrigation district organisations, or groups of farmers such as collectives. National-level water agencies are also end users of RS products, though for the scope of this research, focused on subbasin management, they are only relevant end-users if they are directly involved with subbasin water users in water management decision making. They are of course key stakeholders in the ambition of making RS products accessible to subbasin water users and managers.

The research explores the suitability and utility of low and no cost remote sensing products to provide hydrological information for water balance assessment and water accounting, agricultural water usage and efficiency. This evaluation combined technical assessment with real-world pilot application to examine operational feasibility.

The case study approach allows us to investigate:

- unmet specific data needs of water decision-makers, in this case, subbasin water managers and users, given their existing and emerging water management and regulatory regimes.
- the usability and accessibility of existing data sets and interfaces by these stakeholders.
- the capacity and other requirements to adopt these products.

The project used both technical and qualitative (social) research approaches to identify which accessible RS data products can provide inputs into existing/emerging agricultural water management decision support tools (especially water accounting), and test this in a local-scale, place-based pilot. The usability of products will be considered given local capacity, and establishment and ongoing costs.

Figure 2.1 summarises the four main activities of the project as a whole.

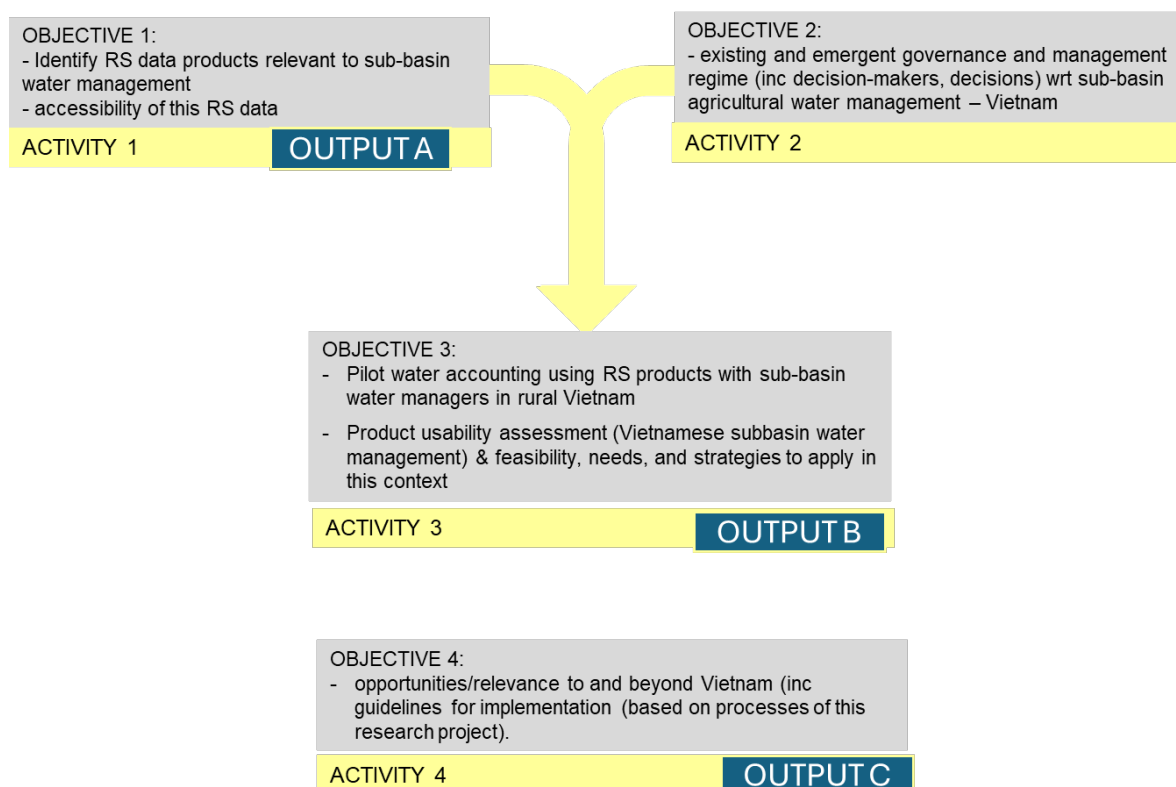


FIGURE 2.1: PROJECT OBJECTIVES, ACTIVITIES AND OUTPUTS.

For the pilot testing and validation of the utility of subbasin scale RS and water accounting products (Objectives and Activities 2 and 3), a coffee growing area of Viet Nam has been selected. The Central Highlands of Viet Nam has been selected because of the use of a diversity of types of water resources in agriculture, allowing the research to explore different hydrological parameters. In this area, groundwater has been vital for the development of cash crops such as coffee, and smallholder coffee growers have been addressing both the demand and supply elements of water use to achieve sustainable management of a limited resource. Here, basaltic fractured rock aquifers, which are particularly susceptible to overexploitation, produce groundwater which is mostly abstracted by irrigation systems resulting from private investment.

Three major outputs have been produced:

A. *Review Of Remote Sensing And Water Accounting Supporting Agricultural Water Management In Subbasins*

A project report outlining which existing and emerging RS datasets are appropriate for use in lower/middle income country contexts for agricultural decision-making at different scales with a focus on subbasin scales, with recommendations on their usability and accessibility to be applied to water accounting tools, based on the technical capacity and computer resourcing required for use, cost to produce/access applicable to South East, South and East Asian contexts. This report will also include a brief methodology and advice on repeating this activity for future updates as required.

B. *Understanding the Role of Remote Sensing and Water Accounting in Supporting Agricultural Water Management in Viet Nam*

(This report) A technical report outlining the aims, methods, and key findings with respect to a small-scale pilot of subbasin water accounting using RS products in Viet Nam (drawing on Objectives 2 and 3). The report describes (i) the management and governance regime, and types of water data users, in Viet Nam (ii) the subbasin water accounts developed and their utility to deliver information to support subbasin water decisions, including changed decision-making practices that could be enabled by the adoption of RS with WA at this scale (iii) recommendations to support uptake of RS and water accounting products by subbasin water managers/decision-makers in rural Viet Nam (including considering capacity development and engagement activities, role of government agencies in improving access to RS data).

C. *Recommendations on the Further Development of Remote Sensing and Water Accounting to Support Subbasin Agricultural Water Management in Asia*

A project brief outlining recommended next steps to progress and extend the study findings to other regions, the application of RS data products to hydrological decision-support tools for subbasin agricultural water management in lower/middle income countries, and guidelines on localising the implementation of subbasin WA using RS in other locations.

WATER MANAGEMENT AND WATER DATA USAGE in VIET NAM

3.1 POLICY REVIEW

3.1.1 OVERVIEW OF WATER RESOURCES MANAGEMENT AND INSTITUTIONAL CONTEXT

In Viet Nam, water resource management is decentralized to local authorities at provincial and commune level according to the type of water source and usage purpose. Within the framework of the project focusing on agricultural water management in the Central Highlands, this section analyses management mechanisms in three key areas: surface water management, groundwater management and exploitation, and the operation of hydraulic works. The objective of this analysis is not only to clarify organizational responsibilities, but to assess how this governance structure influences the feasibility of applying remote sensing and water accounting tools into subbasin decision making processes. The legal basis of the report relies on the Law on Water Resources 2023, the Law on Hydraulic Work 2022, along with relevant subordinate legal documents.

Notably, this report is finalized in the context of Viet Nam having just undergone a national-wide administrative restructuring in 2025. Regarding the organizational structure at the central level, units under the Ministry of Natural Resources and Environment have merged into the Ministry of Agriculture and Rural Development to form Ministry of Agriculture and Environment. Similarly, at the provincial level, the Department of Natural Resources and Environment merged with the Department of Agriculture and Rural Development to form the Department of Agriculture and Environment (DAE) in March 2025. regarding administrative decentralization, there has been a transition from a three-level government model (province, district, commune) to a two-level model; specifically, the district level has been abolished and related tasks were transferred to the commune level as of July 2025. Additionally, the merger of certain provinces and communes was implemented in July 2025 regarding administrative boundaries.

In Dak Lak province specifically, the merger resulted in the establishment of the Department of Agriculture and Environment (DAE). Specialized sub-departments were also consolidated; notably, Decision No. 427/QĐ-UBND dated February 26, 2025, of Dak Lak province established the Sub-department of Irrigation and Water Resources Management based on the consolidation of the former Sub-department of Irrigation and the former Sub-department of Water Resources.

Although there have been organizational changes, foundational legal regulations remain effective, and the rights and obligations of former agencies are transferred correspondingly under the new structure. However, adjustments in documents guiding functions and tasks are expected in the near future. This report was initially drafted in March 2025 to guide subsequent project activities. The final version is a slightly updated and revised edition of that draft, reflecting the current state of the water management landscape in Viet Nam (following significant government restructuring).

3.1.2 DETAILED MANAGEMENT DECENTRALIZATION BY SECTOR

Based on current legal regulations and the practical implementation of the administrative restructuring in Viet Nam in 2025, state management responsibilities for water resources have been specifically redefined. This report focuses on three main pillars: Water Resources Management, Hydraulic Work Management, and Groundwater Management. Management decentralization is organized into three levels: The Ministry of Agriculture and Environment (MAE) plays the leading role in decision-making and consultation at the central level; the Provincial Department of Agriculture and Environment (DAE) is responsible for advisory functions at the provincial level; and the Commune People's Committee (CPC) assumes direct

implementation tasks at the grassroots level following the transfer of professional duties from the district level.

3.1.2.1 WATER RESOURCES MANAGEMENT SECTOR

In the sector of water resources management, the responsibility for *developing legal documents and strategies* is divided between central and local levels. At the central level, the Ministry of Agriculture and Environment (MAE)—specifically the Department of Water Resources Management—is responsible for promulgating legal documents, technical standards, and the national water strategies. At the local level, the Provincial People’s Committee (PPC), advised by the Provincial Department of Agriculture and Environment (P-DAE), has the authority to issue guiding documents and strategic plans suitable to the province's specific characteristics, while the Commune People’s Committee (CPC) participates in the enforcement of these documents at the grassroots level.

Basic investigation of water resources is a core task implemented synchronously from the central to the local level. Both MAE and P-DAE are responsible for organizing basic investigation activities to collect input data for management purposes. The content of basic water resource investigations is diverse, including field surveys, water accounting implementation, and the development of periodic reports. Furthermore, management agencies must maintain continuous monitoring systems and operate decision support systems, while simultaneously building scenarios for water exploitation and usage to respond to fluctuations in water sources. The CPC supports data collection as assigned by the P-DAE.

Regarding *water resource planning*, decentralization is demonstrated through the scope and nature of the water source. The Ministry of Agriculture and Environment is responsible for planning inter-provincial river basins. Planning at this level focuses on the overall assessment of natural and socio-economic factors, analysis of current management status, and water-related risks. Based on this, the central agency provides forecasts on water supply and demand, identifying vulnerable areas, and establishing sustainable water use limits. The central-level planning strategy also defines objectives for development, allocation, protection, restoration of water sources, and damage mitigation, including the orientation of large-scale infrastructure projects along with budgetary solutions and implementation monitoring plans.

At the provincial level, the Provincial People’s Committee and the specialized Department are responsible for formulating and reviewing water resource planning within their administrative boundaries. The content of provincial planning delves into assessing the quantity and quality of local water sources, reviewing the status of protection, exploitation, and use of water, as well as preventing water-induced harm and controlling wastewater discharge into water sources. Provincial planning must also forecast water use demand during the planning period, thereby orienting investment in the construction of local water resource monitoring networks. Specifically, this planning identifies medium and small-scale dams, reservoirs, and works for regulation, storage, and development of water sources to serve intra-provincial needs.

For the work of *protection, restoration, regulation, and allocation of water sources*, responsibilities are shared between MAE at the central level and local authorities (PPC/DAE). One of the key tasks is balancing and distributing water usage by adjusting the operation procedures of dams, reservoirs, hydraulic works, and other water storage activities. Regarding direct exploitation and use of water resources, responsibilities are strongly decentralized to grassroots units such as the Dak Lak Irrigation Management Company (Dak Lak IMC), local irrigation companies (Local IMC), and Commune People’s Committees to ensure water supply for production and daily life.

3.1.2.2 HYDRAULIC WORK MANAGEMENT SECTOR

The management of hydraulic works is strictly regulated in the Law on Hydraulic Work and relevant sections of the Law on Water Resources.

Regarding *state management decentralization and planning*: The Ministry of Agriculture and Environment (MAE) holds the leading role at the central level, responsible for promulgating legal documents and developing strategies and planning for special hydraulic systems and key national works. At the local level, this responsibility belongs to the Provincial People's Committee (PPC), advised by the Department of Agriculture and Environment (P-DAE). These agencies are responsible for issuing guiding documents, establishing intra-provincial hydraulic planning, managing construction investment projects in the area, and simultaneously guiding, inspecting, and examining the management and exploitation activities of subordinate units.

Basic investigation activities in the hydraulic sector are carried out by both central and local agencies to assess the status of works in terms of quantity, quality, service capacity, and actual demand. Investigation contents include assessing organizational structures and policy mechanisms and analysing the environmental and livelihood impacts of hydraulic works. At the same time, this work involves monitoring water resources, climate risks, structural safety, and assessing the impacts of climate change as well as socio-economic activities on the hydraulic system. Based on investigation results, hydraulic work planning is deployed to analyse current conditions and influencing factors, thereby forecasting trends and building development scenarios for the future. This planning clearly defines objectives, development strategies, detailed plans for hydraulic resource management, and proposes implementation solutions and necessary resources.

Management activities for large-scale works (not in-field works) include specific groups of specialized technical tasks. First is data collection and processing: the management unit must collect hydro-meteorological data, organize measurement, monitoring, and forecasting, while simultaneously perform water accounting and analysing actual water use demand. Second is water regulation: based on collected data, the management unit develops and implements reasonable plans for water storage, balancing, and distribution. Third is technical maintenance: involving investment, upgrading, and periodic maintenance of the works and accompanying mechanical equipment to ensure operational safety.

Regarding management authority for this group of works, the MAE directly manages only special systems. The majority of remaining works are decentralized by the Provincial People's Committee or assigned to specialized units for management. Specifically, the Department of Agriculture and Environment typically assigns operational duties to state-owned enterprises such as the Irrigation Management Company (e.g., Dak Lak IMC) to perform the professional tasks.

For in-field hydraulic systems, management responsibilities are decentralized to the grassroots level. These works are directly managed by local irrigation organizations (Local IMC) or the Commune People's Committee (CPC) in cases where the locality has not yet established a specialized irrigation organization. The main task at this level is to ensure water delivery from the transfer point to the field surface for production. The Department of Agriculture and Environment plays a guiding and inspecting role to ensure irrigation efficiency.

The operation of dams, reservoirs, and hydraulic systems must strictly adhere to approved operation procedures. The work owner (management unit) is responsible for developing these procedures to guide operators in performing technical manoeuvres. In practical operation, units must use meteorological forecast information and actual measurement data to make timely regulation decisions, ensuring both dam

safety and effective water distribution. Concurrently, periodic water accounting and early forecasting of water shortages or saltwater intrusion are mandatory requirements for proactive response.

3.1.2.3 GROUNDWATER MANAGEMENT SECTOR

Groundwater management requires strict control due to the vulnerable nature of this resource. At the macro level, the Ministry of Agriculture and Environment is responsible for planning permissible exploitation areas and methods, as well as issuing technical guidelines applicable to inter-provincial contexts.

Licensing and registration for groundwater exploitation are decentralized based on scale and purpose of use. For groundwater exploitation activities serving business purposes with a flow rate greater than 10 m³/day/night, the licensing authority belongs to the Provincial People's Committee (PPC). However, registration for exploitation for this same object (business >10 m³/day/night) is performed at the Commune People's Committee (CPC), demonstrating the on-site supervisory role of the grassroots government.

For smaller-scale exploitation activities, decentralization to the commune level becomes even more distinct. Specifically, the registration of groundwater exploitation for business purposes with a flow rate under 10 m³/day/night falls under the management responsibility of the Commune People's Committee (CPC). Similarly, registration for groundwater exploitation serving household daily life, as well as cultural, religious, and scientific research activities, is also carried out at the commune level.

Finally, the reporting regime on groundwater exploitation status and discharge into water sources is mandated at both provincial and commune levels. The Department of Agriculture and Environment (representing the provincial level) and the Commune People's Committee, along with exploitation units like Dak Lak IMC, are all responsible for implementing this reporting regime to ensure the management database is continuously and accurately updated.

TABLE 3.1 INSTITUTIONAL RESPONSIBILITY FOR SURFACE WATER, GROUNDWATER AND IRRIGATION MANAGEMENT IN VIET NAM

Sector	Task	MAE - Dept of WRM	MAE Dept of HWM	PPC	P-DAE		CPC				Dak Lak IMC	Local IMC
	Responsible agency before 2025 restructure	MONRE-Dept of WRM	MARD-Dept of IW	PPC	P-DONRE	P-DARD	DPC	D-DONRE	D-DARD	CPC	Dak Lak IMC	Local IMC
Water resources management	Legal documents	X		X	X							
	Basic surveys	X		X	X		X	X				
	Strategies for water	X		X	X		X	X				
	Planning and revision	X (Trans- provincial rivers)		X	X		X	X				
	Protection and restoration of the water resources	X		X	X		X	X		X		
	Balancing and allocation of water resources	X		X	X		X	X		X		
	Exploitation and use of water resources									X	X	X
Hydraulic work management	Legal documents		X	X	X	X						
	Basic surveys		X	X	X	X			X			
	Strategies		X	X	X	X			X			
	Planning		X	X	X	X			X			
	Operational procedures of irrigation works		Special systems	X	X	X			X			
	Investment and construction of irrigation works		X	X	X	X			X			
	Provide guides, and inspect the management and exploitation of the irrigation works		X	X	X	X			X			
	Management of irrigation works (not in-field works)		Only special systems			Assigned by PPC						
	Management of irrigation works (in-field works)								Assigned by PPC			
	Operating the irrigation works (not in-field works)										Assigned by P-DAE	
	Operating the irrigation works (in-field works)									Assigned by PPC and if no local IMC		X
Ground water management	Planning on where and how can be extracted	Guidance (or inter provinces)			X							
	Licensing groundwater extraction for business activities (>10 m3/day and night)				X							
	Registration of groundwater extraction for business activities (>10 m3/day and night)							X				
	Registration of groundwater extraction for business activities (<10 m3/day and night)							X				
	Registration of groundwater extraction for household activities, serving cultural, religious and scientific research activities.									X		
	Reporting on groundwater withdrawal, wastewater discharge				X			X		X		

Key to table abbreviations:

- **MAE:** Ministry of Agriculture and Environment (Bộ Nông nghiệp và Môi trường).
- **MAE Dept of WRM:** Department of Water Resources Management (Cục Quản lý Tài nguyên nước).

- **MAE Dept of HWMC:** Department managing Hydraulic Works/Irrigation under MAE (Responsible for hydraulic work management strategies and planning).
- **PPC:** Provincial People's Committee (Ủy ban nhân dân cấp tỉnh).
- **P-DAE:** Provincial Department of Agriculture and Environment (Sở Nông nghiệp và Môi trường) - formed by merging the former P-DONRE and P-DARD.
- **CPC:** Commune People's Committee (Ủy ban nhân dân cấp xã).
- **Dak Lak IMC:** Dak Lak Irrigation Management Company (Công ty khai thác công trình thủy lợi Đắk Lắk).
- **Local IMC:** Local IMC: Local Irrigation Management Organization (Tổ chức thủy lợi cơ sở).
- **MONRE:** Ministry of Natural Resources and Environment (Bộ Tài nguyên và Môi trường).
- **Dept of WRM:** Department of Water Resources Management (Former unit under MONRE).
- **MARD:** Ministry of Agriculture and Rural Development (Bộ Nông nghiệp và Phát triển nông thôn).
- **Dept of IW:** Department of Irrigation/Hydraulic Work (Former unit under MARD).
- **P-DONRE:** Provincial Department of Natural Resources and Environment (Sở Tài nguyên và Môi trường).
- **P-DARD:** Provincial Department of Agriculture and Rural Development (Sở Nông nghiệp và Phát triển nông thôn).
- **DPC:** District People's Committee (Ủy ban nhân dân cấp huyện - level abolished in the new structure).
- **D-DONRE:** District-level Division of Natural Resources and Environment (Task transferred to commune level).
- **D-DARD:** District-level Division of Agriculture and Rural Development (Task transferred to commune level).

3.2 STAKEHOLDER PERSPECTIVES ON WRM AND WATER DATA NEEDS

3.2.1 SURVEY DESIGN AND PARTICIPANT SELECTION

We conducted semi-structured interviews with key stakeholders at both the national and regional levels within the Srepok River Basin. Participants were selected via purposive sampling to ensure representation across different governance tiers:

- National Level: Policy makers and water resource managers.
- Provincial/Local Level: governmental officers responsible for water management and irrigation work managements at the provincial/ district and commune levels (before the administrative changes).
- Managers and Officers from Provincial Irrigation Management Companies in Dak Lak Province and Dak Nong Province (now Lam Dong province).

The detailed interview guide and questionnaire used for these sessions are available in the Appendix.

3.2.2 DATA COLLECTION AND ANALYSIS

Interviews were conducted in Vietnamese, with each session lasting between 30 and 50 minutes. To analyze the qualitative data, we utilized QualCoder, an open-source qualitative data analysis software.

The analysis followed a thematic coding approach, where transcripts were parsed to identify recurring patterns, challenges, and perspectives. This process allowed us to distil complex narratives into actionable insights.

3.2.3 WATER ISSUES

Managers and operators across the project areas from commune to province levels concern a wide range of issues impacting water resource availability, distribution, and quality. While many of the responses were prompted by interviewers, they reflect lived experience from the field and provide a valuable snapshot of current challenges. These issues can be grouped into several key themes:

3.2.3.1 WATER SCARCITY

Water scarcity was a key topic in consultations, mentioned by 16 out of 22 respondents, often after prompting. While significant, **the severity of water shortages varies by locality, presenting a complex rather than uniform challenge**. The situation is expected to be exacerbated due to climate change and unregulated groundwater use.

Provincial Perspective on Water Scarcity

Provinces acknowledge water scarcity during the dry season, affecting all local areas. However, it's often

"time-specific and seasonal, or it will be localized water shortage, meaning within a specific area, there will be water shortage, but it does not mean that the entire province will enter a serious water shortage situation. This localized shortage occurs in some points, some small communes, it's called localized water shortage, not widespread" ("tất nhiên về mùa hạn thì nói chung là địa bàn địa phương nào thì cũng sẽ ở và cái tình trạng đó [thiếu nước]. tuy nhiên thiếu nước ở địa phương nó cũng mang tính gọi thời điểm và thời vụ, hoặc nó sẽ là thiếu nước cục bộ tức là nội bộ trong một cái khu vực đó nó sẽ thiếu nước nhưng không có nghĩa là toàn tỉnh nó sẽ đi vào cái tình trạng thiếu nước nghiêm trọng. cục bộ đó em ở một số điểm một số xã nhỏ một số xã nó là gọi nó gọi là thiếu nước cục bộ chứ không có nghĩa là trên diện rộng."). – manager

Climate change has led to frequent droughts in the Central Highlands since 2016, severely impacting industrial crops like coffee, pepper, and durian. This highlights the significant economic and social consequences of water scarcity in this crop-dependent region. As one respondent noted,

"in fact, in fact, in fact, regarding the climate change impact leading to drought, in this Central Highlands region, it has occurred frequently from 2016 until now. It greatly affects the needs of crops, including rice, coffee, pepper, and durian in the Central Highlands region. It has a huge impact, thus affecting the lives of the people. In fact, for the province, 90% are industrial crops, which have very high value" ("thật ra thật ra thật ra là nếu về cái độ biến đổi khí hậu mà cho cái hạn hán đó thì khu vực Tây Nguyên này từ năm 2016 đến nay đó là xảy ra là cũng là thường xuyên. phải ảnh hưởng rất lớn đến nhu cầu cây trồng rồi về cái cây trồng về cây lúa cà phê tiêu sầu riêng đối với cái vùng Tây Nguyên đã. ảnh hưởng rất lớn do đó là nó sẽ ảnh hưởng đến cuộc sống của bà con. nhu cầu thì thật ra là đối với tỉnh 90% là là cây công nghiệp. giá trị là rất lớn."). – provincial manager

Operational and Local Management Perspectives

From the perspective of irrigation works management and commune-level administration, the challenges of water scarcity are more acutely felt. **Across the province, irrigation works can only meet approximately a low proportion of the irrigation demand in their respective areas**. This low coverage is primarily due to the limited capacity of reservoirs to transfer water and the small storage volume of most reservoirs, which are primarily exploited for water within their own basins.

Water scarcity pressure is severe in many communes. Many staff indicated that there is simply not enough water available during certain periods of the year to meet production needs—especially in areas dominated by high-demand crops. For instance, irrigation works managers at local level report that their facilities can only meet 50-80% of the irrigation demand, especially for small reservoirs. This pressure stems from both **the lack of water and prevailing cultivation practices, such as the continuous, intensive irrigation of coffee plants.** A irrigation operation manager described the severity:

*"Does drought occur commonly and widely? Yes, for us in this district, last year [dry season 23-24], like 2024, was the most severe, **about 26-27 facilities ran out of water. Last season [dry season 24-25], it was around 19-20 facilities that completely ran out of water, meaning the reservoir had no water at all.** Within the province, is our area considered more serious than average? If it's hot, then here and in Cư Jú, it's a lot. So, we see water running out around February-March" (the rainy season starts in April or May) ("Hạn hán thì cái cái tình trạng nó có phổ biến xảy ra nhiều và trên diện rộng không ạ ? có tức là bên em bên huyện này thì năm vừa rồi như năm 2024 là nhiều nhất năm 2024 là khoảng độ 26 27 công trình hết nước, năm vừa rồi thì tầm độ 20 19 20 gì đó công trình là hết nước hết nước luôn hết nước là hồ không có nước giọt nào hết. trong tỉnh thì khu vực của mình nó gọi là nghiêm trọng hơn tương trung bình? là nếu mà nắng nóng thì thì ở đây với cư jút là nhiều. nên thấy cái cái việc mà tầm tháng hai tháng ba hết nước."). – operator*

Reservoirs often dry up before the rainy season begins, with some becoming depleted as early as after the Lunar New Year (end of January to mid-February), a critical period when coffee plants require substantial water. This is exacerbated by the collective irrigation practices:

*"When coffee enters its season, **almost everyone competes for water and irrigates.** It means everyone thinks, I just go to the reservoir and I see hundreds of water pumps. Everyone has to irrigate at the right season, everyone irrigates. Such a huge force means that within a week, the reservoir water is gone. Hundreds of pumps are placed in the reservoir. For the reservoir, in just three days, I see the water level drop tremendously. It's mass irrigation. When almost every household and every person irrigates, it cannot be sustained" ("cà phê là khi vào vụ á. là đường như ai cũng tranh giành cái nước và tưới nước. có nghĩa là ai cũng nghĩ là em cứ ra hồ là em thấy là cả Hàng trăm cái vò nước hàng trăm cái máy bơm. là ai cũng phải tưới đúng vụ ai cũng tưới. một lực mà khủng khiếp lên là chỉ cần trong vòng một tuần là nước hồ không còn. hàng trăm cái máy bơm đặt xuống hồ. hồ là em chỉ cần trong ba ngày là em thấy hồ là nó xuống nước khủng khiếp. là tưới hàng loạt. đường như nhà nhà tưới người người tưới thì không có thể nào chịu nổi."). – manager*

The shortage of water also leads to **unregulated water discharge from reservoirs.** Interviewee mentioned that, particularly during the **dry season, some farmers open irrigation gates without official authorization.** This unregulated access disrupts scheduled distribution, reduces fairness among water users, and can put pressure on system managers who lack the capacity to enforce gate control.

Farmers open gates without authorization - in dry seasons ("Thứ nhất người dân hay tự ý lấy nước, vận hành cổng luôn của công ty mình quản lý mà không phải ngày nào cũng thường xuyên đến kiểm tra đặc biệt là khi mà hạn hán xảy ra người dân sẽ tự lấy nước") – Operator interviewee

Despite these challenges, **the direct impact of water scarcity on local residents is not always severe.** This is largely attributed to farmers' proactive measures, such as the increased prices of agricultural products, and their adoption of water conservation methods like building elevated tanks, utilizing water-saving irrigation techniques, or digging wells.

*"Overall, the area is not severely dry because **people have proactively used groundwater** (2025 is a bit dry due to groundwater shortage)" ("Nhìn chung trên địa bàn khu vực không bị khô hạn quá nhiều do người dân đã chủ động sử dụng nguồn nước ngầm (năm 2025 hơi khô hạn do nước ngầm thiếu)."). – manager*

However, the recent risk of groundwater depletion poses a growing threat, potentially increasing pressure on surface water demand in the near to medium term.

On the other hand, **several communes are highly resilient with abundant water resources, both quantity and quality supplied from large irrigation works**, . This highlights a varied landscape of water availability across the region. For example,

*"overall, **the surface water source ... from the Krong Buk Ha project are very large**, and this Krong Buk Ha reservoir is a large reservoir of the whole country. It only has abnormal indicators like this, including supplying 7 communes in the district. As for the systems across the entire district, there are also many, yes, there are many systems that have not been evaluated yet, currently they are very good" ("đánh giá chung thì cái nguồn Nước mặt và nước nguồn nước mặt thì có công trình krong buk hạ là rất lớn rồi cái hồ cũng hạ này là hồ lớn của của cả nước đấy hồ hồ lớn đấy nó chỉ số bất thường như này thôi gồm đó là nó cấp cho 7 xã trong trong trong huyện rồi đấy còn các cái hệ thống mà mà mà trên toàn huyện thì nó cũng nhiều dạ có nhiều hệ thống thì cũng chưa có đánh giá gì cả hiện tại đang rất."). – manager*

3.2.3.2 GROUNDWATER PRESSURE

The issues were raised mostly by managers at the provincial level and commune level due to **potential groundwater depletion and unregulated groundwater use**.

One of the most consistent patterns reported was the drilling of wells by farmers as a proactive way to mitigate the impact of droughts. In many cases, **farmers take initiative—without coordination—to drill private wells to ensure water availability for their crops**. In some instances, wells are drilled directly into reservoir beds as a desperate measure during dry periods. However, this practice raises **concerns about sustainability and the physical safety of reservoir infrastructure**.

"Households in areas without clean water rely on wells for daily use, as well as for agriculture and irrigation." ("Các hộ gia đình ở những khu vực không có nước sạch phải dựa vào giếng để sử dụng hàng ngày cũng như cho nông nghiệp và tưới tiêu.")– Manager interviewee

"Almost all farmers have drilled wells to proactively secure a reliable water supply. Some drill wells in the inside a reservoir (where there is possibly more groundwater" ("Cơ bản là xung quanh là họ đào giếng hết. và có cái giải pháp nữa là họ đào giếng trong hồ nữa kia.") – Manager interviewee.

It is harder to drill a new well (higher cost, complex technology and drill deeper to get water), potentially due to groundwater depletion and due to local geological conditions. Groundwater scarcity was commonly cited, and in some cases, the underlying geology was said to be unsuitable for extraction. In areas with severe depletion or fragile terrain, interviewees also raised the risk of land subsidence and landslides linked to excessive groundwater withdrawal.

"20 years ago, using groundwater wasn't a problem; however, in recent years, people have had to drill deeper to access water." ("20 năm trước việc sử dụng nước ngầm không có vấn đề gì, tuy nhiên, trong những năm gần đây người dân phải khoan sâu hơn để lấy nước.") – Operator manager

Monitoring groundwater extraction presents significant difficulties due to both objective and subjective factors. Objectively, accurate measurement is challenging. For instance,

"1 hectare of coffee, irrigated for just one year, requires continuous irrigation for about a day and a night. Who says [one day and one night of irrigation is] 10 cubic meters? It's hundreds of times more. But in reality, when people register, they just say it's for personal use and don't have to sign or pay the fees" ("1 ha cà phê một một năm xào thôi người ta tưới thì phải mất khoảng cỡ một ngày một đêm tưới liên tục ai nói 10 m khối gấp bao nhiêu trăm lần nữa chứ dạ nhưng mà thực chất mà người ta đăng ký người ta chỉ là người ta chỉ nói là ở góc độ là dân cá nhân sử dụng không phải ký không phải đóng các cấp."). - manager

Furthermore, **existing irrigation works cannot fully meet the demand for domestic and agricultural water, compelling residents to rely on groundwater.** As one respondent explained,

"it's simple, because from the perspective of wanting good management, the state agency must arrange sufficient minimum conditions for people to live. If we haven't arranged it yet, and now we force them not to do this, yes, it leads to conflict, right? If I complete the tap water supply system, if I complete the canal system, and you continue to drill and use groundwater, I will deal with you immediately, yes, demand punishment" ("đơn giản không vì ở góc độ mà muốn quản lý tốt thì cơ quan nhà nước mình phải có bố trí bố trí cho người ta đủ các cái điều kiện tối thiểu để mà sinh hoạt mình chưa bố trí được mà bây giờ mình ép buộc người ta không được làm việc này vâng dẫn đến là mâu thuẫn đúng chưa nếu như mà tôi hoàn thiện hệ thống cấp nước máy tôi hoàn thiện hệ thống kênh mương mà các anh tiếp tục mò mà mà mà mà mở khoan nước và sử dụng này tôi xử lý anh ngay vâng yêu cầu xử"). - Manager

Subjectively, there are **limitations in human and material resources.**

"There is no one, no means to evaluate that [groundwater use], and no funding to implement this content [monitoring/evaluation of GW]" ("không ai không có một cái phương tiện nào có thể đánh giá được cái đó và không có kinh phí để mà thực hiện nội dung này"). – Operator

3.2.3.3 CHALLENGES FROM CLIMATE CHANGE AND INCREASING OF WEATHER EXTREMES

Local officials described a clear sense that water management is being increasingly complicated by the impacts of climate change. They reported that irregular and shifting rainfall patterns, especially during both drought and rainy periods, are straining the predictability and reliability of water supplies. Some staff described the situation as a general worsening of drought conditions over time, although in some locations, these droughts were not considered severe.

"The weather, or more accurately, climate change, is when the weather doesn't follow the old rules. There are changes in rainfall, the amount of rain, and the timing of rain and droughts. But it's more accurate to call this as a whole 'climate change.'" ("Thời tiết, à gọi là biến đổi khí hậu thì đúng hơn, biến đổi khí hậu tức là thời tiết không theo không tuân theo những cái quy luật à từ xưa đến giờ á nó có thay đổi á về nước mưa lượng mưa và về thời gian mưa hạn hán thì cũng có nhưng gọi chung cái này là biến đổi khí hậu thì đúng hơn.") – Operator interviewee

Moreover, there was agreement that local systems face considerable constraints in forecasting inflow to reservoirs - particularly due to the absence of necessary monitoring tools and technologies. Without reliable equipment and data, operators are unable to make timely and informed decisions regarding reservoir levels, irrigation scheduling, or early drought warnings.

"Right now, the difficulty is that visual observations lack specialized equipment that I could use for measurements." ("Khó khăn là hiện tại là những quan trắc bằng mắt thường nó chưa có các cái cái chuyên dụng như là em có các cái thiết bị chuyên dùng để em đo") – Operator interviewee

Forecasting rainfall inflow to the reservoirs is challenging due to a lack of monitoring devices. ("Việc cảnh báo lưu lượng mưa đến hồ gặp khó khăn do ít cái thiết bị quan trắc dự báo cảnh báo lưu lượng dưới hồ") – Operator interviewee

3.2.3.4 WATER USE CONFLICTS

Although **major conflicts between water users (e.g., between farmers) were not widely reported**, many **local managers observed rising tensions**. Farmers commonly report or **complain about water shortages during peak periods**, and they frequently call on local authorities to improve infrastructure, particularly **requesting upgrades to existing dams or reservoirs**. This places additional administrative and technical burden on local water management agencies, many of which have limited resources to respond.

"Cà phê là khi vào vụ á, là đường như ai cũng tranh giành cái nước và tưới nước. Có nghĩa là em cứ ra hồ là em thấy cả hàng trăm cái vò nước hàng trăm cái máy bơm. Ai cũng phải tưới đúng vụ, chỉ cần trong vòng một tuần là nước hồ không còn" (A lot of coffee planters discharge water at the same time leading to peak demand and quick water depletion) – Manager interviewee

3.2.3.5 LAND USE CHANGES

Land use change was also a recurring concern. **Commune-level officials observed that agricultural land is being converted from rice to industrial crops or perennial trees such as durians**. In some cases, these transitions were not aligned with official land use plans and thus are **not reflected in existing maps or water allocation models**.

However, a few respondents noted that intercropping or switching to crops with lower water demand can have positive effects on reducing pressure on water systems.

"The main crop being grown is durian. Durian is a crop that has been transitioned to, or as we call it, a structural change. Durian doesn't need a large amount of water [at the same time or in short period of time], but it needs a consistent supply." ("Trồng là cây sầu riêng là chủ yếu. Cây sầu riêng là chuyển đổi, chuyển thành gọi là chuyển đổi cơ cấu đó, sầu riêng thì cái lượng nước tưới nó không nó cần đều chứ không nhiều. (Durians - less water demand in dry season) – Manager interviewee

A higher density of intercropping than legally permitted also poses a risk of not having an adequate water supply.

"There are government regulations on intercropping density. However, in reality, farmers often plant more densely than what is specified." ("quy định về mật độ trồng xen á là đã có nhà nước quy định. Nhưng thực ra thực tế người dân họ trồng dày hơn.") - Operator

For short-term crops, especially rice, when farmers change their production activities from the initial plan (by not producing or arbitrarily changing the time they take water), it also affects the operational efficiency of irrigation systems.

3.2.3.6 SEDIMENTATION AND DECLINING RESERVOIR CAPACITY

Sedimentation in reservoirs is a long-standing and growing problem. Interviewees stated that their **reservoirs have not been dredged for many years—sometimes since 2016—**primarily due to the lack of

local budget or concerns about environmental impacts of dredging activities. This lack of action has contributed to significantly reduced storage capacity and lower water levels in the dry season. Additionally, sedimentation was said to reduce the ability of reservoirs to recharge groundwater, further exacerbating local.

The lake experiences heavy silting due to steep terrain and basalt soil. In the dry season, people cultivate the land, but the rainy season quickly washes everything away (“Đặc trưng hồ ở đây thì nó bồi lấp dữ lắm vì độ dốc của địa hình khá cao mà đất thì coi là đất ba zan, mùa nắng người ta canh tác á là bắt đầu là mùa mưa là trôi hết, bồi lấp rất nhanh.”) - Manager interviewee

Support for dredging relied on provincial and central budgets before 2015, but there has been no funding since then. (“Hỗ trợ thì cứ hồi xưa á thì nó có cái trường hợp là có cái nguồn kinh phí. Cách đây năm 2015 2016 về trước thì ngân sách tỉnh cũng như trung ương họ sẽ hỗ trợ cho có vấn đề nạo vét nhưng từ đó giờ đây là không có hỗ trợ.”) - Manager interviewee

3.2.3.7 LAND ENCROACHMENT

Encroachment into lakes and reservoir beds was mentioned in several communes. While in **some cases the encroachment was considered minor**, in others it was described as one of the most serious management issues affecting reservoir function and water storage capacity.

"Encroachment, specifically of the lake's corridor and within the scope of the irrigation systems, is the most painful issue. For example, people dumping soil and taking water to encroach on the land of those irrigation facilities is the most pressing problem." ("Lấn chiếm này đặc biệt là hành lang lấn chiếm lòng hồ, lấn chiếm phạm vi công trình thủy lợi ví dụ như người ta đổ đất xuống, người ta lấy nước lấn đất của cái phần công trình thủy lợi đó là nhức nhối nhất.") – Operator interviewee

"It seems like you see encroachment everywhere. It's a normal occurrence for them to put something down, then remove it and move on. Generally, it's hard to manage this, and the encroachment is not significant." ("Đường như ở đâu cũng thấy chiếm. Cắm xong cái họ tháo đi và họ dời đi là chuyện bình thường. Nói chung quản lý cái này khó mà họ có lấn chiếm cũng không đáng kể".) – Manager interviewee

3.2.4 DATA NEEDS FOR WATER RESOURCE MANAGEMENT AND IRRIGATION OPERATIONS

An assessment of data needs for water resource management and irrigation operations has identified several key requirements based on stakeholder feedback. The most frequently cited need was for **met-hydrology data**, identified by 13 out of 22 respondents. Following this were **water resources data** (8/22) and **data related to the technical designs of irrigation works** (7/22). Less frequently, but still considered significant, were **land use data** (4/22) and **water quality data** (3/22).

While most water resource managers and operators consider more data on water resources important, a few (02) operators of small irrigation works held a different view. Due to the limited impact and lack of flood or water-regulating functions of their facilities, they found additional data to be unnecessary.

3.2.4.1 MET-HYDROLOGY DATA

Met-hydrology data emerged as very essential, with its necessity described by some as "very essential" ("chắc chắn là phải cần").

The primary rationale for this strong emphasis stems from the direct impact of accurate met-hydrological information on water regulation activities. Without precise data, the task of water regulation becomes inherently difficult, leading to potential misjudgements where water sources might be perceived as insufficient, or conversely, excessive conservation efforts could result in surplus water at the end of a season.

"[if there is no accurate information] then our regulation work will face difficulties because we will determine that the water source is lacking, or there may be times when we save too much, leading to a surplus at the end of the year or season" ("[nếu không có thông tin chính xác] thì cái công tác điều tiết của mình sẽ gặp khó khăn bởi vì mình sẽ nhận định nó nguồn nước nó bị thiếu vắng hoặc là có thể là có những thời điểm thì mình tiết kiệm quá thì thì mình cuối năm cuối vụ mình thành ra thừa"). - Operator

Another emphasized its role in monitoring and daily operational awareness, stating, *"firstly, it helps us monitor the amount of water flowing into the reservoir, and we grasp the daily water volume at the facility" ("thứ nhất là nó nó nó giúp mình được mình quan trắc được cái cái cái lượng nước về hồ này rồi cái mình nắm được cái hàng ngày cái lượng nước nó là ở công trình nó là bao nhiêu"). - Operator*

This data serves as a crucial reference for effective operation and provides evidence of operational efficiency, particularly when direct measurements of water levels and flow rates are incomplete.

