



Mapping Potential Groundwater Abstraction Hotspots in Irrigated Paddy Fields Using WaPOR-Derived Crop Water Use: A Case Study of UPRIS Division III, Philippines

Jastine Mae Galang

University of the Philippines Los Baños, Philippines – jjgalang@up.edu.ph

Seth Nathaniel Linga

University of Birmingham, Birmingham, United Kingdom – sx11405@student.bham.ac.uk

Leunell Chris Buela

University of the Philippines Los Baños, Philippines – lmbuela@up.edu.ph

ABSTRACT

Groundwater has increasingly become a supplemental irrigation source in major rice-producing areas of the Philippines, particularly in UPRIS Division III, where surface water reliability is affected by seasonal variability and inefficient irrigation infrastructure. This study used a remote-sensing-based framework to address the challenge of monitoring unrecorded groundwater abstraction (GWabs) by applying a simple water balance approach that integrates FAO WaPOR-derived actual evapotranspiration (ET_a), CHIRPS rainfall data, irrigation delivery records, and soil-based percolation rates from 2018-2022. Results indicate a seasonal water imbalance, with peak inferred groundwater abstraction occurring during the dry season (November–April). Annual abstraction ranges from approximately 620 mm to 950 mm, with an average of about 780 mm/year. Spatial analysis indicates abstraction hotspots in coarse-soil areas with high ET_a. Although large volumes of surface water are delivered to the system, low overall system efficiency resulted in increased dependence on groundwater. Inferred wet-season recharge is not sufficient to offset the dry-season deficit, suggesting a cumulative groundwater stress over time. Overall, the study demonstrates that remote sensing-based water balance can assess groundwater dependency in data-scarce irrigated systems. The identified hotspots can support more targeted groundwater monitoring, improvement of irrigation performance, and planning for sustainable use of both surface water and groundwater resources.

Keywords: groundwater abstraction; WaPOR; water balance; UPRIS Division III.

1. INTRODUCTION

As a rice-consuming country, the Philippines' economy and food security rely greatly on rice production, with Nueva Ecija serving as the main rice-producing province in the country [1]. Despite ongoing efforts to promote water-efficient and modern methods of rice cultivation, rice production in the country remains highly dependent on water-demanding irrigated systems. In major rice-producing regions such as Central Luzon, irrigated agriculture accounts for 99.5% of total production [2]. One of the largest irrigation systems is the Upper Pampanga River Integrated Irrigation System (UPRIIS), which irrigates most of Central Luzon, including Nueva Ecija, with a total service area of about 120,000 hectares [3].

However, due to the changing climate, characterized by prolonged droughts and intensified typhoons, the reliability of surface water resources has become challenging [4]. In response, farmers increasingly rely on groundwater for irrigation during periods of low water flow, through shallow tube wells and solar-powered pumps. Over the years, there has been a growing dependence on groundwater as a supplemental source of irrigation, supported by substantial investments in projects that facilitate pump installation [5,6]. However, despite these efforts to promote climate-resilient agriculture, the condition of groundwater resources remains at risk due to over-extraction and limited monitoring [7]. Currently, the Philippines faces challenges in properly assessing the availability of its groundwater resources [8], placing them in danger of over-depletion, which may eventually lead to increased water and food insecurity.

To promote sustainable groundwater management, information on the magnitude and spatial distribution of groundwater abstraction and recharge rate is needed. This requires an extensive network of monitoring wells and systematic data collection. However, groundwater abstraction in many irrigated areas is largely unmonitored due to limited infrastructure and data availability. Openly accessible satellite-based datasets offer a practical alternative for water resources assessment and planning. In this study, the Food and Agriculture Organization of the United Nations (FAO)'s WaPOR actual evapotranspiration data and CHIRPS rainfall data, together with irrigation delivery and soil information, are used to estimate potential groundwater abstraction and identify spatial hotspots in UPRIIS Division III. The combined use of remote sensing and water balance approaches provides an overview of seasonal and annual groundwater stress patterns, which can support evidence-based decision-making for sustainable irrigation and groundwater management.

2. METHODOLOGY

2.1. STUDY AREA

The UPRIIS is one of the biggest irrigation systems in the country, consisting of six divisions, and serving as the main source of irrigation in Central Luzon [9]. This study focuses on the largest, Division III, with a total serviced area of about 50,000 hectares, and is mainly devoted to rice production. It is located within the province of Nueva Ecija, which has a Type I climate. The dry season lasts from November to April, while the wet season extends throughout the rest of the year. Typically, the months of June to September receive the most amount of rainfall, contributing to an annual mean rainfall of 2,966.5 mm for 2022 [10]. In this region, the dry

season cropping window is from September to February, while the wet season cropping window is from April to August [11].

Using the provided shapefile from the National Irrigation Administration (NIA), the study area boundaries were identified. The land use map shows that Division III is predominantly covered by annual crops (rice), accounting for about 91% of the total area, with the remaining portions classified as urban, shrubs, grasslands, and forest.

