TECHNICAL BRIEF

A New Water Balance Model Leveraging Satellite Observations for Effective Water Management Decisions in Data-Scarce Paddy-Dominated Regions

Smaranika Mahapatra, Shivam Pandey, Naga M. Velpuri, and Petra Schmitter

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Authors

Smaranika Mahapatra, National Researcher – Water Data Modelling, International Water Management Institute (IWMI), New Delhi, India
Shivam Pandey, Consultant, IWMI, New Delhi, India
Naga M. Velpuri, Principal Researcher and Research Group Leader – Water Data Science for Action (WDSA), IWMI, New Delhi, India
Petra Schmitter, Research Group Leader- Climate Mitigation & Adaptation Pathways (CMAP), IWMI, Colombo, Sri Lanka

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CGIAR Sustainable Farming Program

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Contents

Key Messages

- **PaddyWA+ Model** is an updated 30-m, daily Water Accounting Plus (WA+) model designed for paddy systems, integrating satellite data to capture ponding depth, soil water dynamics, and blue/green water use—addressing gaps in traditional WA+ and other water balance models.
- **Why It Matters:** Rice cultivation is highly water-intensive (24–40% of global irrigation withdrawals) and a major methane emitter, yet existing models cannot simulate paddy-specific features like bunded fields, hardpan-limited percolation, or variable irrigation.
- **Improved Accuracy:** Compared to conventional WA+, PaddyWA+ produces more realistic actual evapotranspiration (AET), irrigation demand, and percolation estimates, revealing dominant green/blue water use and significant spatial variability in ponding and soil moisture across Bihar.
- **Decision and Policy Value:** The model supports irrigation scheduling, water budgeting, climate-resilient agriculture planning, and crop diversification by offering actionable field-to-district-scale indicators.
- **Future Applications:** Can assess water management practices, identify intervention hotspots, support sustainable systems (e.g., rice–fish culture), evaluate climate impacts, and help estimate methane mitigation potential.

Introduction

Rice is a major staple food for approximately 50% of the world’s population (Muthayya et al., 2014), with about 90% of production and consumption occurring in Asia (Abdullah et al., 2006). Paddy cultivation accounts for 24% to 40% of global water withdrawals, with half of this occurring in Asia alone (Surendran et al., 2021). This high demand stems from the fact that 75% of global rice production relies on flooded irrigation methods, making paddy consume two to three times more water than most other cereal crops (Bouman et al., 2007). As a result, rice production contributes to regional and seasonal water scarcity across many areas, pressures that are expected to intensify with rapidly increasing global demand for water and food, climate change, and inefficient use of water resources. Beyond growing water scarcity concerns, rice production is also energy-intensive and has a higher carbon footprint than most crops due to irrigation pumping and prolonged field flooding. Anaerobic conditions created by ponded water in rice fields make them a significant source of global greenhouse gas (GHG) emissions, contributing roughly 20% of worldwide methane (CH4) emissions and about 10% of nitrous oxide (N2O) emissions (Linquist et al., 2012). Notably, around 89% of methane emissions from rice cultivation originate from South and Southeast Asia (Yan et al., 2003). As climate change accelerates, improving water and energy use efficiency while reducing the carbon and GHG footprint of rice systems has become a critical global priority.

The unique characteristics of paddy fields shape the complex interactions between surface ponding and subsurface hydrological processes. In rice fields, the hydrological cycle is influenced not only by natural factors but also by human-made structural modifications, such as surface bunding — low, compacted soil embankments —and a semi-impermeable layer below the root zone formed over years of continuous puddling. Water use and soil moisture dynamics in traditionally cultivated paddy fields primarily drive these interconnected processes. Continuously monitoring these factors at scale is challenging, as many monitoring infrastructures are required to capture their inherent heterogeneity. In the absence of spatially detailed, high-resolution water balance data, it becomes challenging to plan, implement, and monitor effective water management strategies in paddy fields, as well as to assess their hydro-environmental impacts on regional water resources.

There are several challenges associated with modelling the impact of water management practices at scale in rice-dominated landscapes. First, at the field or farm level, existing process-based soil water balance models require long-term and extensive datasets for calibration and validation, and depend on detailed inputs regarding irrigation schedules, ponding depth, and various farming practices, data that are rarely available in paddy systems. Second, at the watershed level, existing process-based hydrological models often cannot reliably represent the unique hydrological processes, characteristics, and behaviour of paddy fields. Third, histor-ical information on irrigation water use, field standing water depth, duration, and the frequency of ponding and non-ponding in paddy fields, often crucial for optimal water-use planning, is not readily available or derivable from existing water balance models. Dedicated process-based models, such as ORYZA or HYDRUS, employ a bottom-up approach, requiring detailed field information, agronomic practices, irrigation, and schedules as inputs to simulate soil moisture.

With the advancement of remote sensing (RS) applications, it is now possible to address some of these data scarcity issues. Model frameworks like Water Accounting Plus (WA+) is a monthly pixel-based water balance model at the basin scale requiring minimal data. However, the initial findings of the WA+ application in Bihar under the CGIAR Excellence in Agronomy Initiative, the model underperformed in paddy-dominated areas, due to ponding water table complexities. Therefore, under the Sustainable Farming Science Program, we developed a new module for the WA+ framework to simulate the water ponding table and soil water regime at a daily scale with high-resolution earth observation ET data, making it suitable for paddy-dominated landscapes.