Within the group of data on met-hydrology, **water level data** was the most frequently mentioned specific need. Several individuals explicitly stated, *"mainly water level monitoring" ("chủ yếu là quan trắc mặt nước")* and *"first, we need water levels" ("Đầu tiên là mình cần có mực nước")*. This particular need was predominantly proposed by operators of irrigation works, highlighting its immediate relevance to their daily tasks. The current challenges associated with obtaining accurate water level data were also brought to the discussion, with one operator noting,

"Regarding current water levels, are there any difficulties in measuring current water levels? Currently, it's mainly done manually, so the deviation is large" ("Tại mực nước hiện tại thì cái việc đo mực nước hiện tại thì nó có gặp khó khăn gì ạ? Thì hiện tại bây giờ là chủ yếu bằng thủ công thì nó cái mà sai lệch nó lớn"). - Operator

There is a strong desire for water measurements to be *"more accurate" ("more accurate")* and *"automatic" ("tự động")*, indicating a clear demand for technological advancements in data collection.

Water inflow data was also recognized as highly important, largely due to the current lack of any or accurate measurements for this information. Existing software developed for this purpose has either *"broken down completely" ("hỏng hết rồi")* or is *"no longer accurate" ("không chính xác nữa")*, underscoring a significant technical deficit.

Beyond water levels and inflow, other meteorological data, such as **rainfall amounts and forecasts**, are crucial. Currently, only a limited number of large reservoirs possess automatic rain gauges. While this data is available through specialized channels like Vrain, regional hydro-meteorological forecasts, directives from superiors (during extreme weather), or local media, there is a demand for more stringent requirements. Specifically, **stakeholders desire rainfall information for smaller, more localized areas**. In terms of timing, **the ability to make accurate forecasts further into the future, ideally "one year prior is good" ("một năm trước là tốt")**, is needed to facilitate local water distribution planning. Regarding data dissemination, there is a strong preference for integration into a unified system that allows for easy extraction, although not explicitly mentioned.

3.2.4.2 WATER RESOURCES DATA

Data on **water resources** was the second most commonly mentioned general category. The overarching reason for this demand is the desire for greater autonomy and precision in planning.

"if we have it, we are more proactive with specific, accurate data to place orders [for water]" ("có thì mình chủ động hơn các số liệu cụ thể chính xác để mà đặt hàng"). - Operator

This highlights the importance of having a clear inventory and understanding of water assets to enable more effective resource allocation and management.

A specific and critical need within this category is for **aquifer maps**. This information is considered **highly necessary by state management agencies at central, provincial, and local levels**. The consensus is that there **"must be tools to quantitatively measure"** ("phải có công cụ đo đếm được định lượng được") water resources to provide a basis for licensing in accordance with the water resources law, a capability that is currently lacking.

For **operators of irrigation works**, particularly those utilizing groundwater for rural domestic water supply, aquifer maps are equally vital. This underscores the current **reactive approach to groundwater management and the urgent need for predictive tools**. One operator expressed,

"we need this information, if the project is well-forecasted, that would be great, of course it's needed. Currently, it's not available. The company doesn't know [how much groundwater there is] because when the pump reaches a point where it's submerged and weak, then we pull it up to check. That means we are being reactive" ("mình có cần cái thông tin nếu mà dự án được báo được tốt quá cái đấy thì tất nhiên là cần chứ. hiện tại chưa có. công ty chưa biết là [lượng nước ngầm bao nhiêu] tại vì cái bơm đến thời điểm mà thấy nó ngụt thấy nó yếu thì khi đó kéo lên để kiểm tra thôi. Tức là mình đang bị động."). - Operator

Additionally, **water accounting** was emphasized as being *"very important in water resource planning"* ("kiểm đến nguồn nước trong quy hoạch thủy lợi rất quan trọng này.", Operator), highlighting the need for systematic tracking and balancing of water inputs and outputs.

3.2.4.3 DATA ON UPDATED CONDITIONS OF IRRIGATION WORKS

The need for data on the **updated conditions of irrigation works** is significant, primarily driven by the aging infrastructure and a lack of consistent maintenance records. Many reservoirs have not had their technical designs updated for decades since their initial construction, with some having

"not had a technical design for decades since acceptance" ("Nhiều hồ từ khi tiếp nhận mấy chục năm không có thiết kế kỹ thuật"). - Operator

This long-standing issue means that the current status of many reservoirs is not reflected in their operational procedures or technical designs. A critical problem arising from this is **sedimentation**, which alters the original design of the reservoir bed and leads to inaccuracies when using outdated ZFW relationship curves for operational calculations.

The essential information required includes **sedimentation data**, the **re-drawing of reservoir beds**, the **recalculation of reservoir storage capacity**, and the **establishment of new ZFW rating curves**. Some irrigation works operators **only recognized the value of information regarding reservoir beds and capacity** after being introduced to remote sensing applications for reconstructing the current status of facilities, especially reservoirs.

"Remote sensing technology can build a 3D image of the reservoir bed cross-section, for example, to let us know the current status or how it has changed over the years. So, it's needed, if it can be done, that would be great" ("Công nghệ viễn thám có thể xây dựng hình ảnh 3D cái mặt cắt lòng hồ chẳng hạn để cho mình biết được là hiện trạng hiện tại hoặc là đã thay đổi như thế nào trong các năm. Thế thì cần chứ nếu làm được thì tốt quá", Operator).

"Yes, it should be necessary, currently we are only estimating, and if there is accurate data like that, it would be great" ("có nên có cần thiết chứ bên mình hiện tại bây giờ nó chỉ đang là ước lượng thôi, vâng và nếu mà có số liệu chính xác khác như thế thì tốt quá", Operator).

However, a small minority believed that for "small reservoirs, the bed can be observed from above" ("những hồ nhỏ, đứng ở trên có thể quan sát được lòng hồ" - Operator), making this review less necessary for them.

Interestingly, information concerning the **land encroachment**, despite product introductions, did not garner significant interest. This is because local branches have personnel who conduct almost weekly reviews, and they can detect issues simply by observing the accumulation of materials.

"We detect it as soon as materials are gathered" ("chỉ cần tập kết vật liệu là chúng tôi phát hiện ra") - Operator.

Therefore, while information about violations of the protective corridor of irrigation works is necessary, it holds less significance as a warning tool and primarily serves for historical record-keeping.

3.2.4.4 THE ROLE OF LAND USE DATA

Land use data was identified by four out of twenty-two respondents as important for operational units. The rationale behind this need is its utility in understanding the characteristics and production demands of agricultural users.

This data can be "used to see the characteristics and production needs of farmers" ("dùng dữ liệu này để thấy đặc tính và nhu cầu sản xuất của người nông nghiệp") and provides "image data on actual cultivated crops to serve water regulation" ("dữ liệu hình ảnh về cây trồng đang sản xuất thực tế phục vụ điều tiết nguồn nước"). - Operator

Furthermore, this information needs to be updated seasonally, as indicated by the statement, *"Yes, this information must be updated seasonally, at the beginning of the year, we will sign [irrigation water supply] contracts at the beginning of the season" ("Có chứ, thông tin này phải được cập nhật theo theo mùa là đầu năm thì bên mình sẽ đi ký hợp đồng đầu vụ" - Operator).*

The specific types of data required include *"cultivated area, household names, plot numbers, sheet and plot numbers, area, and crop type" ("diện tích trồng, tên hộ dân này, lô số thửa này, số tờ và lô này rồi diện tích này rồi loại cây trồng"- Operator).*

More accurate land use information is **particularly crucial for large reservoirs**, as differences in land use can significantly impact operational decisions.

Despite its mention, the perceived necessity of this type of information was moderate. Some users expressed **skepticism about the feasibility of accurately calculating land use using remote sensing** or other tools, primarily because farmers engage in extensive intercropping, making precise measurement challenging. Additionally, they noted that local operators already update plots that have changed their land use purpose, which serves as a basis for calculating irrigation fees. Thirdly, they believed that a moderate

margin of error (within a few hundred square meters) would not significantly affect management, and the conversion of some long-term crops from coffee to durian would not substantially alter water demand.

3.2.4.5 WATER QUALITY DATA

Water quality data (with no specific indicators) was mentioned by three water resource managers as a necessary component for effective management. The key need highlighted was **the ability to access water quality information at the local level**, rather than having to wait for specialized agencies to conduct measurements and processing. This suggests a desire for more immediate and decentralized access to water quality parameters, enabling quicker responses to potential issues and more integrated local water management practices.

3.2.4.6 REQUIREMENTS ON THE DATA

Digitalized data is a key requirement, with stakeholders emphasizing the need for synchronized information from central to local levels. One respondent stated that *"digitalized data, if provided to the locality, would be great for management and operation"* ("là số hóa đấy thì cung cấp lại cho địa phương quá tốt để quản lý và để vận hành") – Manager.

Software is seen as a crucial tool for processing this data ("Software is a tool that processes all that data").

For managers of water resources, while a larger quantity of data is generally preferred, it is primarily used for reference. The data to be officially used for management and operations must comply with existing regulations.

3.2.5 INITIAL PERSPECTIVES ON CAPACITY FOR DATA-INFORMED WRM

Assessment on the current capacity of personnel involved in water resource management and irrigation operations reveals **varying levels of expertise and technological adoption** across different administrative and operational tiers, highlighting areas where targeted interventions could significantly enhance overall efficiency and responsiveness.

3.2.5.1 UNDERSTANDING OF WATER RESOURCES

Understanding of water resources varies by administrative level. At central and provincial state management levels, **all water resource managers hold relevant qualifications in WR or Irrigation management**. However, at the local level, 2/4 districts have officials from other backgrounds; long-serving staff understand laws and operations very well, but newer personnel often lack this knowledge.

For irrigation works operating units, company-level managers and engineers possess strong water resource and irrigation knowledge. Operational workers typically have an intermediate diploma in irrigation. Commune-level operational staff are usually cum-position (they have multiple responsibilities, operating the irrigation systems is only one of these), but some developed a good understanding through experience.

3.2.5.2 UNDERSTANDING OF REMOTE SENSING

The understanding of remote sensing technology presents a notable disparity across the different levels. Only management officials at the central level demonstrate **extensive knowledge of remote sensing**. At the provincial level, **officials have been introduced** to the technology, but they have not yet mastered or even consistently utilized it in their work. This finding indicates a gap between awareness and practical application at this crucial intermediate level. More significantly, officials at the local level and below have **received almost no training or workshops on remote sensing technology**.

This limited understanding often restricts their perception of the importance or applicability of remote sensing products in water resource management. Relying solely on brief introductions or discussions about remote sensing during interviews, they have not fully processed the information to provide answers regarding what data they consider important or feasible.

3.2.5.3 ABILITY TO RECEIVE REMOTE SENSING PRODUCTS

Despite the varying levels of understanding of remote sensing, the overall capacity to receive and utilize digital products, including those derived from remote sensing, is **relatively high**.

In terms of human resources, all units possess hydrology engineers, although the situation regarding personnel at the commune level, particularly after recent mergers, remains uncertain. This suggests that while specialized expertise exists, its distribution and availability at the very local level might be inconsistent.

In terms of software and tools, most units are already using various software, albeit with differing levels of sophistication. Central and provincial management units employ more specialized software, such as **MIKE for hydrology and hydraulics**, and **ARCGIS** for geographic information systems. This finding indicates their engagement with advanced analytical and modeling tools. For the majority of operating units, 7/8 branches surveyed, there is widespread use of digital mapping tools like **Google Maps** and **Google Earth** for information retrieval. As one respondent noted, *"for managing facilities, currently we use Google Map" ("dùng quản lý công trình thì hiện nay có Google Map")*. Furthermore, common calculation tools such as **Excel** and **Google Spreadsheets** are also widely utilized across operating branches. Notably, in 5/8 branches, even operational workers are proficient in using these tools, indicating a pervasive basic digital literacy that can serve as a foundation for further technological integration.

A number of other projects have been developed locally to support water level measurement and water source forecasting. Regarding the hardware, most of it is currently broken, and the local authorities do not have the funds to pay for repairs. As for the software, local staff are mostly able to read and understand the data or input figures to get results, but they have not mastered the technology.

3.2.5.4 TRAINING OPPORTUNITIES

Most local officials currently resort to **self-learning**, acquiring skills in software like AUTOCAD and Google Earth from provincial engineers, rather than participating in structured, formal training programs. This demonstrates a commendable capacity for self-learning and proactive engagement with technology among local staff.

However, they express a strong desire for more systematic and formal training. One participant stated

"if we want to do it properly, we need [training] and people; currently, we have to find it ourselves, do it ourselves" ("nếu mà để mà làm bài bản thì phải cần phải có [đào tạo] có người hiện tại là ta là phải tự tìm hiện tại tự tìm tự làm"). – Operator and manager

This statement powerfully conveys the current reliance on informal, self-directed learning and the urgent need for structured training programs and dedicated personnel to truly professionalize and enhance the capacity for water resource management and irrigation operations across all levels.

Their primary need is to be able to read and effectively use information derived from these technologies, rather than fully mastering the underlying technology itself, which they perceive as challenging. An exception to this general trend is one district-level operating unit, which explicitly desires to fully adopt the technology to ensure self-reliance and proactive problem-solving in case of breakdowns.

MATURITY OF DATA-INFORMED WATER GOVERNANCE & OPPORTUNITIES TO STRENGTHEN

4.1 OVERVIEW

Water resources management (WRM) requires frequent and regular decision-making, at scales from daily through to decadal, and irrigation schemes to basins. Many factors need to be considered, spanning economic, social and environmental considerations. Understanding the status of water resources is critical to support these decisions. The current status helps to guide decisions about how, how much, and where to use and protect water resources now and in the future.

The effective application of water-related data to support evidence-based WRM requires water-related data products to be tailored to suit their intended application. To assist in assessing and identifying opportunities to strengthen the use of water-data, and to guide the development of water-related data products, an understanding of the current status of WRM and use of data can be helpful.

This component tests the usefulness of a WRM framework (refer Project Report 1: *Review of Remote Sensing and Water Accounting Supporting Agricultural Water Management In Subbasins*) for assessing the maturity of water resources management in terms of the use of water-related data, and specific opportunities to enhance data-informed water management.

4.2 PURPOSE & SCOPE OF THE FRAMEWORK FOR MATURITY OF WATER RESOURCES MANAGEMENT AND THE USE OF WATER-RELATED DATA

The purpose of this framework is to support the strengthening of evidence-based, subbasin water management by *identifying opportunities to strengthen the use of water-related data in water management decisions*. Identifying the management functions that already use water-related data indicates the existing ‘maturity’ of the water management regime operating at subbasin levels. It also enables identification of management functions not currently informed, or incompletely informed, by water-related data – these represent opportunities to strengthen the water management regime.

The specific objectives of the framework are to:

- identify the many ways that water-related data can usefully inform subbasin level water management
- be used as a basis for a conceptual framework against which the maturity of water management of any subbasin, basin, province or country can be determined.
- enable stakeholders working in or supporting subbasin water management to understand the extent to which this is already underpinned by water-related data, and the scope for and opportunities to further strengthen evidence-based subbasin water management.

The focus of the framework is on water management and operations that are best made with hydrological data – that is, decisions about what actions to take to ensure sustainable and resilient water supplies to meet all agreed needs, including the environment. It does not include assessing institutional arrangements or governance processes (how and who to be involved in making decisions).

As outlined above, the focus is also on management decisions best made using hydrological or related data. Using relevant environmental data to inform decisions is good water management practice. Understanding the water and environmental situation is an essential step in developing basin plans and guiding subbasin operations and determining and monitoring ongoing management decisions. However, water management decisions should not be made solely based on water-related data; data forms an important evidence-base to be considered during decision-making, alongside other factors such as social and environmental values and data, which should be considered through a participatory governance process.

This research project is interested in subbasin water management. As such, this framework incorporates subbasin level management tasks and decisions, though does not exclude basin or other levels, as they will influence subbasin management.

The Framework does not attempt to diagnose the reasons for the results, for example, resource limitations, capacity gaps, accessibility of data.

Additionally, having access to and the capability to use water-related data on its own, cannot achieve the full range of water management functions / tasks possible; other management instruments are required, such as policies, plans, regulations, stakeholder communications, and participatory decision-making.

4.3 ASSESSMENT APPROACH AND OUTCOMES

4.3.1 FRAMEWORK DEVELOPMENT

Through a review of literature ¹ relating to agricultural water management and water resources management more broadly, a list of typical water resources management (WRM) tasks was identified (refer to Box 4.1. This was reviewed and updated by our expert team and further refined following a review of water management policy in Viet Nam, in an effort to ensure key water resources management tasks relevant to Viet Nam were identified. The workshop activities described below further refined the framework.

¹ Key sources included:

Sheffield et al., 2018. Satellite Remote Sensing for Water Resources Management: Potential for Supporting Sustainable Development in Data-Poor Regions. *Water Resources Research*, 54, 9724–9758. <https://doi.org/10.1029/2017WR022437>

CapNet, 2008. Integrated Water Resources Management for River Basins organisations

(<https://www.gwp.org/globalassets/global/toolbox/references/iwrm-for-river-basin-organisations-capnet-2008.pdf>).

AWP, 2020. A Guide to River Basin Planning (<https://waterpartnership.org.au/wp-content/uploads/2024/03/BasinGuide-full-web.pdf>)

BoM, 2013. Australian Water Resources Assessment (http://www.bom.gov.au/water/about/publications/document/InfoSheet_10.pdf)

Box 4.1: WATER RESOURCES MANAGEMENT TASKS, ORGANISED BY HIGH-LEVEL FUNCTIONAL CATEGORIES

PLANNING

- Water resources assessments to inform capacity for future / additional economic development / productivity in specific subbasins
- Water resources capacity assessments to guide investment and design of water infrastructure
- Designing irrigation systems
- Designing water supply systems (community, towns, cities)
- Input to (environmental, drinking) water quality guidelines (alongside other ecosystem health, human health & values-based inputs)
- Determining water discharge license conditions and fees
- Designing flood control works
- Basin / Subbasin level allocations for major water use groups (subbasin level totals for each water user type e.g. agriculture, hydroelectricity, forestry, mining, industry, urban/domestic, environment, etc)
- Annual license allocations for major individual water users (agriculture, industry, hydroelectricity), including extraction locations
- Informing/forecasting Urban / domestic water supply service levels; Guiding (urban) demand management need & actions
- Measuring and predicting impacts of externalities such as climate change, population growth, industrial changes (à forecasting future water resource regimes)
- Determine groundwater/SW extraction licensing fees

MANAGEMENT & OPERATIONS

- Enforcing extraction allocations / compliance monitoring
- Guiding water infrastructure operations decisions e.g. opening or closing storage regulators, timing of pumping or irrigation or irrigation headworks operations, or access restrictions
- Identifying pollution problems for attention (evidence base for managers and polluters; spatial and temporal scale important)
- Compliance monitoring enforcing pollution requirements
- Monitoring sustainability/appropriateness of water allocations (comparing actual to projected balances to identify adjustments)
- Inform water markets / trading
- Determine location and number of groundwater extraction points

RISK & DISASTER MANAGEMENT

- Monitoring crop productivity (early warning food insecurity)
- Drought early warning and management
- Flood early warning and management

It is anticipated that not all tasks are undertaken in every place, depending on the complexity of the system (e.g. simple systems not requiring all of these), capacity and resourcing, catchment/land use activities and scale. The framework thus includes some tasks that are more sophisticated/mature versions of others in the same list.

WRM tasks were categorised into 3 high-level functional categories, for easier interpretation by stakeholders. These groupings followed the lead of Sheffield et al (2018) but were modified to the specific list of WRM tasks in this framework. The 3 functional categories of WRM tasks are:

- Management and operations
- Planning
- Risk and disaster management

These three are not mutually exclusive, and some WRM tasks will contribute to all of these functional needs; the categorisation was only a guide to assist in interpreting the nature of the WRM task by stakeholders.

The list of WRM tasks above, are used as the basis of the framework, which is structured to encourage stakeholders to self-assess, for each WRM task:

- The current status of implementation / actioning of each task in the country (using a rating of green, yellow and red)
- The spatial and temporal scales at which each task is conducted

- The agencies involved
- How well water data is used to support this task (using a scoring of 1-5)
- The types of water data that is used

4.3.2 WORKSHOP TO REFINE THE FRAMEWORK LIST AND STATUS OF WRM TASKS IN VIET NAM

To test the usefulness of the framework and identify improvements, it was applied to a case study of Viet Nam, as part of the larger research project case study.

The draft framework was shared with stakeholders in workshop format to encourage interrogation and improvement of the framework, and a deliberative process of self-assessment. The participants intentionally included water managers expected to be involved in the range of water management tasks, from high-level, longer-term planning through to day-to-day operations of irrigation works. The 20 participants included:

- Irrigation Management Company in Dak Lak (4)
- Irrigation Management Company in Dak Nong (4)
- Dak Lak Provincial Sub-Department of Irrigation works and Disaster Risk Prevention and Response (3)
- Lam Dong Provincial Sub-Department of Irrigation works (2)
- University of Da Lat (1)
- Western Highlands Agriculture and Forestry Science Institute (1)
- Institute of Water Resources Planning, Ministry of Agriculture and Environment (5).

In three self-formed small groups, participants were asked to review the list of WRM tasks and to identify

- Whether any tasks were not relevant to the Vietnamese context (this did not mean WRM tasks that are not conducted but could/should be, but rather, tasks that have no relevance to the Vietnamese context and therefore would not add any useful information to water resources management).
- Whether additional WRM tasks should be added
- For each listed WRM task each group made a 3-tiered rating (green, yellow, red) assessment of whether the WRM task is conducted anywhere in Viet Nam.

Table 4.1 is a summary of the group work for this first part of the workshop.

Conducting the above activity in smaller groups was essential to allowing different stakeholders a greater



opportunity to share their perspective – whether positive or negative - compared with a large group discussion and assessment, particularly with various levels of governments and status of individuals and organisations.

TABLE 4.1: REVIEW OF LIST OF WRM TASKS, WITH ADDITIONS / MODIFICATIONS TO SUIT VIETNAMESE CONTEXT (*MARKED), AND SELF-ASSESSMENT OF STATUS OF WRM TASKS CURRENTLY IN VIET NAM, FROM STAKEHOLDERS' PERSPECTIVE

Functional Group	WRM task	WRM task status (we do this WRM task in <u>anywhere</u> Viet Nam? green = yes; yellow = maybe / not sure / sort of; orange = no)		
PLANNING	Designing irrigation systems	●	●	●
	Designing water supply systems (community, towns, cities)	●	●	●
	Input to (environmental, drinking) water quality guidelines (alongside other ecosystem health, human health & values-based inputs)	●	●	●
	Designing flood control works	●	●	●
	Determining water discharge license conditions and fees	●	●	●
	Determine groundwater/SW extraction licensing fees. Including determining pricing mechanisms for different crops	●	● ●	●
	Design and implement (infrastructure) restoration works	●	●	●
	Basin / Subbasin level allocations for major water use groups (basin / subbasin level totals for each water user type e.g. agriculture, hydroelectricity, forestry, mining, industry, urban/domestic, environment, etc)	●	●	●
	Informing/forecasting Urban / domestic water supply service levels; Guiding (urban) demand management need & actions	●	●	●
	Measuring and predicting impacts of externalities such as climate change, population growth, industrial changes (→ forecasting future water resource regimes)	●	●	●
	Water resources assessments to inform capacity for future / additional economic development / productivity in specific subbasins	●	●	●
	Water resources capacity assessments to guide investment in water infrastructure	●	●	●
	Applying technologies (e.g. water accounting) in water management		●	
MANAGEMENT & OPERATIONS	Enforcing extraction allocations / compliance monitoring – Surface water	●	●	●
	Enforcing extraction allocations / compliance monitoring – Ground water	●	●	● ●
	Monitoring irrigation infrastructure performance status according to the design	●	●	●
	Determine extraction licenses for major individual water users (agriculture, industry, hydroelectricity), including extraction locations	●	●	●
	Compliance monitoring enforcing pollution requirements	●	●	●
	Identifying pollution problems for attention (evidence base for managers and polluters; spatial and temporal scale important)	●	●	●
	Determine location and number of groundwater extraction points	●	●	●
	Monitoring sustainability/appropriateness of water allocations (comparing actual to projected balances to identify adjustments)	●	●	●
	Inform water markets / trading		●	●
RISK & DISASTER MANAGEMENT	Crop productivity (early warning food insecurity)	●	●	●
	Drought early warning and management	●	●	●
	Flood early warning and management	●	●	●

Following the group work, a plenary discussion of the results of each group focused on the WRM tasks that groups had assessed as having a different current status. As above, the group format made it easier for all perspectives to be raised and discussed in the facilitated plenary discussion and led to further elicitation of information. During this discussion, two additional WRM tasks were added to the framework by one group: Applying new technologies (e.g. water accounting) in water management; Developing a water pricing mechanism for each type of crop/ water uses. This emphasises the importance of a process that allows for localisation of the WRM framework.

The reasons given for the status of some WRM tasks as being considered not implemented, or only partially / maybe / not sure, included:

- The WRM task is required by law but is not undertaken
- The data doesn't exist to support the specified WRM task
- The WRM task is undertaken in some areas but not others (different regions of Viet Nam, or urban but not rural), or for some sectors and not others (e.g. industrial, agricultural, domestic water sectors)
- Implementation is not complete or adequate
- Some WRM tasks are only conducted in ad hoc manner as a part of research projects
- There is a lack of coordination (synchronization) of tasks



4.3.3 WORKSHOP TO ASSESS CURRENT WATER DATA USE

Following assessment of the status of WRM tasks in Viet Nam, each group was assigned a subset of the listed WRM tasks, to complete the following information:

- Spatial and temporal scales
- Agencies/ organisations involved
- Rating of use of water data to support WRM task
- Types of water-related data being used
- Comments on use of data

An extract of the extensive information gathered is shown in Table 2. Table 3 summarises the scores provided by participants, for the level of use of water-related data for each WRM task.

TABLE 2: EXAMPLE OF INFORMATION COLLECTED REGARDING WRM TASKS AND USE OF WATER DATA TO SUPPORT THEM (A DATA USE RATING: 1 = LOW (NOT USED); 5 = HIGH (COMMON USE, GOOD DATA); NS: NOT SCORED).

WRM tasks	WRM task status			Spatial and temporal scales (e.g. province, basin/catchment, commune, irrigation cluster, other...)	Agencies/ organisations/ others involved?	Rating of use of water data to support WRM task ^A	Types of water-related data being used	Group comments on water data use
	Group 1	Group 2	Group 3					
Enforcing extraction allocations / compliance monitoring – Surface water	●	●	●	Basin level – Daily	IMC, Government Agencies	3	Water level Water flow Water demand	• Lack of equipment, esp. automatic sensors
Enforcing extraction allocations / compliance monitoring – Ground water	●	●	●	From provincial to communal levels Monthly, quarterly and annually	Provincial Department of Agriculture and Environment (P-DAE) Communal Department of Economy and Infrastructure	3	Current status of ground water Water licensing	• Applying technologies • Building capacity for the IMCs
Designing irrigation systems	●	●	●	Organizations/ individuals who make the investment decisions	Government Agencies; Consultants	3	Water demand Met-hydro data Drainage data	• Some infrastructure works' performance is not satisfactory
Designing water supply systems (community, towns, cities)	●	●	●	Organizations /individuals who make the investment decisions	Government Agencies; Consultants	3	Water demand Drainage data	• Some infrastructure works' performance is not satisfactory
Input to (environmental, drinking) water quality guidelines (alongside other ecosystem health, human health & values-based inputs	●	●	●	National, provincial, communal, basin, irrigation teams levels Every five years	IMC, Government Agencies	3	Water inflow Water demand Specialized materials	• Some regulations have not been met
Crop productivity (early warning food insecurity)	●	●	●		Specialised agencies	3	Water demand by different types of plants/crops Met-hydro data Water inflow	• Depending on multiple factors
Designing flood control works	●	●	●	Organizations/ individuals who make the investment decisions	Government Agencies; Consultants	4	Met-hydro data	
Monitoring irrigation infrastructure performance status according to the design	●	●	●	Government Agencies at different levels, operating agencies/ Daily	IMC, Government Agencies	4	Water level Water flow Rainfall	

4.3.4 MATURITY OF DATA-INFORMED WATER RESOURCES MANAGEMENT

The above detailed assessments give the most constructive results from the assessment with the detail for each task providing guidance as to which tasks could be considered for further attention, to strengthen overall water management.

To assist in creating a synthesis and snapshot perspective of the maturity of the water resources management and the use of data the data representing the WRM status was aggregated (average of scores on the basis of green = 3, yellow = 2, orange = 1) – these results are shown in Table 3, alongside the complete set of scores of level of water data use for WRM tasks.

TABLE 4.3: SUMMARY SCORES FOR WRM STATUS, AND SCORES FOR WATER-RELATED DATA USE FOR EACH WRM TASK (BLANK CELLS WERE NOT COMPLETED BY STAKEHOLDERS)

Functional Group	WRM task	WRM task status (average as % of coloured dot scores)	Data use score (1 = low (not used); 5 = high (common use, good data))
PLANNING	Designing irrigation systems	3.0	3
	Designing water supply systems (community, towns, cities)	3.0	3
	Input to (environmental, drinking) water quality guidelines (alongside other ecosystem health, human health & values-based inputs)	3.0	3
	Designing flood control works	2.7	4
	Determining water discharge license conditions and fees	2.7	5
	Determine groundwater/SW extraction licensing fees. Including determining pricing mechanisms for different crops	2.5	3
	Design and implement (infrastructure) restoration works	2.7	3
	Basin / Subbasin level allocations for major water use groups (basin / subbasin level totals for each water user type e.g. agriculture, hydroelectricity, forestry, mining, industry, urban/domestic, environment, etc)	2.7	5
	Informing/forecasting Urban / domestic water supply service levels; Guiding (urban) demand management need & actions	2.3	
	Measuring and predicting impacts of externalities such as climate change, population growth, industrial changes (à forecasting future water resource regimes)	2.7	
	Water resources assessments to inform capacity for future / additional economic development / productivity in specific subbasins	2.7	
	Water resources capacity assessments to guide investment in water infrastructure	2.7	
	Applying technologies (e.g. water accounting) in water management	2.0	
MANAGEMENT & OPERATIONS	Enforcing extraction allocations / compliance monitoring – Surface water	3.0	3
	Enforcing extraction allocations / compliance monitoring – Ground water	1.8	3
	Monitoring irrigation infrastructure performance status according to the design	2.7	4
	Determine extraction licenses for major individual water users (agriculture, industry, hydroelectricity), including extraction locations	2.7	3
	Compliance monitoring enforcing pollution requirements	2.7	3
	Identifying pollution problems for attention (evidence base for managers and polluters; spatial and temporal scale important)	2.7	3
	Determine location and number of groundwater extraction points	2.3	3

	Monitoring sustainability/appropriateness of water allocations (comparing actual to projected balances to identify adjustments)	2.3	
	Inform water markets / trading	2.3	
RISK & DISASTER MANAGEMENT	Crop productivity (early warning food insecurity)	2.0	3
	Drought early warning and management	3.0	3
	Flood early warning and management	3.0	

A very high-level summary of the maturity of water resources management and the use of water-related data can be represented by averaging the above scores, for each functional grouping of WRM tasks. The results are represented in Figure 1. Although only a very high-level assessment, this indicates there are opportunities to further strengthen the implementation of water resources management – the tasks considered as relevant to Viet Nam – and more scope to strengthen the application of water-related data to support evidence-based water resources management.

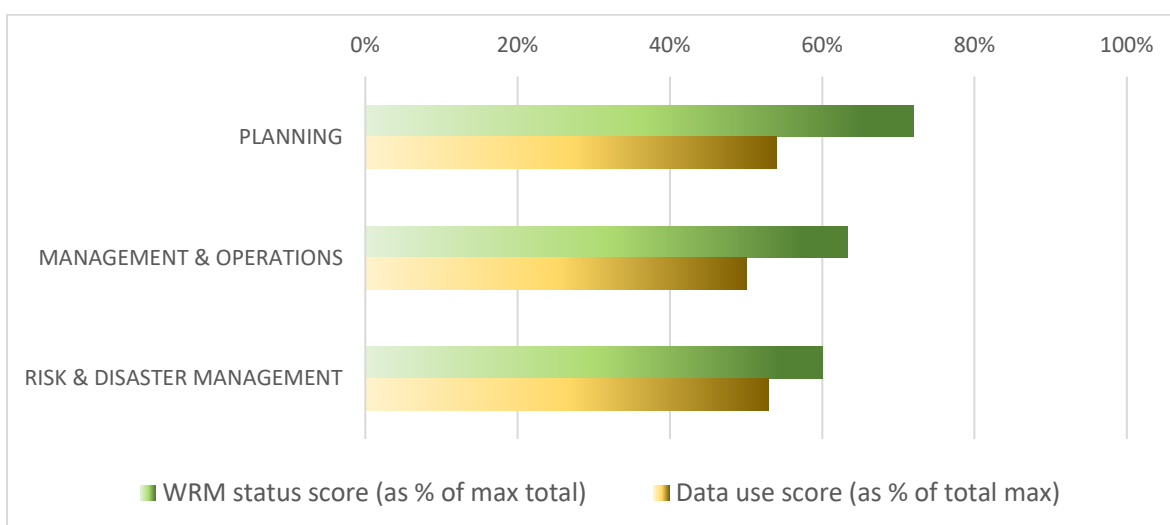


FIGURE 4.1: AVERAGE % OF MAXIMUM SCORE FOR THE CURRENT STATUS OF WRM TASKS (REFER TABLE 3), AGGREGATED BY FUNCTIONAL GROUP, AND AVERAGE % MAX SCORES FOR WATER-DATA USE TO SUPPORT WRM (REFER TABLE 3), AGGREGATED BY FUNCTIONAL GROUP. THE SCORES ARE BASED ON SELF-ASSESSMENT BY STAKEHOLDERS, ARRIVED AT THROUGH A GROUP-BASED DELIBERATIVE PROCESS.

4.3.5 WORKSHOP DISCUSSION OF WRM, WATER DATA, REMOTE SENSING AND WATER ACCOUNTING

Key points raised during the broader discussion following the above workshop activity were as follows:

- Unified Water Management Framework: Participants** emphasised the need to streamline policies and data systems
 - “Currently, policies and regulations from two ministries overlap... We hope to use a single water dataset and water accounting system,” said Mr. Kiên (P-DAE, Đắk Lắk).
 - There was a call for better integration of water and irrigation laws, with supporting guidelines and technologies to aid provincial and commune-level officers who often lack specialized water resource expertise.
- Expanded Use of Remote Sensing and Automation:** Strong interest was expressed in applying advanced technologies:
 - “Remote sensing is a technology we are very interested in... We want data (e.g., evaporation, groundwater, hydrology) to be automatically connected and updated weekly or monthly for more timely decisions,” highlighted Mr. Tường (IMC Đắk Lắk).

- Mr. Trung (Tay Nguyen Institute) suggested *“building projects to use remote sensing for irrigation forecasts and to manage groundwater better”*, citing potential benefits for crops like coffee and pepper.
3. **Practical and Tiered Training Programs:** Many participants stressed tailored capacity building:
- IMC Đắk Lắk and Đắk Nông representatives urged training technical staff at branch or *headwork* levels, rather than all levels, to focus resources where they are most needed.
 - Ms. Loan (Dalat University) noted: *“Direct management agencies must understand these tools... training is needed for both central and local authorities and even for large-scale farmers.”*
 - Peer-to-peer learning was encouraged: *“...train key farmers so they can share knowledge with others.”*
4. **User-Friendly and Reliable Software Tools:** A common need was for accessible, accurate, and standardized tools:
- Ms. Nhung (IMC Đắk Lắk) stressed the importance of *“a single platform to share data to reduce workloads”*.
 - Mr. Bách (IMC Đắk Lắk) requested *“one consistent source for remote sensing data to avoid discrepancies”* and suggested piloting the system in areas with existing automatic monitoring.
 - Participants highlighted the need for verification of algorithms and calculation methods to ensure *trust* in the results.
5. **Practical Application and Policy Alignment:** The recommendations also emphasized ensuring tools support decision-making at all levels:
- Ms. Nhung referred to the regulatory requirement under Decree 144 to record data *frequently* (e.g., every 15–30 minutes during extreme events), calling for systems that can *“reduce workload and comply with national standards.”*
 - Ms. Loan highlighted the need for alignment across administrative levels and with local farmers, stressing *that* training and adoption must be *“coordinated from central agencies to operators and farmers.”*

4.4 CONCLUSION

Understanding of the current status of Water resources management (WRM) and use of data can be helpful in assessing and identified opportunities to strengthen the WRM regime, improve the use of water-data, and guide the development of water-related data products.

WRM will be implemented differently in different places, depending on governance systems, environmental, especially water situations, social systems and resources available for WRM. However, a list of typical WRM tasks that would be conducted in a strong – or mature – water resource management regime, can be identified from literature. To use as the basis of a framework to identify opportunities to strengthen WRM and data use in any place, such as this pilot application in Viet Nam, that list can and should be further localised through stakeholder engagement.

In the case of Viet Nam, the framework of maturity of WRM regime and water-related data use indicated:

- The WRM tasks list identified from literature were relevant however some additions and modifications were made to suit Viet Nam
- This provided a useful framework for group-base deliberations about current status of WRM tasks
- There is scope to further strengthen WRM in Viet Nam, such as greater monitoring and enforcement of groundwater extraction allocations, applying advanced technologies (e.g. water accounting) to water management; assessing crop productivity (for early warning of future food insecurity).

- The use of water-related data to support WRM tasks was typically considered to be happening at a moderate level for most WRM tasks, with some challenges relating to lack of data sensing equipment, capacity of staff to use water-related data, and the need to link water-related data more clearly to regulations.

Most importantly, the framework offered (i) a structured process to guide stakeholder discussions helps to ensure constructive and focused discussions around the current status of water resources management and opportunities to strengthen it, and (ii) guidance to water data product developers about the end use of data products and tools. Both are important outcomes to improving evidence-based water resources management, for agricultural and broader economic and social development and environment protection.

In summary, the WRM maturity assessment confirms that while Viet Nam possesses foundational governance structures for water management, the integration data systems remain uneven, especially spatially explicit data systems. Scaling remote sensing and water accounting therefore will require not on technical demonstrations but also targeted institutional strengthening, particularly in surface- and groundwater monitoring and data harmonization.

5 REMOTE SENSING AND WATER ACCOUNTING – APPLICATION TO SUBBASINS IN VIET NAM

5.1 OVERVIEW

Subbasins can range in size, using the Mekong-Lancang River Basin as an example, from transnational subbasins such as the SrePok, 30757 km² in area, to headwater subbasins where reservoirs provide water for irrigation command areas such as Krong Buk, 464 km² in area. The complexity of management decisions also varies with scale, ranging from the management of transnational water issues within the SrePok subbasin, involving national governments and international treaties, down to management of water supplies to and within irrigation command areas or “irrigation clusters” involving irrigation management companies. Due to the range of scales of subbasins and the complexities of management decisions being undertaken and the different data needs at the different scales, the pilot study consisted of three study areas at different scales. The largest study area was the Ban Don subbasin, 10,850 km² in area, the second study area was the Krong Buk subbasin, a headwater subbasin providing water for irrigation and domestic needs, and the third was an irrigation cluster (Figure 5.1).

The range of subbasin scales provides an opportunity to investigate the different data needs as well as the ability of remote sensing data to provide hydrological data at these different scales. Any limitations in downscaling remote sensing data for the different scales will also be explored.