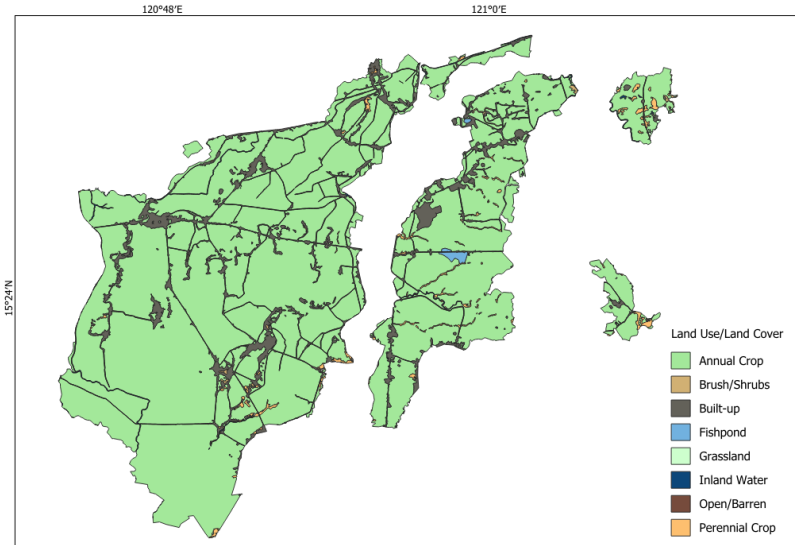


Figure 1. 2020 Land Use Map of UPRIS Division III

2.2. DATA SOURCES AND PRE-PROCESSING

2.2.1. Rainfall

Due to the limited availability of observed rainfall data within UPRIS Division III, precipitation data were obtained from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) with a spatial resolution of 0.05° (approximately 5.5 km). Rainfall data from 40 CHIRPS grid points were extracted for the area bounded by UPRIS Division III. To perform bias correction, the CHIRPS grid cell encompassing the PAGASA National Agrometeorology Station (NAS) in Muñoz, Nueva Ecija, was first identified. The CHIRPS rainfall data at this location were then compared with the corresponding observed station rainfall through monthly linear correction. For each month, the ratio between the observed rainfall ($P_{obs,m}$, mm) and the CHIRPS-derived rainfall ($P_{CHIRPS,m}$, mm) at the station location was calculated to obtain a monthly correction factor (CF_m):

$$CF_m = \frac{P_{obs,m}}{P_{CHIRPS,m}}$$

The derived monthly correction factors were then applied to all CHIRPS grid points to obtain corrected rainfall values. This method preserves the seasonal variation while adjusting for differences between CHIRPS estimates and observed rainfall.

After bias-correction, the effective rainfall (P_{eff}) at each CHIRPS grid point was computed using the USDA Soil Conservation Service method to account for the portion of rainfall available for crop use. The effective rainfall was calculated as follows:

If $P_{total} < 250 \text{ mm}$:

$$P_{eff} = P_{total} \left(\frac{125 - 0.2P_{total}}{125} \right)$$

If $P_{total} > 250 \text{ mm}$:

$$P_{eff} = 125 + 0.1P_{total}$$

where P_{total} is the monthly bias-corrected rainfall (mm) at each grid point. The areal average effective rainfall for Division III was then obtained by averaging the computed P_{eff} values from all 40 CHIRPS grid points for each month.

The resulting rainfall patterns across Division III are shown in Figure 2. Data indicate that rainfall is relatively higher in the eastern part of the area, primarily due to the Sierra Madre Mountain Range, which acts as a barrier to moisture-laden winds from the Pacific Ocean. In terms of annual variability, the study area exhibited significant inter-annual fluctuations from 2018 to 2022. As shown in the figure, 2018 was the driest year, while 2020 was the wettest, likely influenced by the intense tropical cyclone activity in the last quarter of that year, including Typhoons Rolly and Ulysses [13].