Eastern Gangetic Plains: Paddy-Dominated Agricultural System

The state of Bihar, which covers a significant part of the Eastern Indo-Gangetic Plains, is mainly dominated by rice cultivation (Figure 1). Global rice production accounts for about 1.8 % of global GHG emissions, while livestock rearing accounts for 12 % of global GHG emissions, and the use of agrochemicals accounts for 2.1 % of global GHG emissions (Wang et al., 2023). Continuous flooding in rice cultivation causes prolonged waterlogging, leading to higher methane emissions than other crops, and positioning the Gangetic plains of Bihar as a significant global source of methane.

Despite abundant water resources, the state of Bihar suffers from persistent yield gaps, low agricultural productivity, and limited crop diversification. Due to limited irrigation infrastructure and farmers' economic constraints (e.g., fuel costs, pump purchase costs). Rice is largely cultivated under rainfed conditions. However, if farmers can invest in irrigation, supplemental irrigation is practiced managing rainfall deficits. Hence, with the increasing occurrence of dry spells during the Kharif Monsoon (Jun-Sep/Oct), the irrigation demand raises, Yet reliable information on actual water use and the impact of irrigation expansion on water resources availability and potential risks remains scarce. For these reasons, Bihar was chosen to develop and test the PaddyWA+ model.

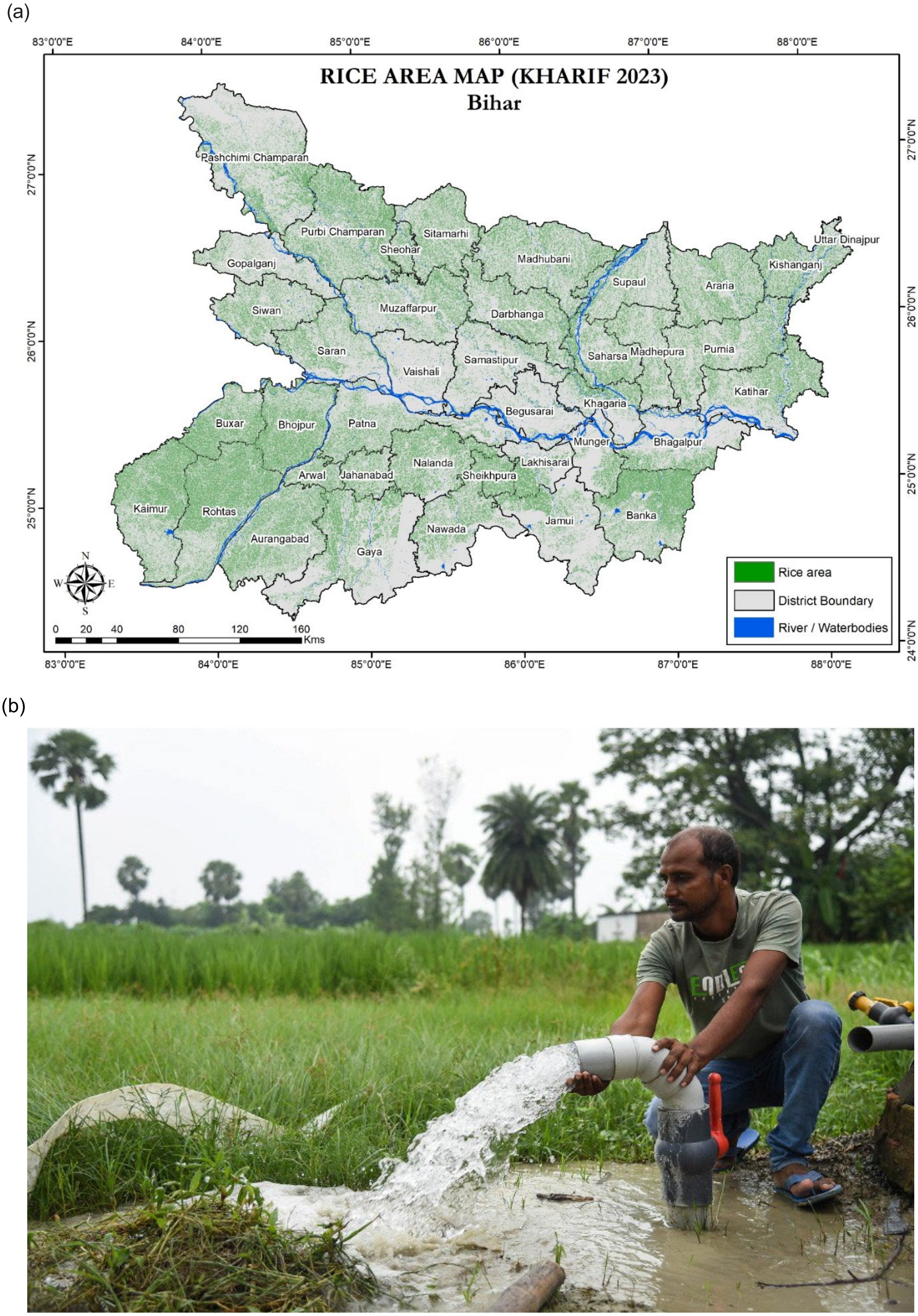


Figure 1. (a) Rice area map of Bihar in the Kharif season, credit: International Rice Research Institute (IRRI), and (b) a farmer irrigating a paddy field in Chakhaji, Samastipur District of Bihar, India (photo:Tanmoy Bhaduri/IWMI).