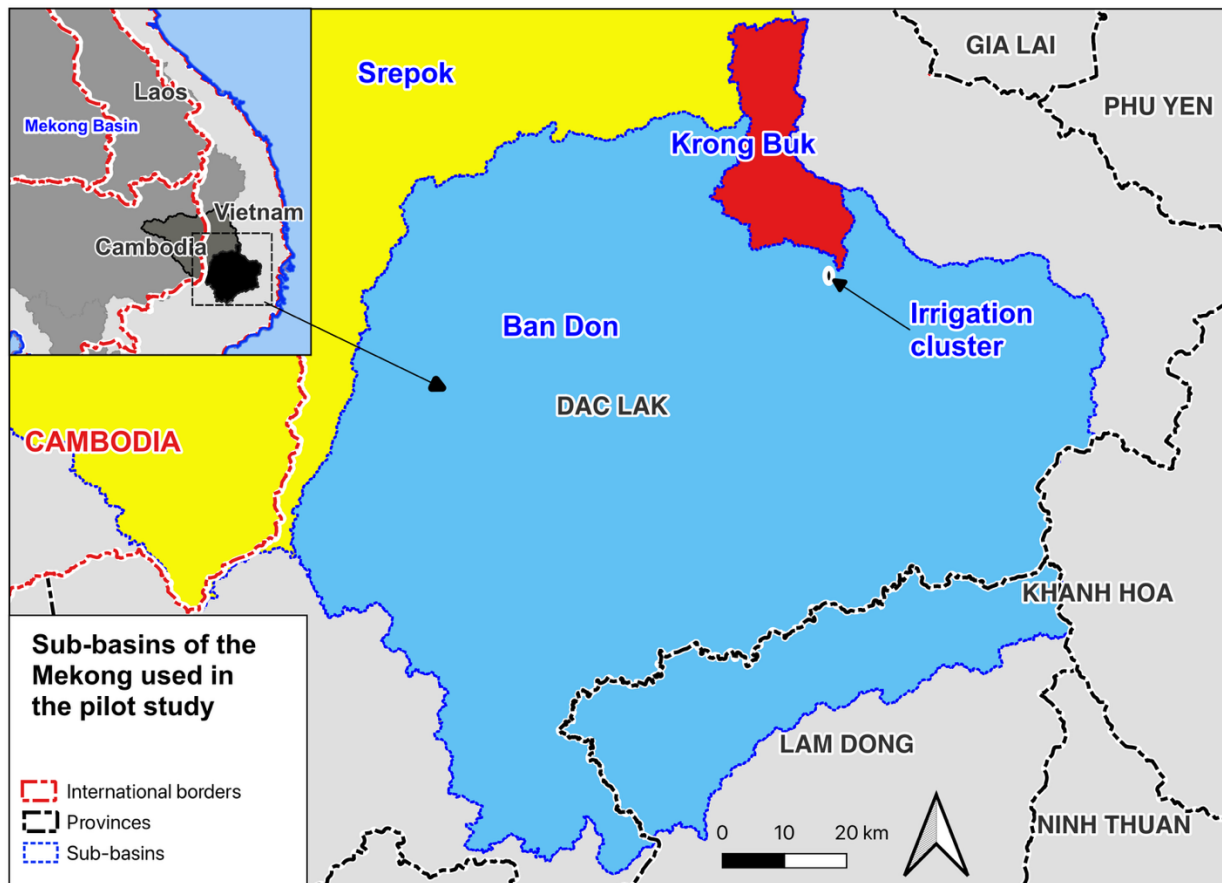


FIGURE 5.1 STUDY AREAS FOR THE PILOT PROJECT

The water balances for subbasins are derived from the conservation of mass where inflows (I_n) plus changes in stocks or storages (ΔS) equals outflows (O) Equation (i).

$$O = I_n + \Delta S \quad (1)$$

The components of a basin water balance are shown in Figure 5.2 and expressed mathematically in Equation (ii)

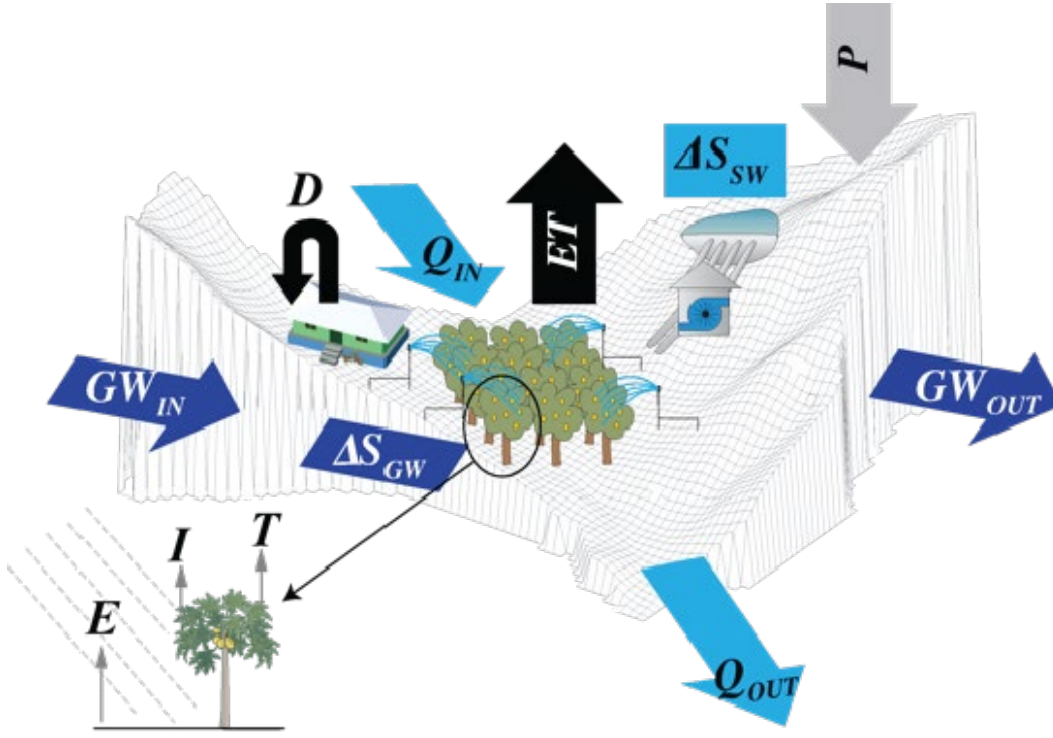


FIGURE 5.2 COMPONENTS OF A BASIN WATER BALANCE

$$Q_{OUT} + GW_{OUT} + ET = P + Q_{IN} + GW_{IN} + \Delta S_{SW} + \Delta S_{GW} \quad (ii)$$

Where for **Outflow**, ET is evapotranspiration, Q_{OUT} is surface water flow out of study area and GW_{OUT} is groundwater flow out of the study area. For **Inflow**, P is precipitation, Q_{IN} is surface water flow into the study area and GW_{IN} is groundwater flow into the study area. With **Changes in storage**, ΔS_{SW} is change in surface water storage (lakes, dams etc.) and ΔS_{GW} is the change in groundwater storage. Domestic water supplies (D) withdraw for households and other users, except agriculture, are assumed to be recycled, return flow (RF) and included in storage and outflow terms; ET , ΔS_{GW} , Q_{OUT} and GW_{OUT} .

Evapotranspiration can be further separated into transpiration (T), water transpired by plants for photosynthesis, evaporation (E), water evaporated directly from soil and water, and interception (I), rainfall intercepted by plants and evaporated before reaching the ground (iii).

$$ET = T + E + I \quad (iii)$$

The Water Accounting Plus framework (Karimi et al., 2013; Mul et al., 2020), based on subbasin water balances was adopted as the methodology to support decision making at the different subbasin scales. The Water Accounting framework was modified and simplified as shown in Figure 5.2.

SIMPLIFIED WATER ACCOUNTING FRAMEWORK

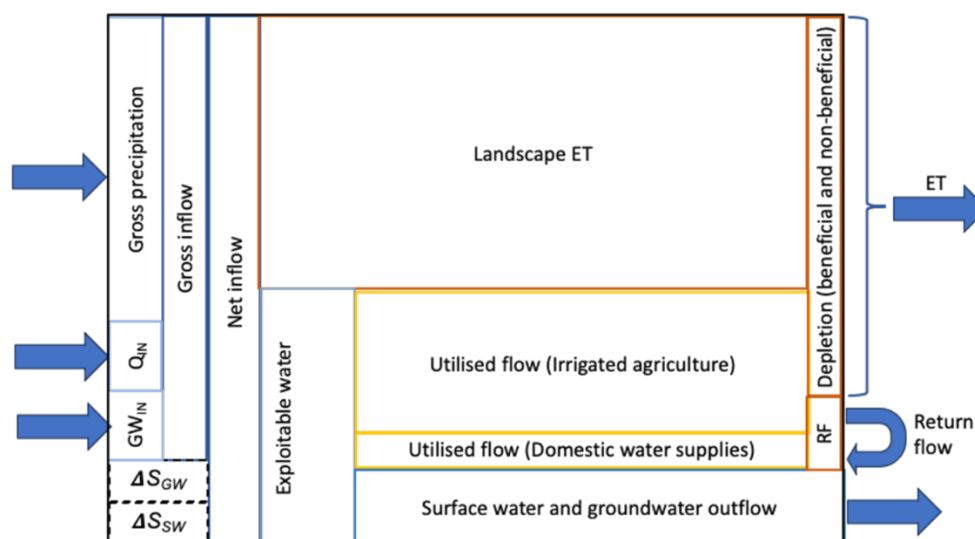


FIGURE 5.3 SIMPLIFIED WATER ACCOUNTING PLUS FRAMEWORK TO BE USED IN THE PROJECT

The simplified framework only considered the Water Accounting Sheets 1 to 4 (Table 5.1). Sheets 5 (Surface water) and 6 (Groundwater) were not used pilot project as it required the calculation of flows. This is achieved within the Water Accounting Plus framework through development of an in-built model, WaterPix, to estimate flows. However, the model requires calibration, with the data not always available at subbasin scales. Additionally, the WaterPix model lacks predictive capability to explore issues such as climate change, so was not used in the project.

TABLE 5.1 WATER ACCOUNTING SHEETS INCLUDED IN THE PILOT PROJECT

Water Accounting sheet	Purpose
Sheet 1: The Resource base	The sheet shows the water balance for the entire basin and a summary of data presented in other sheets (e.g. Figure 5.3)
Sheet 2: Evapotranspiration	Quantifies water consumption for all land use classes within the basin as well as understanding human impact on water resources
Sheet 3: Agricultural Services	Quantifies agricultural production, tonnes or kilograms per hectare, within the basin. It differentiates between irrigated and rainfed systems presenting water productivity in kilograms of produce/ biomass per cubic metre of water consumed
Sheet 4: Utilized Flows	Provides an overview of all human-induced and natural withdrawals

As the complexity of decision making varied with different basin scales, the water accounting framework was designed so as scale and complexity decreased, the water accounting framework could be modified to only use the hydrological components needed at that scale Figure 5.4.

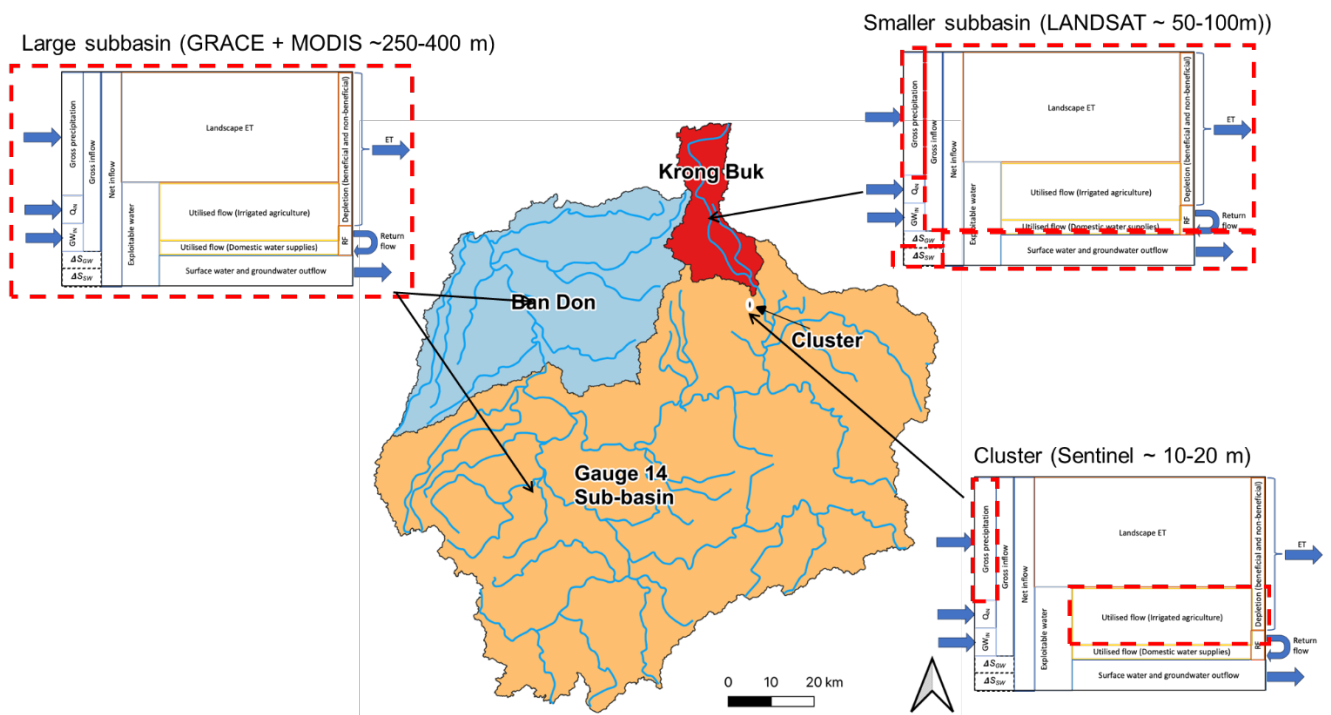


FIGURE 5.4 SIMPLIFIED WATER ACCOUNTING FRAMEWORK DESIGNED TO MODIFIABLE TO DIFFERENT SCALES AND LEVELS OF DECISION-MAKING COMPLEXITY

5.2 METHODOLOGY AND CALCULATIONS

This section outlines the technical methodology used to derive key hydrological components of the water balance, i.e., precipitation (P), actual evapotranspiration (ET), evaporation (E), transpiration (T), canopy interception (Int), and biomass production (B) across different spatial scales.

The approach combines remote sensing inputs with the Water Accounting Plus (WA+) framework, customized for three nested case studies:

- Ban Don subbasin
- Krong Buk subbasin,
- Irrigation cluster level.

The components were computed at daily, dekadal (10 day), monthly and annual time steps to match management and cropping cycles, depending on data availability.

5.2.1 REMOTE SENSING DATA

PRECIPITATION

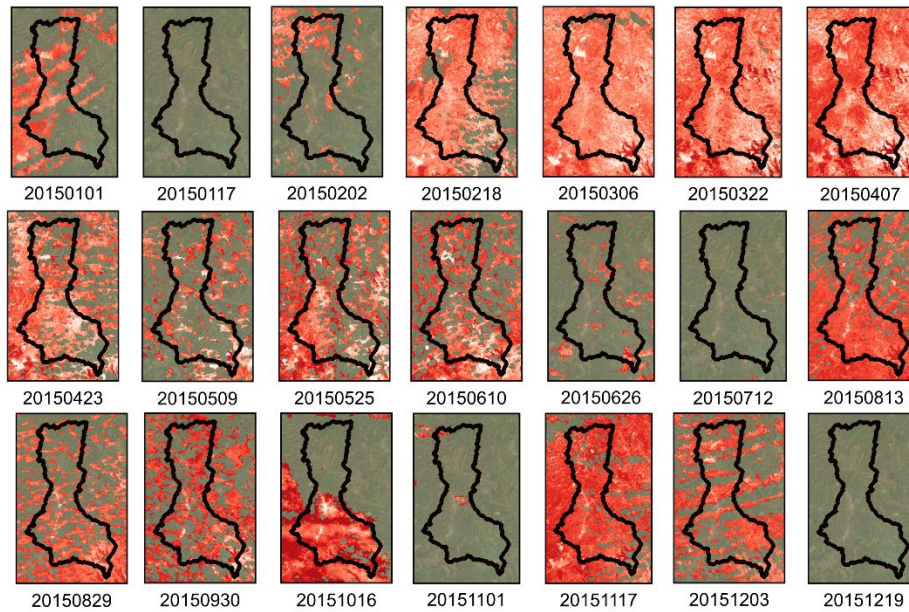
The Climate Hazards Center Infrared Precipitation with Stations (CHIRPS version 3) is a 40+ year, high-resolution quasi-global rainfall dataset. It spans 60°N to 60°S and covers all longitudes, providing data from 1981 to near-present. CHIRPS v3 combines satellite-based thermal infrared rainfall estimates with in-situ station observations to produce a 0.05° gridded rainfall time series over land. Two CHIRPS products are available – a rapidly updated preliminary product and a final product. CHIRPS Preliminary incorporates rapidly updated station observations and is available 2 days after the end of a pentad (on the 2nd, 7th, 12th, 17th, 22nd and 27th day of each month). CHIRPS v3 is available in multiple timesteps (daily, pentad, dekadal, monthly and annual) and in several formats (GeoTIFF, NetCDF, BIL, and COG). In this study, we used monthly CHIRPS v3 rainfall data, period from 2002 - 2024 for Ban Don basin.

EVAPOTRANSPIRATION

At the basin scale, actual evapotranspiration (ET) for Ban Don was estimated using the SSEBop datasets (Senay et al., 2013), which applies a simplified surface energy balance approach using MODIS and Landsat thermal imagery. It provides spatially distributed ET estimates at ~1 km resolution, suitable for regional assessments.

The smaller scale basins such as Krong Buk and Irrigation clusters require higher resolution satellite data. The availability of fine resolution (30m) actual evapotranspiration data for the Krong Buk Basin using Landsat 8 SSEBop derived data for the period 2015-2016 was investigated. Out of the 40 scenes only four had complete coverage of Krong Buk catchment (10%). Therefore, direct satellite evapotranspiration data was unavailable for the study areas so evapotranspiration needed to be derived using other methods, specifically the ETLook model. The Landsat 8/9 satellite data could be sufficient to derive other secondary products such as spatial yield and water productivity estimates for the study area to identify underperforming areas.

2015



2016

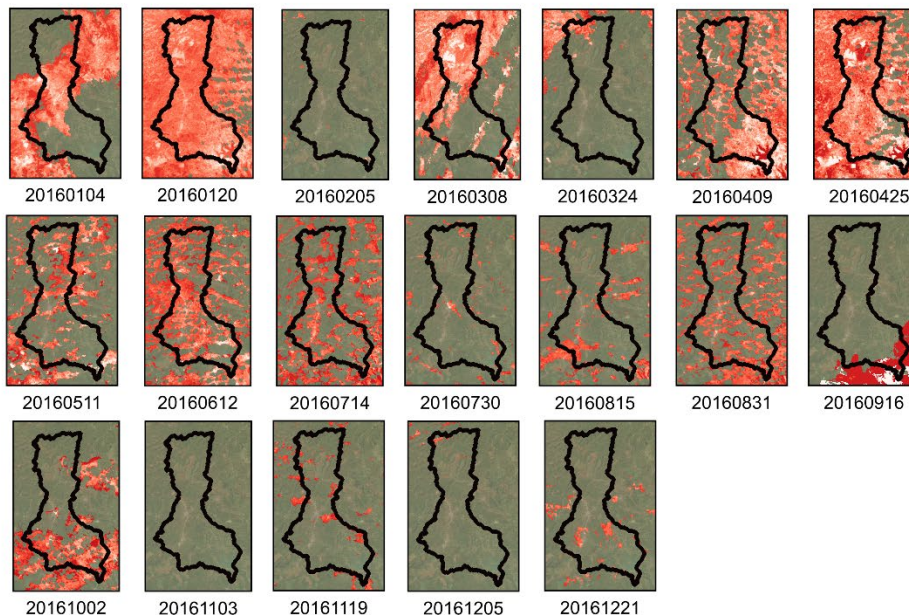


FIGURE 5.5 LANDSAT 8 30M DERIVED SSEBOP ACTUAL EVAPTRANSPIRATION DATA - THE DATE OF THE SCENE WAS TAKEN IS SHOWN AT THE BOTTOM OF THE FIGURE (YYYY (YEAR) - MM (MONTH) - DD (DAY) FORMAT)

At finer scales (Krong Buk and irrigation clusters), ET was disaggregated into its components—transpiration (T), soil evaporation (E), and interception loss (Int)—using the ETLook model as implemented by the FAO WaPOR Level 2–3 data (20m resolution). ETLook uses the Penman–Monteith approach, integrating land surface temperature, NDVI, net radiation, wind speed, and humidity data to estimate fluxes. The model separates T and E by simulating moisture and energy fluxes through a two-layer soil-vegetation system, allowing pixel-level estimation of the green (productive) and blue (non-productive) water use pathways

CHANGE IN STORAGE

NASA GRACE data is data collected by two GRACE (Gravity Recovery and Climate Experiment) satellites, which measure changes in the Earth's gravitational field to track the distribution and movement of water on the planet. One of the applications of this data is used to monitor fluctuations in groundwater levels, soil moisture, and sea levels, providing insight into the water cycle and water resources. The methodology for downscaling and processing of GRACE data to estimate changes in total water storage (Δ TWS) for the

Ban Bon Basin is detailed in Appendix A. The downscaled changes in Total Water Storage are shown in Figure 5.6.

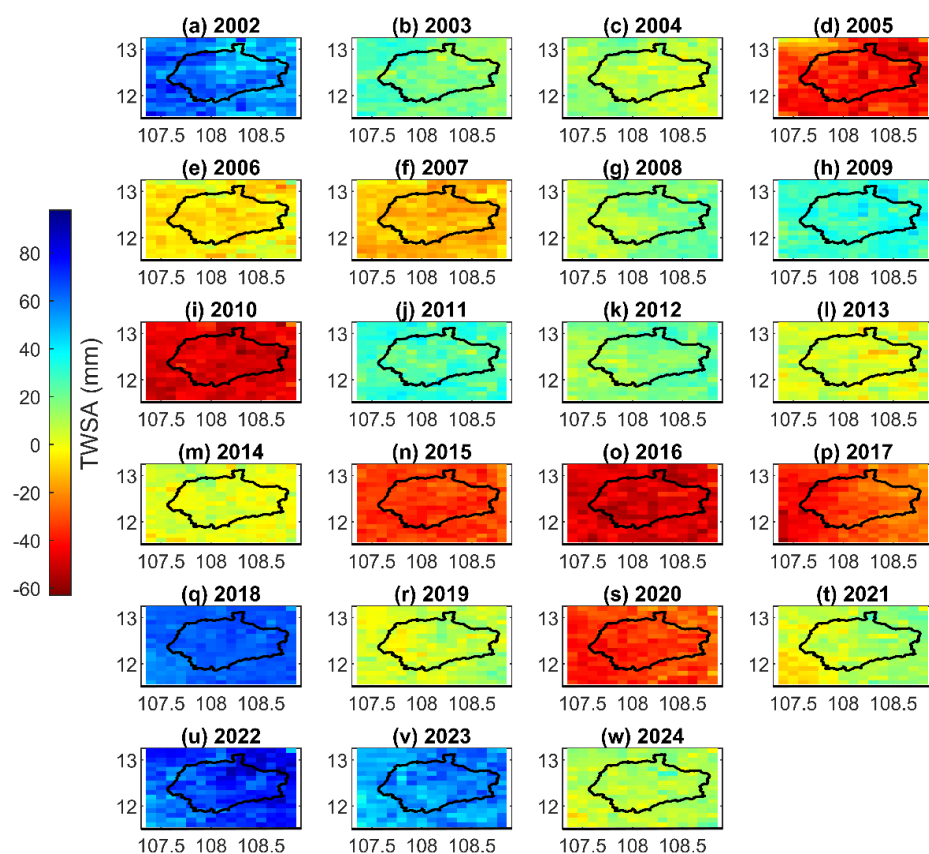


FIGURE 5.6 DOWNSCALED GRACE CHANGES IN TOTAL WATER STORAGE DERIVED USING MACHINE LEARNING ALGORITHMS, RESAMPLED TO A SPATIAL RESOLUTION OF 0.1° . THE HIGH-RESOLUTION ESTIMATES INCORPORATE FINE-SCALE VARIABILITY USING PREDICTOR VARIABLES SUCH AS PRECIPITATION, EVAPOTRANSPIRATION, AND RUNOFF

LAND USE LAND COVER

The Japan Aerospace Exploration Agency (JAXA) Earth Observation Research Center (EORC) developed High-Resolution Land Use Land Cover (LULC) products for Mainland Viet Nam (HRLULC-Vietnam) to provide basic information for a variety of applications such as biodiversity evaluation, natural disaster management and planning tasks (Figure 5.7). The "2020VNM_v23.09" product used in the analysis, reflects the LULC status over Mainland Vietnam as of 2020 with a spatial resolution of 10m (Japan Aerospace Exploration Agency, 2023). The JAXA LULC product has 12 land use categories that were mapped to Water Accounting Plus land use categories (Table 5.2); Protected (Conservation areas), Utilised (little interference), Modified (significantly changed by human activity) and Managed (water cycle is actively managed by humans).

TABLE 5.2 JAXA LULC CLASSES MAPPED TO WATER ACCOUNTING PLUS CATEGORIES FOR BAN DON

Water Accounting Plus Categories	JAXA LULC category class
Protected land uses	Evergreen forest, Deciduous forest
Utilized land uses	Grass/Shrub
Modified land uses	Plantation Forest, Barren, Other Crops
Managed water uses	Woody crops/Orchard, Rice, Urban/Built-up, Water, Aquaculture

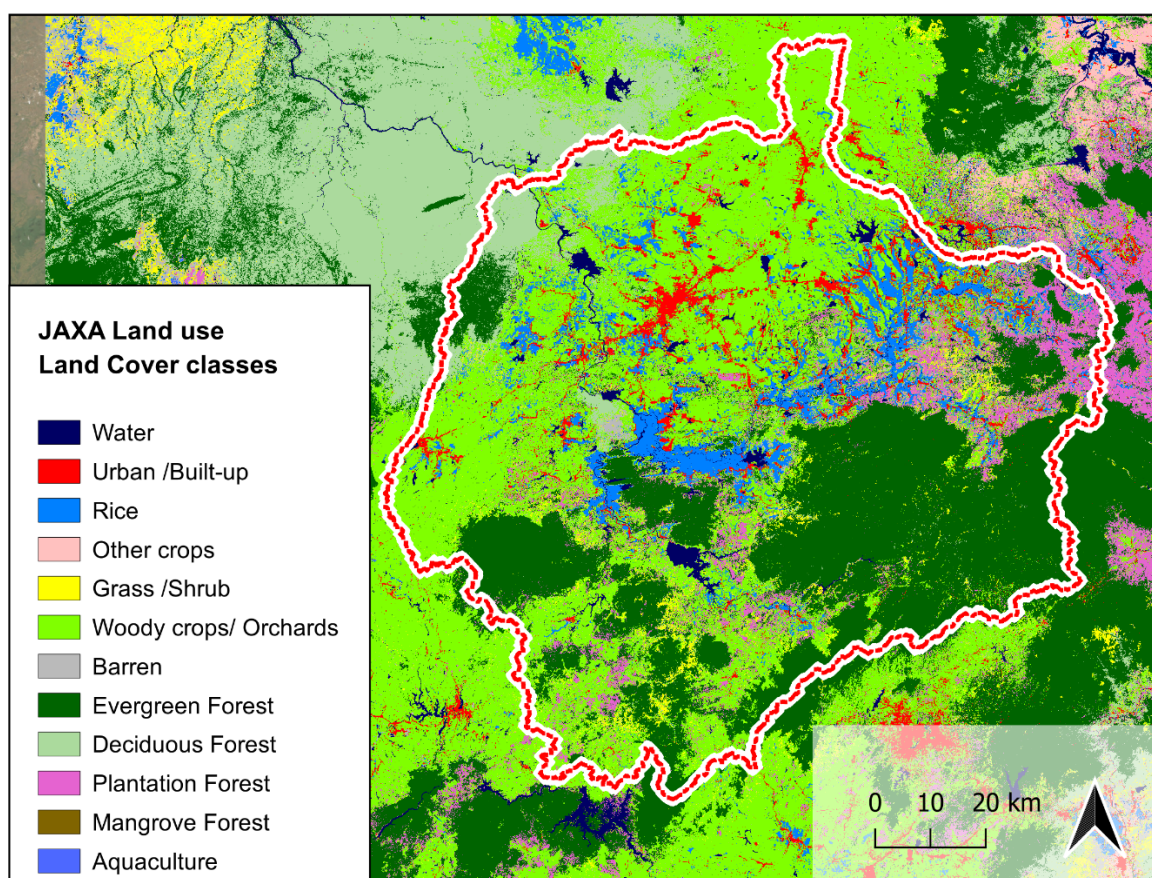


FIGURE 5.7 LAND USE LAND COVER MAP OF VIET NAM, 10 M GRID, DEVELOPED BY THE JAPAN AEROSPACE EXPLORATION AGENCY (JAXA)

For the Krong Buk subbasin the Woody crops / Orchards category was considered too broad to assess water consumption by different perennial crop types that occurred in the basin. Therefore, the perennial crops were further classified using supervised classification machine learning algorithms. Training data, using Pepper, Coffee, Other crops, Durian and Rubber categories (Figure 5.8) verified by field visits was used to classify Sentinel-2 satellite imagery with cloud cover below 10%. The revised perennial crop categories were combined the JAXA data to produce a 20m resolution LULC map for Krong Buk (Figure 5.9). The Krong Buk LULC land use categories were mapped to the Water Accounting Plus land use categories for calculation of water balances and use in sheets (Table 5.3)

TABLE 5.3 KRONG BUK LULC CLASSES MAPPED TO WATER ACCOUNTING PLUS CATEGORIES

Water Accounting Plus Categories	JAXA LULC category class
Protected land uses	Evergreen forest, Deciduous forest
Utilized land uses	Grass/Shrub
Modified land uses	Plantation Forest, Barren, Other Crops
Managed water uses	Pepper, Coffee, Other Plants, Durian, Rubber, Rice, Urban/Built-up, Water, Aquaculture

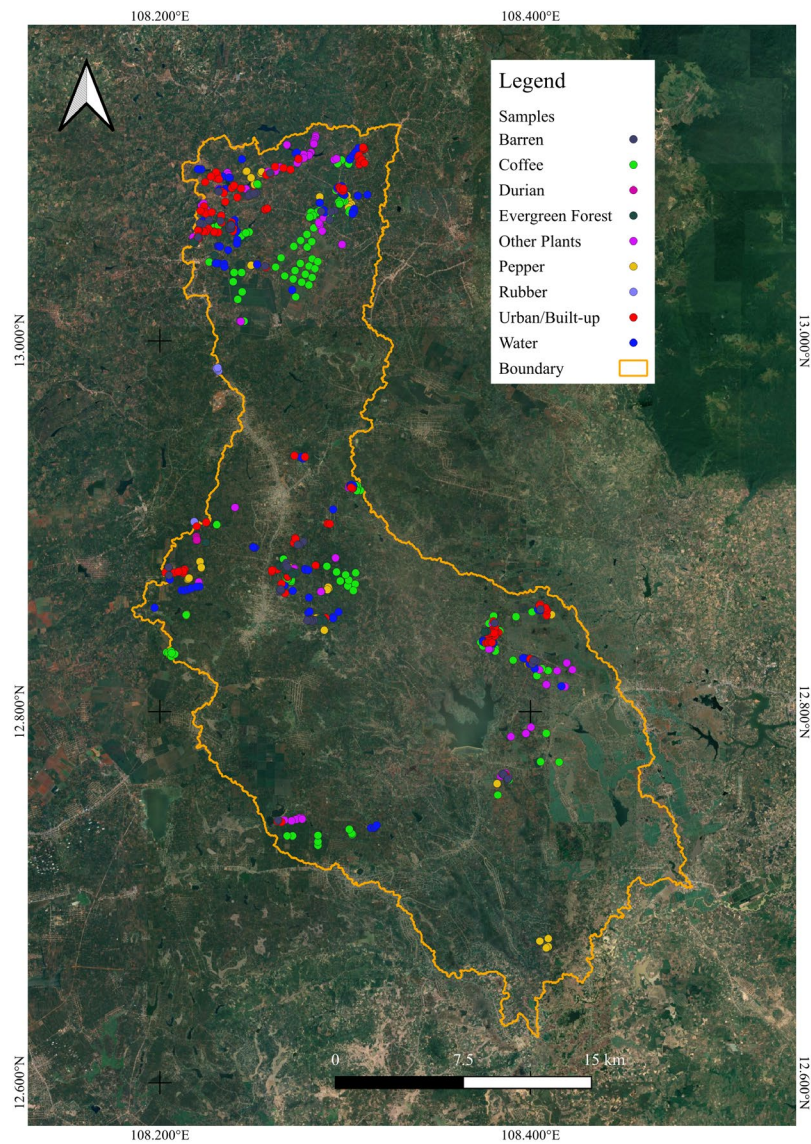


FIGURE 5.8 PERENNIAL CROP TRAINING DATA USED TO RECLASSIFY REMOTE SENSING DATA. TOP FIGURE SHOWS TRAINING LOCATIONS AND BOTTOM FIGURES SHOW CROP TYPES (PEPPER, LEFT AND COFFEE, RIGHT)

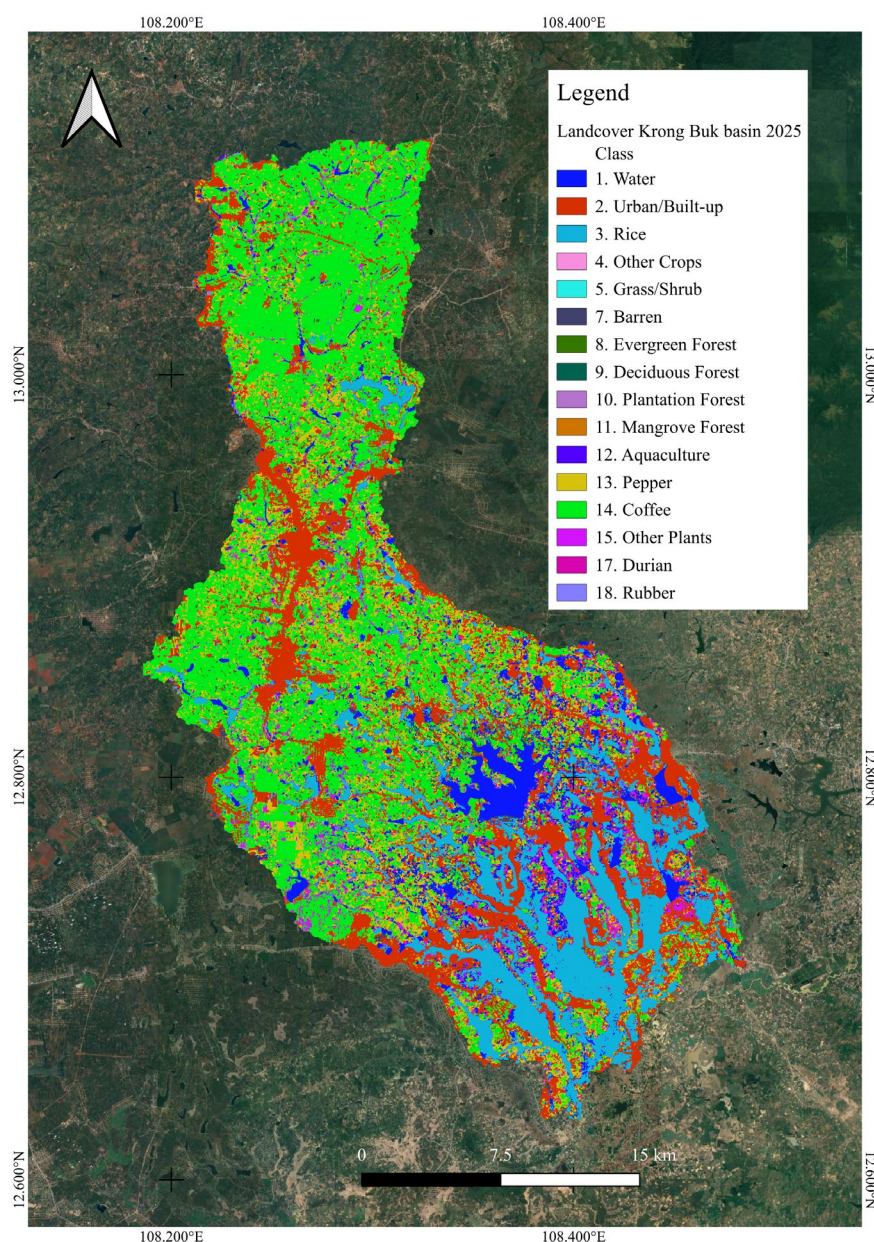


FIGURE 5.9 LAND USE LAND COVER CLASSES FOR THE KRONG BUK SUBBASIN

NET PRIMARY PRODUCTION AND WATER PRODUCTIVITY

WaPOR Global Level 1 Net primary production data was available for Ban Don at 300 m grid was explored and considered not useful for the context of the project. However, for the smaller subbasins and irrigation clusters biomass data was calculated. For the irrigation cluster, biomass, yield and crop productivity maps were developed.

TABLE 5.4 A SUMMARY OF REMOTE SENSING DATA USED FOR THE SUBBASINS

Remote Sensing data	Name	Spatial resolution	Data type	Time collected
All subbasins				
Precipitation	CHIRPS	~ 5km (0.05°)	Monthly	2002 - 2024
Ban Don				
Evapotranspiration	SSEBop	1 km	Monthly	2012 - 2024
Change in storage	GRACE	10 km	Monthly	2002- 2024

Remote Sensing data	Name	Spatial resolution	Data type	Time collected
Krong Buk				
Evapotranspiration - Transpiration (T) - Evaporation (E) - Interception (Int)	ETLook	250 m	Daily	2024
Biomass	ETLook	250 m	Daily	2024
Soil moisture	ETLook	250 m	Daily	2024
Irrigation cluster				
Evapotranspiration - Transpiration (T) - Evaporation (E) - Interception (Int)	ETLook	20m	Daily	2024
Biomass	ETLook	20m	Daily	2024
Soil moisture	ETLook	20m	Daily	2024

5.2.2 WATER BALANCE CALCULATIONS FOR WATER ACCOUNTING SHEETS

Precipitation, evapotranspiration and storage change remote sensing data are usually recorded as depth measurements typically as millimetres (mm). Land use and land cover (LULC) classes derived from remote sensing data can be used to calculate areas of different land use types. The remote sensing data was imported into a geographic information system (GIS) where the areas for different LULC classes within the subbasin were calculated. The average depth of evapotranspiration and precipitation were calculated for the different subbasin LULC classes and multiplied by the area of the LULC classes to obtain a volume for the respective classes on monthly time steps. This allowed for identification of water usage by different LULC classes. The changes in storage were calculated at the subbasin scale and multiplied by subbasin area to obtain a volume on monthly timesteps. The calculated volumes are then aggregated by Water Accounting Plus categories to derive mass balances for the subbasin and shown in water accounting sheets on annual time steps.

For the Ban Don subbasin Sheets 1 (Resource base) and Sheet 2 (Evapotranspiration) were developed for the years 2013-2024. For Krong Buk Sheets 1 (Resource base) and Sheet 2 (Evapotranspiration) were developed for the years 2023-2024 as well as productivity data. For the irrigation clusters, evapotranspiration, production, yield and water productivity maps were produced for the year 2024.

5.2.2.1 ESTIMATION OF WITHDRAWALS FOR IRRIGATED AGRICULTURE

One of the most important components of Water Accounting Plus are the estimates of water being consumed or depleted by human uses, which requires an estimate of withdrawals from surface or groundwater storages. It was initially proposed to use a method developed by van Eekelen et al. (2015), which was subsequently successfully used by Msigwa et al. (2021) to estimate irrigation withdrawals. In this method actual evapotranspiration (ET_a) for irrigated areas is assumed to consist of water from rainfall ($ET_{rainfall}$) and irrigation ($ET_{irrigation}$). Therefore, evapotranspiration from irrigation ($ET_{irrigation}$) can be calculated from ET_a and $ET_{rainfall}$ (Equation i). ET_a can be estimated from remote sensing data. It is assumed that ET in rainfed land uses is from rainfall therefore this data can be used to estimate $ET_{rainfall}$ in irrigated

systems. To allow that not all precipitation is not lost through evaporation and is variable, $ET_{rainfall}$ is normalized by precipitation Equation (ii)

$$ET_{irrigation} = ET_a - ET_{rainfall} \text{ (i)}$$

$$ET_{rainfall} = (ET/P)_{rainfed} \times P \text{ (ii)}$$

Initial analysis of remotely sensed data showed that there was little variation in actual evapotranspiration between the wet and dry seasons (Figure 5.10) for Ban Don. Figure 5.11 shows the spatial variation in rainfall deficit (precipitation – actual evapotranspiration) for the dry season (Jan 2018) noting that it occurs across all land uses. This assessment indicated that actual evapotranspiration was not rainfall limited and water from storage (groundwater and surface water storages) provided the additional water for all land uses. GRACE data confirmed water was being taken from storage. This meant that the proposed van Eekelen method, which assumed water was limited by rainfall, would not work in this subbasin.

As an alternative approach where actual evapotranspiration exceeded rainfall in Figure 5.10, the rainfall deficit volume (P-ET) was calculated for the different land use categories and assumed to come from storage and so was treated as utilized flow (withdrawals) in the Water Accounting sheets.

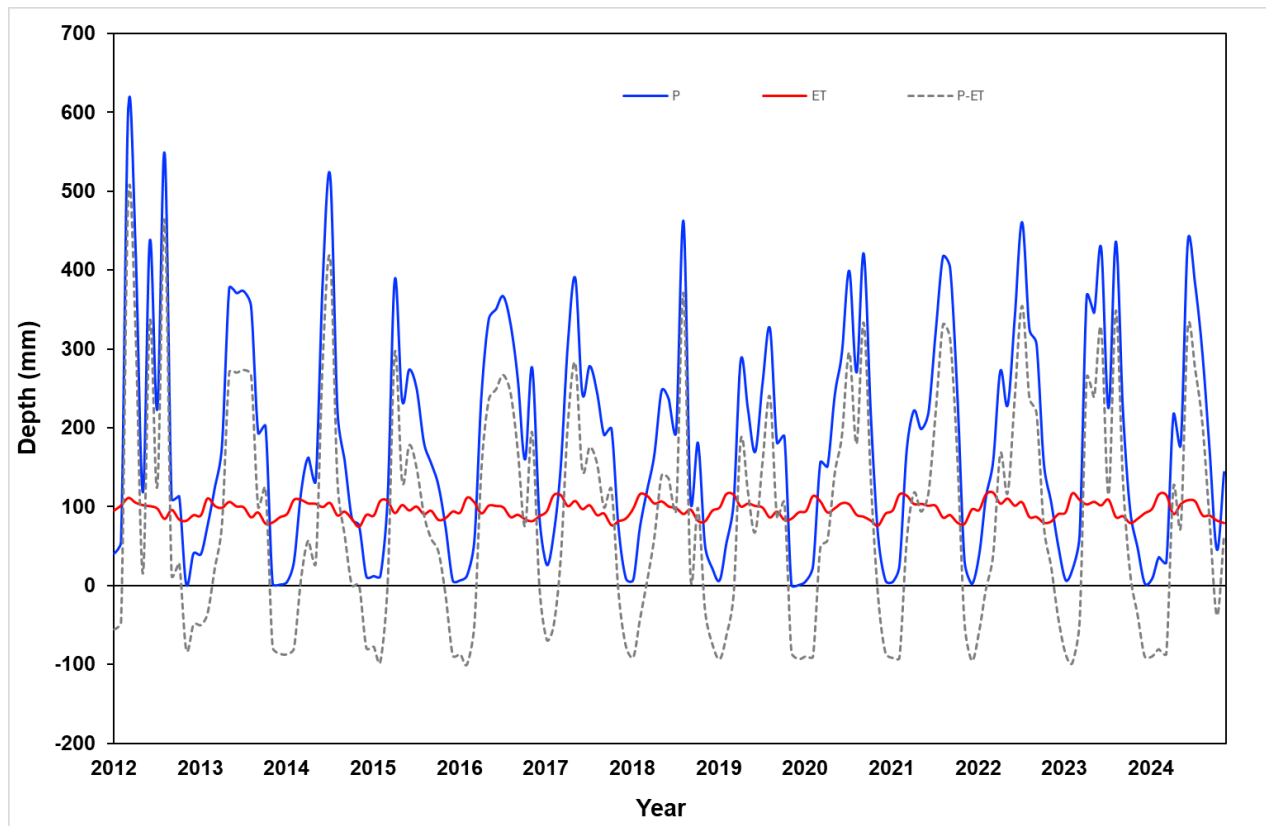


FIGURE 5.10 WATER BALANCE COMPONENTS FOR THE BAN DON BASIN

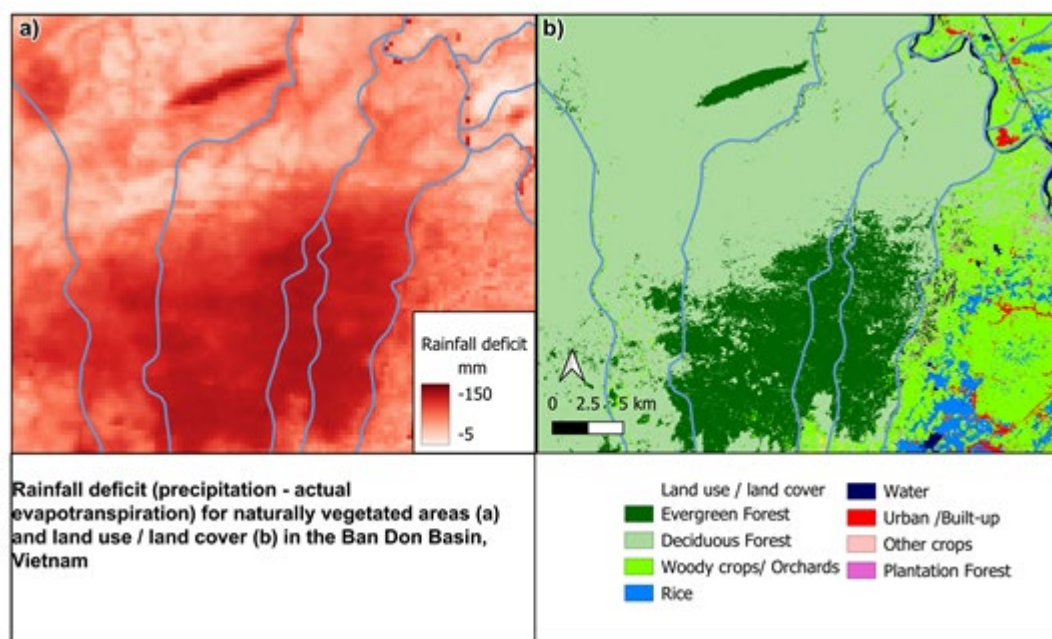


FIGURE 5.11 THE DRY SEASON RAINFALL DEFICIT (JAN 2018) FOR DIFFERENT LAND USES FOR PARTS OF THE BAN DON BASIN

5.2.2.2 REPRODUCIBILITY OF WATER ACCOUNTS USING DIFFERENT METHODOLOGIES FOR THE BAN DON BASIN

To investigate the robustness and reproducibility of water accounts for the Ban Don basin, water accounts for the basin were developed using different methodologies and datasets. The primary method to develop water accounts utilised SSEBop, CHIRPS and Downscaled GRACE remote sensing data, as outlined above. In the first alternate method, water accounts were developed for separate Ban Don subbasins, each approximately $\sim 30\text{-}40 \text{ km}^2$ (Figure 5.12) and summed to establish a total for the Ban Don basin. For the headwater basins, Giang Son and Duc Xuyen, outflows were estimated on a monthly timestep for 2018-2019 using the water balance $Q_{\text{out}} = P - ET \pm \Delta S$. P (precipitation) was derived from WaPOR Level 1 Global monthly precipitation data, ET was derived from WaPOR Level 1 Global monthly Actual Evaporation Transpiration Interception (AETI) data and ΔS was derived from monthly downscaled GRACE data.

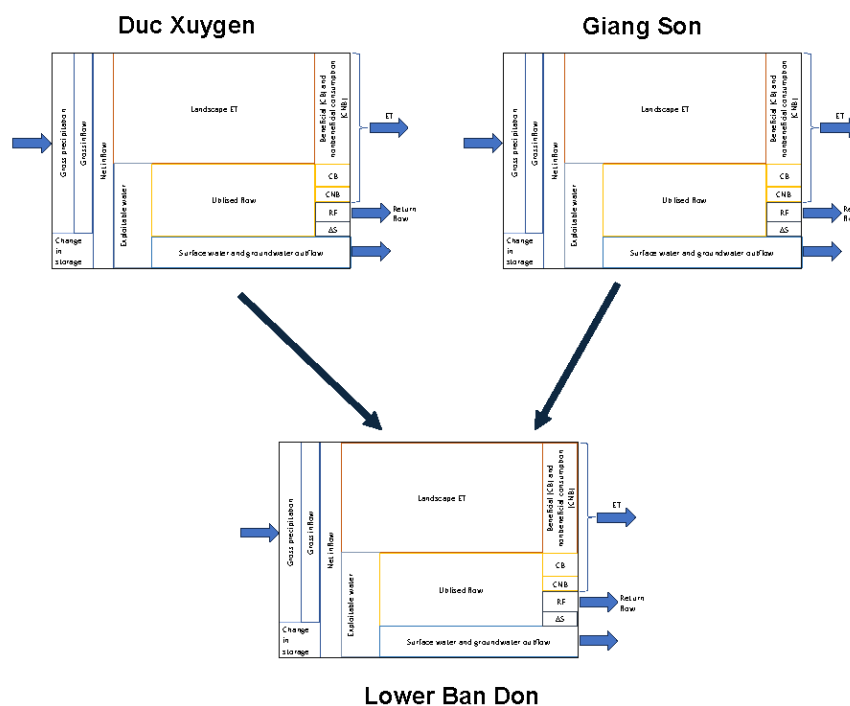
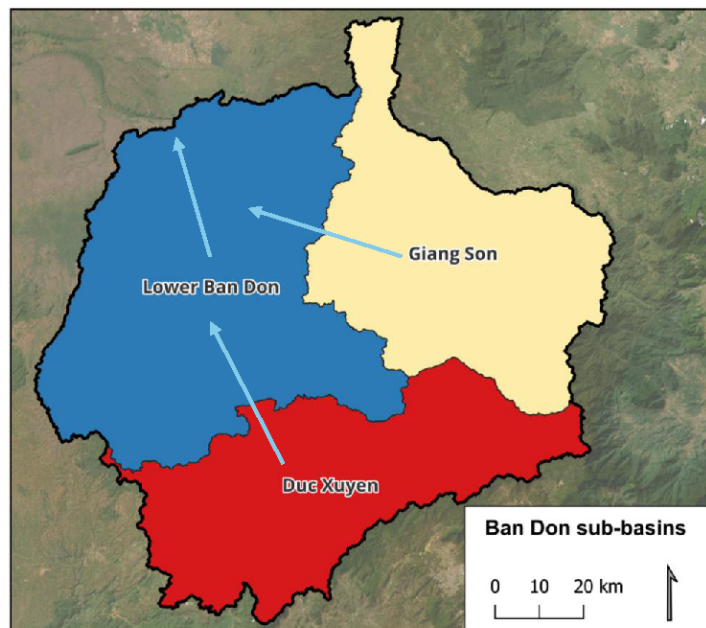


FIGURE 5.12 METHODOLOGY FOR CALCULATING WATER ACCOUNTS FOR BAN DON SUBBASINS TO DERIVE OUTFLOWS FOR THE BAN DON BASIN

The outflows of the headwater subbasins formed the inflows for the Lower Ban Don subbasin (Figure 5.12), and the outflows of the Lower Ban Don subbasin represent the outflows of the entire Ban Don basin. In the alternate second method outflows for the entire Ban Don basin, as a whole, were calculated for the years 2018-2019 using WaPOR data on monthly and annual timesteps. Outflows for Ban Don were also calculated for the years 2018-2019 using annual CHIRPS and SSEBop data. The hydrological data generated from WaPOR data, on both monthly and annual timesteps was then compared with hydrological data derived from SSEBop/CHIRPS data, above, to investigate the variability and robustness of different data sets and water accounts.

5.2.3 WATER ACCOUNTING OUTPUTS

Sheet 1 presents the annual water resources balance for the Ban Don Basin for 2024, expressed in km³/year (Figure 5.13), and summarizes the source, use, depletion and outflow of water within the basin. The resource sheets for the years 2013-2023 are in Appendix B. The total gross inflow to the basin in 2024 is 21.8 km³/year, primarily originating from precipitation (20.9 km³/year), with a small contribution from recycled precipitation (0.9 km³/year). After accounting for changes increases in storage (–1.2 km³), the net inflow is 20.6 km³/year, representing the total water available within the basin during the accounting period.

Of this total, a substantial proportion is consumed through evapotranspiration (ET) processes across different land uses. The areas of the different land uses and average depths for Ban Don are shown in Table 5.5 and 5.6 respectively. Landscape ET amounts to 8.3 km³/year and includes water use across protected, utilised, modified, and managed land uses. In addition, ETgreen accounts for 8.3 km³/year, reinforcing the dominant role of precipitation-driven processes in the basin’s hydrology.

Sheet 1: Resource Base (km³/year)

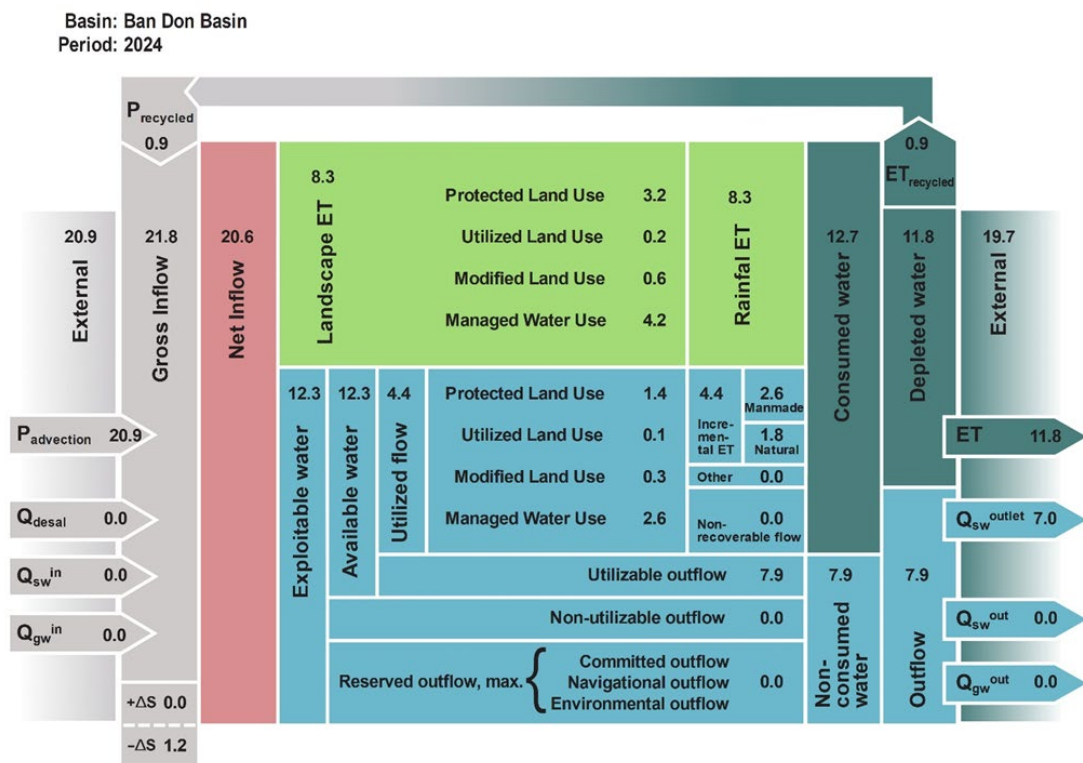


FIGURE 5.13: WATER ACCOUNTING SHEET 1 IN BAN DON BASIN

The basin has 12.3 km³/year of exploitable water, which corresponds to the volume of water potentially available for managed use after accounting for natural system requirements. A total of 4.4 km³/year is categorized as utilised flow, a third was used by natural process (1.4 km³/yr) and two-thirds (2.6 km³/yr) reflecting water actively used for managed land uses and economic activities. Overall, the total consumed water amounts to 12.7 km³/year, of which 11.8 km³/year is classified as depleted water (water that is evaporated, transpired or removed from the basin). The basin generates 7.9 km³ of utilizable outflow in 2024, representing water that leaves the basin and is available for downstream uses.

TABLE 5.5 AREAS OF DIFFERENT LAND USE CLASSES AND WATER ACCOUNTING PLUS CATEGORIES

JAXA land use classes	Class area (km ²)	Water Accounting Plus Categories	Category area (km ²)
Evergreen forest	3323	Protected	3763
Deciduous forest	440		
Grass/Shrub	262	Utilized	262
Other Crops	22	Modified	797
Barren	102		
Plantation Forest	673		
Water	268	Managed	6017
Urban/Built-up	498		
Aquaculture	1		
Woody crops/Orchard	4390		
Rice	860		

From the water accounting sheet 1 for 2024, it can be concluded that:

- The basin is highly dependent on rainfall, which is relevant for this Köppen climate.
- A large proportion of available water is consumed through evapotranspiration.
- The balance between consumed water (12.7 km³/year) and the utilizable outflow (7.9 km³/year) suggests that moderate pressure on the water resources, especially when inflow is reduced and demand increases.
- The negative storage changes (−1.2 km³) derived from GRACE indicates that water is being added to storage either filling dams or aquifers. This finding indicates that what is being taken from storages is being replenished.

For WA+ Sheet 2 in 2024, evapotranspiration for Ban Don (Figure 5.14) shows the evapotranspiration for the different land uses. Forests and irrigated agriculture are the largest consumers of water, with Evergreen forests having the largest annual water usage (1234 mm) followed by Grass/ shrub land uses and Deciduous forest land uses, 1162 mm and 1150 mm respectively (Table 5.6). Plantation forests and Woody crop / orchards are largest human managed users of water, at 1145 mm and 1135 mm respectively, with only the Woody crop / orchards land uses being actively irrigated. As the Woody crop / orchards land use has the largest area of all land uses, 4390 km², it consumes the most water overall, 5.96 km³ (Figure 5.14), with roughly a quarter being provided by irrigation and the rest by rainfall (Table 5.5, Figure 5.13).

The monthly components of the water balance from Feb-2012 to Dec 2024, shown as depth (mm), can be seen in Figure 5.15. The depth measurements were all obtained from remote sensing data and provide an overview of the state of water resources within the Ban Don basin. The only time the water balance goes into negative, no outflow, is when water was going into storages eg refilling dams or aquifers. The only year when there was no net outflow was 2018, when storages were refilled after a succession of years, 2014-2017, when storages, either aquifers or dams, were depleted. Overall, if the human usage of water resources remains less than water usage by natural systems, Table 5.5, then the resource base should be sustainable, though this becomes increasing uncertain with changes in climate. This demonstrates that remote sensing and water accounting frameworks can successfully be used to gain an understating of the state of water resources within smaller basins e.g. Ban Don.

Sheet 2: Evapotranspiration (km3/year)

Period: 2024
Basin: Ban Don

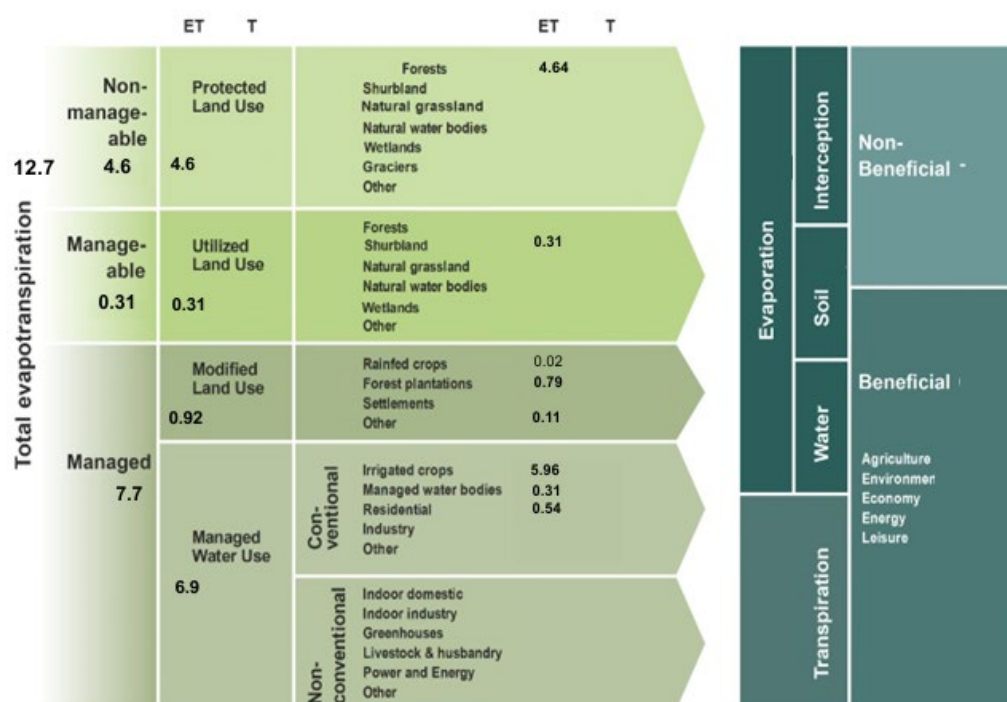


FIGURE 5.14 THE 2024 SHEET2: EVAPOTRANSPIRATION FOR BAN DON

Evaporation or evapotranspiration, though one of the most important outflows is usually poorly parameterised. Evaporation or evapotranspiration in basins are poorly measured (Sheffield et al., 2018) and often estimated by a water balance approach where evaporation equals precipitation minus discharge (e.g. (Berghuijs et al., 2020). In hydrology it is generally treated as a lumped parameter with various methods to provide estimates of evaporation or evapotranspiration such as pan evaporation or equations deriving evapotranspiration from energy balances such as the Penmen-Monteith and Priestly-Talyor equations (Chiew et al., 2002; Ladson, 2008). These estimates are often used in hydrological models but may not reflect actual evapotranspiration. There are methods to estimate point evapotranspiration, e.g. (Allen et al., 1998) but require detailed knowledge of crop phenology and constants. There are also methods to calculate areal evapotranspiration such as Mortons' complementary relationship (Morton, 1983), which when used for estimating evapotranspiration in Australia required calibration using the water balance approach (Chiew et al., 2002). However, remote sensing estimates of actual evapotranspiration provide both temporal and spatial variability, not available in other methods.

In Table 5.5 , monthly averages of actual evapotranspiration are provided for different land uses. The data provides some detailed insights that would not have been identified by traditional hydrological evaporation estimate methods. For example, at the start of the wet season, March onwards, deciduous forests and grass/shrublands show a marked increase in evapotranspiration, which makes ecological sense, as mid-level deciduous trees develop the canopies and grasses begin their growth (Hutley et al., 2022; Paudel et al., 2025).

In Figure 5.15 actual evapotranspiration for Ban Don shows little variance between the wet and dry seasons indicating it is not rainfall limited. During the dry season evergreen forests use around 400 mm of water (Table 5.5), which could only be provided by stores such as groundwater. The GRACE data (Figure 5.15) confirms the seasonal change in water storage, decreasing during the dry season as its being used and

replenished during the wet season. This highlights the strength of remotes sensing to help understand hydrological processes.

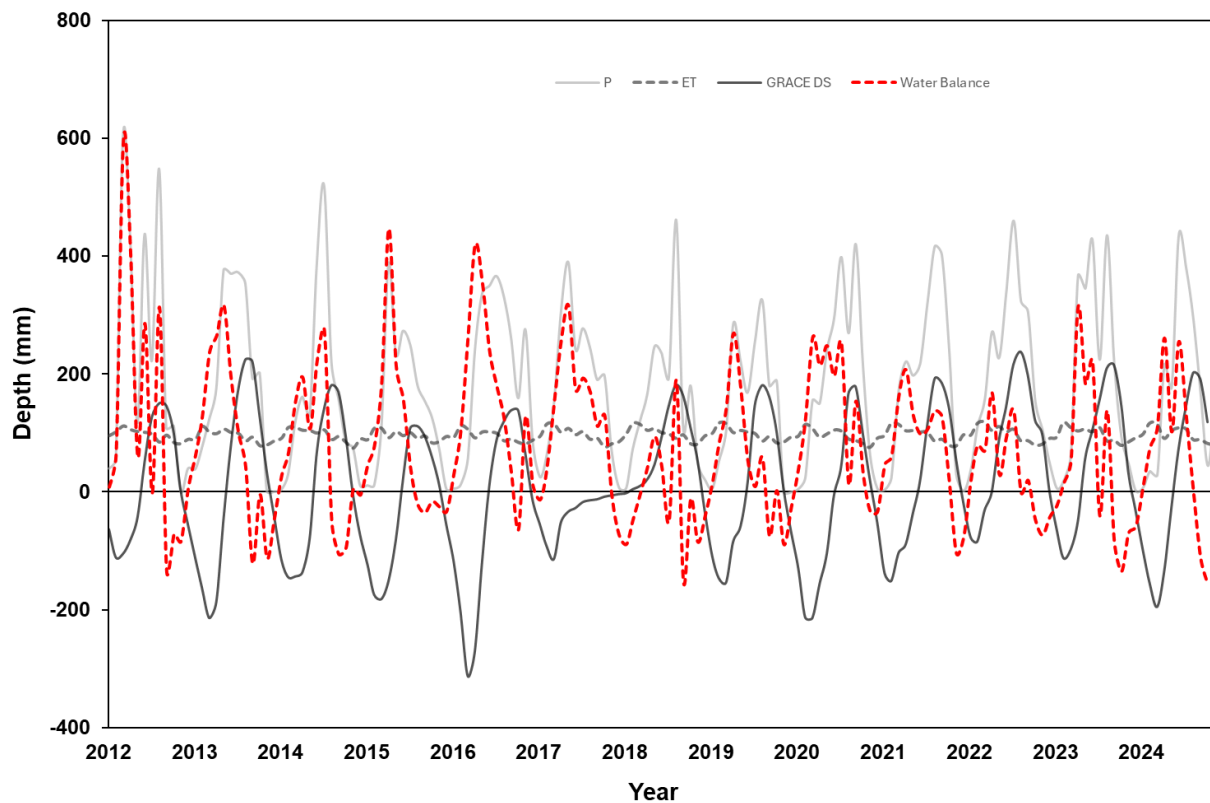


FIGURE 5.15 MONTHLY WATER BALANCE COMPONENTS FOR BAN DON FROM 2013-2024

The understanding of the natural hydrological processes provides insights into how hydrological systems will behave when perturbed by agriculture development, such as large scale clearing of native vegetation for perennial crops such as coffee. The wholesale clearing of native vegetation for agriculture in Western Australia, provided a natural laboratory of how basins adjust hydrologically when cleared (see Journal of Hydrology, Volume 94 1987). The reduction in evapotranspiration due to vegetation clearing increased groundwater recharge, resulting in rising water tables. Stream systems that were previously ephemeral also became perennial due to increased baseflow. Over time, the basins reached a new hydrological equilibrium to match climatic forcings.

Although the climatic and hydrogeological conditions of the Central Highlands differ from those of Western Australia, the underlying processes are comparable. The strong surface water-groundwater interactions evident in the Ban Don basin (Figure 5.15, Table 5.6), indicate that land use change would have significant, non-stationary effects on the basin hydrology. Clearing of deep-rooted vegetation and expansion of irrigated perennial crops alter evapotranspiration regimes, groundwater recharge patterns, and baseflow contributions. In theory, reduced natural evapotranspiration may increase recharge; however, this effect was offset by increased groundwater withdrawals for irrigated agriculture in Central Highlands, as seen in the Change in storage section.

TABLE 5.6 AVERAGE MONTH DATA FOR DIFFERENT LAND USES WITHIN THE BAN DON SUBBASIN

WA+ Categories	Protected				Utilized		Modified						Managed									
JAXA Classes	Evergreen forest		Deciduous forest		Grass/ Shrub		Other Crops		Barren		Plantation Forest		Water		Urban/Built-up		Aquaculture		Woody crops/ Orchard		Rice	
Month	P	ET	P	ET	P	ET	P	ET	P	ET	P	ET	P	ET	P	ET	P	ET	P	ET	P	ET
1	24	100	15	86	17	95	15	83	23	78	24	90	25	87	17	82	14	88	16	88	16	79
2	19	107	9	76	21	97	12	87	13	80	15	95	14	90	8	85	13	87	11	89	10	88
3	59	129	29	88	63	113	39	106	43	95	44	113	40	110	28	106	40	104	38	107	36	109
4	133	123	102	93	149	106	115	101	103	92	105	108	96	109	89	105	115	103	108	107	100	105
5	248	110	247	96	261	96	263	88	222	82	228	96	227	95	233	90	268	93	250	96	245	86
6	290	110	245	113	313	103	275	97	227	94	239	101	220	101	215	98	279	101	252	103	250	96
7	350		305	113	349	99	314	97	264	97	275	98	257	101	258	97	327	100	303	101	290	101
8	384	102	316	114	400	102	355	100	281	101	297	103	270	103	269	99	360	99	319	102	315	103
9	325	89	345	98	369	89	342	87	285	85	295	89	281	88	298	84	352	86	323	88	325	85
10	235	92	223	101	228	93	214	88	241	85	247	91	260	90	231	86	223	91	225	92	223	83
11	178	84	131	88	115	84	117	76	200	73	207	80	227	80	162	75	111	80	137	82	140	72
12	92	86	68	84	54	85	57	73	104	71	108	81	121	77	81	73	54	81	65	80	69	69
Average annual total	2337	1234	2035	1150	2339	1162	2118	1083	2006	1033	2084	1145	2038	1131	1889	1080	2156	1113	2047	1135	2019	1076

P: Average monthly precipitation (mm)

ET: Average monthly actual evapotranspiration

The Water Accounting Plus framework focuses on identifying sources of water depletion and has limited ability to partition and quantify surface and groundwater flows. One way to understand these processes is through the use of integrated surface water groundwater models. The natural hydrology under native vegetation provides the reference or starting point for the model, land use change scenarios, such as forest conversion to irrigated coffee are then introduced into the model to replicate likely responses in recharge, baseflow, storage and stream discharge. The availability of gridded earth observation data makes it feasible to calibrate soil and vegetation process parameters that would otherwise be difficult to estimate. In ungauged or data scarce basins such as the Central Highlands, remotely sensed precipitation and evapotranspiration data can be used to calibrate or constrain hydrological models and reduce uncertainty.

In many developed countries, all water resource decision making is supported using hydrological models. However, the cost of commercial hydrological software can be a barrier to adoption in low to middle income countries. Hence, open source software is becoming available that can model surface water groundwater interactions, for simpler situations like unconfined aquifers, SWAT+ with gwflow (Bailey et al., 2020), and in more complicated hydrogeological environments, coupled SWAT+ (surface water) MODFLOW (groundwater) models are available (Bailey et al., 2025). The advent of new open-source hydrological modelling tools and remote sensing data to help calibrate models provides opportunities to build capacity in hydrological modelling for water resource managers. This will then give managers the capacity to investigate the effects of climate change and other risk scenarios on water resources within basins and help with planning.

The other aspect of water accounting sheets is water productivity. The annual total biomass production for Ban Don in 2024 (Figure 5.17 a) was taken from WaPOR 3 Level 1 data on a 300 m grid. The average values for different JAXA and WA+ land use classes (Table 5.7) were also calculated. The annual net biomass water productivity, using Level 1 WaPOR 300m data, for 2024 is shown in Figure 5.17 b) and average values were calculated for different JAXA and WA+ categories (Table 5.7).

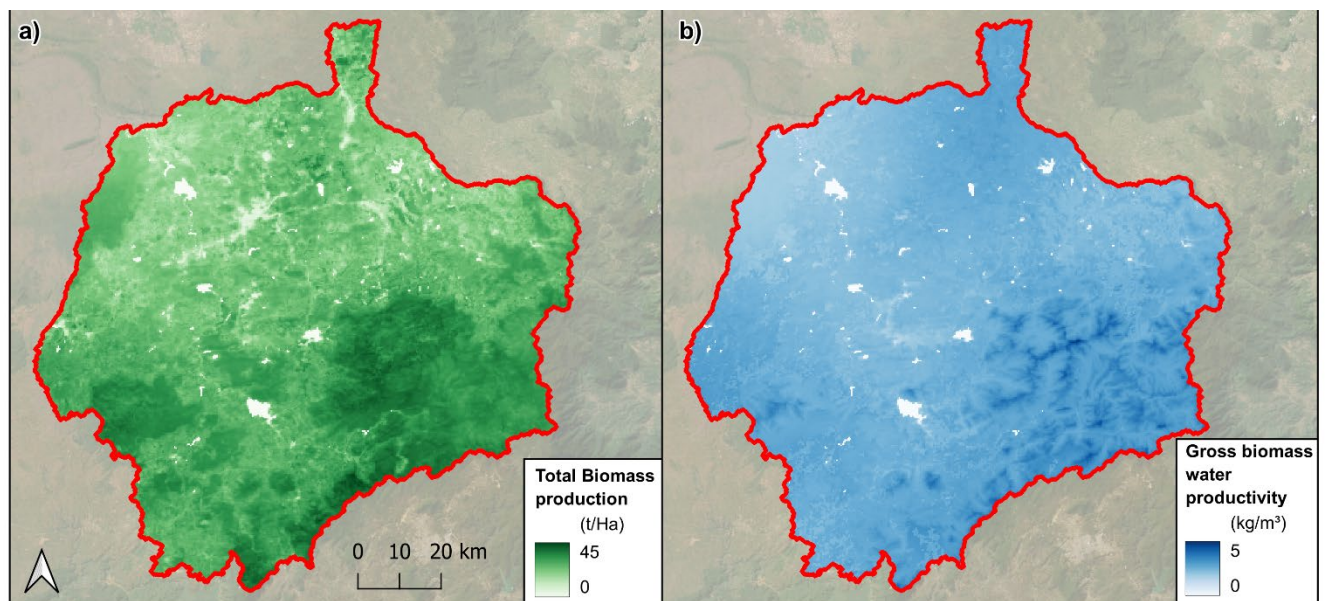


FIGURE 5.16 ANNUAL NET PRIMARY PRODUCTION, A, AND ANNUAL NET BIOMASS WATER PRODUCTIVITY, B, FOR BAN DON FOR 2024

TABLE 5.7 ANNUAL NET BIOMASS PRODUCTION AND NET BIOMASS WATER PRODUCTIVITY FOR THE BAN DON BASIN

JAXA land use classes	JAXA classes annual total biomass production (t/ha)	JAXA classes annual net biomass water productivity (kg/m ³)	Water Accounting Plus Categories	WA+ categories annual total biomass production (t/ha)	WA+ categories annual net biomass water productivity (kg/m ³)
Evergreen forest	22.3	2.1	Protected	32.1	2.8
Deciduous forest	33.4	2.9			
Grass/Shrub	27.6	2.6	Utilized	27.6	2.6
Other Crops	24.3	2.4	Modified	26.2	2.5
Barren	22.6	2.4			
Plantation Forest	26.8	2.6			
Water	15.4	1.6	Managed	23.3	2.5
Urban/Built-up	18.4	2.5			
Aquaculture	14.8	1.7			
Woody crops/Orchard	24.3	2.5			
Rice	23.6	2.3			

Table 5.7 presents the annual total biomass production and net biomass water productivity across land use classes in the basin. The highest biomass production and biomass water productivity occur in deciduous forest at 33.4 t/ha and 2.9 kg/m³ respectively. Evergreen forest also shows relatively high biomass production (22.3 t/ha) and water productivity (2.1 kg/m³), though lower than deciduous forest. Grass/shrub and plantation forest display moderate biomass production and water productivity values, reflecting their intermediate vegetation density and water use characteristics.

Among agricultural land uses, woody crops/orchards (24.3 t/ha; 2.5 kg/m³) and other crops (24 t/ha; 2.4 kg/m³) demonstrate relatively strong productivity. Rice shows moderate biomass production (23.6 t/ha) with slightly lower water productivity (2.3 kg/m³), which is consistent with higher water requirements and over irrigation practices. Aquaculture, water bodies and barren land show lower biomass production and water productivity, reflecting limited vegetation growth or non-vegetated surfaces.

When integrated into WA+ sheets, the Protected Land Use (PLU) category (primarily forest areas) records the highest total biomass production (32.1 t/ha) and highest biomass water productivity (2.8 kg/m³). The Modified Land Use (MLU) and Utilized Land Use (ULU) categories show intermediate levels of biomass production (26.2 and 27.6 t/ha, respectively) and comparable water productivity values (2.5-2.6 kg/m³). The Managed Water Use (MWU) category, which includes irrigated agricultural areas, records slightly lower total biomass production (23.3 t/ha) but maintains moderate water productivity (2.5 kg/m³).

From the water accounting perspective, these results suggest that:

- A significant share of basin water consumption is allocated to managed agricultural land.
- Variations of biomass water productivity across crop types indicate scope for optimization of irrigation scheduling and water allocation, especially when droughts occur.
- Improving water productivity in irrigated systems, particularly for rice and other high water demand crops could reduce the overall consumptive water use without compromising production.
- Spatial targeting of interventions (e.g., drought management, deficit mitigation, improved irrigation methods, crop selection) could enhance agricultural water efficiency at subbasin scale.

To conclude, the biomass water productivity analysis reinforces the importance of linking evapotranspiration-based water accounting with crop productivity assessment. For the Ban Don basin, strengthening irrigation efficiency and crop water management within the MWU category offers a practical pathway to improving basin level water sustainability while maintaining agricultural output.

To test the reproducibility of water accounting frameworks different remote sensing datasets and methodologies were used to derive water accounts for the Ban Don basin. Monthly and annual WaPOR actual evapotranspiration (Level 1 AETI) and precipitation data for 2018-2019 were used to derive water balances for the Ban Don basin. In the first method monthly water balances for three subbasins of the Ban Don (Giang Son, Duc Xuyen and Lower Ban Don) were calculated and summed to derive the total water balance for the Ban Don basin (Table 5.8). In the second method, monthly water balances were calculated for the whole basin using WaPOR. The above approaches were then compared with water balances derived from annual WaPOR data and the CHIRPS / SSEBop data (Tables 5.8 and 5.9).

The monthly and annual evapotranspiration totals for all methods using WaPOR data gave similar totals approximately between 11.3 and 11.5 km³ for 2018 and between 12.01 and 12.06 km³ for 2019. There were major differences in the WaPOR precipitation totals when comparing summed monthly and annual totals, 18.33 and 20.10 km³ respectively for 2018 and 14.8 and 19.6 km³ respectively for 2019 (Table 5.8).

TABLE 5.8 CALCULATION OF ANNUAL WATER BALANCES USING TWO DIFFERENT REMOTE SENSING DATASETS FOR 2018 AND 2019

	Gross inflow Precipitation	Inflow (QGW+QSW)	dS (GRACE)	Net inflow	Protected -rainfall	Utilised - rainfall	Modified - rainfall	Managed - rainfall	Total ET - rainfall	Protected - utilised	Utilised- utilised	Modified - utilised	Managed - utilised	Total ET - utilised	Total ET	Outflow (QGW+QSW)
2018																
Giang Son	5.16	0.00	2.70	2.45	0.81	0.05	0.34	1.35	2.56	0.17	0.01	0.07	0.35	0.60	3.17	-0.71
Duc Xuyen	5.71	0.00	2.51	3.19	1.61	0.11	0.19	0.84	2.75	0.41	0.03	0.06	0.24	0.73	3.48	-0.29
Lower Ban Don	7.47	0.00	2.62	4.85	1.01	0.05	0.12	2.31	3.50	0.43	0.02	0.04	0.85	1.34	4.84	0.01
Total Ban Don	18.33		7.84	10.50	3.43	0.22	0.66	4.50	8.80	1.01	0.06	0.17	1.44	2.68	11.48	-0.99
WAtotal†	20.10	0.00	8.76	11.34	3.73	0.24	0.73	5.06	9.77	0.92	0.06	0.17	1.68	2.83	12.59	-1.25
2019																
Giang Son	3.86	0.00	0.25	3.61	0.71	0.05	0.31	1.21	2.27	0.38	0.03	0.16	0.59	1.16	3.43	0.18
Duc Xuyen	4.85	0.00	-0.07	4.92	1.46	0.10	0.18	0.79	2.53	0.68	0.04	0.08	0.33	1.13	3.66	1.26
Lower Ban Don	6.13	1.44	0.18	7.38	0.98	0.05	0.12	2.23	3.38	0.50	0.03	0.05	1.01	1.59	4.97	2.41
Total Ban Don	14.83		0.36	14.47	3.14	0.20	0.60	4.23	8.18	1.56	0.09	0.29	1.93	3.88	12.06	2.41
WAtotal†	19.66		0.39	19.28	3.41	0.24	0.66	4.50	8.81	1.23	0.07	0.25	2.24	3.80	12.60	6.67

†WAtotals are CHIRPS/ SSEBop totals calculated for the WA+ sheets

TABLE 5.9 COMPARISONS OF CALCULATED WATER BALANCES FOR THE BAN DON BASIN USING DIFFERENT METHODOLOGIES FOR THE YEARS 2018-2019

	Gross inflow Precipitation	dS (GRACE)	Net inflow	Protected - total	Utilised - total	Modified - total	Managed – total	Total ET	Outflow (QGW+QSW)
2018									
WaPOR - annual	20.10	9.02	11.08	4.39	0.28	0.81	5.86	11.34	-0.26
WaPOR monthly	18.33	7.84	10.50	4.44	0.28	0.83	5.93	11.48	-0.99
WAtotal [†]	20.10	8.76	11.34	4.65	0.30	0.90	6.74	12.59	-1.25
2019									
WaPOR - annual	19.63	0.28	19.35	4.68	0.30	0.89	6.18	12.05	7.58
WaPOR – Ban Don monthly [*]	14.87	0.28	14.60	4.68	0.34	0.93	6.07	12.01	2.86
WaPOR summed subbasins [#]	14.83	0.36	14.47	4.71	0.30	0.89	6.16	12.06	2.41
WAtotal [†]	19.63	0.28	19.36	4.64	0.31	0.91	6.93	12.80	6.84

^{*} WaPOR monthly totals summed for the Ban Don basin

[#] The summed monthly totals for subbasins (Giang Son, Duc Xuyen and Lower Ban Don) were totalled

[†] WAtotals are the CHIRPS/ SSEBop totals calculated for WA+ sheets

There were also differences in evapotranspiration totals between the SSEBop and WaPOR data. The total evapotranspiration for 2018 using SSEBop was 12.59 km³ compared with 11.4 km³ using WaPOR data. The ET results were closer for 2019 with total evapotranspiration using SSEBop, being 12.8 km³ and 12.05 km³ for WaPOR Table 5.9). The annual precipitation totals were similar as both used CHIRPs data.

The total changes in storage, estimated using the downscaled GRACE method also varied across the different approaches but all were in similar ranges. The largest source of difference was in the precipitation estimates. Given the differences in totals between the different datasets, remote sensing data needs to be compared against terrestrial data especially the precipitation measurements.

When developing hydrological models using remote sensing data as the main inputs, evapotranspiration is relatively robust, precipitation could be problematic and ideally validated with terrestrial data. GRACE data is too crude for calibration but can be used to help validate the outputs of a hydrological model, particularly changes in groundwater storage.

5.2.4 Krong BUK

5.2.4.1 REMOTE SENSING DATA

EVAPOTRANSPIRATION AND PRECIPITATION

ID	Remote Sensing data	Name	Spatial resolution	Data type	Time collected
1	Precipitation	CHIRPS	~ 5km (0.05°)	Daily/Monthly	2024
2	Evapotranspiration - Transpiration (T) - Evaporation (E) - Interception (Int)	ETLook	20m	Daily	2024
3	Biomass	ETLook	20m	Daily	2024
4	Soil moisture	ETLook	20m	Daily	2024

The method to calculate evaporation (E) and transpiration (T) is based on the ETLook model as outlined by (Bastiaanssen et al., 2012). This model is based on the Penman-Monteith (P-M) method with remote

sensing as input data. Originally developed by Penman (1948), this approach has been employed by FAO as the standard method for calculating crop reference evapotranspiration (Allen et al., 1998).

5.2.4.2 WATER ACCOUNTING SHEETS

Similar to the case of Ban Don, sheet 1 was generated for Krong Buk subbasin summarizing the annual water resources balance for 2024, expressed in km³/year. The sheet presents the source of water inflows, its utilization and depletion within the basin, and the resulting outflows. The basin receives a total gross inflow of 1.2 km³/year, primarily from advective precipitation (1.1 km³/year), with a small contribution from recycled precipitation (0.1 km³/year). After accounting for storage change (−0.1 km³/year), the net inflow is 1.1 km³/year, representing the effective volume of water available within the basin during the accounting year.

Sheet 1: Resource Base (km³/year)

Basin: Krong Buk Basin
Period: 2024

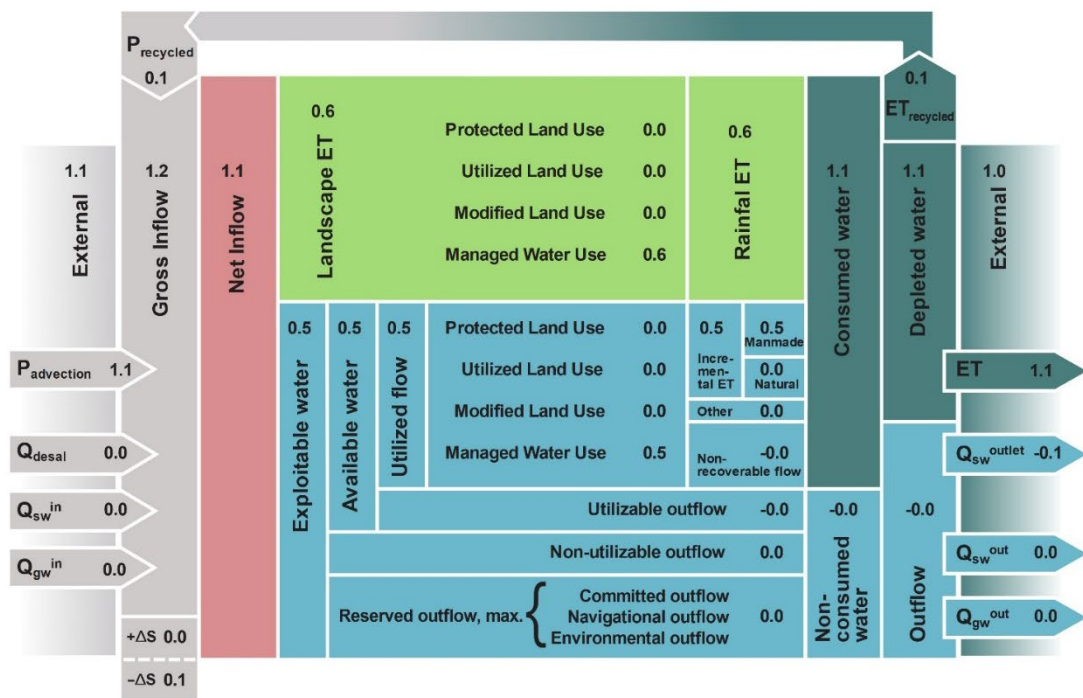


FIGURE 5.16 WATER ACCOUNTING PLUS SHEET 1 IN 2024 OF KRONG BUK BASIN

ET represents the dominant pathway of water depletion. ET for different land uses for Krong Buk is shown in Figure 5.19. The total ET amounts to 1.1 km³/year associated with managed land use (Figure 5.19). Rainfall provides 0.6 km³/year and the irrigation is 0.5 km³/year. Therefore, the basin has limited exploitable and available water, reflecting its relatively small size and hydrological setting. Of the total water entering the basin, there is no utilisable outflow as all water is consumed within the basin. Total consumed water amounts to 1.1 km³/year indicating that most consumed water is effectively removed from immediate reuse within the basin through evapotranspiration. This reflects the intensive land and water use in the subbasin.