Methodology

Traditional Water Accounting Plus (WA+) Framework

The traditional WA+ framework integrates open-source global data, RS data, and geospatial information with a pixel-based soil water balance model (Figure 2). All input data are stored in cloud platforms such as Amazon Web Services (AWS) and are directly linked to the WA+ framework. The pixel-based soil moisture balance model provides the foundational layers for WA+ and key wa-ter availability indicators. These foundational layers and indicators are then used to generate water accounts (Figure 2).

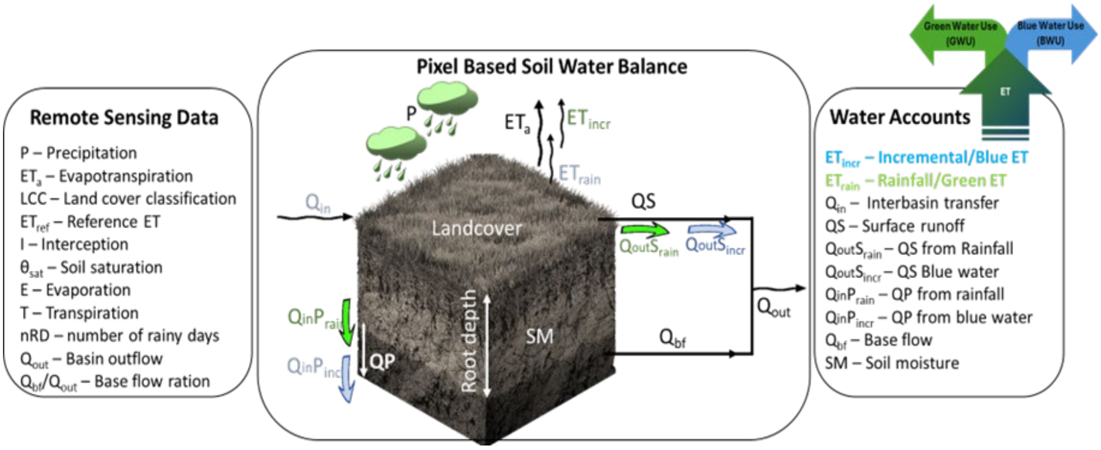


Figure 2. Combined use of satellite remote sensing (RS) and a pixel-based soil water balance model for water accounts and partitioning of blue and green evapotranspiration (Source: authors' creation)

With the availability of high-resolution RS datasets, the conventional WA+ can now capture micro-scale variations in water use within a basin. However, WA+ was originally developed to provide basin-scale water accounts at seasonal and annual scales and was not designed for daily water balance assessment (Mahapatra et al., 2024). In addition, WA+ was also not designed for the paddy region, where individual fields act as small, temporary water retention ponds and collectively influence the basin-scale water balance. The depth and duration of standing water, along with daily soil water levels in paddy fields, play a crucial role in determining total water use in these areas. Therefore, it is essential to model these variables to support effective water-use planning in paddy-dominated regions.

Innovation: Modified Water Accounting Plus Framework (PaddyWA+)

To extend the applicability of WA+ for paddy-dominated regions, we developed the PaddyWA+ framework. This model can be parametrized to run daily at 30 m spatial resolution using Landsat-based evapotranspiration data. It provides additional field-scale information, including daily variations in water balance components, ponding depth and duration, soil water level, total water use, and segregated blue and green water use (Figure 3).

By contrast, PaddyWA+ integrates RS and open-source spatial datasets into the soil water balance model, enabling application across large, data-scarce regions with minimal field-level inputs while covering multiple locations. This framework, therefore, offers a scalable solution for monitoring water use in paddy-dominated regions, eliminating the need for costly in situ networks. This allows water resource planners and managers to make informed decisions on water use and irrigation requirements.

The overall methodology and processes included in the PaddyWA+ framework are illustrated in Figures 3 (a) and (b) and described in the following sections.