Overall, the resources base sheet revealed that:

- The basin is highly dependent on precipitation, and ET accounts for all of the available water.

- Water availability is tightly constrained, emphasising the importance of careful allocation, irrigation efficiency improvements, and groundwater monitoring.

The resource base sheet provides a critical foundation for evaluating water productivity, allocation sustainability, and operational decisions.

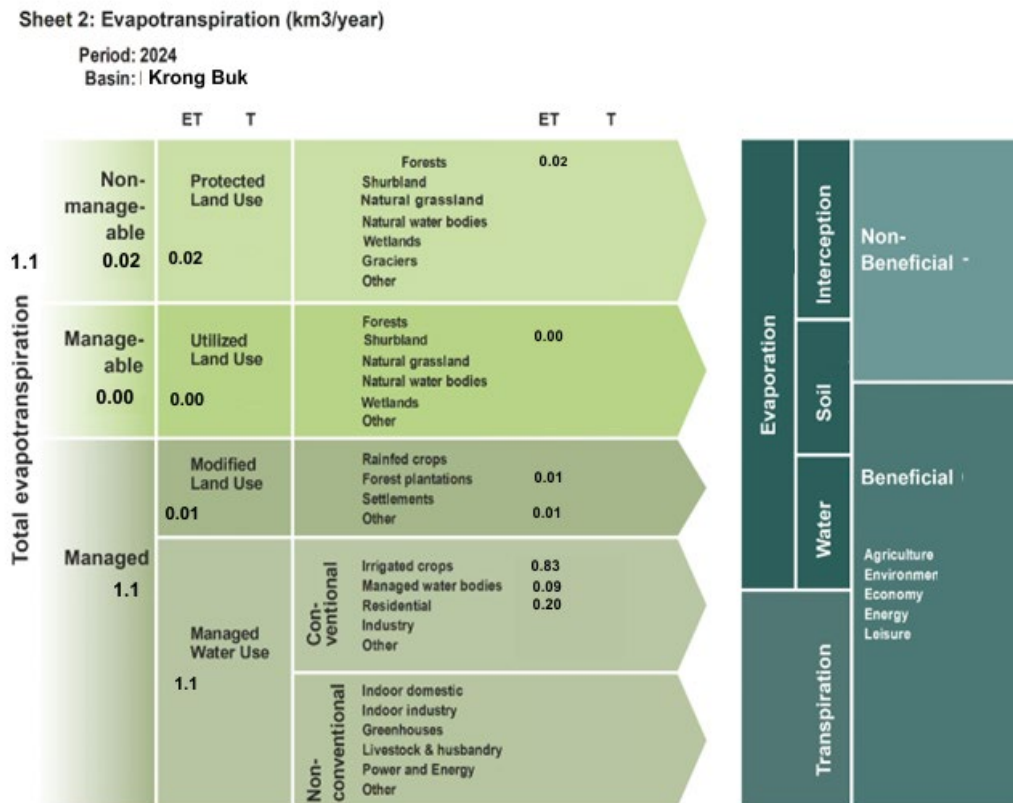


FIGURE 5.17. WATER ACCOUNTING PLUS SHEET 2 IN 2024 OF KRONG BUK BASIN

Apart from precipitation, ET and biomass data, an important issue which was raised during the consultation workshops was the need to improve water accounting for reservoirs. Reservoirs are crucial for water supply and irrigation and improved water accounting routines can help with improved water allocation and supply capacity.

As the reservoir was constructed several decades ago, the original design information and capacity estimates are no longer fully aligned with current conditions. The purpose of this analysis is to reassess and update the reservoir's water level–area–capacity relationships, providing an improved and reliable basis for estimating storage capacity and supporting reservoir operation and water management decisions.

Google Earth Engine was used to calculate the reservoir's surface area using Sentinel-1 and Sentinel-2 remote sensing imagery with a resolution of 10m, collected between 2015 and 2021, combined with actual water level monitoring data from the Department of Water Resources, to determine the reservoir's capacity (Figure 5.20).

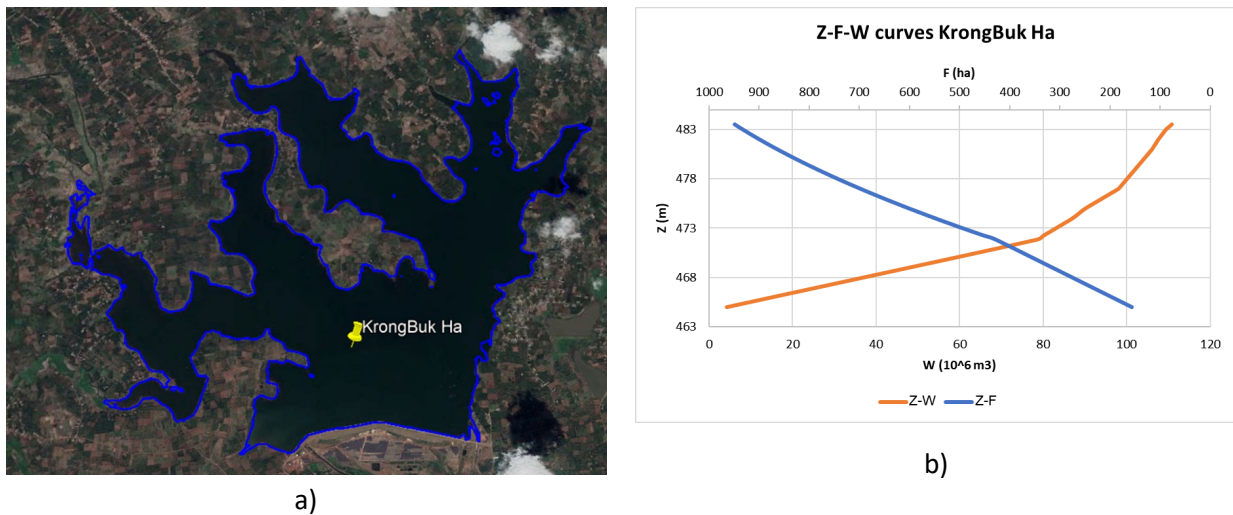


FIGURE 5.18. KRONG BUK HA RESERVOIR WATER BOUNDARY (A) AND RATING CURVE (B) DERIVED FROM REMOTE SENSED SURFACE AREA USING SENTINEL IMAGES

5.2.5 IRRIGATION CLUSTER

5.2.5.1 REMOTE SENSING DATA

Remotely sensed ET and biomass maps provide important insights into water use and crop performance within the irrigation clusters. These datasets support subbasin water accounting by identifying patterns of consumptive water use, irrigation efficiency, and potential areas of water stress or inefficiency.

The cluster area covers approximately 1.88 km², located downstream of Krong Buk Ha reservoir, and is a paddy field. The 2024 ET map for the irrigation cluster (Figure 5.21 a) illustrates the spatial distribution of ET across the irrigation cluster. The average evapotranspiration across the irrigation cluster is approximately 1700 mm/year. Though ET values vary across the command area, reflecting differences in crop type, irrigation intensity, soil moisture content, and management practices. Higher ET zones generally correspond to actively irrigated and productive agricultural areas, while lower ET areas may indicate fallow land, limited irrigation supply, crop stress, or lower water demand. The spatial distribution observed in the cluster highlights the importance of fine-scale monitoring, as aggregated basin-level averages may mask significant intra-cluster differences in water consumption.

Biomass distribution for 2024 (Figure 5.21b) complements the ET analysis by providing an indicator of vegetation growth and productivity with the average of biomass of 19.4 tons/ha. Areas with higher biomass typically correspond to well-managed and adequately irrigated plots, while lower biomass zones may indicate reduced crop performance due to water stress, soil limitations, crop type differences, or management constraints. When interpreted together, ET and biomass data allow for assessment of water productivity patterns at cluster scale.

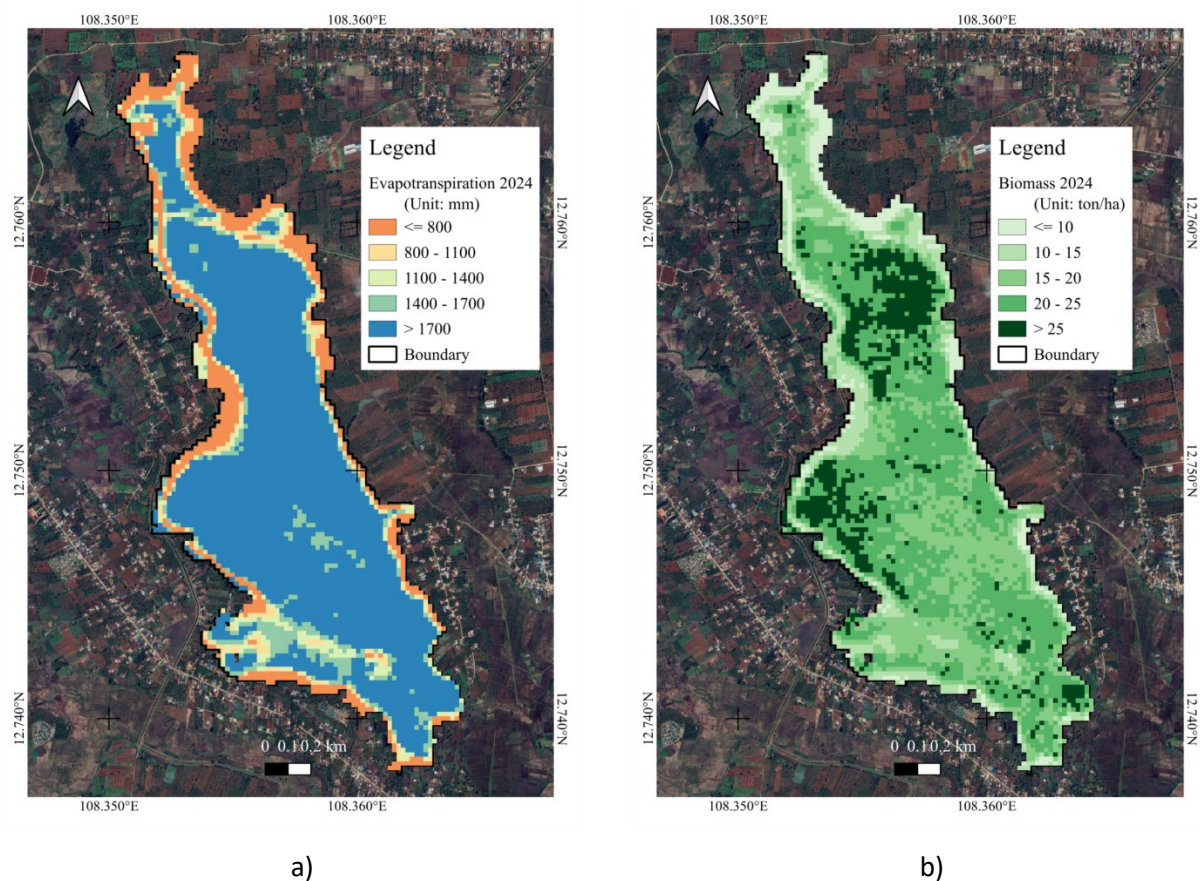


FIGURE 5.19. EVAPOTRANSPIRATION (A) AND BIOMASS (B) MAPPING IN 2024 OF IRRIGATION CLUSTER

In the context of water accounting, ET represents the primary component of consumptive water use. Therefore, explicit spatial mapping of ET improves the estimation of depleted water within the irrigation command area. Biomass mapping when analysed alongside ET, provides a proxy for evaluating whether water consumption is translating into productive agricultural outputs. This relationship is particularly relevant for assessing water productivity and guiding improvements in irrigation efficiency. The biomass production provides a broad overview though when combined with specific crop land use data then estimates of crop yield, and economic benefits, can be obtained (Figure 5.22 a). This can be used to guide crop management practices through the identification of high and low performing areas. The biomass and yield data can be combined with evaporation data to derive water productivity estimates. Total biomass production divided by actual evapotranspiration provides information on biomass production per cubic metre of water used (Figure 5.22 b) and identifies areas of high and low productivity so better manage water resources. For example, when combined with land use data can identify areas where the high productivity is due to weeds or other non-beneficial uses or water evaporating from bare soil. When yield data is combined with actual evapotranspiration (Figure 5.22c) it also identifies high and low productivity which can lead to over or under irrigated areas as well as identification of areas that need improved agronomic inputs. Thus, helping to guide operational and management decisions for the area.

The combined analysis of ET and biomass support several irrigation management functions, including:

- Identifying areas with over- or under-irrigation.
- Assessing relative irrigation performance across different zones.
- Detecting potential water stress hotspots during dry season.
- Supporting planning of water allocation and distribution within the irrigation cluster.

The formula for calculating water productivity is:

$$WP = Y/ET \text{ (kg/m}^3\text{)}$$

Which:

+ WP is water productivity (kg/m³)

+ Y is Yield (ton/ha), $Yield = HI \times AOT \times fc \times (TBP / (1 - mc))$

Where HI is harvest index (average for rice is 0.5), AOT is above ground over total biomass production ratio where the average for rice is 0.81, fc is light use efficiency taken to be 1 (one), TBP is total biomass production derived from ETlook, and mc is moisture content the average for rice is 0.2.

+ ET is total Evapotranspiration (mm), this amount of evapotranspiration is considered as the amount of water consumed during the growth process.

Calculation table for evaporation, biomass by month, and yield, water productivity of cluster in 2024.

Date	ET (mm)	Biomass (ton/ha)
Jan-24	152.90	3.73
Feb-24	295.97	4.06
Mar-24	347.45	3.12
Apr-24	296.77	1.91
May-24	142.29	0.76
Jun-24	51.62	0.50
Jul-24	54.71	1.00
Aug-24	167.77	3.01
Sep-24	108.23	1.64
Oct-24	26.66	0.17
Nov-24	152.89	1.12
Dec-24	26.97	0.02
Total	1824.21	21.03
Yield (ton/ha)		10.6
Water Productivity (kg/m3)		0.58

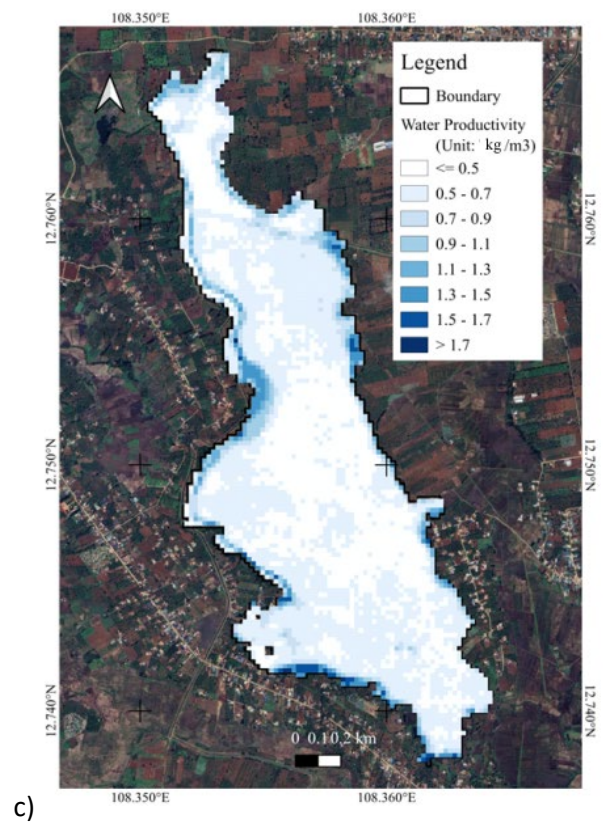
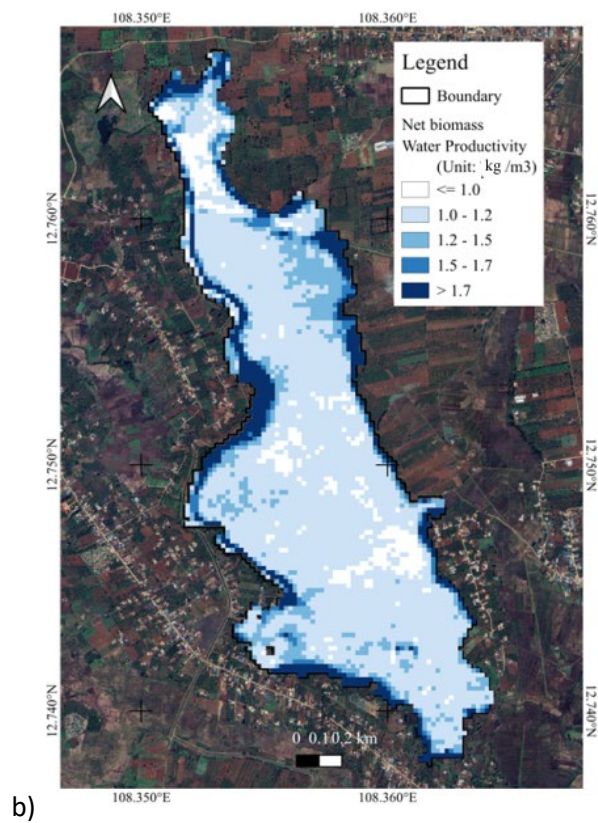
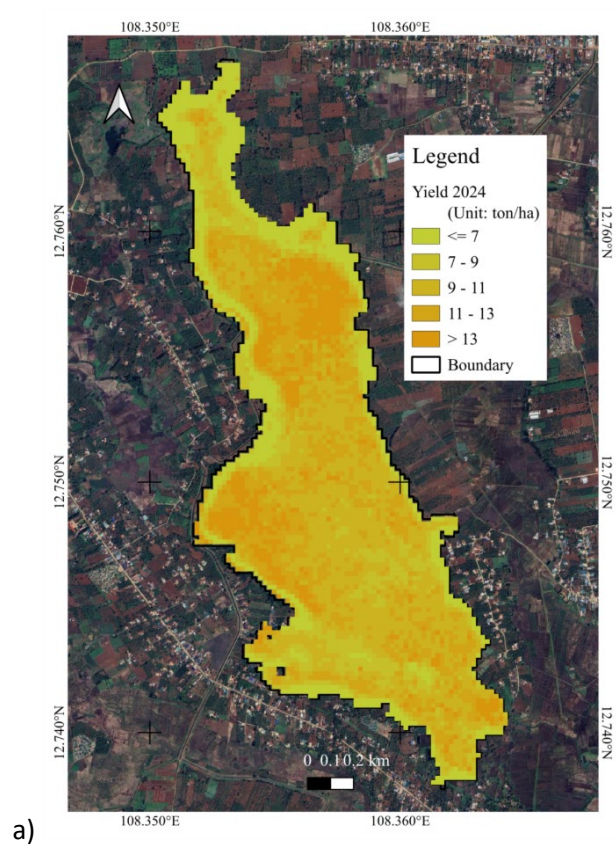


FIGURE 5.20 CROP YIELD (A); NET BIOMASS WATER PRODUCTIVITY MAPPING (B) AND WATER PRODUCTIVITY (C) OF IRRIGATION CLUSTER IN 2024

5.3 SIMPLIFIED TOOLS AND TRAINING

There are existing training programs in the use of Water Accounting Plus as well as the use of remote sensing data such as WaPOR products developed by IHE Delft (see the following link <https://ocw.un-ihe.org>). The training programs use Python code which freely available at a Github repository (<https://github.com/wateraccounting>). The IHE-Delft training programs require a basic knowledge of Python. The feedback from surveyed stakeholders found this approach complex. Therefore, as part of the ACIAR project, an alternative approach was developed based around the use of an open-source GIS environment, QGIS. GIS tools were specifically developed to help make water accounting and analysis of remote sensing data more accessible. Remote sensing data can be imported directly into GIS using plugins and or downloaded from websites and imported into the GIS

The GIS tools developed do a range of functions:

- i) Basin land use / land cover tool (Figure 5.24), using basin and land use GIS layers, calculates different land uses and areas within basins for later analysis
- ii) Basin statistics tool (Figure 5.25) uses remote sensing data inputs to calculate statistics for different basin land uses
- iii) Basin error correction tool (Figure 5.26) which can correct any common error that could prevent the downloading of remote sensing data.

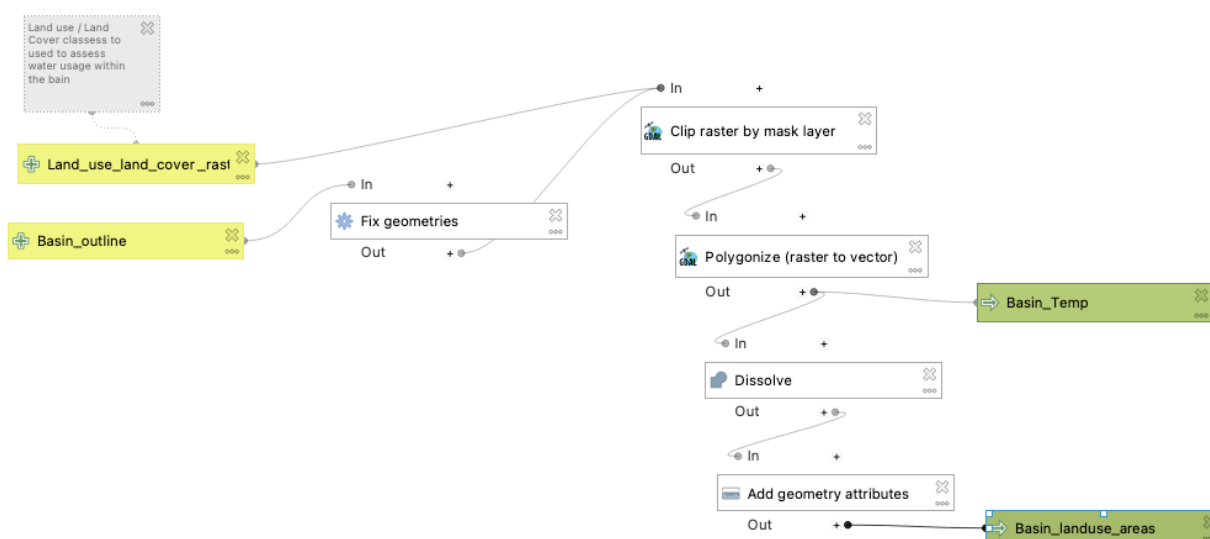


FIGURE 5.21 QGIS MODEL THAT DEVELOPS LAND USE / LAND COVER LAYER AND CALCULATES AREAS OF DIFFERENT LAND USES FOR BASIN

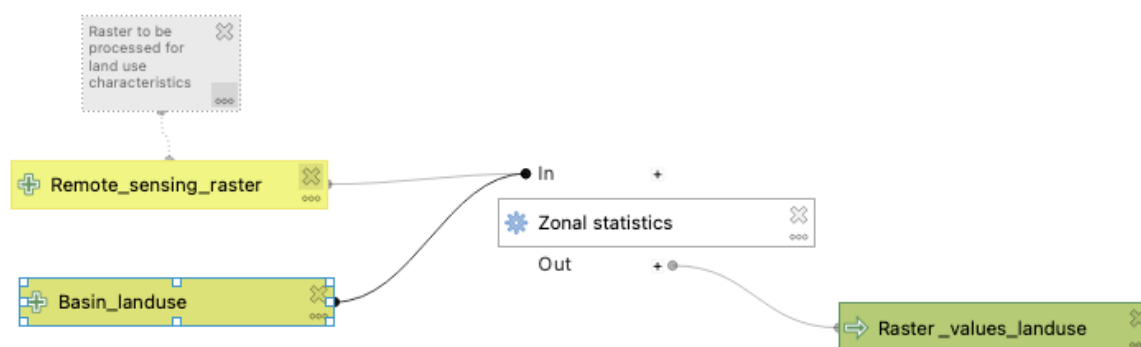


FIGURE 5.22 QGIS MODEL THAT CALCULATES REMOTE SENSING STATISTICS FOR DIFFERENT LAND USES

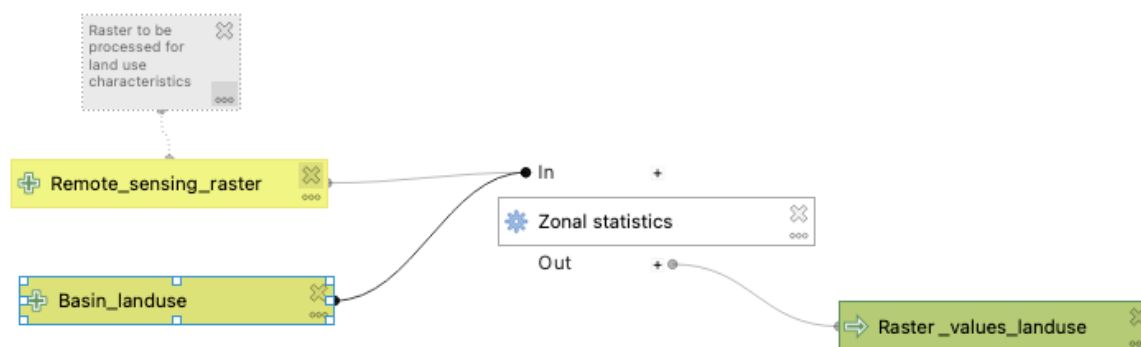


FIGURE 5.23 QGIS MODEL TO CORRECT ANY COMMON ERRORS THAT COULD PREVENT THE DOWNLOADING OF WAPOR REMOTE SENSING DATA

The hydrological data derived from remote sensing data in the GIS is further analysed in spreadsheets to derive basin water balances.

Training resources and activities on how to obtain remote sensing data and how to calculate hydrological water balances for Water Accounting using the GIS tools was developed. This was delivered with stakeholders during a half-day training workshop in November, prior to the final stakeholder workshop. This ensured the participants at the stakeholder workshop were sufficiently familiar with the remote sensing and water accounting tools to offer informed perspectives on them. These perspectives are reflected in the following section.

6. STAKEHOLDER ENGAGEMENT WITH REMOTE SENSING AND WATER ACCOUNTING IN VIET NAM

After the initial stakeholder interviews, two workshops were held in September and November 2025. These workshops provided opportunities to inform and update stakeholders on current remote sensing and water accounting technologies and their potential applications, while simultaneously enabling the proactive collection of their updated and more informed perspectives.

The workshops engaged two distinct stakeholder groups. The September workshop focused on stakeholders from the Srepok River Basin, including provincial government officials, irrigation management company (IMC) representatives, and researchers from local institutions. The second group, engaged during the November workshop, comprised stakeholders from other regions—namely the Mekong and Northern provinces—including IMC representatives and provincial government officials.

During and after each workshop, the opinions of stakeholders was gathered in a number of ways:

- Post workshop surveys to capture individual awareness and perspectives on the applications of remote sensing and water accounting, anonymously.
- Group discussions and individual qualitative and semi-quantitative feedback via structured activities (e.g. to assess Usefulness, Usability, Accessibility, and Interest).
- Open, semi-structured discussion with participating stakeholders, particularly regarding future steps to progress remote sensing and water accounting in Viet Nam.

6.1 POST TRAINING & WORKSHOP SURVEYS

6.1.1 REMOTE SENSING PERSPECTIVES

AWARENESS OF REMOTE SENSING

SREPOK BASIN STAKEHOLDERS:

Survey results show varying levels of familiarity with remote sensing with the majority having never used remote sensing (more than 85%). Particularly, 7% of the participants had never heard of it; 43% had heard of it but knew very little, 36% knew about it but had never used it. Among the 14% who were familiar but not for water-related applications, none had direct experience using RS for water management. This suggests that while remote sensing is not new to most participants, practical applications remain limited.

MEKONG/ NORTHERN PROVINCIAL STAKEHOLDERS:

Similar to the Srepok Basin stakeholders, survey results for the Mekong/Northern provincial stakeholders indicate that most participants had little to no practical experience with remote sensing prior to the workshop, despite a wider range of familiarity levels. Specifically, 14% had never heard of remote sensing, 43% had heard of it but knew very little, and 29% were familiar with remote sensing but had not used it. Only 14% of respondents had prior experience using remote sensing, all of which was related to water data.

As with the first group, these findings suggest general awareness of remote sensing but limited hands-on experience in water management applications.

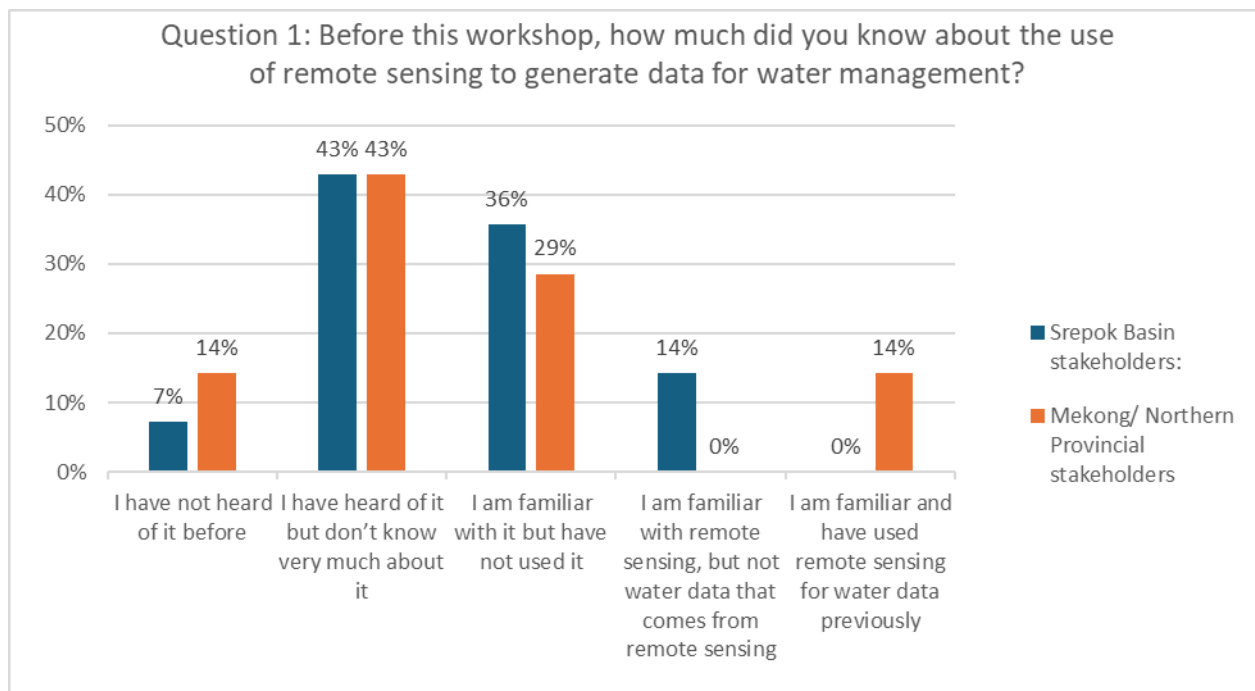


FIGURE 6.1 FAMILIARITY WITH REMOTE SENSING PRIOR TO THIS PROJECT

PERCEIVED USEFULNESS

SREPOK BASIN STAKEHOLDERS:

All respondents (100%) agreed that remote sensing is useful for water management in Viet Nam, and 93% also considered it useful for their own professional tasks.

MEKONG/ NORTHERN PROVINCIAL STAKEHOLDERS:

Similarly, all respondents (100%) from Mekong and Northern regions agreed that remote sensing data would be useful for water management in Viet Nam. Furthermore, 83% believed that remote sensing data would be useful for their own job tasks, while 17% considered it somewhat useful or of limited usefulness.

This reflects strong perceived value of remote sensing both at the national policy level and within daily professional practice at a local government level.

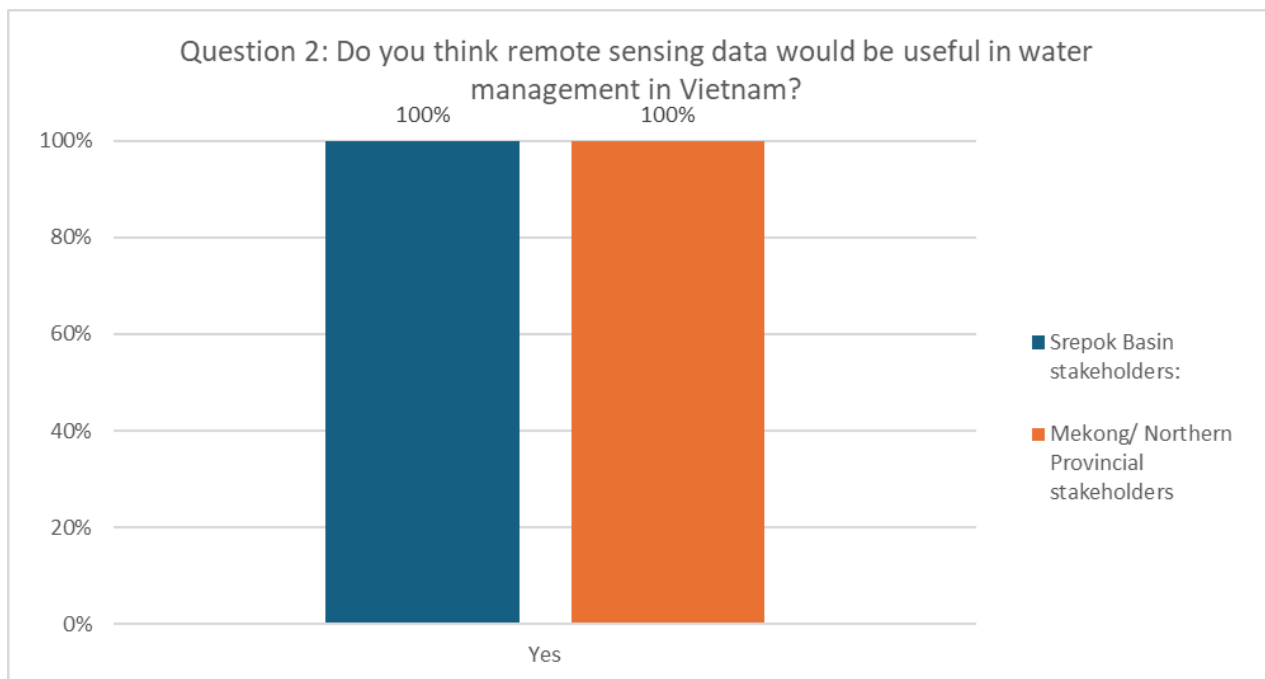


FIGURE 6.2 PERCEIVED USEFULNESS OF REMOTE SENSING FOR VIET NAM WATER MANAGEMENT

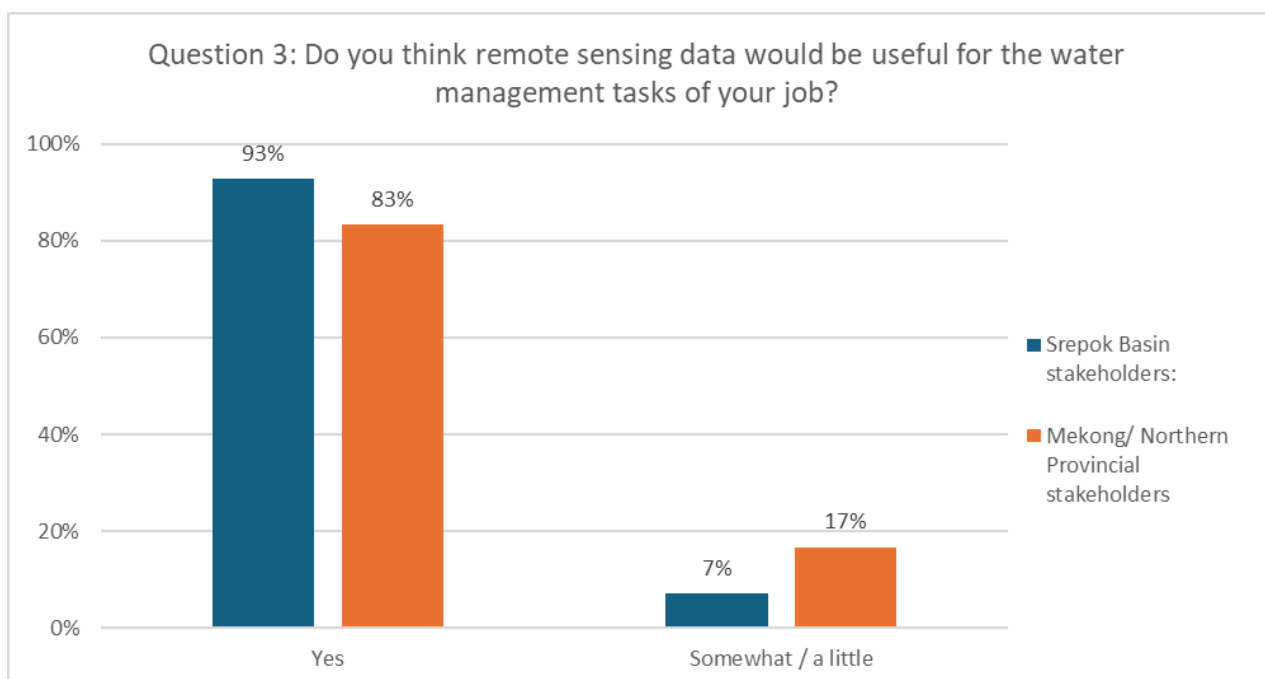


FIGURE 6.3 PERCEIVED USEFULNESS OF REMOTE SENSING DIRECTLY FOR EXISTING JOBS IN WATER MANAGEMENT

GIS CAPACITY

SREPOK BASIN STAKEHOLDERS:

There was a disparity between general awareness and practical application. While 71% of stakeholders reported some familiarity with GIS, this knowledge is largely superficial; only 7% have utilized the technology for actual water management. Furthermore, a small 7% remain entirely unaware of the tool.

MEKONG/ NORTHERN PROVINCIAL STAKEHOLDERS:

The November follow-up reinforced these gaps, showing a hierarchy of limited engagement despite universal basic awareness. While 100% of respondents have heard of GIS, 43% lack understanding of its functions. The remaining stakeholders are split between general familiarity and those who understand the

tool but have never applied it to their sector. Critically, the survey recorded a 0% rate of operational GIS use for water management.

These findings highlight that while the professional community acknowledges the theoretical importance of GIS (and similarly remote sensing), there is a clear disconnect between "knowing" the technology and "deploying" it. Unless this systemic gap in technical capacity is addressed, it will remain difficult to meaningfully integrate remote sensing and GIS into regional decision-making.

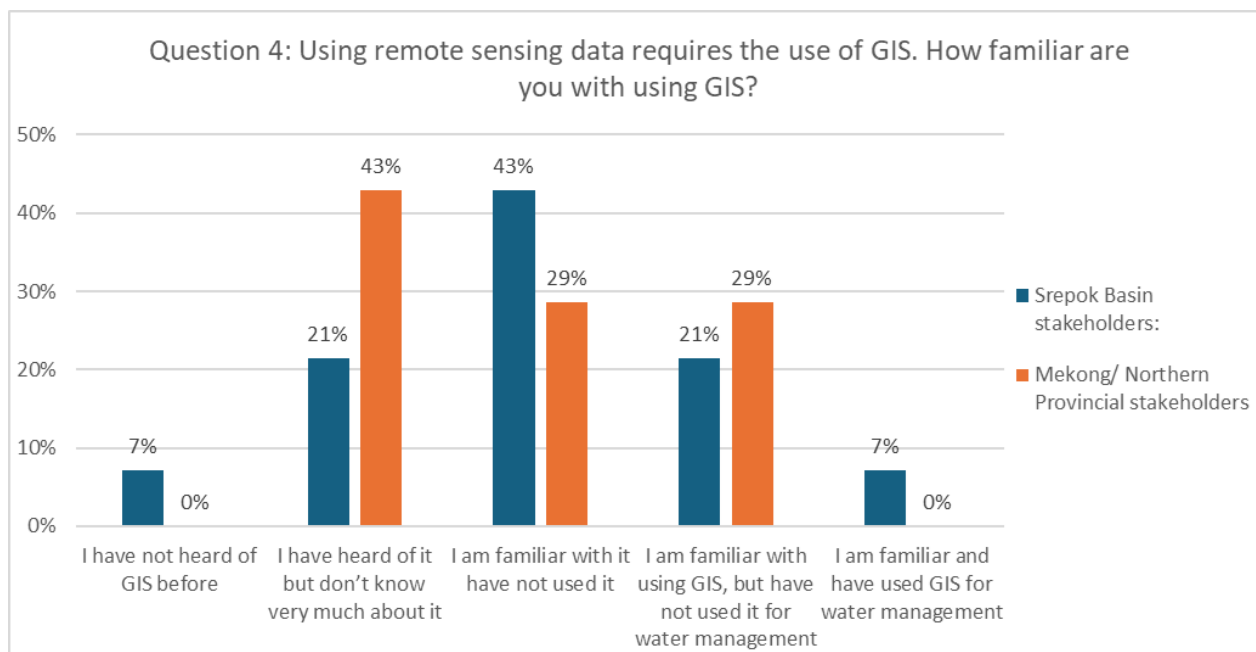


FIGURE 6.4 FAMILIARITY WITH GIS

PREFERRED MECHANISM TO ACCESS REMOTELY SENSED DATA

6.1.1.1.1.1 SREPOK BASIN STAKEHOLDERS:

Significant majority (**93%**) of stakeholders expressed a preference for receiving processed datasets and reports from specialized institutions/divisions. This high percentage highlights the perceived value of expert support in complex data interpretation. In contrast, only **7%** felt confident in their ability to independently learn and master GIS tools for direct remote sensing analysis. This signals a substantial skills gap and a clear opportunity for targeted technical development.

6.1.1.1.1.2 MEKONG/ NORTHERN PROVINCIAL STAKEHOLDERS:

Likewise, strong preference for centralized expert support remained the dominant theme. Approximately **86%** of respondents preferred that specialized teams produce water data and share it as management-ready reports, while only **14%** believed their own teams could eventually analyze remote sensing data independently.

Collectively, these results indicate that most regional stakeholders currently view their roles as "**data users**" rather than "**data producers**." This widespread reliance on external expertise emphasizes the critical need for **intermediary technical institutions/divisions/teams** to bridge the gap between complex satellite raw data and practical water management applications.

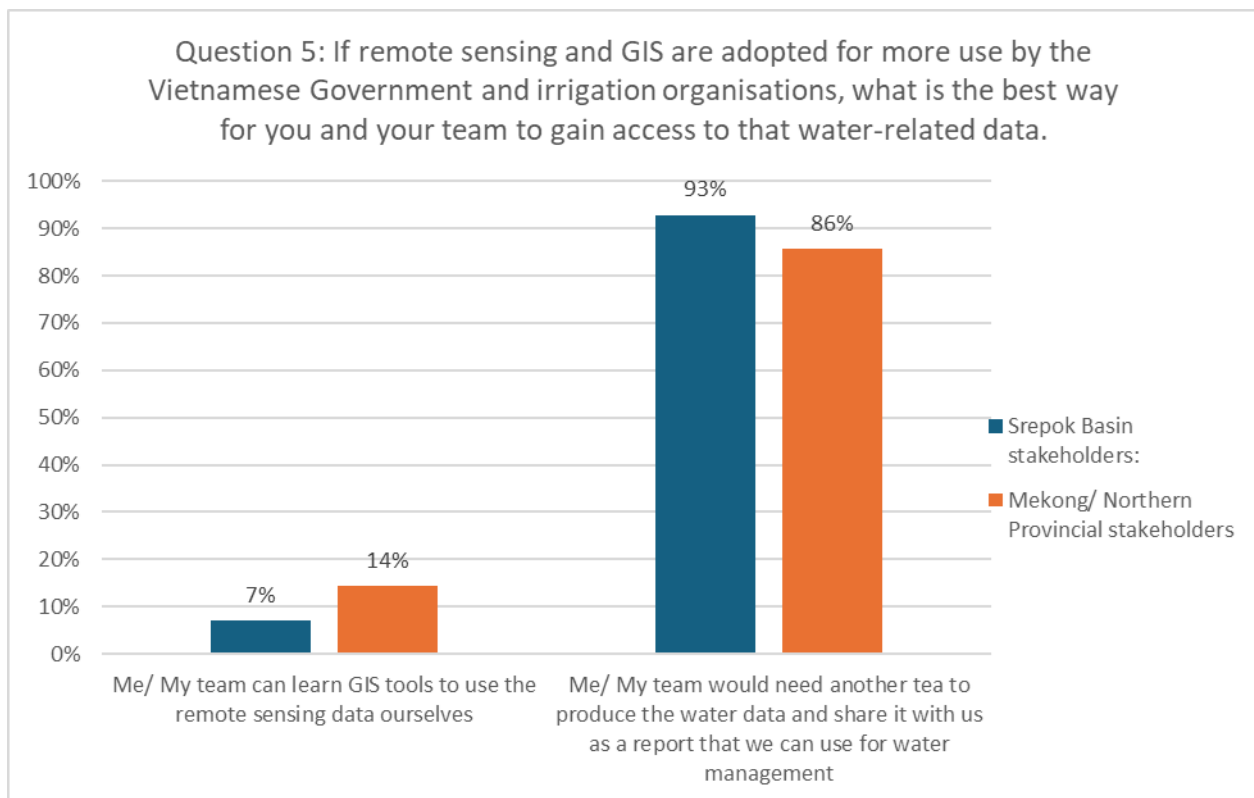


FIGURE 6.5 PREFERRED MECHANISM TO ACCESS SPATIAL WATER DATA

THE NEED FOR USING REMOTE SENSING TO GENERATE WATER DATA FOR VIET NAM WATER MANAGEMENT

Respondents were asked for any other feedback or comments regarding the use of remote sensing to generate water data for Viet Nam water management. The following are the key points raised.

Efficiency and Timeliness: The stakeholders from both regions shared parallel expectations that remote sensing should be applied more widely to support the entire lifecycle of water management—from assessment to early warnings of disasters.

- Srepok stakeholders emphasized that remote sensing makes planning and operations more *"timely and cost-effective"*.
- Similarly, the Mekong/Northern stakeholders viewed the technology to improve *"operational efficiency"* while saving management costs.

The need for accurate validation of the data:

- Srepok stakeholders suggested that greater confidence and accuracy of remotely sensed data is needed. They shared that *"accuracy issues might remain."* There is a need to integrate remote sensing with ground-based monitoring, at least to ensure confidence and provide ongoing quality assurance (of both remotely sensed and ground-based data).
- The Mekong/Northern participants agreed that while remote sensing provides extensive spatiotemporal coverage, it *"must be combined with ground-based data"* to be legally and practically viable for Viet Nam's water management standards.

Knowledge Transfer: The most common perspective between the two groups of stakeholders was the urgent demand for standardized capacity development.

- Srepok stakeholders requested *"specific instructions, detailed training courses, and user manuals"* for learning.

- Mekong/Northern stakeholders shared that "specific guidance documents" and "free-to-use software" are necessary to democratize access.
- Both groups are essentially asking for a unified national curriculum that enables local officials to transition from being passive observers to active tool operators and/or data users.

Operational Infrastructure: Both cohorts expressed a nearly identical desire for a complete remote sensing tool platform or "Ready-to-Use" Tools characterized by:

- Open-Source Data: A mutual preference for free satellite sources (like Sentinel or Landsat) to avoid licensing barriers.
- Centralized Processing: Both regions prefer a workflow where raw data is processed by specialized units and delivered to provincial agencies for "self-assessment" and "independent evaluation."

Regional specific needs for remotely-sensed water data:

- The Srepok Basin focuses on the technical nuances of groundwater and surface water volumes.
- The Mekong/Northern provinces highlighted high infrastructure costs and data-sharing constraints as primary hurdles.

6.1.2 WATER ACCOUNTING

AWARENESS OF WATER ACCOUNTING

SREPOK BASIN STAKEHOLDERS:

There is still a significant proportion (86%) who either have low or no awareness: only 14 % of the respondents are familiar with the concept. This highlights the need for targeted training and communication efforts to enhance understanding.

MEKONG/ NORTHERN PROVINCIAL STAKEHOLDERS:

Awareness of water accounting before the workshop was low with 14% had never heard of it and 71% had heard of it but did not know much about it. Only 14% were familiar but had not used it. This demonstrates a significant need for capacity building and communication to improve understanding of WA concepts and applications.

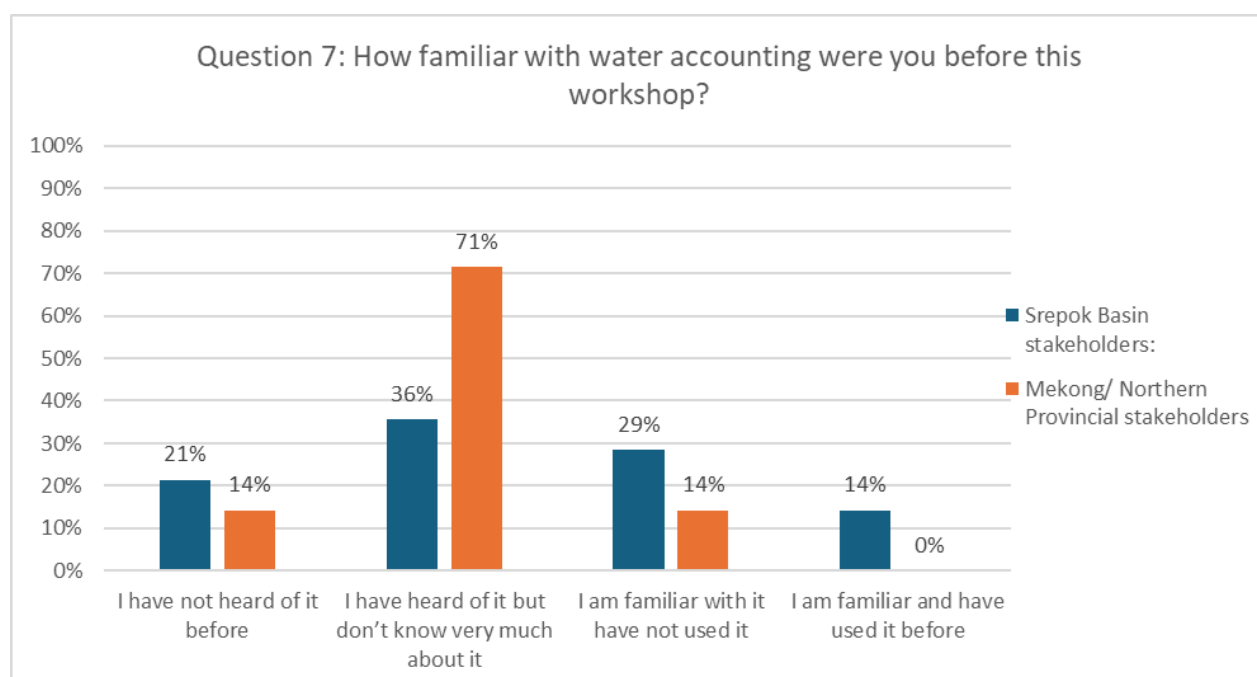


FIGURE 6.7 PRIOR FAMILIARITY WITH WATER ACCOUNTING

PERCEIVED USEFULNESS

SREPOK BASIN STAKEHOLDERS:

Stakeholders in the Srepok Basin showed **100% agreement** on the utility of water accounting. For these professionals, water accounting is not just a theoretical concept but a necessary component for their individual job performance and the broader Vietnamese water sector.

MEKONG/ NORTHERN PROVINCIAL STAKEHOLDERS:

Over 71% were firm believers in its national importance, while the remaining 29% viewed it as "somewhat useful," meaning 100% of respondents saw some level of value for Viet Nam. Even more striking is that 86% believed WA would directly improve their own job tasks, suggesting that stakeholders see immediate practical applications for the tool in their local jurisdictions.

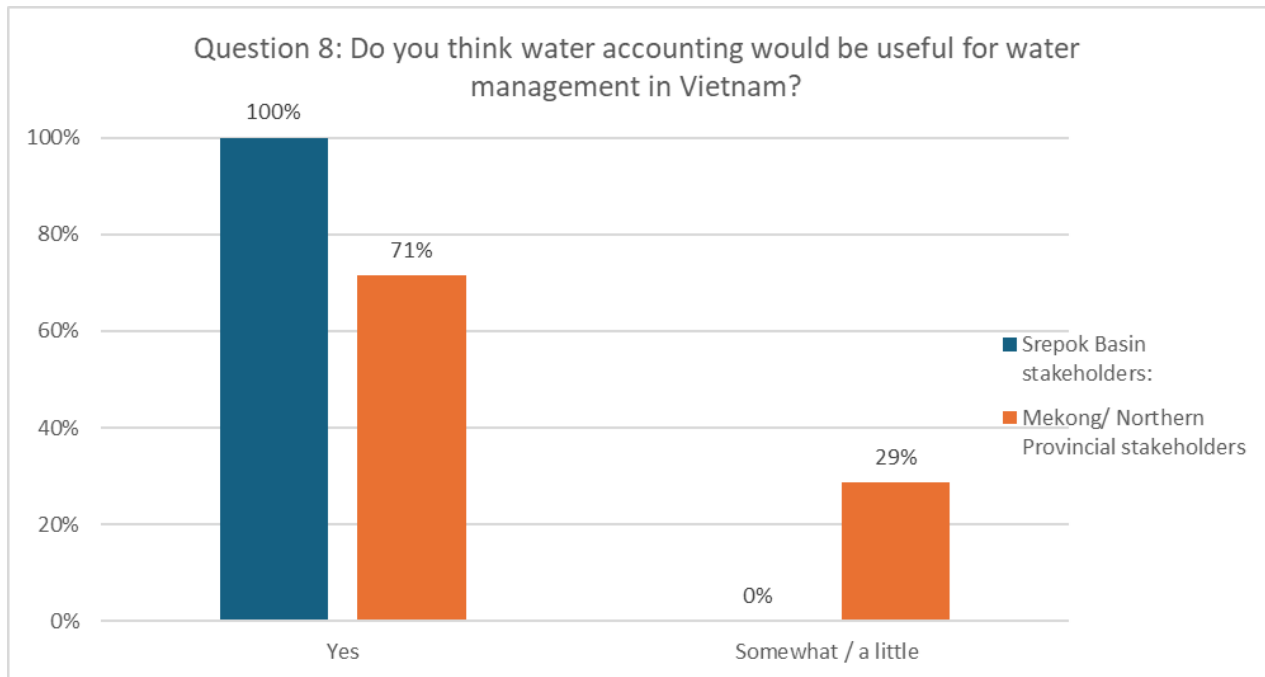


FIGURE 6.8 PERCEIVED USEFULNESS OF WATER ACCOUNTING FOR VIET NAM WATER MANAGEMENT

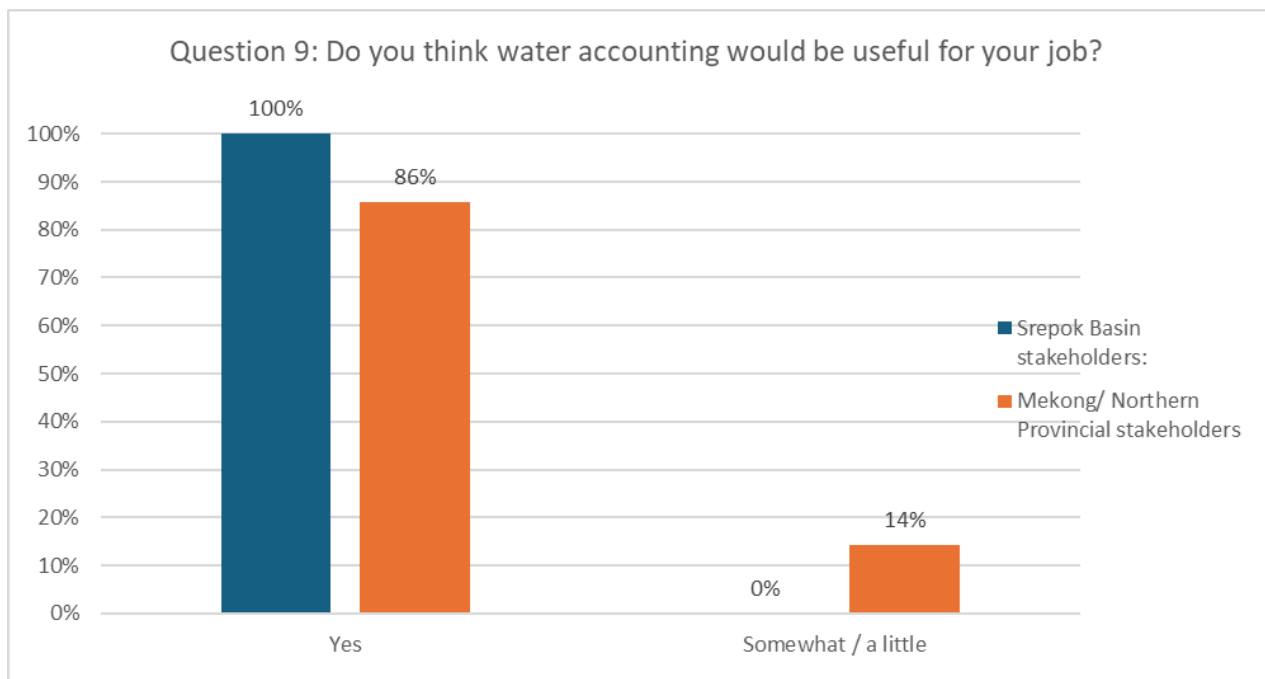


FIGURE 6.9 PERCEIVED USEFULNESS OF REMOTE SENSING DIRECTLY FOR EXISTING WATER MANAGEMENT JOBS

POTENTIAL APPLICATIONS

Respondents were asked about “*specific water management tasks you would like to use Water Accounting data to assist with?*”. Responses included:

Infrastructure & Database Digitalization

- Srepok Basin: Prioritizes digitizing and standardizing databases related to water exploitation infrastructure and integrating WA into national reservoir regulation systems using automatic monitoring data.
- Mekong/Northern: Similarly emphasizes digitizing and standardizing infrastructure databases and integrating WA into national regulation databases for easier managerial access.

Water Balance & Resource Allocation

- Srepok Basin: Focuses on calculating water balance for irrigation and domestic use to improve allocation efficiency and reduce losses.
- Mekong/Northern: Aims to calculate supply needs for production and implement rational regulation across localities to avoid waste.

Groundwater Management

- Srepok Basin: Highlights the need for parameters, data, and distribution maps to forecast and calculate groundwater reserves.
- Mekong/Northern: Also identifies groundwater data and distribution management as a key priority for their managed areas.

Forecasting & Disaster Mitigation

- Srepok Basin: Specifically looks for early forecasts on drought, water shortages, and natural disasters, particularly during rainy seasons.
- Mekong/Northern: Emphasizes early forecasts for drought and shortages but adds a specific focus on disaster prevention during the flood season.

Agricultural Optimization

- Srepok Basin: Focuses on irrigation management for crops like coffee, requiring weekly/monthly updates before planting seasons.
- Mekong/Northern: Echoes the focus on coffee and agricultural production, stressing the need for timely updates to support crop-season decision-making.

SUGGESTIONS FOR ENHANCING THE PRACTICAL USE OF WATER ACCOUNTING DATA

Stakeholders proposed several ways to make WA data more functional for their specific agencies:

Accessibility & Sharing

- Srepok Basin stakeholders: Call for an online, free, and inter-sectoral system. They propose a "toolkit" to democratize data access for all management levels.
- Mekong/Northern stakeholders: Indicated a general need for "more details" but did not specify technical sharing features.

Visualization & Decision Support

- Srepok Basin stakeholders: Suggest using digital maps, charts, and dashboards to present data visually. They recommend linking these tools to regulatory tasks, such as drought forecasting and water extraction permit management.

Guidance & Training

- Srepok Basin stakeholders: Emphasize the necessity of expert-led training and technical guidance for staff. They also suggest developing standardized guidelines, definitions, and implementation documents.
- Mekong/Northern stakeholders: No specific training or guidance suggestions were mentioned by this group in the provided feedback

Integration

- Srepok Basin stakeholders: Propose pilot projects to integrate WA data with existing systems like agricultural management and urban water supply. They also advocate for synchronizing local efforts with national-level data systems.

KEY BARRIERS IDENTIFIED

Regarding the barriers and challenges to using water accounting, both stakeholder groups identify Training for staff as the most common critical hurdle, though other technical obstacles were identified.

SREPOK BASIN STAKEHOLDERS:

100% reported a barrier in *Training* for staff. While still significant, their technical challenges are slightly lower than the northern group, with 64% citing *Software systems* and 57% citing *Access to the data* used in water accounting. However, a larger portion of this group (29%) identified *Other complex barriers*, including the lack of Automated systems for monitoring and management, the need for modernization and synchronization, and restrictive Legal frameworks that currently do not allow for the use of data generated by (external and research) study teams.

MEKONG/ NORTHERN PROVINCIAL STAKEHOLDERS:

Likewise, the most universal challenge identified was *Training* for staff, cited by 100% of respondents. This group also faces high technical hurdles, with 86% identifying *Software systems* and 71% identifying *Access to the data* used in water accounting as significant barriers. Beyond these primary categories, 20% mentioned other factors, specifically highlighting *Costs* as an additional constraint.

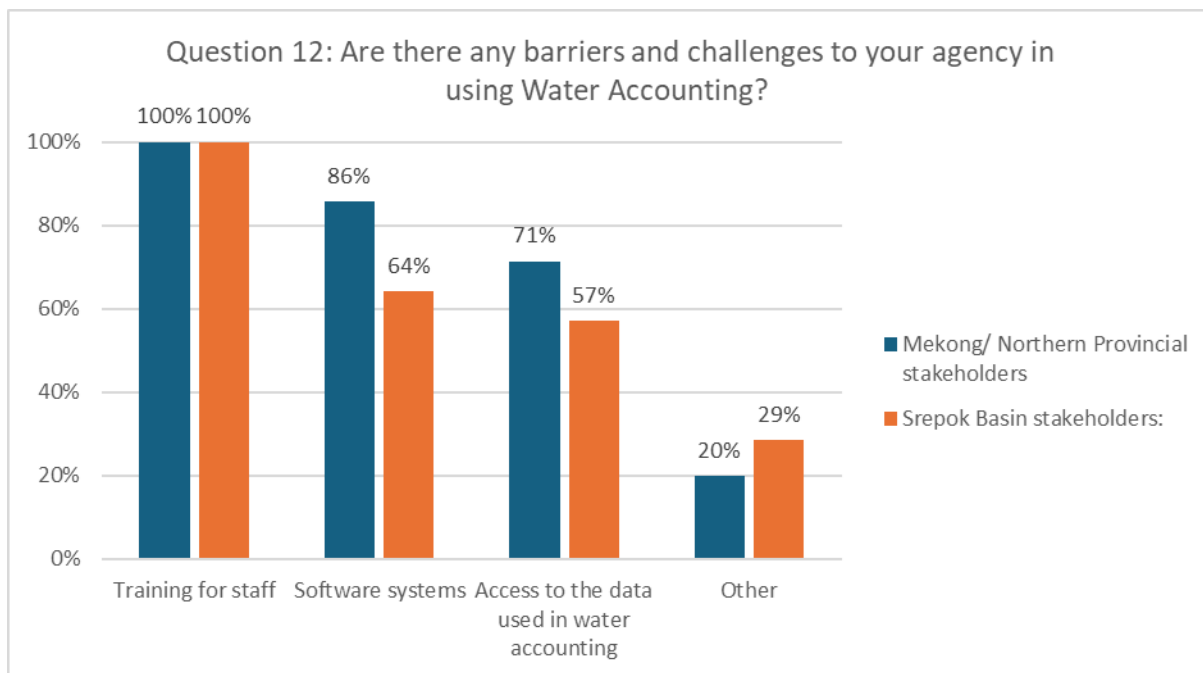


FIGURE 6.12 BARRIERS TO APPLICATION OF WATER ACCOUNTING

WATER ACCOUNTING TRAINING NEEDS

Participants were asked about the types and formats of training preferred.

SREPOK BASIN STAKEHOLDERS:

The Srepok stakeholders focused on technical self-reliance and field application:

- Requested training on how to use the software, including a detailed understanding of its specific applications in management and implementation.
- Identified a need to improve the capacity to collect and input data, alongside processing data using GIS and remote sensing technologies.
- Requested sessions on the advantages and disadvantages of the software to better evaluate its practical use.
- Emphasized in-person, hands-on training combined with place-based training in specific locations to ensure technology transfer for self-reliance.
- Focused on how to apply the technology effectively to daily management tasks.

Mekong/ Northern Provincial Stakeholders: while providing fewer individual responses, this group focused on specialized, high-level technical training:

- Requested training specifically on software applications.
- Expressed a clear need for "in-depth training" sessions.

PREFERRED MECHANISM TO ACCESS WATER ACCOUNTING OUTPUTS

SREPOK BASIN STAKEHOLDERS:

64% of stakeholders prefer to rely on a specialized institution to operate the tools and provide finished reports, and approximately 36% expressed a willingness to self-learn and operate water accounting tools independently.

MEKONG / NORTHERN PROVINCIAL STAKEHOLDERS:

86% of respondents prefer a specialized external team to operate the water accounting tools and deliver management reports and only 14% expressed a willingness to learn and operate the tools themselves.

The stakeholder preferences regarding the operation of Water Accounting tools reveal a strong nationwide inclination toward a "data consumer" model, though readiness for self-reliance varies by region.

14. If water accounting is adopted for more use by the Vietnamese Government and irrigation organisations, what is the best way for you and your team to gain access to the data results from water accounting tools?

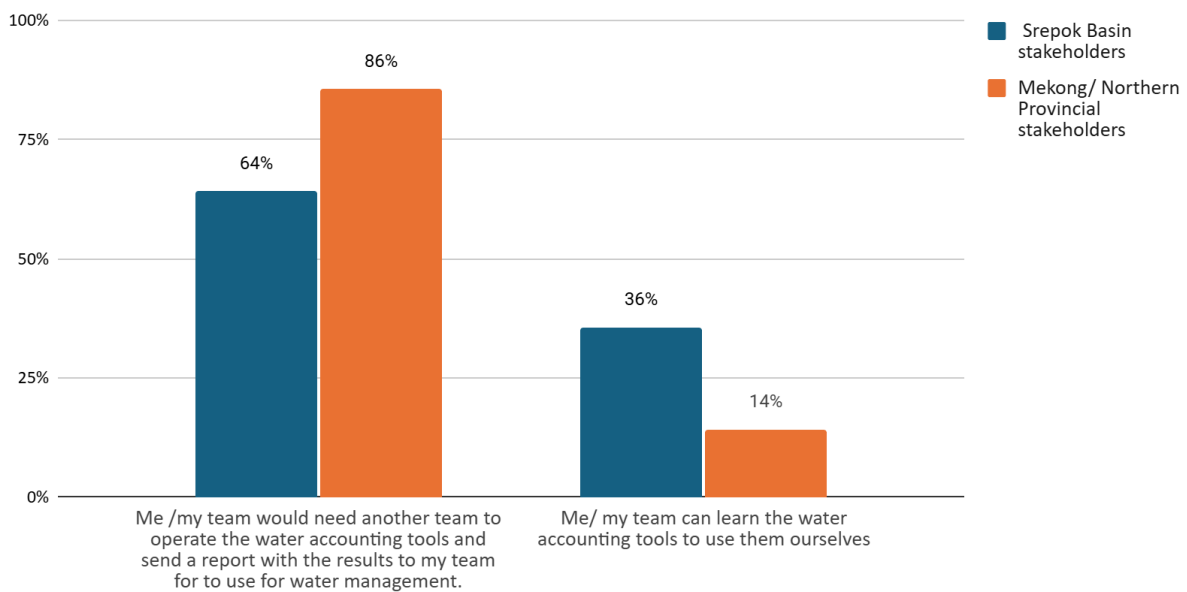


FIGURE 6.13 PERCEIVED USEFULNESS OF REMOTE SENSING FOR VIET NAM WATER MANAGEMENT

SREPOK BASIN STAKEHOLDERS:

Participants also shared the following comments on the use of water accounting to generate water data for water management in Viet Nam:

- Water accounting is very necessary for proactive water resource management, especially to support future operations and planning.
- There is a strong need for specific guidance documents and training, together with free-to-use software, so that more people can access and apply water accounting.
- The application of water accounting will help make data more transparent and support more effective water resource management and allocation. However, Viet Nam still faces challenges related to data availability, human resources, and coordination mechanisms. Therefore, pilot projects and gradual improvements are needed before large-scale implementation.
- The legal framework should be strengthened by integrating water accounting into the (revised) Water Resources Law and related legal documents, with clear regulations on data provision responsibilities.
- It is necessary to transfer water management tools to local authorities to facilitate effective and decentralized management.
- Water accounting is truly necessary in Viet Nam and should be more widely promoted and implemented.
- Implementation should be carried out early and in a synchronized manner across sectors and administrative levels.
- Water accounting supports efficient water use, helping to reduce water loss and waste.
- Several participants expressed “Water accounting helps make water resources transparent, balance supply and demand, and monitor usage efficiency, but a system of indicators and standardized methods suitable for Viet Nam’s conditions is needed.”
- “Implementation still faces difficulties due to scattered data and lack of interoperability between sectors; therefore, a coordinated mechanism and synchronized data sharing from central to local levels are required.”
- Participants agreed with using water accounting to generate data for water management, based on the positive results already achieved through its application.
- It is necessary to develop specific crop planning in order to calculate and allocate water resources appropriately.

These views reinforce findings from the remote sensing section, indicating that most agencies currently prefer to act as informed data users rather than technical operators of data tools such as Water Accounting.

Mekong / Northern Provincial Stakeholders did not comment on this question.

6.2 USEFULNESS, USABILITY, ACCESSIBILITY, AND INTEREST

To inform further development of remote sensing and water accounting in Vietnam, additional, targeted, stakeholder data was gathered to assess:

- Usability - the potential for stakeholders to use the tools in their current form
- Usefulness – the potential to use the outputs from the tools to assist with water resources management
- Accessibility & Feasibility – the potential for stakeholders to acquire the resources, facilities and systems to implement and use remote sensing / water accounting tools e.g. to acquire the required input data, to access required computing equipment to use the tools.
- Interest – the attitude of stakeholders (those present as well as the colleagues / supervisors they work with) to adopt remote sensing / water accounting approaches.

Data representing stakeholders' opinions on these 4 aspects was derived from:

- Initial interviews with stakeholders (as described and summarized in Part 3.2)
- Individual post-workshop surveys (as described and summarized in Part 6.2)
- Group discussions during the workshops
- A structured activity to capture individual, anonymous ratings of each of these four dimensions, using a simple traffic light system (green/yellow/red dots) and sticky notes for additional comments.

Table 6.1 summarises the key points raised by stakeholders at different times during the project; the sections following provide a synthesis of feedback for each of the 4 criteria of usefulness, usability, accessibility and interest.

TABLE 6.1: SUMMARY OF FEEDBACK RELATING TO USEFULNESS, USABILITY, ACCESSIBILITY AND FEASIBILITY, AND INTEREST, FROM DIFFERENT STAKEHOLDER DATA COLLECTION ACTIVITIES (RS: REMOTE SENSING; WA: WATER ACCOUNTING)

Activity	Usefulness (Potential of Outputs)	Usability (Current Ability to Use)	Accessibility & Feasibility (Resource/System Potential)	Interest (Attitude to Adopt)
Initial Interviews (May 2025)	Remote sensing is considered a cost-effective source of information for monitoring and forecasting reservoir inflows. Critical data on reservoir bathymetry and hydro-meteorological conditions can be collected through remote sensing technologies, providing valuable support for water managers and the operation of hydraulic infrastructure.	Accuracy of the data: Concerns remain about the accuracy of RS outputs in complex field realities and confidence needs to be built. Limited capacity: Current operational capacity is severely limited by a reliance on manual monitoring methods, which result in large data deviations. The ability to use existing forecasting tools is hampered by technical failures in software or a total absence of localized monitoring devices.	Data accuracy: There are ongoing concerns regarding the accuracy of remote sensing (RS) outputs under complex field conditions; therefore, building and strengthening trust in this technology is essential. In particular, these datasets and tools should be validated and/or formally recognized by relevant institutions before being used in decision-making processes. Limited capacity: Technical capacity among officials at different administrative levels and among irrigation infrastructure operators varies considerably. Most have not been trained in the use of technical tools, remote sensing, or GIS.	Strategic Motivation: Respondents identified water scarcity as a complex, non-uniform threat, highlighting an urgent need for more effective management of both surface and groundwater across all administrative levels. Consequently, stakeholders view RS-derived data as highly important and relevant for modernizing irrigation practices and improving overall water work management.
September Workshop (Post-Surveys)	Operational Efficiency: 100% of respondents agreed RS is useful for national water management. It is expected to make planning and operations more "timely and cost-effective" and provides an evidence base for regional water planning.	Training Demand: Stakeholders demand detailed training, specific instructions, and user manuals to transition from being "passive observers" to "active tool operators". There is a call for a unified national curriculum for independent learning.	Open-Source Preference: There is a clear mandate for open-source data (Sentinel/Landsat) to avoid licensing barriers. Provincial agencies prefer a workflow where raw data is processed centrally by specialized units.	Job Relevance: 100% of Srepok stakeholders agreed on the utility of WA for their individual job performance. Stakeholders see immediate practical applications for WA in their local jurisdictions.
November Workshop (Post-Surveys)	National Importance: Over 71% of respondents were "firm believers" in the national importance of Water Accounting. 85.71% believed WA outputs would directly improve their specific job tasks.	Operational Familiarity Gap: 0% rate of operational GIS use was recorded for water management among Northern stakeholders. Most provincial stakeholders have heard of these tools but have never	External Reliance: 85.71% of provincial operators prefer to be recipients of processed reports from specialized external teams rather than being tool producers themselves. Only 14.29% were willing to learn to operate tools independently.	Adaptation Readiness: Agencies recognize these tools as essential for future drought and flood challenges. There is a strong desire for automated connections for evaporation and groundwater data to enable weekly updates.

		applied them to their sector.		
Workshop Discussions	Compliance Tool: Technology is seen as a way to reduce workloads while complying with national standards like Decree 144. Stakeholders want verification of algorithms to ensure trust in output results.	Tiered Training Need: Capacity building must be tailored to specific branch-level needs and technical staff. Stakeholders requested specific guidance documents and free-to-use software to democratize access.	System Barriers: The lack of automated monitoring and restrictive legal frameworks currently prevent the use of study-generated data in official management. Costs and software system limitations are significant hurdles.	Institutional Alignment: Stakeholders insist on a single, synchronized water dataset to resolve overlapping regulations between the Ministry of Agriculture and the Ministry of Environment. Integration of water and irrigation laws is a top priority.
Sticky Board Feedback	Integration Capacity: Stakeholders highly value the capacity for data integration to support real-world planning and monitoring. Findings must be transformed into practical products for Vietnamese management contexts.	Complexity Barriers: Existing tools are perceived as too complex for non-technical users, requiring simplified interfaces and clearer guidance for daily use. Many users are "not yet exposed" to the technology.	Procurement Obstacles: Rigid state budget mechanisms make it nearly impossible for local agencies to purchase high-resolution, real-time imagery. Free imagery is available but suffers from a "time lag".	Engagement & Attitude: Strong engagement reflects a readiness to move forward, provided technical, institutional, and capacity barriers are addressed. Sustainable adoption requires experts who can train others.

This comprehensive assessment synthesizes findings from the initial field interviews in May 2025 through the technical workshops and surveys conducted in late 2025. It specifically integrates qualitative data from the sticky board activity and plenary discussions during the November 2025 workshop to provide an expansive view of how these technologies intersect with the complex realities of water management in Viet Nam.

6.2.1 USEFULNESS: POTENTIAL TO ASSIST WITH WATER MANAGEMENT

The potential for remote sensing and water accounting outputs to assist in water resources management is viewed as a high strategic priority across all sectors.

During the initial interviews, stakeholders recognized remote sensing as a cost-effective source of information for monitoring and forecasting reservoir inflows and outflows. Bathymetry and met-hydrology data were identified as critical types of remotely-sensed-derived data for daily management, although concerns remain regarding the accuracy of these outputs in complex field realities.

By the September workshop, 100% of respondents agreed that remote sensing is useful for water management, as it provides an evidence base for regional planning and makes operations more "timely and cost-effective".

During the November workshop's sticky board activity and post-workshop surveys, participants generally perceived the tools as introduced in the workshop as highly useful for Vietnamese management contexts. Most feedback highlighted that remote sensing and water accounting have strong potential to support planning, monitoring, and decision-making processes, with several participants noting that results could be applied to real management tasks such as water allocation, resource assessment, and policy support. Over 71% of November survey respondents were identified as "firm believers" in the national importance of Water Accounting.

6.2.2 USABILITY: POTENTIAL TO USE TOOLS IN CURRENT FORM

The ability to utilize remote sensing and water accounting tools is currently significantly constrained by operational capacity at the local level. Initial assessments indicate that technical capacity in remote sensing and GIS remains limited, largely confined to basic map reading rather than the active use and development of these technologies.

This skills and application gap was quantitatively confirmed in November 2025, when a 0% rate of operational-level GIS use in water resources management was recorded among the Northern provinces group. Feedback collected through the sticky board activity further revealed that tool utilization is severely restricted because target users have “not been trained, have not had access to, and have never used” these technologies.

While participants acknowledged the inherent usefulness of the tools, many felt the systems and data formats remained too complex, requiring much clearer guidance for non-technical users to operate without constant external support. It is noteworthy there is a preference for reliance on external support in operating the remote sensing and water accounting tools directly, with a preference for a specific team / unit with MAE to provide the outputs of water accounting. This should not be confused with a desire for independent ability to interpret and apply the outputs / data in local settings. This model would potentially alleviate some of the skills gap that exists at local levels, with instead at focus at that level on interpreting, interrogating and verifying, and applying data outputs from water accounting / remote sensing.

A "tiered solution" was discussed by stakeholders, rather than a one-size-fits-all approach. Future development must focus on tools that "simplify the process and concepts," such as building specific apps for each system to expand the user base rather than relying on a general, complex platform. Implementation requires "deep/specialized training" for key staff or small group training disseminated directly to relevant divisions. Stakeholders participating in the pilot highly valued the system's capacity for data integration but stressed that usability will only improve significantly if the information provided is transformed into practical, field-ready products. This transformation requires standard procedures, step-by-step instructions, and simplified interfaces provided alongside detailed user manuals explaining how to interpret and apply validated outputs in daily management tasks.

Another critical factor affecting this current usability is the validity and accuracy of the data. Stakeholders expressed concern regarding the accuracy of remotely sensed data because field reality in Viet Nam is highly complex and varied. Participants emphasized that for these tools to improve transparency and efficiency, the outputs must be verified against ground-based monitoring systems to ensure they are legally and practically viable. Without this validation, users lack the trust necessary to apply the information in daily operations, such as water allocation or reservoir regulation.

6.2.3 ACCESSIBILITY & FEASIBILITY: RESOURCE AND SYSTEM POTENTIAL

The potential for stakeholders to acquire and implement these systems on a large-scale and with sustained use, is currently restricted by systemic infrastructure and financial bottlenecks. Accessibility was identified as a primary challenge, with participants pointing to limitations in financial resources, human capacity, and equipment availability.

As described above, many agencies, especially at local level government of IMC offices, lack staff with sufficient technical skills in GIS and data processing, which restricts their ability to independently use the tools. The feasibility to scale-up the application of remote sensing and water accounting could be improved by adopting the approach describe above, in which local level users receive the data outputs, ready for operational application, from specialized national teams, provided local level teams are sufficiently trained and have confidence in the quality of the data.

An additional potential barrier to accessibility is the procurement of suitable imagery. While free images are accessible, they suffer from a time lag and still require data processing. High-resolution, purchased, images are more suited to operational tasks but difficult to acquire because state agencies have fixed budget mechanisms and regulations, which do not yet allow implementation units to easily spend state budget on data services. To improve feasibility, stakeholders have issued a mandate to continue to use open-source data (such as Sentinel or Landsat), as was the case for this pilot project, but simultaneously to address the institutional budgeting processes to release funds for data acquisition.

Ultimately, the system requires timeliness to be viable for commercial operation plans, making investment in human resources and data access essential for long-term sustainability.

6.2.4 INTEREST: ATTITUDE TOWARD ADOPTION

Despite technical and resource hurdles identified, the level of interest among participants was high, reflecting a motivation to support proactive water management, assisted by adopting remote sensing and water accounting approaches. Respondents in early 2025 identified water scarcity as a complex threat, highlighting an urgent need for more effective management of surface and groundwater at all administrative levels. Stakeholders view remotely sensed data as highly important and relevant for modernizing irrigation practices. Most stakeholders showed strong engagement with the project and expressed a desire to see these tools applied more widely in Viet Nam to address challenges related to drought, floods, and increasing water demand.

Importantly, although there is strong interest for the sector to adopt remote sensing and water accounting approaches, not all respondents want to use the tools themselves to generate water parameters; the majority preferred to be “outputs users”, receiving the outputs from water accounting, and remote sensing, as reports that are ready to use for operational purposes.

Participants also emphasized that successful implementation would require coordinated efforts among institutions, clearer legal frameworks, requiring interest and motivation from senior levels of government. Stakeholders insist that institutional alignment is needed, calling for a single, synchronized water dataset to resolve overlapping regulations between the newly joined Agriculture and Environment divisions within the Ministry of Agriculture and Environment.

The highly active engagement of stakeholders throughout this project confirms a strong interest and motivation to move forward, provided that technical, institutional, and capacity barriers are systematically addressed.

6.3 STAKEHOLDER PERSPECTIVES ON PROGRESSING REMOTE SENSING AND WATER ACCOUNTING

The final activity of the Project closing stakeholder workshop involved an activity to discuss what stakeholders consider to be useful ways forward, if remote sensing and water accounting are to be adopted in Viet Nam. Their points are summarized below.

6.3.1 GEOGRAPHIC FOCUS AND APPLICATIONS

One group of participants proposed that a future project target specific locations such as *Lâm Đồng* and *Nghệ An*, which span coast, mountains, and plains. The potential applications of remote sensing and water accounting are likely to vary by terrain: in mountainous areas, the focus is on warnings for landslides, forest fires, and context regarding reservoirs, while in the plains, applications might target serving agricultural production and irrigation.

A significant technical challenge needing attention, in a range of areas, is identifying the storage capacity of long-standing reservoirs that lack data/records, specifically the need to build the Water Surface Area vs. Volume (Z-F-W) relation curves to determine reservoir volume.

The other group think the next step of the project should focus on the *Mekong River Delta*, the *Red River Delta*, and areas with high reservoir density like the *Northern Mountains*. The goals include overall water accounting for the entire province and handling transboundary contexts (potential application for the Mekong Delta regarding upstream flows). Specific environmental applications involve determining the extent of salinity intrusion and trends, identifying pollution sources [to] inform operation decisions, and monitoring groundwater levels (in response to subsidence issues).

The immediate next steps recommended involved utilizing platforms like *hochua.com* (Reservoir management), developing digital maps, and building early warning systems.

Capacity development should be split into two tracks: Data / tool operators with a focus on acquiring datasets and using the GIS and water accounting tools; and data users with a focus on interpreting, interrogating, validating and applying data outputs.

7. SCALING-UP SUBBASIN REMOTE SENSING AND WATER ACCOUNTING IN VIET NAM

7.1 CONCLUSIONS

This research explored the potential application and scaling-up of remote sensing and water accounting to support agricultural water management in Viet Nam using two integrated approaches:

- Exploring the technical feasibility to downscale water accounting, supported by remotely sensed data, in subbasin pilots.
- Exploring stakeholders perspectives on the potential usefulness of such tools and data outputs, as well as the usability, interest, and accessibility and feasibility to implement such tools. To maximise the likelihood of satisfying these criteria, stakeholders were involved throughout the project, giving input and guidance on the technical aspects.

This study demonstrated that integrating remote sensing-based information with water accounting approaches and validating through local decision-making realities can produce practical and meaningful inputs into subbasin water management in Viet Nam. In contexts where in-situ hydrological and biophysical measurements are absent, inaccessible or scattered, for example, groundwater abstraction, crop yield, drought conditions, publicly available remote sensing products offer a viable primary source of data for water management decisions.