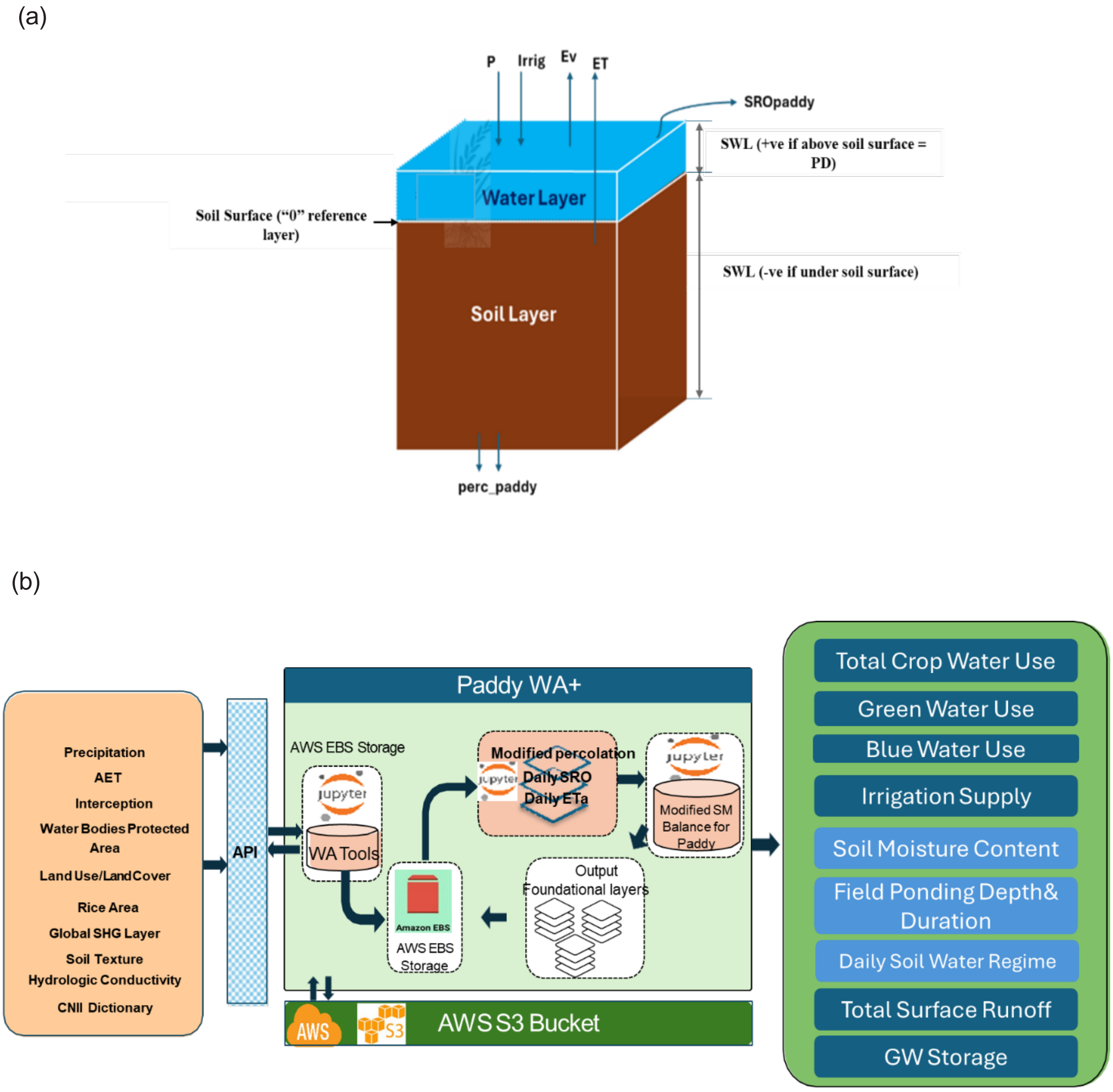


Figure 3. (a) Modified water balance at the pixel level and (b) WA+ framework for paddy-dominated landscapes (PaddyWA+). Note: P – rainfall; Irrig – irrigation; Ev – Evaporation; ET – evapotranspiration; SROpaddy – surface runoff from paddy fields; perc_paddy – percolation from paddy fields; SWL – soil water level; PD – ponding depth. (*Source:* authors' creation)

Enhancing surface runoff, percolation and soil moisture dynamics

With PaddyWA+, daily surface runoff is calculated using the modified SCS-CN approach (Boughton, 1989). In paddy fields, surface runoff is affected by changes in surface and subsurface water flow dynamics, driven by the presence of surface bunds and hard pans below the root zone. Therefore, in the modified SCS-CN method, this was addressed by introducing bund heights and modified percolation rates to capture subsurface hardpans in paddy areas, resulting in a dedicated runoff component for paddy fields (SROpaddy). For other land uses and the non-paddy areas, runoff and percolation were estimated by accounting for the moisture content of the root zone, which is also dependent on the soil characteristics of the root zone. If the soil moisture content exceeds field capacity, percolation occurs at an exponential rate. However, in paddy fields, the percolation (perc_paddy) is controlled by the hardpans. Therefore, the perc_paddy is limited by a maximum percolation rate, which is often determined from field observations or model calibration. In the study area, the maximum percolation rate was set at 2 mm/day, which was refined for districts found to be sensitive to the simulated soil water level (SWL).

High-resolution actual evapotranspiration (AET) to drive the water balance

The conventional WA+ model was run at a 1-km pixel resolution, representing approximately 250 acres (100 ha) of land per pixel. However, the average farm holding in the region is only 1–2 acres (Singh et al., 2018), resulting in substantial variability among rice fields due to differences in planting patterns and irrigation practices, which can affect water use. To meaningfully capture this field-level heterogeneity, high-resolution evapotranspiration data were required to map water consumption more accurately across the rice-growing landscape. A 30-m daily AET was generated using the United States Geological Survey (USGS) on-demand ET fraction (ET_f) datasets (produced based on Landsat 8-9 thermal imagery, based on Simplified Surface Energy Balance operational (SSEBoP) algorithm (Senay et al., 2023) in conjunction with reference evapotranspiration data. However, these Landsat ET_f products are often limited by data gaps caused by cloud cover, which were filled by an extensive gap-filling procedure. Temporal gap filling was performed using linear interpolation over a 48-day time window within the same year (Kagone et al., 2024). During the monsoon months, gaps were filled by utilizing data from the same month in the years preceding and following the target year.