The user-centred research process, involving stakeholders in Srepok and Mekong basins, indicated:

- **Demand and interest in water data is high**, as it is seen as a necessary and appropriate advancement to meet legal requirements, support operational activities, and provide independent data that can validate efficiency and performance of operations.
- Through engagement in this project, awareness about the potential usefulness and availability of remote sensing data was improved, and created stronger demand and interest for new technologies to improve water data.
- Although stakeholders have high interest there is currently **insufficient technical capacity** and practical experience, especially at provincial and commune levels, for both remote sensing and water accounting. This makes the existing tools **less usable by all interested staff in their current forms**.
- Demand for **simplified tools** was expressed, however, a complimentary approach discussed was an internal **service-provider model**, in which mandated units / teams within MAE and IMC, nationally or in provincial offices (where the base level of skills exists), act as 'data producers' - acquiring and processing data, operating GIS and water accounting tools, and distributing data outputs to data users in local level government and IMC offices. This could increase the usability of tools, although some simplification to user interfaces is still required.
- Demand for training is strong: Stakeholders stressed the need for **hands-on, tiered training** (differing levels of complexity, potentially relating to the service-delivery model described above), **practical guidelines, and reliable, user-friendly software tools** to help decision-makers at all levels. Regardless of who produces water accounting outputs, there was widespread demand for training all data users to be able to interpret, verify and apply the outputs.
- Certain organisations have more autonomy and resources than others, making it easier for them to develop capacities and update procedures and systems, to adopt new technologies. Future projects to scale-up remote sensing and water accounting need to accommodate different levels of resourcing and autonomy.

- **Accessibility** is also hampered by **limited access to no cost but high resolution** (spatial and temporal) datasets. Some datasets, particularly larger, lower resolution datasets are easy and inexpensive to access, while datasets at smaller scales often require a higher skill level to access and process the data. Access to computing equipment is moderate, although much monitoring and data management is currently manual; better access and skills in computing would assist with efficiency of accessing data. Feasibility to implement requires development of capacities of data producers and data users, and systems to enable the requesting/sharing of data outputs for WRM use.
- There is a desire for automated, continuously updated data systems linking remote sensing, hydrology, and water accounting to improve the timeliness of application of data to operations and reduce workload.
- Policies and data systems are fragmented: Current overlapping regulations from different ministries and fragmented data sources hinder efficient water resource planning and operations.
- **An emphasis on collaboration:** There is strong interest in continued pilot testing, feedback loops, and joint problem-solving amongst practitioners, and between researchers and practitioners, to ensure solutions are practical and scalable. Practitioners identified the benefits of participating in workshops alongside practitioners from other areas, in particular learning from each other's experiences with agricultural water management, remote sensing and potential application of water accounting.

Stakeholder involvement

The project took an intentional research-to-impact strategy by integrating structured qualitative social research and policy engagement from the outset. This user-centred approach clarified existing water management tasks, data gaps and institutional constraints. Importantly, the social research findings revealed that limitations in data use are not only driven by a mismatch in the technical complexity of the tools and existing technical GIS and water accounting skills of staff, but also relate to institutional fragmentation and limited accessibility of data products. For many participants, the opportunity to shape technical outputs according to their operational needs was novel and highly valued, strengthening ownership and relevance of the result.

The application of a localised water resources management (WRM) maturity framework (as shown in Chapter 4, Maturity Of Data-Informed water management) proved valuable not only as an analytical tool to identify existing strengths and weaknesses, but also as a structured, participatory process for stakeholder reflection. The framework enabled water managers, irrigation management companies, and government agencies at central and local levels to jointly assess current WRM practices and data availability and use, and identify and discuss gaps. While most core water resources management tasks are already being undertaken across planning, management, and operations of water resources infrastructure, systematic use of water data, particularly advanced datasets for groundwater and surface water management, monitoring of allocation, water-use efficiency and productivity and water accounting remains limited.

Pilot testing of remote sensing-supported water accounting at various levels (basin, subbasin and irrigation cluster), with regular engagement with stakeholders, indicated strong potential to enhance situational awareness of water availability and use, support seasonal and annual planning, and improve transparency in allocation and compliance discussions. However, the study also showed that such tools are most effective when they are tailored to the spatial and temporal scales at which decisions are made, embedded with existing management protocols, and accompanied with targeted capacity development.

This research process was novel for technically-oriented projects in this context, and generated its own conclusion, relating to the contribution of qualitative research and the inclusive user engagement and participatory approach. Rather than being positioned only as end-users of predefined technical works, stakeholders were co-developers, actively engaged in shaping the direction of the research, articulating decision-making needs, and guiding the designing and presentation of remote sensing and water accounting outputs. Throughout the process, participants particularly valued the opportunity to communicate the specific types of water data, indicators, spatial units, and temporal frequencies required to support their operational and management opportunities.

Conclusions relating to technical aspects of remote sensing and water accounting

The technical research indicated there are many water accounting and related parameters that can be produced by drawing upon remotely sensed data, and which are useful to water resources management in Viet Nam, including at subbasin scales.

Remote sensing data was able to successfully produce annual water balances for use in water accounts for the Ban Don basin for the years 2013-2024 to determine if water was being sustainably used. The water accounts showed more water was available than currently being used. On monthly timesteps irrigation withdrawals could be estimated during the dry season from the difference between water being used by different land uses, actual evapotranspiration, and precipitation. Remote sensing data can provide first order estimates of the state of basin water resources to investigate water availability, water usage and where it is being used. However, being depletion-based water accounting processes, tracking where water is being used, lacked the ability to partition excess rainfall into surface and groundwater flows. As elaborated in Section 5, different remote sensing datasets can produce different water balance results with actual evapotranspiration being the most robust and precipitation the least. Precipitation should be validated with terrestrial data if available.

Evapotranspiration is one of the most important but poorly measured parameters in hydrology and is often used as a lumped parameter. Actual evapotranspiration data derived from remote sensing data showed temporal and spatial variability in evapotranspiration at basin scales not achievable by other methods used in hydrology. The remote sensing data has provided significant insight into hydrological and ecological processes such as surface water ground water interactions that would not have been identified by traditional means. For example, in the Ban Don basin, evergreen forests consumed 400 mm of water during the dry season, showing strong groundwater dependence. This interpretation was confirmed by GRACE-derived storage data, which showed seasonal decreases in terrestrial water storage during the dry season. Storage was subsequently replenished during the wet season. These findings illustrate how remote sensing data, particularly actual evapotranspiration can augment traditional methods and provide additional insight into hydrological studies, previously unavailable.

A key strength of the Water Accounting Plus (WA+) framework is the incorporation of biomass estimates and water productivity for different land uses. For the Ban Don basin, biomass and water productivity estimates were derived for different land uses. However, for smaller basins and land use clusters biomass and yield estimates as well as water productivity becomes more meaningful as underperforming or over irrigated areas can be identified and can help manage operational decisions and practices.

Depending upon the spatial scale, and methodology involved for each parameter, there are varying levels of complexity in acquiring and computing these datasets. Table 7.1 summarises the main parameters, and categorises them according to three categories of complexity of computation:

- Least complex: hydrological indicators that are easiest to access, using web-based data inputs and preexisting layers easily incorporated and interpreted in GIS (accessible at provincial level government, IMC Districts).
- Moderate complexity: some calculations in GIS required to derive desired indicators.
- Most complex: requires some kind of modelling to generate the desired indicators.

TABLE 7.1: SUMMARY OF WATER ACCOUNTING AND RELATED PARAMETERS DERIVED USING REMOTE SENSING DATA AND THE LEVEL OF COMPLEXITY INVOLVED IN DERIVING THEM

Useful Parameters	Temporal and spatial scale of input datasets and scale of application	Examples of WRM tasks for which these indicators are useful, and scale of application	Level of complexity in generating the parameters / indicators
1. Precipitation	• CHIRPS / WaPOR, daily 0.05° (~5.5 km). – Applicable to all subbasin scales	• Irrigation planning, allocation and management • Domestic and industrial water supply planning and allocation and management • Reservoir operations • Management of irrigation clusters • Flood and disaster management	Least complex
2. Evapotranspiration	• SSEBop dekadal (10 days), monthly, annually, ~ 1km – applicable to basins ~ > 9000 km² • WaPOR Level 1, dekadal (10 days), monthly annually, ~ 300m – applicable to basins ~ > 900 km² • SSEBop / EEFlux dependent on Landsat Passover and cloud cover, ~30 m > Applicable to irrigation clusters and larger • ETLook – modelling ET data at all scales	• Crop water demand • Irrigation cluster and scheme operations (identifying over- or under-irrigated areas) • Catchment water balances • Drought preparedness and response • Prioritisation of water distribution during dry season	SSEBop / WaPOR; Least complex ETLook; Most complex
3. Change in storage	• GRACE – Downscaled, monthly, annual, ~ 10 km resolution – applicable to basins > 10,000 km²	• Basin water balances • Groundwater risk screening - changes in groundwater storage • Targeted monitoring assessment • Supporting groundwater level commune assessment	Most complex
4. Rainfall deficit (Precipitation minus actual evapotranspiration)	• Depends on rainfall and actual ET data	• Irrigation cluster / scheme operations - Used to estimate irrigation or withdrawals from storage for different land use classes	Moderate complexity
5. Land use land cover	• Land use Land cover, annually, 10m - applicable to all scales	• Identify water depletion for different land uses	Least complex
6. NVDI (Normalised difference vegetative index)	• USGS composite, dekadal, 1000 m – applicable to basins > 10,000 km² • Landsat Passover and cloud cover, ~30 m – applicable to irrigation clusters and larger	• Productivity of biomass	Least complex
7. Net primary production	• WaPOR Level 1, dekadal (10 days), monthly annually, ~ 300m – applicable to basins > 900 km² • ETLook – modelling ET data at all scales	• Combined with land use maps to identify unproductive areas	Moderate complex
8. Yield	• Depends on resolution of net primary production and land use datasets	• Crop productivity and identification of underperforming areas	Moderate complexity

Useful Parameters	Temporal and spatial scale of input datasets and scale of application	Examples of WRM tasks for which these indicators are useful, and scale of application	Level of complexity in generating the parameters / indicators
9. Water productivity	• WaPOR Level 1, annually, ~ 300m (Gross and Net primary production only) – applicable to basins > 900 km² • ETLook – modelling data at all scales	• Assessing irrigation efficiency and effectiveness • Supporting agricultural water use optimisation • Informing investment and extension priorities	Net biomass water productivity – Least complexity ETLook – Most complex
10. Basin water balance (Precipitation – evapotranspiration +/- change in storage)	• Dependent on input datasets	• Provides estimation of water surplus / deficit (scarcity) can be on monthly or annual time steps	Moderate complexity
11. System outflows	• Requires modelling of input data	• Provides projections of surface and groundwater outflows	Most complex

Note: Using different remote sensing datasets for example WaPOR or SSEBop for evapotranspiration and WaPOR and CHIRPS for precipitation on different timesteps can give different total results. Remote sensing data of evapotranspiration was found to be more robust than precipitation data. Remotely-sensed precipitation data, particularly using monthly timesteps, should be validated if possible, against observed terrestrial data.

The FAO (2023) study on remote sensing determination of evapotranspiration found that there were large uncertainties in upscaling locally measured evapotranspiration data using flux towers, energy balance methods and soil lysimeters to larger areas. Similarly, it was also found that evapotranspiration estimates using catchment water balances also contained uncertainties. They concluded that the only tool that is readily available to measure changes in evapotranspiration both spatially and temporally is remotely sensed, derived evapotranspiration. There are different methodologies to calculate evapotranspiration from remote sensing data, from complex to relatively simple, though the level of complexity is not necessarily an indicator of robustness or uncertainty. The report found that evapotranspiration estimates at larger temporal and spatial (i.e. grid size) scales were more robust due to the availability of satellite data, but uncertainty increased with finer resolutions (eg ~ 30m) due limited satellite return intervals and cloud cover among other things. The acceptable error ranges of remote sensing data was 5-10% for basin studies.

Aligning data processing complexity with capacity

Larger basins had freely available remote sensing data available, smaller basins such as Ban Don (~10,000 km²), had freely available precipitation and evapotranspiration data but changes in storage, using GRACE needed to be downscaled and calculated. With even smaller basins such as Krong Buk (~ 250 km²), and irrigation clusters, finer scale remote sensing data is not always available, so required data had to be computed using algorithms like ETLook, which required higher skill levels not available amongst the stakeholders managing those smaller scales (Figure 7.1).

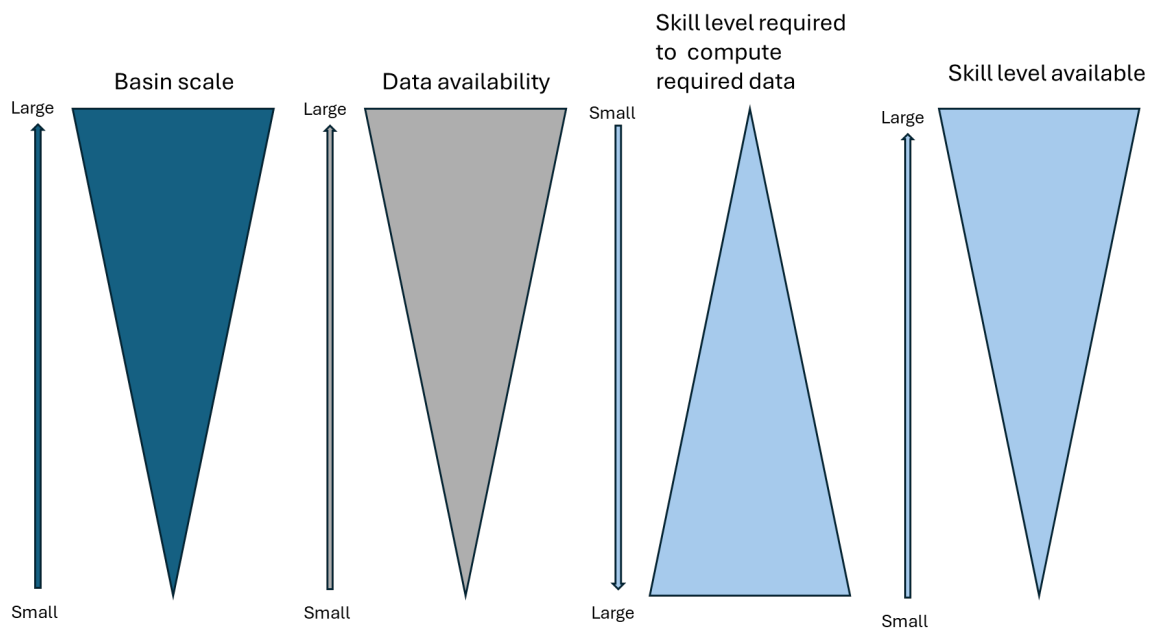


FIGURE 0.1 SUMMARY OF LINKS BETWEEN BASIN SIZE, DATA AVAILABILITY, COMPLEXITY TO COMPUTE DATA, AND CAPACITY AVAILABLE. LARGE BASINS HAVE HIGH DATA AVAILABILITY WITH LOWER SKILL LEVELS NEEDED TO CALCULATE WATER BALANCES, THOUGH WITH HIGH SKILL LEVELS AVAILABLE. CONVERSELY, SMALL BASINS HAD LIMITED DATA AVAILABILITY AND REQUIRED ADVANCED SKILL LEVELS TO COMPUTE THE REQUIRED DATA TO DERIVE WATER BALANCES BUT HAD LIMITED CAPACITY.

With Water Accounting Plus estimating detailed basin-scale surface or groundwater flows ultimately requires the application of hydrological models. The ability of remote sensing data to provide insights into hydrological processes means it could be used to develop hydrological models in ungauged and low data availability areas. In developed countries, hydrological model-based decision support systems are obligatorily used to support water resource decision making. The combination of open-source hydrological models and remote sensing data provides an opportunity to develop similar modelling capacity in low- and middle-income countries. In basins with significant surface water-groundwater interactions, such as Ban Don, an integrated surface water groundwater modelling approach (e.g., SWAT+ gwflow) would be needed to evaluate effects of agricultural clearing of native forests, conjunctive water use, climate change impacts and extreme event scenarios.

In summary, this project demonstrated:

- the maturity of water resources management and governance is good but opportunities to strengthen data-informed WRM exists
- the potential for remote sensing and water accounting to provide useful and usable data to support WRM in Viet Nam at subbasin scales
- however, at the smallest scales, such as irrigation clusters/schemes, models are required to fill spatial data gaps
- there is strong stakeholder interest for Vietnamese WRM to be strengthened with greater data-informed management systems and practices.
- however, further attention to accessibility is required, primarily relating to the capability of staff, at differing levels of government and irrigation management, to access the data outputs from remote sensing and water accounting.

7.2 RECOMMENDATIONS

Based on the technical findings, and stakeholder interest and demand, it is recommended that water accounting be developed for application to agricultural water management in Viet Nam. This application should extend from basins to sub-basins, drawing on in-situ data, as well as data derived from remote sensing and modelling.

The following recommendations reflect the opportunities remote sensing and water accounting offer, and seek to address the accessibility challenges outlined above, to progress the scaling-up of remote sensing and water accounting in Viet Nam.

REMOTE SENSING – TECHNICAL DEVELOPMENT OF DOWNSCALED TOOLS

Remote sensing tools should continue to be refined and tested at the subbasin and irrigation scheme scales, where operational decisions are made. Priority should be given to:

- Include scaling out to new geographical zones which have different climates, terrains and crops to improve the robustness and applicability of the tools
- Translating geospatial into easy-to-understand outputs such as bulletins and maps, so they are accessible and comprehensible for local authorities in their routine planning and operational decisions
- Coupling remote sensing with hydrologic models that link surface and groundwater flows to (i) improve spatial resolution of data, which remote sensing alone cannot achieve across all useful hydrological parameters and (ii) improve projection capabilities, such as to enable scenario testing.

WATER ACCOUNTING TOOLS

With existing / emerging capacities and interests, water accounting outputs are most likely to be generated at provincial government and IMC management levels, with less interest and capacity in commune and local IMC operators to prepare their own water accounting analyses. It is therefore recommended that:

- Continuing the user-centred approach by guiding tool development with practical *use cases* such as seasonal/monthly water balance assessments, drought hotspot identification and management, irrigation performance assessment. Water accounting applications should be established and defined, based on clear decision use cases at each level:
 - Provincial government: to support annual/seasonal allocation planning, drought mapping and response, groundwater abstraction licensing and control, including compliance.
 - Commune government: water accounting as a tool to support hotspot detection (unsustainable groundwater use, abnormal water use efficiency), scheduling of demand management, substitution for statistics and in-situ measurements such as accounting for yield, resources, rainfall etc.
 - Irrigation management companies: water accounting as a tool for irrigation scheme/cluster scheduling and performance tracking (i.e., ET, biomass production, water productivity, irrigation efficiency, equity), benchmarking between upstream/downstream, irrigation clusters.
- A “service delivery model” be considered to increase the usability of water accounting, whereby mandated units / teams within MAE and IMC, nationally or in provincial offices, act as ‘data producers’ - acquiring and processing data, operating GIS and water accounting tools, and distributing data outputs about surface and groundwater resources, to data users in local level government and IMC operations offices

- Water accounting output visualization should be done in two practical formats: (i) standardized sheets summarizing key metrics and maps for spatial display; (ii) simple interactive dashboards/webs that allow users to filter by the level of details and administrative boundaries.
- Capabilities to generate water accounting outputs should include hydrological modelling of surface and groundwater resources, which has the capability to assess the impact of seasonal and longer climate projections on water resources.

IMPROVED DATA QUALITY AND INTEGRATION

- Enhance the accuracy of remote sensing data by integrating it with ground-based monitoring systems.
- Invest in automatic monitoring devices and software with real-time linking with hydrological models and updating functions to support forecasting, drought management, and water allocation.
- Promote research to improve remote sensing and water accounting methodologies and their adaptation to Viet Nam's hydrological and agricultural conditions.
- Ensure algorithm transparency and data verification to build user trust in system outputs.

CAPACITY DEVELOPMENT AND TRAINING

- Implement an ongoing system of tailored, hands-on training programs on the use of remote sensing, GIS, modelling and water accounting for water management in Viet Nam. These programs should include step-by-step user manuals, online tutorials, and periodic refresher courses to support continuous capacity building. Training of Trainers (ToT) can also be considered as a good approach to ensure continuity.
- Integrate technology transfer into future remote sensing, model and water accounting development to enhance the autonomy of agencies in applying advanced tools. Efforts should prioritize the needs of water resource managers and operators at the local level, particularly at commune and provincial scales.
- Consider "scaling out" opportunities with other Southeast Asian countries, sharing amongst practitioners from different geographic locations, with different cultures and context, which is especially relevant in term of transboundary water management (e.g., Mekong region).
- Establish a regional community of practice to sustain learning and integration. This can be done in technical cooperation framework such as ASEAN, ASEAN-6 (six advanced countries in ASEAN comprising Singapore, Indonesia, Malaysia, Philippines, Thailand and Vietnam). A practical mechanism, such as periodic regional diagnostic exchanges, joint case studies, and shared technical guidelines, would welcome continuous exchange on WRM challenges and solutions, including those relevant to transboundary basins and broader ASEAN cooperation.

PILOT PROGRAMS AND SECTORAL APPLICATIONS

- To complement capacity development and training, launch pilot projects integrating remote sensing, modelling and water accounting data for surface and groundwater management in priority areas such as agriculture water allocation (e.g., for coffee plantations), reservoir regulation, and urban water supply planning. These will:
 - Enhance capacity development through hands-on action learning
 - Identify and support development of internal systems for data management and data product systems
 - demonstrate cost savings, efficiency gains, and sustainability improvements
 - build trust and motivate adoption by stakeholders.

CENTRALIZED AND INTEGRATED DATA SYSTEM

- Establish a national, standardized, and centralized database that integrates RS, modelled and WA+ data with other water-related datasets to enable seamless data sharing among sectors—irrigation, agriculture, urban water supply, and disaster management—to avoid fragmentation. The database and the related software should be user-friendly and be able to provide outputs in practical formats (maps, charts, dashboards, automated reports).
- Prioritize the development of open-source or low-cost software tools and RS-based applications.

LEGAL AND POLICY FRAMEWORK

- Develop clear legal definitions and policy frameworks to promote the application of WA and RS in water management.
- Facilitate dialogue between the water resource and irrigation sectors to streamline policies and develop a unified water data and accounting framework.

ONGOING RESEARCH AND COLLABORATIVE SUPPORT

- Continue research to improve data accuracy, especially for remote sensing-based estimates of evapotranspiration, groundwater, and crop water use.
- Create a feedback mechanism for end-users to report practical challenges to research teams for responsive improvement.
- Promote technology transfer and co-development with local agencies to strengthen long-term autonomy.

Next steps to progress the above recommendations

It is recommended that a multi-year research and capacity development project be designed and delivered in Viet Nam to establish and pilot a water accounting & remote sensing (WA+RS) service delivery model that is used by water managers for basin and sub-basin agricultural water management of surface and groundwater resources. Specifically, the project would aim to:

- promote the use of water accounting and remote sensing for water-related decision-making (1-2 years)
- strengthen the technical robustness of the remote sensing and water accounting tools, with additional landcover and crop types, and hydrogeological situations (1-3 years)
- expand the technical capabilities of national and provincial government staff and support them to establish a service delivery model, delivering basin and sub-basin water accounting reports for use by other provincial, commune and irrigation management company water managers (2-3 years)
- develop the capabilities of provincial, commune and IMC staff intending to use water accounting and remote sensing 'reports' (2-3 years)
- institutional integration and long-term systems development (3-4 years)

This would entail:

- (f) Agreeing with MAE a model and program to **develop WA+RS service delivery teams at provincial government levels** (and if appropriate, provincial IMC departments), which will be supported by IWRP (MAE). As shown in Figure 7.2, these teams would function as specialised “data producers”, responsible for:
 - Acquiring and processing remote sensing and modelled datasets
 - Operating GIS, modelling and water accounting workflows
 - Generating standardised maps, reports, dashboards and seasonal bulletins on state of surface and groundwater resources
 - Distributing these outputs to operational water managers and planners

This model recognises that the technical complexity of generating WA+RS outputs currently exceeds the operating capacity available at commune and local irrigation management levels, while local actors still require timely and accessible information to support decision-making.

- (g) We recommend this commence with the Central Highlands provinces of Lam Dong and Dak Lak, building on the work of the existing ACIAR SRA project, developing a suitable approach to establishing these service teams, before expanding to additional provinces. Appropriate **governance arrangements** will need to be agreed between stakeholders, including arrangements for basins and sub-basins that span provincial boundaries. This includes addressing data management and policy and regulatory frameworks to ensure cohesive basin/sub-basin management is possible.
- (h) Delivering **capacity development programs for the provincial service delivery teams** that combines structured training in foundational skills and knowledge, with practical real-world use of remote sensing and water accounting tools, and development of outputs for basin and sub-basin water managers in their provinces. A key focus will be on defining (with water managers), specific applications of water accounting and/or remote sensing data (beyond those identified herein). Skills developed will include: GIS data sourcing, processing, analysis and reporting; hydrological modelling of surface and groundwater for water accounting; water accounting calculations and water accounting reporting for water managers; validating reports with on-ground data and insights from water managers.
- (i) Delivering **capacity development programs for provincial, commune and IMC water managers** in the use of the reports / outputs of water accounting and remote sensing for agricultural water management of surface and groundwater resources. This capacity Development will similarly apply a mix of structured training in foundational water accounting and GIS concepts, and hands-on application of real-world water accounting and GIS outputs produced by the service delivery team in their province.

Joint training workshops, bringing together the WA+RS teams with water managers in a given province, will strengthen the mutual knowledge of the strengths and limitations of applying the data and tools to real management decisions, and, establish a practice of ongoing two-way feedback so as to avoid one-way communication from data providers to data users (this can lead to data reports that do not meet the needs to water managers).
- (j) Identifying additional sub-basins across Viet Nam with different land cover, crops and hydrogeology to **expand the technical validity of the remote sensing and water accounting tools**. These sub-basins will align with the agreed program of expansion of WA+RS across Viet Nam, to ensure technical tools are available for those provinces in which WA+RS will be piloted and expanded

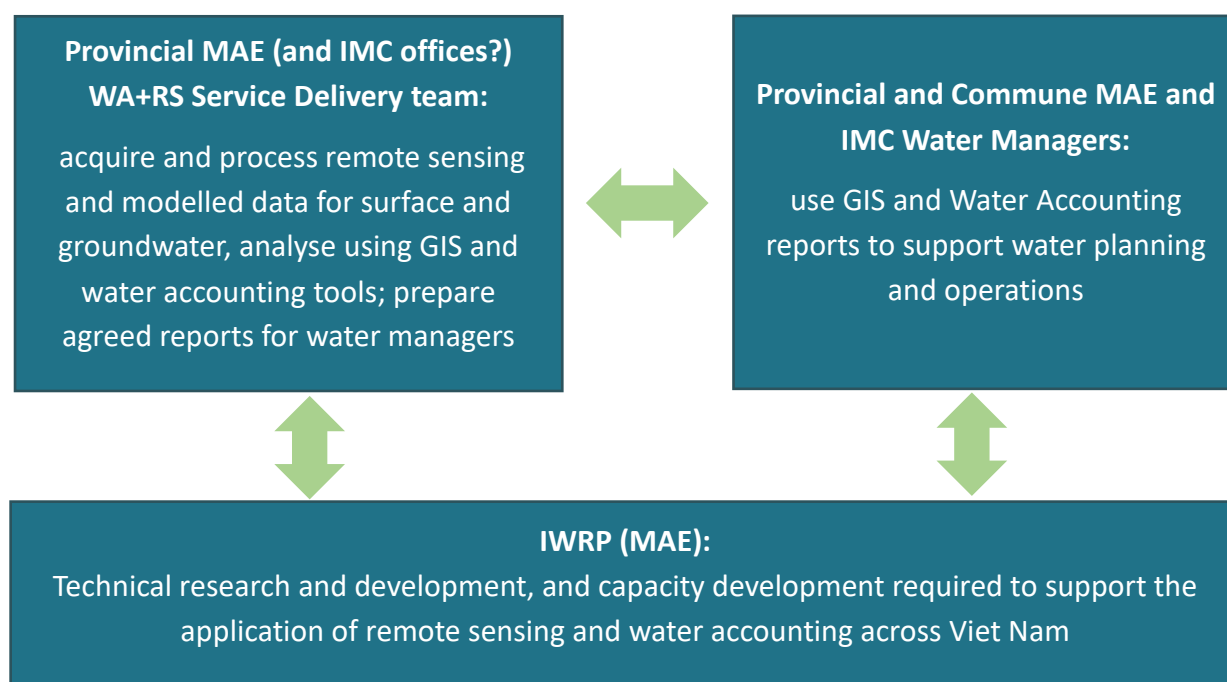


FIGURE 7.2: SERVICE DELIVERY MODEL TO ACHIEVE THE APPLICATION OF REMOTE SENSING AND WATER ACCOUNTING TO AGRICULTURAL WATER MANAGEMENT IN VIET NAM

Additional next steps

Two additional key findings warrant further progress:

3. Managing groundwater (over) extraction in Viet Nam

The finding of overextraction of groundwater in some locations in the Central Highlands should be further pursued in two ways:

- A groundwater study to establish the scale of groundwater over extraction across selected priority regions (where pressure on groundwater is high) to better understand groundwater dependence, groundwater abstraction pressures, seasonal storage dynamics, and implications for water security, including interactions with climate change. This will inform the need for improved ongoing monitoring and management of groundwater, in which areas, of Vietnam.
- Review current groundwater monitoring and management practices to assess how Water Accounting Plus and remote sensing can augment these practices to strengthen groundwater management across Viet Nam.

Future work should consider the strong interaction between groundwater, surface water, evapotranspiration and land use change observed in the Central Highlands or areas with expanding perennial crop systems and increasing irrigation demand.

4. Water Accounting sub-basin technical underpinnings.

To address the lack of existing formulas and models to accurately estimate groundwater and surface water flows, using remote sensing data, and which are suitable for sub-basin scales, it is recommended:

- A multi-institution, technical project, be established, collaborating across key Water Accounting developers, such as IHE Delft and IWMI. This project would focus on developing and assessing suitable formulas, and models as needed, for use at sub-basin scales, in a range of settings, including and beyond Viet Nam.

REFERENCES

- Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration - Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56, Food and Agriculture Organisation, Rome.
- Alsilibe, F., Bene, K., Bilal, G., Alghafli, K., Shi, X.G., 2023. Accuracy Assessment and Validation of Multi-Source CHIRPS Precipitation Estimates for Water Resource Management in the Barada Basin, Syria. *Remote Sensing*, 15(7). DOI:ARTN 1778 10.3390/rs15071778
- Asian Development Bank, 2020, Asian Water Development Outlook 2020: Advancing Water Security across Asia and the Pacific. Asian Development Bank, Manila
- AWP (Australian Water Partnership), 2020. A Guide to River Basin Planning.
- Bailey, R., Abbas, S., Arnold, J., White, M., 2025. SWAT+MODFLOW: A New Hydrologic Model for Simulating Surface-Subsurface Flow in Managed Watersheds. *EGU sphere*, 2025: 1-28. DOI:10.5194/egusphere-2025-300
- Bailey, R.T., Bieger, K., Arnold, J.G., Bosch, D.D., 2020. A New Physically-Based Spatially-Distributed Groundwater Flow Module for SWAT+, *Hydrology*, pp. 75. DOI:10.3390/hydrology7040075
- Bastiaanssen, W.G.M., Cheema, M.J.M., Immerzeel, W.W., Miltenburg, I.J., Pelgrum, H., 2012. Surface energy balance and actual evapotranspiration of the transboundary Indus Basin estimated from satellite measurements and the ETLook model. *Water Resources Research*, 48(11). DOI:<https://doi.org/10.1029/2011WR010482>
- Berghuijs, W.R., Gnann, S.J., Woods, R.A., 2020. Unanswered questions on the Budyko framework. *Hydrological Processes*, 34(26): 5699-703. DOI:<https://doi.org/10.1002/hyp.13958>
- BoM (Bureau of Meteorology), 2013. Australian Water Resources Assessment. (http://www.bom.gov.au/water/about/publications/document/InfoSheet_10.pdf)
- CapNet, 2008. Integrated Water Resources Management for River Basins organisations. <https://cap-net.org/wrm-for-river-basin-organisations/>
- Chiew, F., Wang, Q.J., McConachy, F., James, R., Wright, W., deHoedt, G., 2002. Evapotranspiration maps for Australia, *Hydrology and Water Resources Symposium*. Institution of Engineers, Australia, Melbourne, 20-23 May, 2002,.
- Dell'Angelo, J. et al. (2014). Multilevel Governance of Irrigation Systems and Adaptation to Climate Change in Kenya. In: Bhaduri, A., Bogardi, J., Leentvaar, J., Marx, S. (eds) *The Global Water System in the Anthropocene*. Springer Water. Springer, Cham. https://doi.org/10.1007/978-3-319-07548-8_21;
- Du, H.R., Tan, M.L., Zhang, F., Chun, K.P., Li, L.H., Kabir, M.H., 2024. Evaluating the effectiveness of CHIRPS data for hydroclimatic studies. *Theoretical and Applied Climatology*, 155(3): 1519-39. DOI:10.1007/s00704-023-04721-9
- Ferreira, V., Yong, B., Montecino, H., Ndehedehe, C.E., Seitz, K., Kutterer, H., Yang, K., 2023. Estimating GRACE terrestrial water storage anomaly using an improved point mass solution. *Scientific Data*, 10(1). DOI:ARTN 234 10.1038/s41597-023-02122-1
- FAO, 2023. Remote sensing determination of evapotranspiration – Algorithms, strengths, weaknesses, uncertainty and best fit-for-purpose. Cairo. <https://openknowledge.fao.org/handle/20.500.14283/cc8150en>
- Heung, B., Bulmer, C.E., Schmidt, M.G., 2014. Predictive soil parent material mapping at a regional-scale: A Random Forest approach. *Geoderma*, 214: 141-54. DOI:10.1016/j.geoderma.2013.09.016
- Hutley, L.B., Beringer, J., Fatichi, S., Schymanski, S.J., Northwood, M., 2022. Gross primary productivity and water use efficiency are increasing in a high rainfall tropical savanna. *Glob Chang Biol*, 28(7): 2360-80. DOI:10.1111/gcb.16012
- Japan Aerospace Exploration Agency, 2023. High-Resolution Land-Use and Land-Cover Map of Vietnam for 2020 (Released in September 2023 / Version 23.09).
- Kalu, I., Ndehedehe, C.E., Ferreira, V.G., Janardhanan, S., Currell, M., Kennard, M.J., 2024a. Statistical downscaling of GRACE terrestrial water storage changes based on the Australian Water Outlook model. *Scientific Reports*, 14(1). DOI:ARTN 10113 10.1038/s41598-024-60366-2

- Kalu, I., Ndehedehe, C.E., Ferreira, V.G., Kennard, M.J., 2024b. Machine learning assessment of hydrological model performance under localized water storage changes through downscaling. *Journal of Hydrology*, 628. DOI:ARTN 130597 10.1016/j.jhydrol.2023.130597
- Kalu, I., Ndehedehe, C.E., Okwuashi, O., Eyoh, A.E., 2021. Assessing Freshwater Changes over Southern and Central Africa (2002-2017). *Remote Sensing*, 13(13). DOI:ARTN 2543 10.3390/rs13132543
- Karimi, P., Bastiaanssen, W.G.M., Molden, D., 2013. Water Accounting Plus (WA+) - a water accounting procedure for complex river basins based on satellite measurements. *Hydrology and Earth System Sciences*, 17(7): 2459-72. DOI:10.5194/hess-17-2459-2013
- Ladson, A.R., 2008. *Hydrology: An Australian Introduction*. Oxford University Press, South Melbourne, Vic, 326 pp.
- Morton, F.I., 1983. Operational estimates of areal evapotranspiration and their significance to the science and practice of hydrology. *Journal of Hydrology*, 66(1-4): 1-76. DOI:http://dx.doi.org/10.1016/0022-1694(83)90177-4
- Msigwa, A., Komakech, H.C., Salvatore, E., Seyoum, S., Mul, M.L., van Griensven, A., 2021. Comparison of blue and green water fluxes for different land use classes in a semi-arid cultivated catchment using remote sensing. *Journal of Hydrology: Regional Studies*, 36: 100860. DOI:https://doi.org/10.1016/j.ejrh.2021.100860
- Mul, M., Karimi, P., Coerver, H.M., Pareeth, S., Rebelo, L.M., 2020. *Water Productivity and Water Accounting Methodology Manual*. Project report, IHE Delft Institute for Water Education, The Netherlands and the International Water Management Institute, Sri Lanka.
- Mulungu, D.M.M., Mukama, E., 2023. Evaluation and modelling of accuracy of satellite-based CHIRPS rainfall data in Ruvu subbasin, Tanzania. *Modeling Earth Systems and Environment*, 9(1): 1287-300. DOI:10.1007/s40808-022-01555-8
- Paudel, P., Olin, S., Tjoelker, M., Pontarp, M., Metcalfe, D., Smith, B., 2025. Savanna ecosystem structure and productivity along a rainfall gradient: the role of competition and stress tolerance mediated by plant functional traits. *Biogeosciences*, 22(20): 6153-71. DOI:10.5194/bg-22-6153-2025
- Penman, H.L., 1948. Natural Evaporation from Open Water, Bare Soil and Grass. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 193(1032): 120-45.
- Schmidt, R., Flechtner, F., Meyer, U., Neumayer, K.H., Dahle, C., König, R., Kutsche, J., 2008. Hydrological Signals Observed by the GRACE Satellites. *Surveys in Geophysics*, 29(4-5): 319-34. DOI:10.1007/s10712-008-9033-3
- Senay, Gabriel B., Stefanie Bohms, Ramesh K. Singh, Prasanna H. Gowda, Naga M. Velpuri, Henok Alemu, James P. Verdin, 2013. Operational Evapotranspiration Mapping Using Remote Sensing and Weather Datasets: A New Parameterization for the SSEB Approach. *Journal of the American Water Resources Association (JAWRA)*. 49(3): 577-591
- Senay, G.B., Schauer, M., Friedrichs, M., Velpuri, N.M., Singh, R.K., 2017. Satellite-based water use dynamics using historical Landsat data (1984-2014) in the southwestern United States. *Remote Sensing of Environment*, 202: 98-112. DOI:10.1016/j.rse.2017.05.005
- Senay, G.B., Friedrichs, M., Morton, C., Parrish, G.E.L., Schauer, M., Khand, K., Kagone, S., Boiko, O., Huntington, J., 2022. Mapping actual evapotranspiration using Landsat for the conterminous United States: Google Earth Engine implementation and assessment of the SSEBop model. *Remote Sensing of Environment*, 275. DOI:ARTN 113011 10.1016/j.rse.2022.113011
- Sheffield, J., Wood, E.F., Pan, M., Beck, H., Coccia, G., Serrat-Capdevila, A., Verbist, K., 2018. Satellite Remote Sensing for Water Resources Management: Potential for Supporting Sustainable Development in Data-Poor Regions. *Water Resources Research*, 54(12): 9724-58. DOI:https://doi.org/10.1029/2017WR022437
- Shen, Z.H., Yong, B., Gourley, J.J., Qi, W.Q., Lu, D.K., Liu, J.F., Ren, L.L., Hong, Y., Zhang, J.Y., 2020. Recent global performance of the Climate Hazards group Infrared Precipitation (CHIRP) with Stations (CHIRPS). *Journal of Hydrology*, 591. DOI:ARTN 125284 10.1016/j.jhydrol.2020.125284
- van Eekelen, M.W., Bastiaanssen, W.G.M., Jarman, C., Jackson, B., Ferreira, F., van der Zaag, P., Saraiva Okello, A., Bosch, J., Dye, P., Bastidas-Obando, E., Dost, R.J.J., Luxemburg, W.M.J., 2015. A novel approach to estimate direct and indirect water withdrawals from satellite measurements: A case study from the Incomati basin. *Agriculture, Ecosystems & Environment*, 200: 126-42. DOI:https://doi.org/10.1016/j.agee.2014.10.023

Waalewijn, Pieter, Remi Trier, Jonathan Denison, Yasmin Siddiqi, Jeroen Vos, Eeman Amjad, and Mik Schulte. 2020. "Governance in Irrigation and Drainage: Concepts, Cases, and Action-Oriented Approaches—A Practitioner's Resource." World Bank, Washington, DC

APPENDICES

APPENDIX A ESTIMATION OF CHANGES IN STORAGE USING GRACE

A1 Terrestrial Water Storage Anomalies

Terrestrial Water Storage (TWS) represents the total water stored in the subsurface aquifers, soil moisture, snow, surface water and vegetation canopy. The dynamics in these components are fundamental to understanding the hydrological cycle (Kalu et al., 2021). The quantity was estimated for the Ban Don subbasin using level 3 mass concentration (mascon) data from the Gravity Recover and Climate Experiment (GRACE) and GRACE-Follow On (GRACE-FO) mission. The GRACE and GRACE-FO mission measures changes in total water storage (ΔTWS) by detecting small variations in the Earth's gravity field caused by the redistribution of mass, primarily water, across the planet (Ferreira et al., 2023). The GRACE and GRACE-FO missions consist of two satellites orbiting the earth in tandem at approximately 220 km apart. As they orbit Earth, changes in mass beneath them, which include the groundwater recharge or depletion, alter the gravitational pull, thereby causing slight changes in the distance between the satellites (Schmidt et al., 2008). The changes in their distance apart are measured precisely using a microwave ranging device and are used to infer changes in mass. At a 0.5-degree resolution, this quantity was obtained from the Centre for Space Research (CSR) over the Ban Don subbasin. However, the poor resolution of the GRACE and GRACE-FO missions resulted in a spatial scale mismatch between the mascon data and the relatively small Ban Don subbasin, whose area was 10,850 km². This is because the mission has a very coarse resolution, which limits its application on subbasin scales. More details on the statistical downscaling procedures undertaken on the mascon data to suit our study area is provided in A3.

A2 Data sources

A2.1 FLDAS Rainfall

The Famine Early Warning Systems Network Land Data Assimilation System (FLDAS) is a collaborative initiative developed through partnership among the U.S Geological Survey (USGS), the Climate Hazards Group at the University of California, Santa Barbara (UCSB), NASA's Goddard Space Flight Centre (GSFC), and the Earth Resources Observation and Science (EROS) Centre (Kalu et al., 2024b). The FLDAS precipitation dataset used in this study was derived from the simulations conducted with the Noah Land Surface Model version 3.6.1 at a spatial resolution of 0.10 degrees. These simulations were forced by a combination of the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) meteorological inputs and high-resolution 6-hourly rainfall data from the Climate Hazards Group InfraRed precipitation with station data (CHIRPS). The integration of CHIRPS data ensures improved spatial and temporal representation of rainfall, particularly in data-sparse regions like the Ban Don subbasin making the FLDAS precipitation produced well-suited as a predictor to downscale the coarse GRACE data and provide meaningful and estimable TWS quantities over the region.

A2.2 CHIRPS Rainfall

The Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) is a quasi-global precipitation dataset developed by the Climate Hazards Centre in collaboration with the USGS Earth Resources Observation and Science (EROS) Centre. Spanning from 1981 to the near-present, CHIRPS combines satellite imagery with in-situ station data to generate high-resolution (0.05°) gridded precipitation estimates. It was specifically designed for regions with sparse observational networks, making it well-suited for drought early warning, trend analysis, and water accounting applications (Alsilibe et al., 2023).

By correcting satellite-derived precipitation fields with terrain-aware climatology and interpolated station observations, CHIRPS minimises systematic biases and enhances rainfall representation in complex terrains (Du et al., 2024; Mulungu and Mukama, 2023; Shen et al., 2020). This robust methodology supports reliable

assessments of rainfall variability deficits, particularly in data-scarce environments like the Ban Don subbasin.

A2.3 FLDAS Evapotranspiration

The FLDAS evapotranspiration (ET) dataset was required as part of the predictors to downscale the GRACE data over the study area. It represents model-simulated estimates of actual ET, produced using the Noah 3.6.1 land surface model at a 0.10-degree spatial resolution. ET is calculated based on surface energy balance components and is driven by meteorological forcing from MERRA-2 and CHIRPS rainfall. The FLDAS ET was helpful in downscaling GRACE as it provides reliable, spatially continuous information on water loss from soil and vegetation, which is a key part of the land water storage information required from the GRACE data.

A2.4 SSEBop actual Evapotranspiration

The Simplified Surface Energy Balance Operational model (SSEBop) is a remote sensing-based approach for estimating actual evapotranspiration (ET) at regional to global scales. Developed by the U.S. Geological Survey (USGS), SSEBop combines satellite thermal imagery (e.g., from MODIS or Landsat) with reference evapotranspiration data to produce spatially distributed ET estimates.

SSEBop relies on the surface energy balance principle, simplifying the computation of ET by using land surface temperature as a proxy for moisture availability. The model applies a thermal index to scale reference ET, capturing spatial variation while maintaining computational efficiency. Its estimation is based on a satellite psychrometric principle (Senay et al., 2017) and is based on a two-step process where the ET fraction is first estimated as the difference between the measured land surface temperature and the reference surface temperature as,

$$ETf = 1 - \gamma^s(T_s - T_c) \quad (1)$$

Where, ETf is the daily ET fraction (0.0 to 1.0) for each pixel, γ^s represents the surface psychrometric constant (1/K) over a dry surface, the T_s parameter is gotten from the Landsat thermal band, representing the dry-bulb surface temperature (K), while T_c is gotten from the daily maximum air temperature, representing the wet-bulb reference surface temperature (K). The constant 1 is the ET fraction value whenever T_s is equals T_c (Senay et al., 2022).

Products are typically available at daily to monthly time steps and at resolutions ranging from 1 km to 30 m, depending on the satellite source.

A2.5 FLDAS Runoff

The FLDAS runoff product provides estimates of water that is not absorbed by the soil and instead flows over or through the land surface. It is generated using the Noah 3.6.1 land surface model at a 0.10-degree spatial resolution, the dataset simulates both surface and subsurface runoff processes. It is driven by meteorological inputs from MERRA-2 and rainfall observations from CHIRPS, ensuring consistency with other hydrological variables in FLDAS. In regions like the Ban Don subbasin, the FLDAS runoff dataset improves understanding on how precipitation contributes to immediate water flow across the landscapes. This product also served as a useful predictor for the downscaling of the GRACE data by helping to separate rapid water movements from long-term water storage changes.

A3 Statistical Downscaling of GRACE data

The coarse spatial resolution of the GRACE data limits its application over the Ban Don subbasin, which constrains its usability for local-scale freshwater reporting and accounting. A pre-processed sample of the original GRACE grids obtained at 0.5-degree grids from the CSR for the Ban Don subbasin are shown in Figure A1. The grids do not show any localised samples of terrestrial water storage movements around this region.

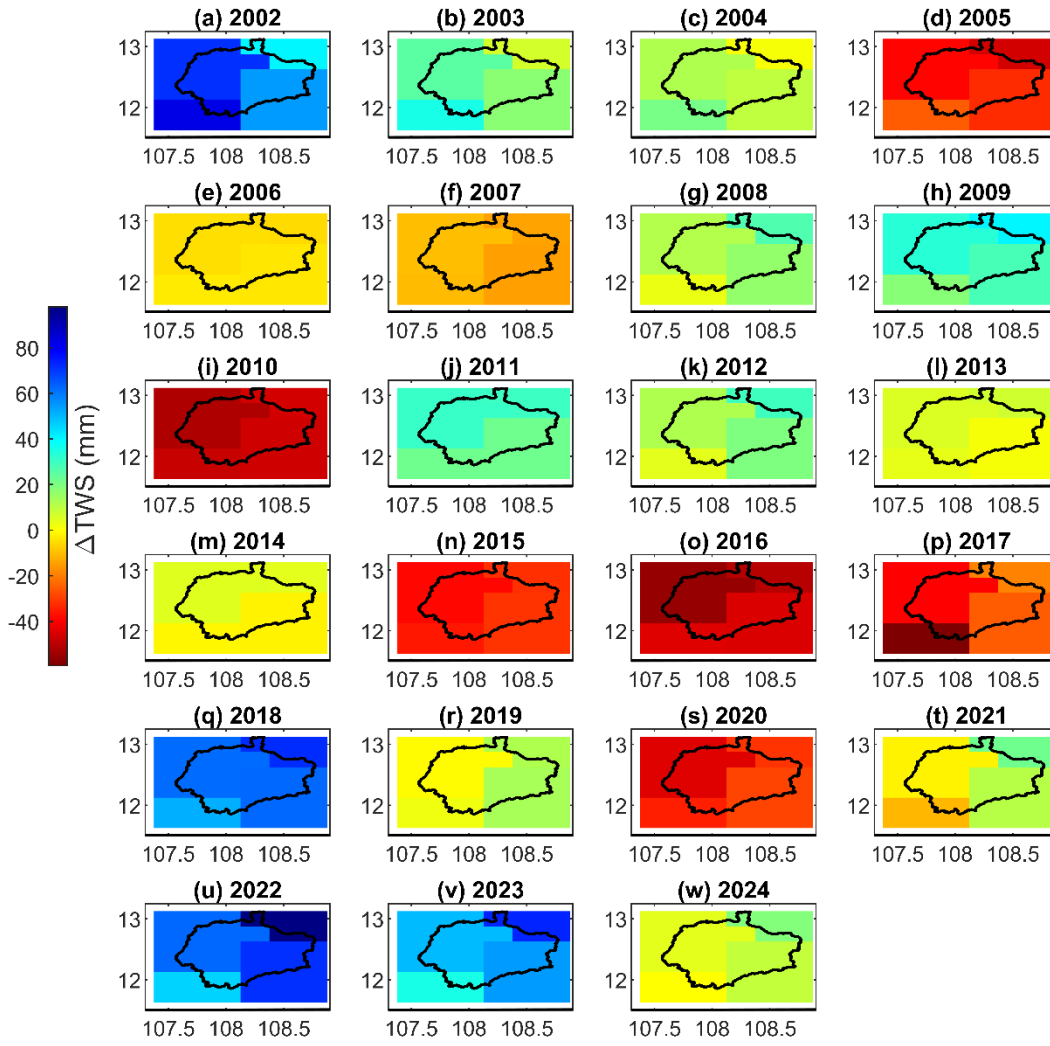


Figure A1. Annual original GRACE-TWS data over the Ban Don subbasin from 2002 to 2024

To improve the spatial resolution of the GRACE data in Figure A1, a statistical downscaling operation using the random forest (RAF) method was implemented. Random forest is an ensemble learning algorithm that constructs a collection of decision trees to improve predictive performance and model stability. Each tree is trained on a bootstrap sample of the data, and randomness is introduced during the splitting process to enhance generalization (Heung et al., 2014; Kalu et al., 2024b). By applying it to our statistical downscaling operation, it aggregated the outputs of individual trees by averaging their predictions.

Generally, statistical downscaling approaches attempt to establish spatial relationships between the GRACE data and hydrological variables (FLDAS in this case). This relationship allows high resolution predictions to be made with these hydrological variables to estimate finer scale ΔTWS data over any region of interest. The specific steps of our regression-based downscaling approach are summarized below;

(i) *Data resampling and aggregation*: The variables from FLDAS (i.e., precipitation, evapotranspiration, and runoff) were spatially resampled to the same coarse resolution of the original GRACE samples using pixel averaging method. This step was important to achieve consistency between the spatial size of the independent (FLDAS estimates) and dependent (GRACE) variables.

(ii) *RAF Machine Learning*: The RAF approach was employed to develop a functional relationship between the coarse-scale GRACE ΔTWS and the high-resolution hydrological flux variables from FLDAS (i.e., precipitation, evapotranspiration, and runoff), which were already spatially aggregated to match the resolution of the GRACE observations (as described in step i). This trained model was subsequently used to estimate GRACE ΔTWS at a 0.1° spatial resolution.

(iii) *Model Residuals*: To estimate the discrepancy between the observed and predicted GRACE values, model residuals were derived by subtracting the RAF-predicted Δ TWS from the original GRACE data at 0.5° resolution. These residuals were then spatially interpolated to a finer resolution of $0.1^\circ \times 0.1^\circ$ using ordinary kriging interpolation method.

(iv) *Downscaling procedure*: The initial downscaling explained in step (ii) used high-resolution FLDAS predictors to generate a finer-scale GRACE Δ TWS estimate. While this process captures broader regional patterns, it may lack details at smaller spatial scales. Therefore, an additional residual correction step was necessary to enhance spatial integrity.

(v) *Residual correction*: To refine the downscaled GRACE Δ TWS estimates, interpolated residuals from the earlier steps were added back to the predicted values. This correction was essential to account for fine-scale variability that may not be fully represented in the initial downscaling output, even after regional-scale improvements. Incorporating these residuals ensures that the final downscaled produced more accurately reflects both regional trends and localized hydrological variations (Kalu et al., 2024a; Kalu et al., 2024b) across the Ban Don subbasin (Figure A2)

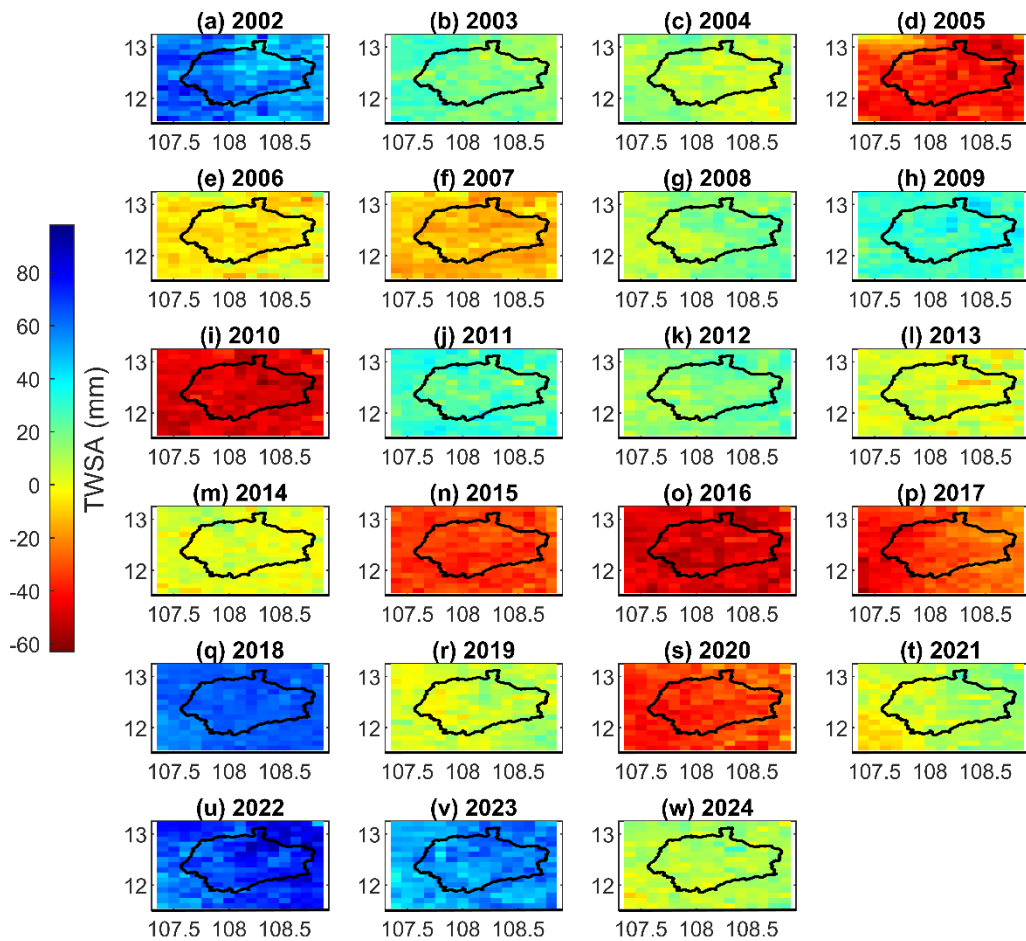


Figure A2. Downscaled GRACE change in total water storage derived using machine learning algorithms, resampled to a spatial resolution of 0.1° . The high-resolution estimates incorporate fine-scale variability using predictor variables such as precipitation, evapotranspiration, and runoff.

APPENDIX B: WATER ACCOUNTING SHEETS

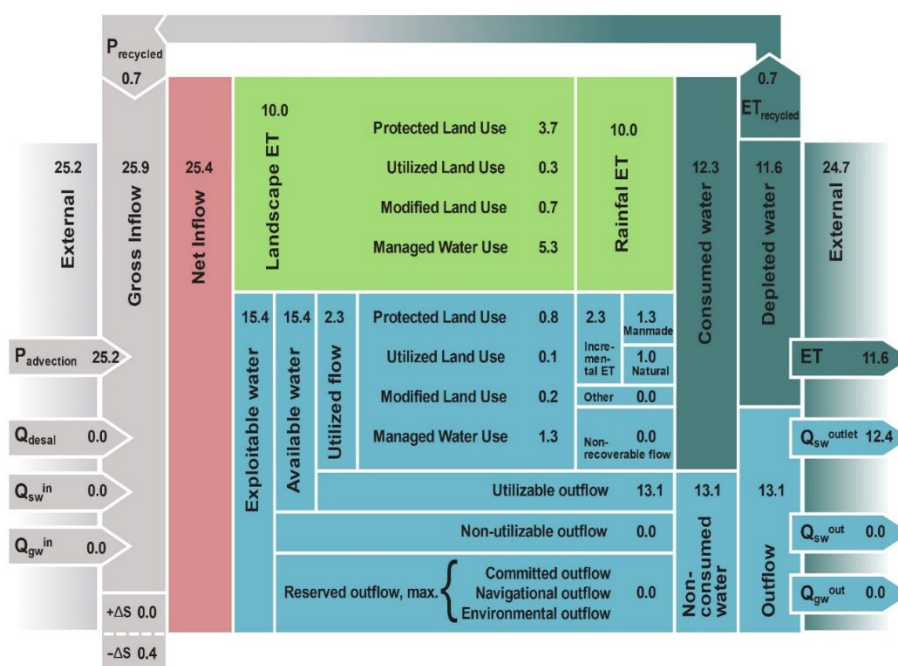
1. Ban Don basin
- a) Sheet 1

Table B1: Input data sheet 1 in Ban Don basin

Input	Type	Resolution	Period
CHIRPS v3	Precipitation	5 km	2013 – 2024
SSEBop	Evapotranspiration	1 km	2013 – 2024
GRACE	Water storage	10 km	2013 – 2024

Sheet 1: Resource Base (km³/year)

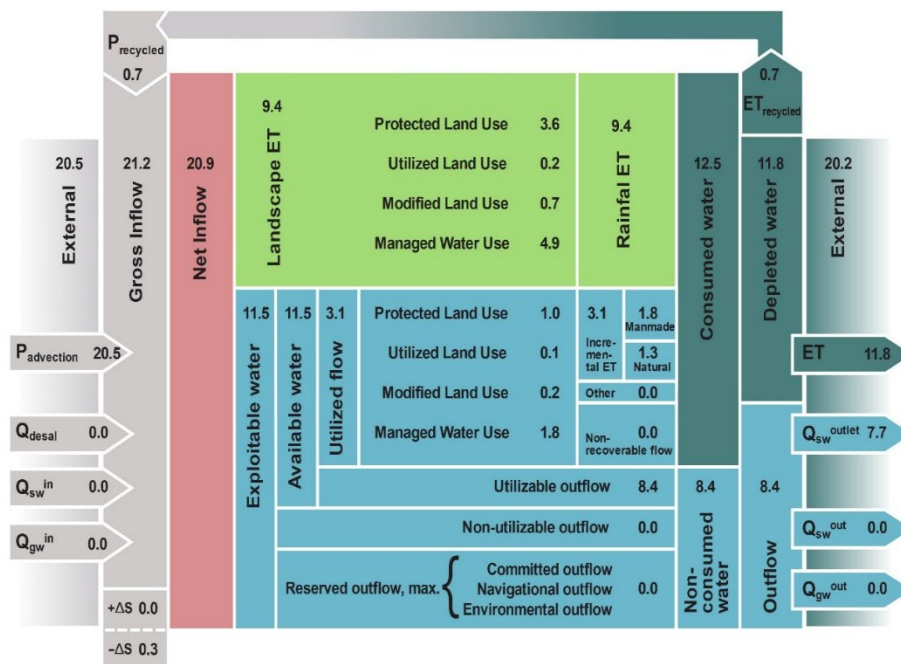
Basin: Ban Don Basin
Period: 2013



Water Accounting sheet 1 2013

Sheet 1: Resource Base (km3/year)

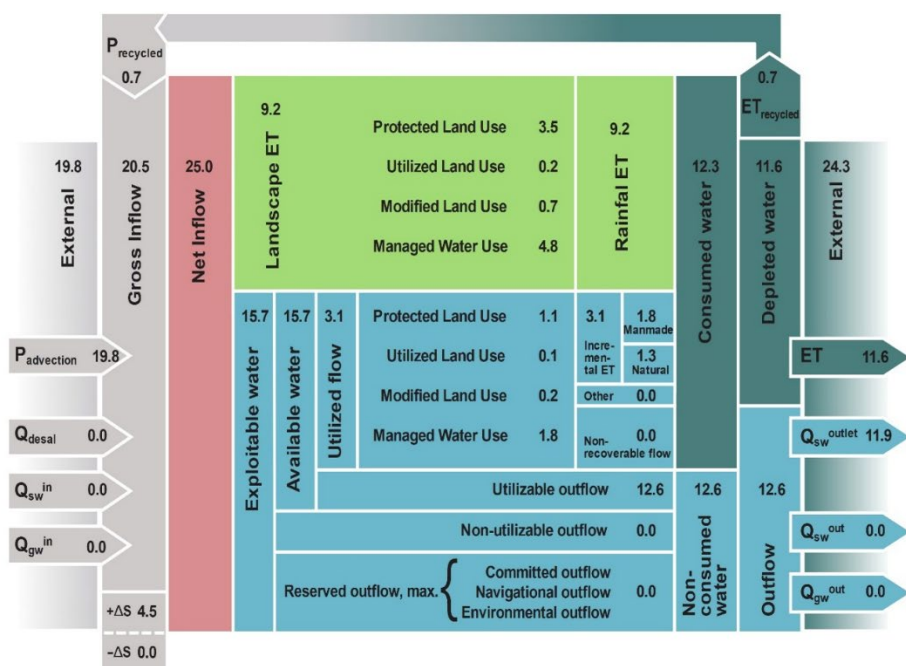
Basin: Ban Don Basin
Period: 2014



Water Accounting sheet 1 2014

Sheet 1: Resource Base (km3/year)

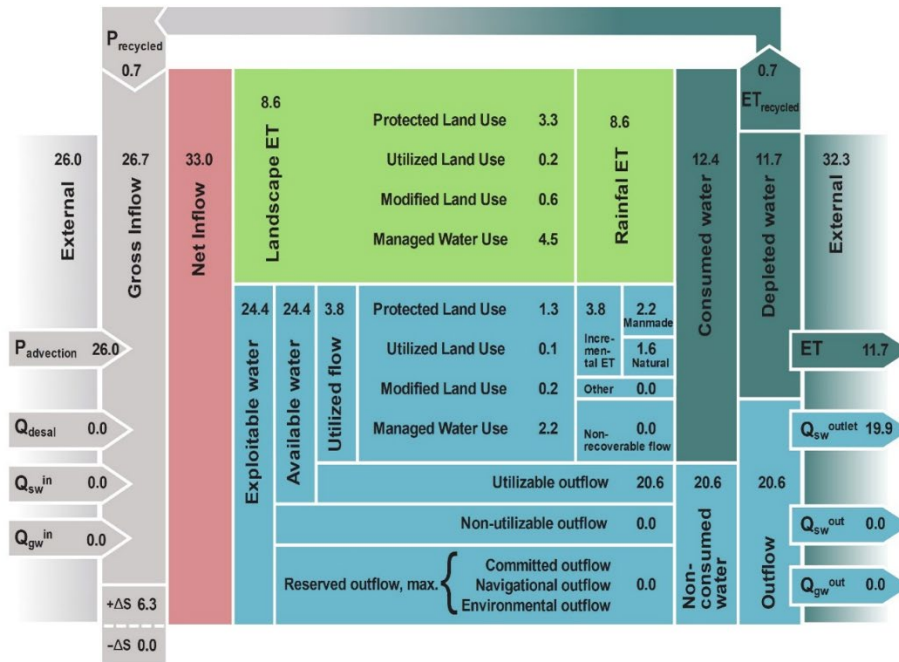
Basin: Ban Don Basin
Period: 2015



Water Accounting sheet 1 2015

Sheet 1: Resource Base (km3/year)

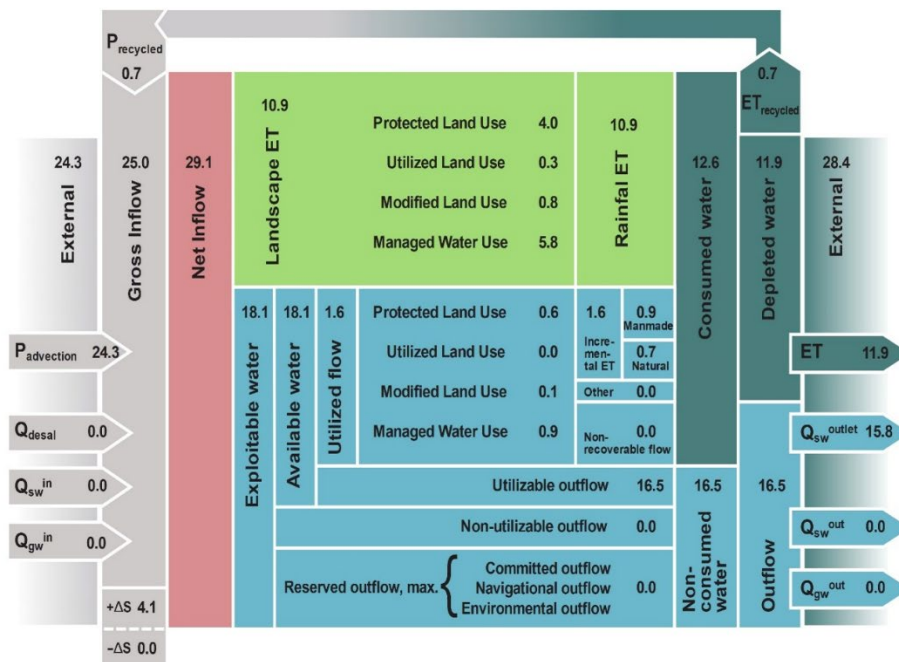
Basin: Ban Don Basin
Period: 2016



Water Accounting sheet 1 2016

Sheet 1: Resource Base (km3/year)

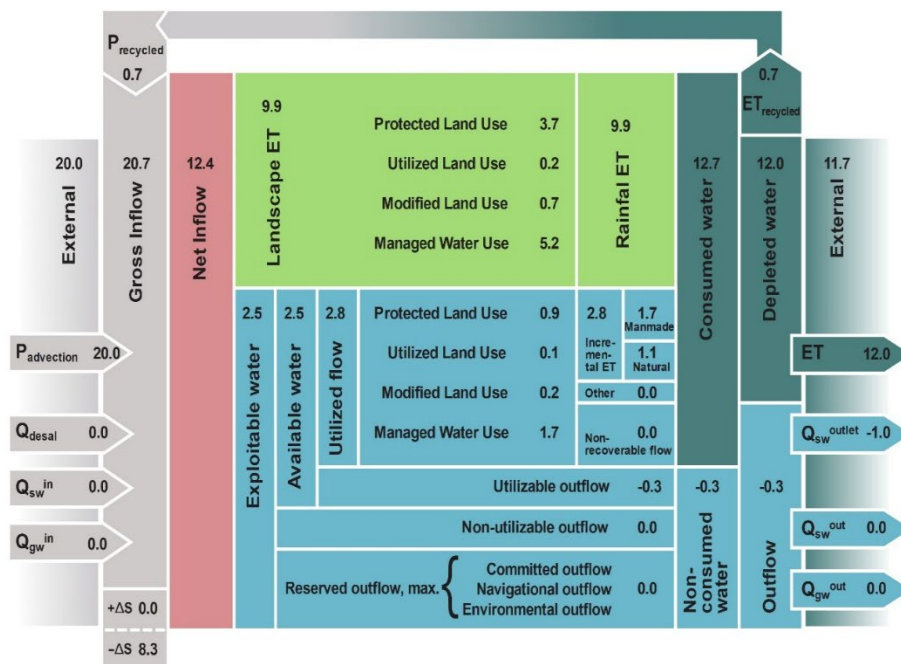
Basin: Ban Don Basin
Period: 2017



Water Accounting sheet 1 2017

Sheet 1: Resource Base (km3/year)

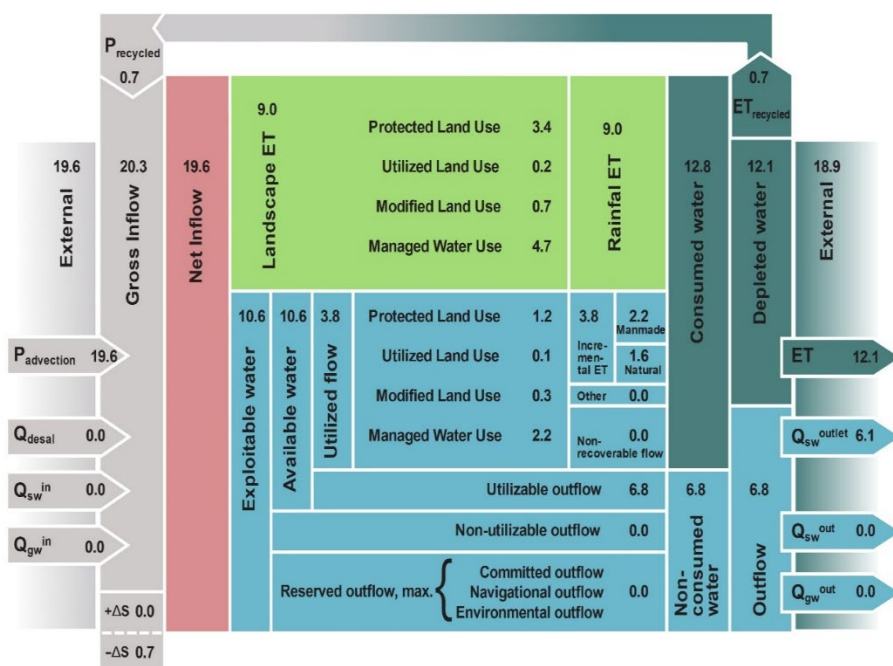
Basin: Ban Don Basin
Period: 2018



Water Accounting sheet 1 2018

Sheet 1: Resource Base (km3/year)

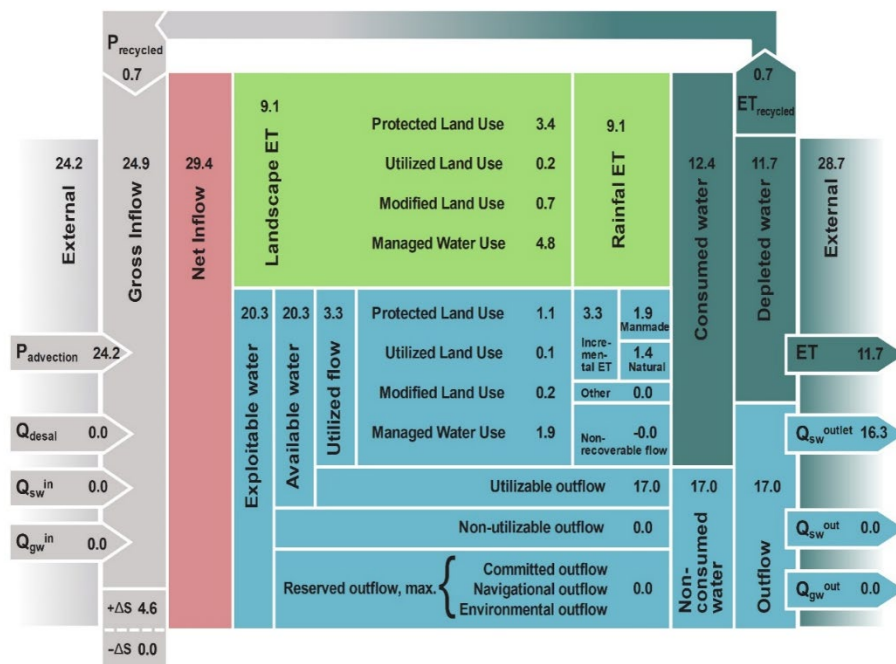
Basin: Ban Don Basin
Period: 2019



Water Accounting sheet 1 2019

Sheet 1: Resource Base (km3/year)

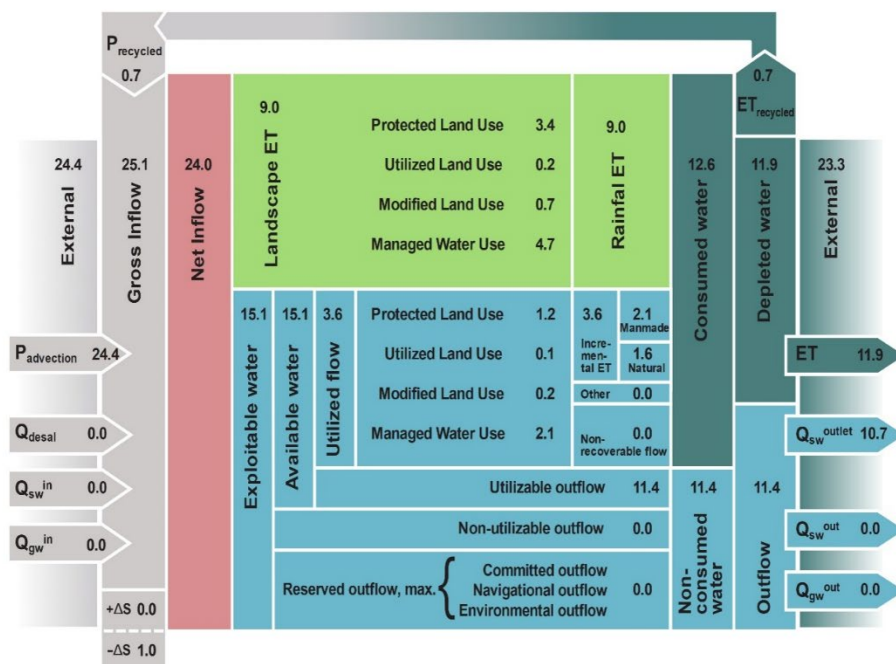
Basin: Ban Don Basin
Period: 2020



Water Accounting sheet 1 2020

Sheet 1: Resource Base (km3/year)

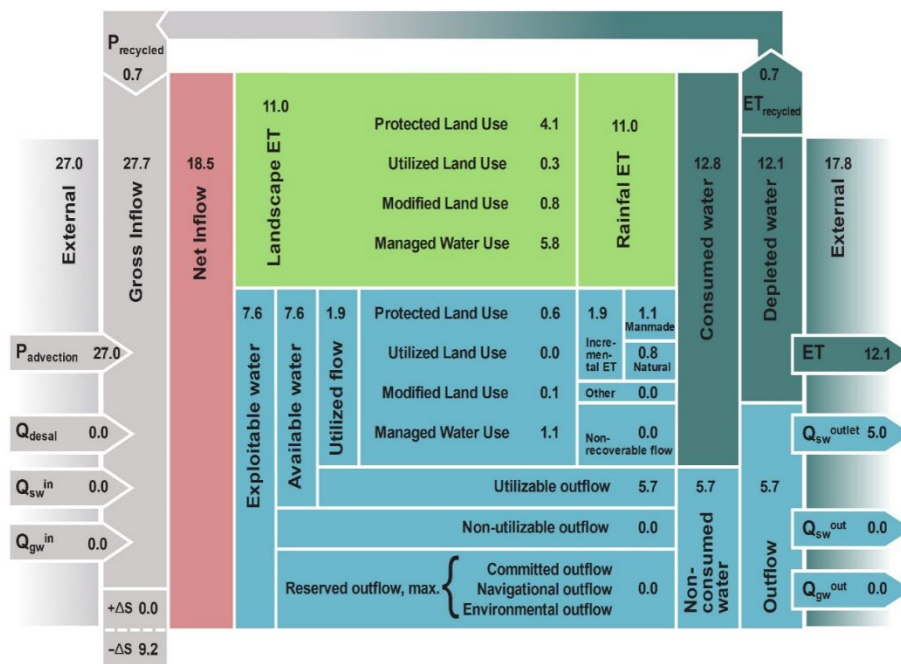
Basin: Ban Don Basin
Period: 2021



Water Accounting sheet 1 2021

Sheet 1: Resource Base (km3/year)

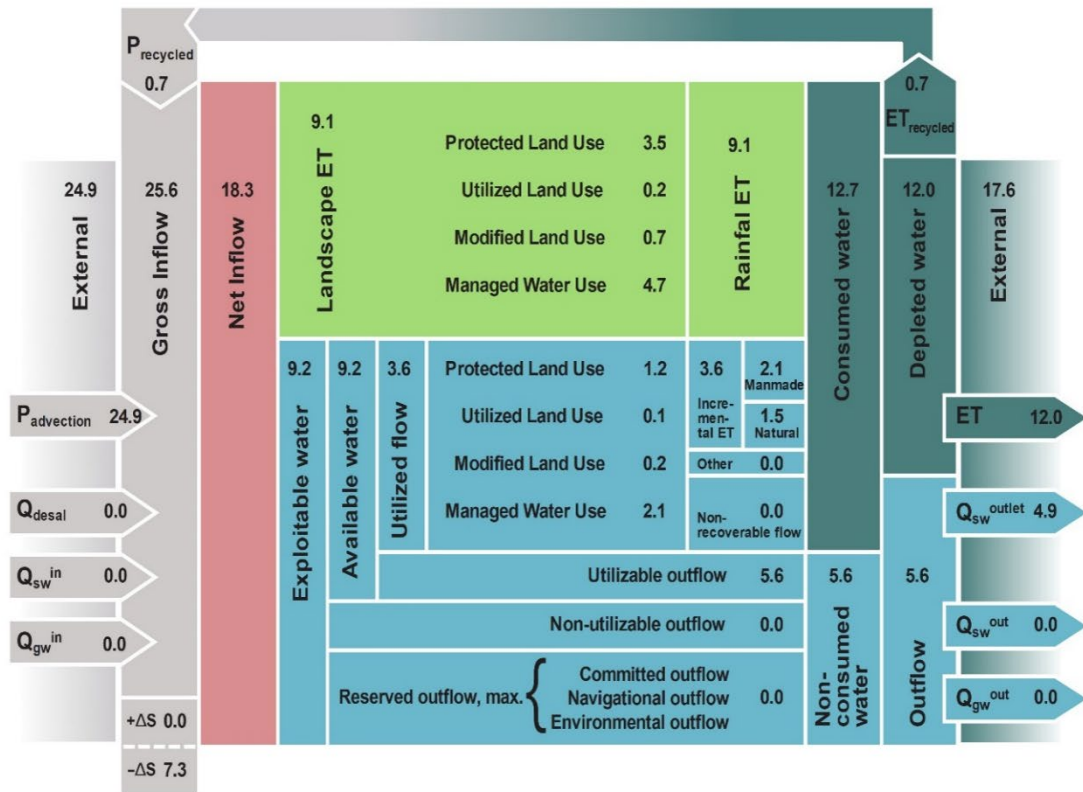
Basin: Ban Don Basin
Period: 2022



Water Accounting sheet 1 2022

Sheet 1: Resource Base (km3/year)

Basin: Ban Don Basin
Period: 2023



Water Accounting sheet 1 2023

Water Accounting sheet 1 2023

b) Sheet 2

Input data sheet 2 in Ban Don basin

Sheet 2: Evapotranspiration (km3/year)

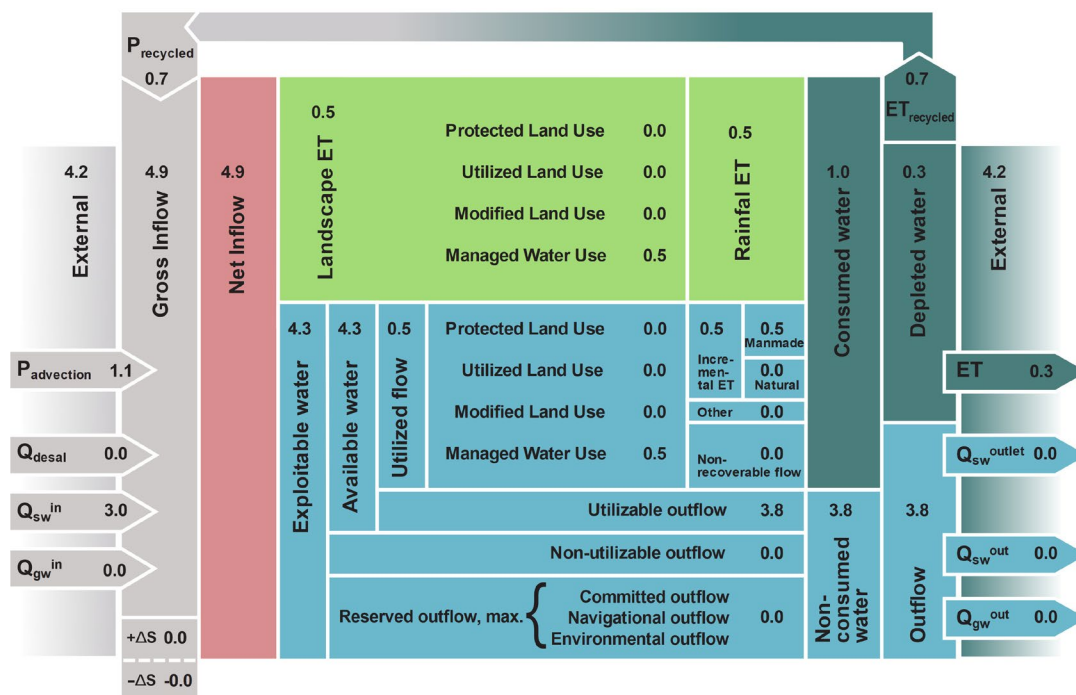
Period: 2023

Basin: Ban Don Basin

		ET	T			ET	T					
7.9 Total evapotranspiration	Non-manage-able 5.5	Protected Land Use			Forests	5.5	2.6	4.2	Interception 0.2	Non-Beneficial 0.0		
					Shurbland	0.0	0.0					
					Natural grassland	0.0	0.0					
					Natural water bodies	0.0	0.0					
					Wetlands	0.0	0.0					
					Graciers	0.0	0.0					
					Other	0.0	0.0					
	Manage-able 0.3	Utilized Land Use			Forests	0.0	0.0	3.9	Soil			
					Shurbland	0.3	0.1					
					Natural grassland	0.0	0.0					
					Natural water bodies	0.0	0.0					
					Wetlands	0.0	0.0					
					Other	0.0	0.0					
	Managed 2.2	Modified Land Use			Rainfed crops	0.0	0.0	0.1	Water	Beneficial 0.0		
					Forest plantations	-	-					
					Settlements	0.0	0.0					
					Other	0.1	0.0					
		Managed Water Use	Con-ventional	Irrigated crops	-	-	3.7				Transpiration	Agriculture 0.0 Environment 0.0 Economy 0.0 Energy 0.0 Leisure 0.0
				Managed water bodies	-	-						
				Residential	-	-						
				Industry	-	-						
				Other	-	-						
				Non-conventional	Indoor domestic	-						
			Indoor industry		-	-						
			Greenhouses		-	-						
			Livestock & husbandry		-	-						
Power and Energy	-		-									
					</							

Sheet 1: Resource Base (km3/year)

Basin: Krong Buk Basin
Period: 2023



Water Accounting sheet 1 2023

b) Sheet 2

Input data sheet 2 in Krong Buk basin

Sheet 2: Evapotranspiration (km3/year)

Period: 2024

Basin: Krong Buk Basin

				ET	T					ET	T				
Total evapotranspiration 1.4	Non-manage-able 0.0	Protected Land Use 0.0	0.0	Forests		0.0	0.0	1.0	Interception 0.1	Non-Beneficial -					
				Shurbland		0.0	0.0								
				Natural grassland		0.0	0.0								
				Natural water bodies		0.0	0.0								
				Wetlands		0.0	0.0								
				Graciers		0.0	0.0								
				Other		0.0	0.0								
	Manage-able 0.0	Utilized Land Use 0.0	0.0	Forests		0.0	0.0	0.8	Soil	Beneficial 0.0					
				Shurbland		0.0	0.0								
				Natural grassland		0.0	0.0								
				Natural water bodies		0.0	0.0								
				Wetlands		0.0	0.0								
				Other		0.0	0.0								
	Managed 1.4	Modified Land Use 0.0	0.0	Rainfed crops		0.0	0.0	0.3	Water	Agriculture 0.0 Environment 0.0 Economy 0.0 Energy 0.0 Leisure 0.0					
				Forest plantations		-	-								
				Settlements		0.0	0.0								
				Other		0.0	0.0								
		Managed Water Use 1.3	0.3-	Con-ventional	Irrigated crops		-							-	Transpiration 0.3
					Managed water bodies		-							-	
					Residential		-							-	
					Industry		-							-	
					Other		-							-	
					Non-conventional	Indoor domestic								-	
				Indoor industry		-	-								
				Greenhouses		-	-								
				Livestock & husbandry		-	-								
				Power and Energy		-	-								
				Other		-	-								