Paddy Field Water Dynamics in Bihar

PaddyWA+ simulation results reveal high spatial variability in ponding depth and duration across Bihar’s 55,642 km² of paddy fields, showing diverse hydrological conditions in the state’s paddy-growing regions. Nearly 99% of fields experience some level of flooding during the Kharif season. Most fields maintain an average ponding depth between 3-5 cm, conditions generally favorable for rice growth.

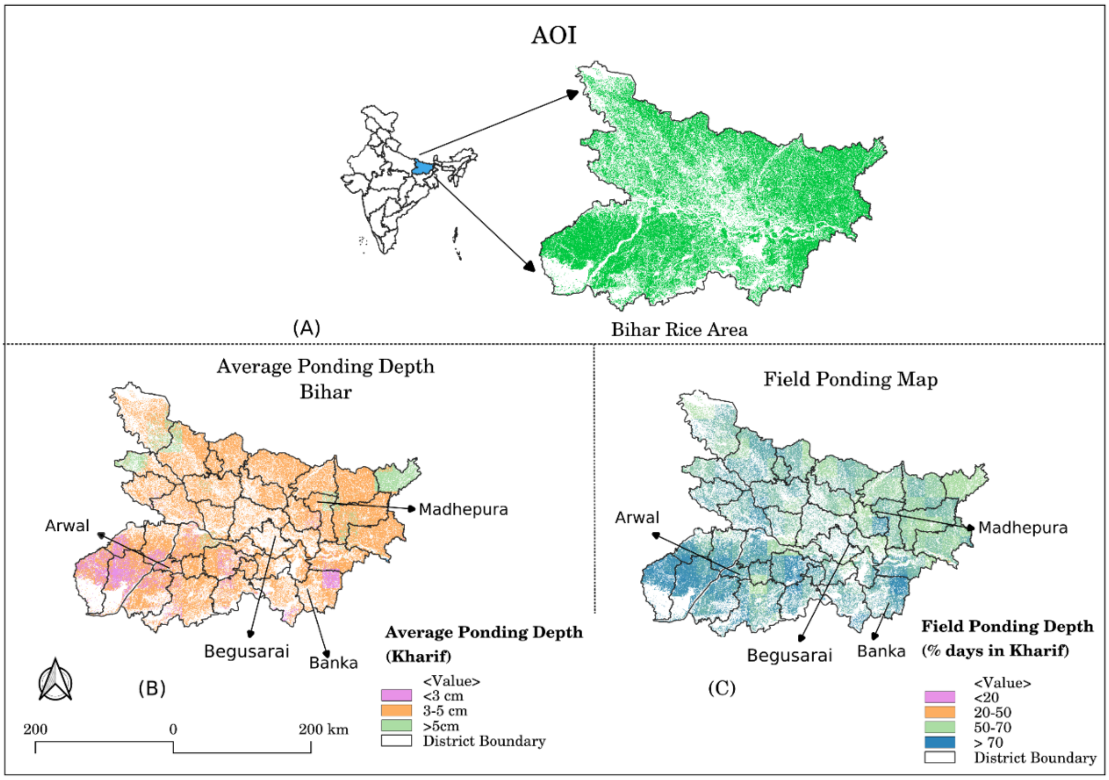
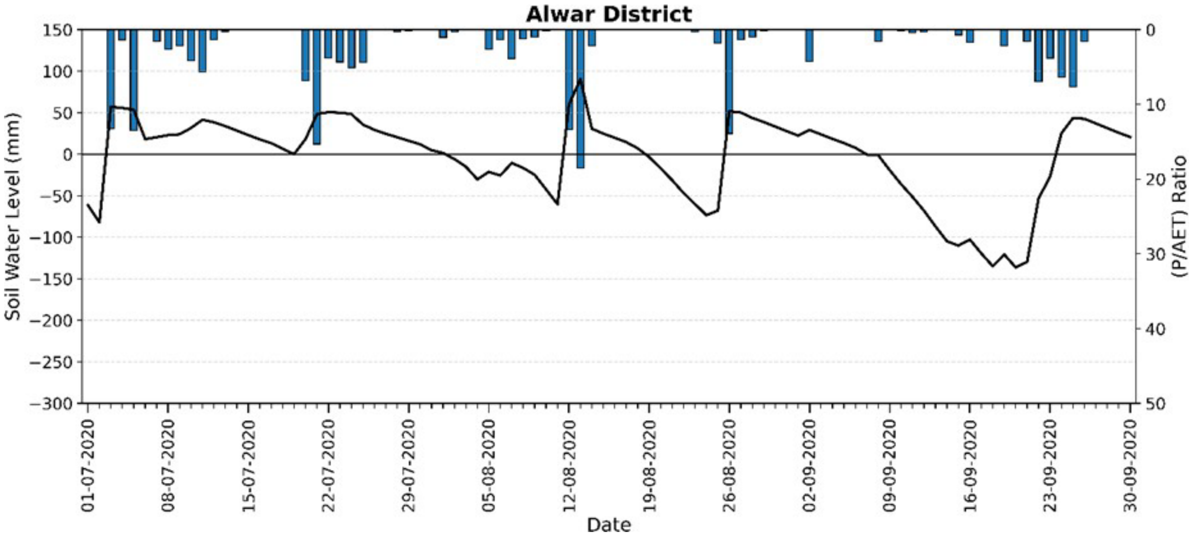


Figure 4. (A) Area of Interest and Rice area map (B) Simulated Average Ponding depth in Rice area during Kharif season (C) Simulated Field ponding durations in the rice cultivated area of Bihar during the crop growth period in the Kharif season (*Source*: authors' creation)

Clear regional contrasts emerge: the drier southwest records ponding depths below 3 cm due to low rainfall, whereas northeast Bihar, with higher rainfall, records depths above 5 cm (Figure 4). The literature recommends maintaining shallow submergence (around 5 cm) throughout the crop period to support optimal yield and weed suppression. It also recommends a water level of about 1.5 cm during transplanting, followed by a gradual rise to 5 cm (Surendran et al., 2021).

PaddyWA+ outputs, including the field ponding map (Figure 4), indicate that, for most of the Kharif season, ponding depths across Bihar's paddy fields remain below the 5 cm optimum. In the northern region, ponding depths are generally closer to 5 cm, with a smaller proportion of time showing depths below this threshold due to the reliable availability of irrigation. In contrast, some parts of the southern region, which receive less rainfall and have limited irrigation facilities, show consistently lower ponding depths (<3 cm). These spatial differences underscore the combined effect of precipitation patterns and irrigation distribution on field water conditions during the Kharif growing season.


Alwar District
Soil Water Level (mm)
150
100
50
0
−50
−100
−150
−200
−250
−300
(P/AET) Ratio
0
10
20
30
40
50
01-07-2020
08-07-2020
15-07-2020
22-07-2020
29-07-2020
05-08-2020
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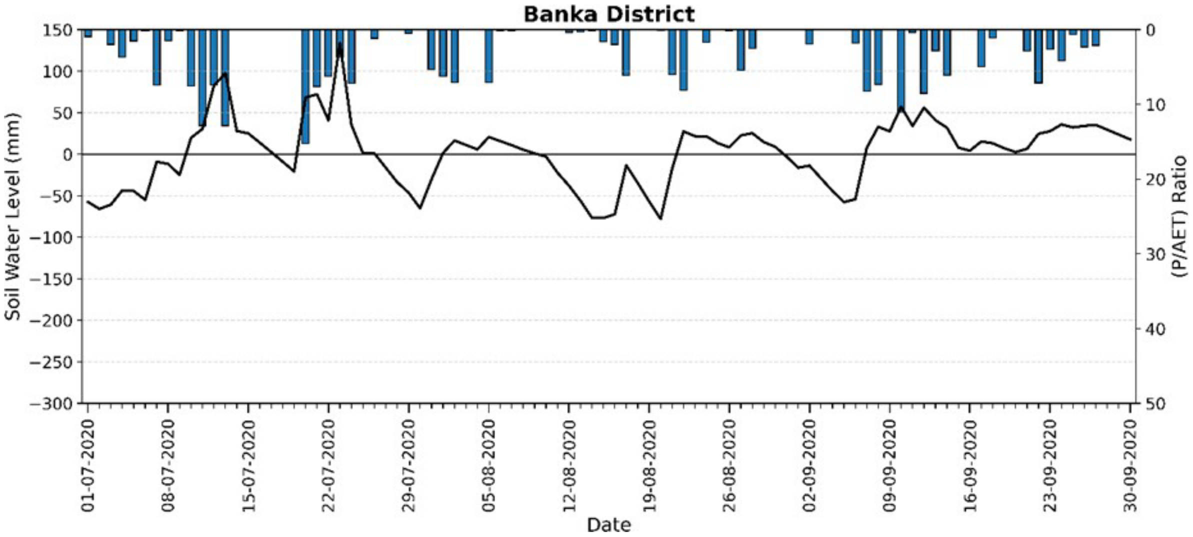
23-09-2020
30-09-2020
Date


Banka District
Soil Water Level (mm)
150
100
50
0
−50
−100
−150
−200
−250
−300
(P/AET) Ratio
0
10
20
30
40
50
01-07-2020
08-07-2020
15-07-2020
22-07-2020
29-07-2020
05-08-2020
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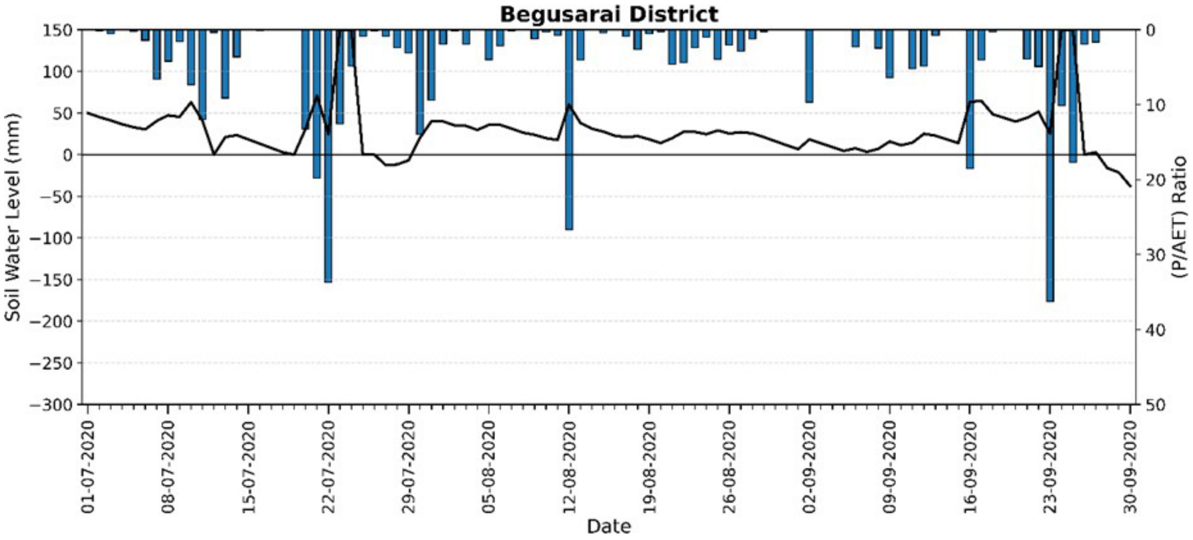
Date


Begusarai District
Soil Water Level (mm)
150
100
50
0
−50
−100
−150
−200
−250
−300
(P/AET) Ratio
0
10
20
30
40
50
01-07-2020
08-07-2020
15-07-2020
22-07-2020
29-07-2020
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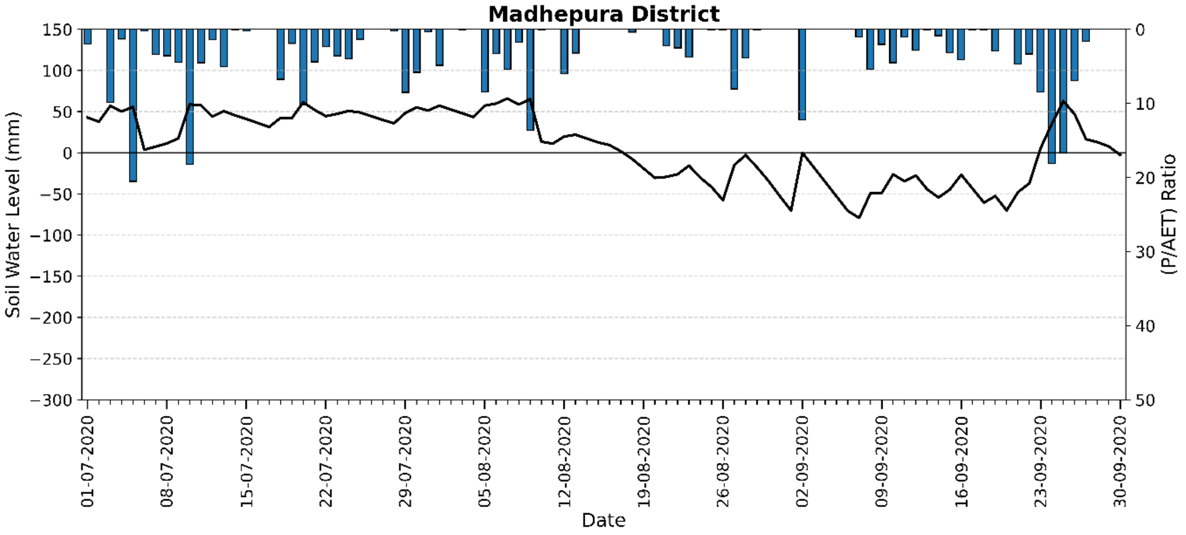

Figure 5. Simulated mean soil water levels of monitoring sites in four different districts, located in four different agroclimatic zones of Bihar. The black line indicates the surface water level (SWL), and the blue bars indicate P/AET ratio (*Source*: authors' creation)

For instance, the Arwal district, with the lowest seasonal P/AET ratio of 2.02, experienced the deepest SWL at –136 mm, indicat-ing significant water stress during the period. The Banka district, with a more consistent rainfall pattern and a relatively higher seasonal P/AET ratio of 2.48, maintained SWL between –77 mm and 134 mm, reflecting stable higher soil water content in the root zone. The Madhepura district, having a seasonal P/AET ratio of 3.2, exhibited SWL that remained above the soil surface early in the season, dropped below during dry spells, and recovered towards the season end, with levels ranging from –79 mm to 65 mm. In contrast, Begusarai district, with the highest seasonal rainfall and the highest P/AET ratio of 3.85, maintained SWL mostly above ground, resulting in multiple field water-ponding events throughout the season, with few ponding events attaining a maximum ponding height of 150 mm due to the presence of field bunds. These patterns demonstrate how seasonal and daily P/AET ratios, along with paddy field characteristics, jointly shape SWL variability, underscoring the need for targeted water management strategies to support sustainable agriculture across diverse agro-climatic zones. The comparison of water balance components between the traditional WA+ and the PaddyWA+ frameworks underscores clear differences in how hydrological processes in rice-dominated landscapes (Figure 6).

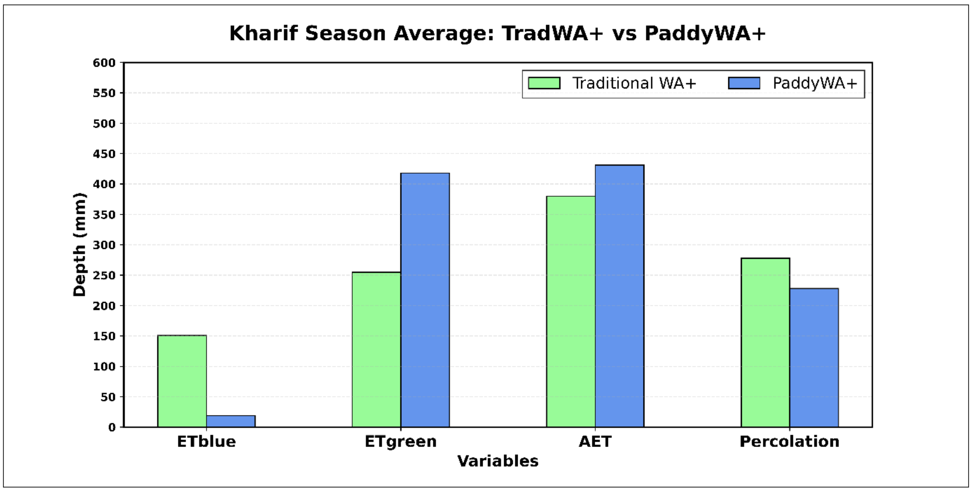

Figure 6. Traditional WA+ vs. PaddyWA+ for rice area in Bihar – Kharif season comparison (ETblue: Irrigation Water use; ETgreen: Rainfed crop water use, AET: Actual Evapotranspiration) (*Source*: authors' creation)

The PaddyWA+ model captures a wider, generally higher range of average annual actual evapotranspiration (AET), reporting values from 0 to 884 mm annually, compared to the traditional WA+, which estimates AET between 0 and 850 mm at annual timescales. During the Kharif season, the difference becomes more pronounced, as PaddyWA+ indicates AET ranges from 0 to 431 mm, whereas the traditional WA+ only captures a range from 0 to 380 mm. These variations indicate coarser spatial resolution and simplified field assumptions in traditional WA+, leading to underestimation of AET in paddy fields. When focusing on the sources of evapotranspiration, the traditional WA+ framework estimates an average annual blue water (ETblue) consumption of 340 mm, whereas PaddyWA+ records a much lower value of 90 mm. Conversely, the average green water (ETgreen) use is markedly higher in PaddyWA+ at 784 mm than in the traditional WA+ at 450 mm, indicating the dominance of green water use in these landscapes. The traditional WA+ framework suggests nearly equal contributions from blue and green water sources to total ET, whereas PaddyWA+ reflects field-level dynamics, in which most paddy fields rely primarily on rainfall. These patterns persist during the Kharif season (Figure 6). Additionally, percolation losses estimated by traditional WA+ are higher as it does not account for unique paddy field management practices, unlike PaddyWA+, which models these dynamics explicitly. Thus, PaddyWA+ provides a more accurate depiction of hydrological reality in rice-based agricultural systems, crucial for water resources planning and management in such regions.

From Satellite to Policy Insight

The integration of satellite-derived datasets with the PaddyWA+ framework demonstrates how RS can provide insights for on-ground decision-making in data-scarce, paddy-dominated regions.

- By translating daily 30-m water balance outputs—such as ponding duration, soil water level fluctuations, AET, and blue water consumption—into actionable indicators, including the occurrence of water stress, quantifying supplemental irrigation needs, and inefficient water use.
- The development of the paddy water balance module can be used to develop irrigation scheduling forecasts, optimize the distribution of limited groundwater and canal water, and guide investments for improved irrigation infrastructure in chronically water-limited blocks.
- Additionally, by quantifying blue water consumption more accurately than conventional models, PaddyWA+ provides a scientific basis for developing district-level water budgets, improving climate-resilient agriculture schemes.
- For state-level planning bodies, such as the Department of Agriculture and Minor Irrigation in Bihar, the high-resolution maps can support crop diversification efforts and targeted promotion of water-saving practices.

Thus, the PaddyWA+ workflow from satellite observation to model simulation to policy-relevant insights establishes a scalable pathway for strengthening climate-smart water management and agricultural planning in the Eastern Gangetic Plains.

Applicability and Way Forward

The innovative PaddyWA+ framework provides a holistic approach to capturing the complex flow dynamics of paddy-dominated landscapes, linking field-level water dynamics to the regional water balance. Its potential applications include:

- Developing and evaluating hydro-environmental impacts of paddy water management practices such as continuous flooding, alternate wetting-drying, and irrigation scheduling at a regional scale.
- Identifying hotspots for intervention targeting water management practices using historical field ponding dynamics in data-scarce areas.
- Supporting the identification of suitable sites for rice–fish mixed farming systems, enabling environmentally sustainable, economically viable, and socially beneficial agricultural development.
- Evaluating the climate impacts on water use and climate adaptation options.
- Additionally, by quantifying green/blue water consumption more accurately than conventional models, PaddyWA+ could be further developed to estimate carbon mitigation potential linked to methane emissions from flooded fields.

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Contact

Naga M. Velpuri, Principal Researcher and Research Group Leader – Water Data Science for Action (WDSA), IWMI, New Delhi, India (N.Velpuri@cgiar.org)