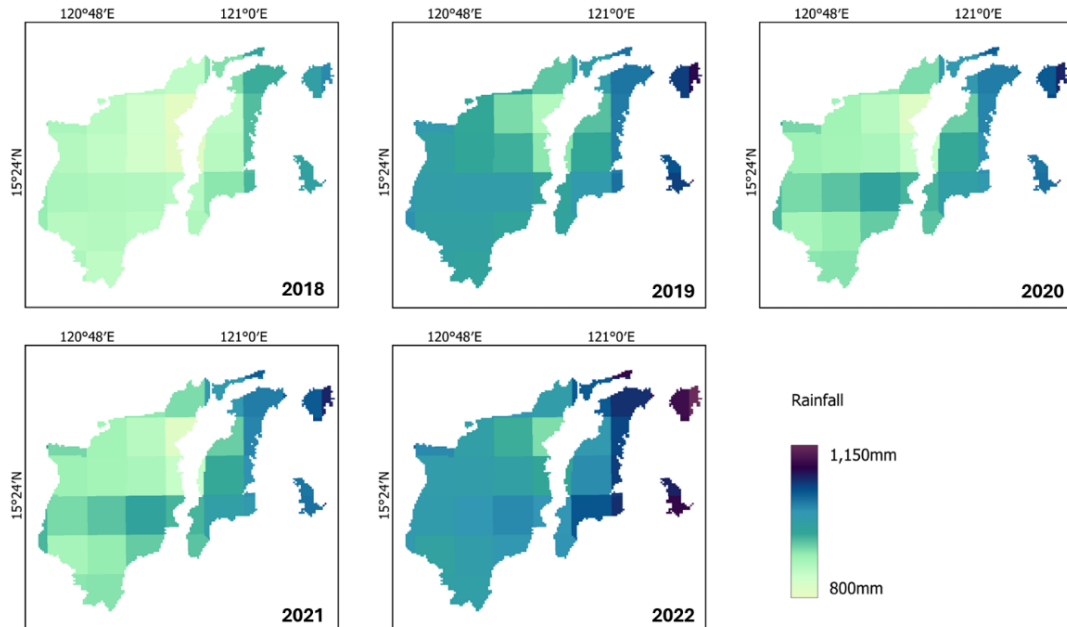


Figure 2. Annual Bias-Corrected Rainfall Maps of UPRIS Division III from 2018 to 2022 from CHIRPs Data

2.2.2. Actual Evapotranspiration

Actual evapotranspiration (ET_a) data were obtained from FAO's WaPOR Project (30 m \times 30 m). Annual total ET_a raster files were used for spatial analysis, while monthly total ET_a CSV data were extracted for seasonal analysis. Since the ET_a values downloaded from WaPOR are provided as integer values, the raster files were multiplied by a scaling factor of 0.1 to convert the data into actual evapotranspiration expressed in mm/year. This conversion is a standard requirement for WaPOR Level 2 and 3 products to translate raw data into physical units of depth, expressing the actual evapotranspiration in millimeters (mm).

The spatial distribution of ET_a across Division III (Figure 3) closely reflects the existing land use pattern, with urban areas showing the lowest ET_a and cropped areas showing high values (red zones), indicating high productivity. ET_a values in 2018, 2021, and 2022 remained consistent, while the highest values were observed in 2019 and 2020. This is likely because these years were relatively wet, and the availability of water allowed crops to reach their maximum transpiration potential. It is important to note, however, that no ET_a data were available for April 2022, which may have affected the total annual ET_a for that year.

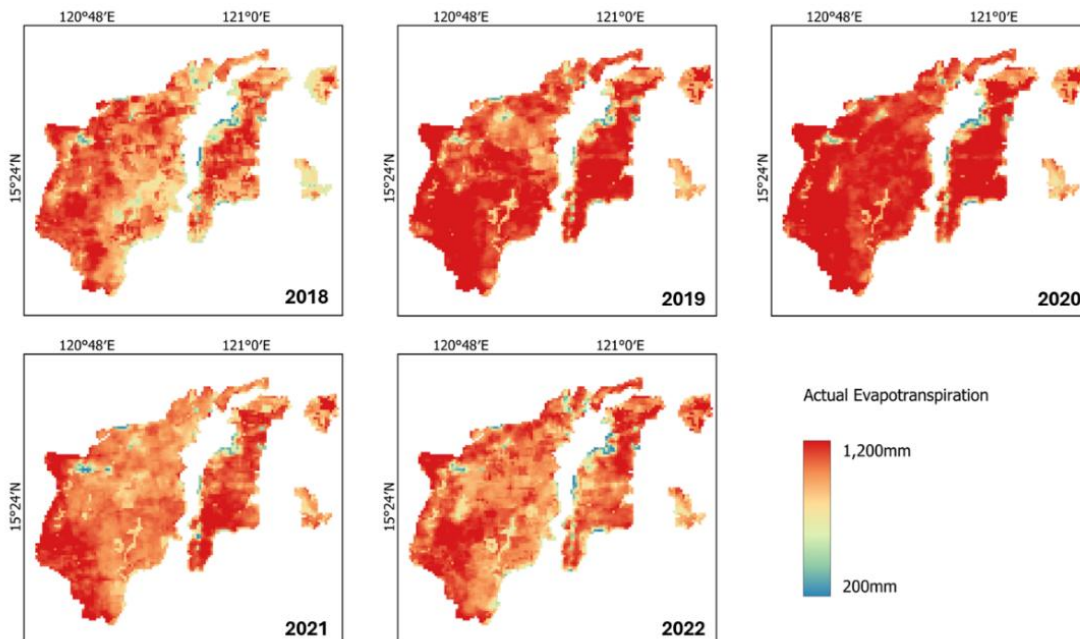


Figure 3. Annual Actual Evapotranspiration Maps of UPRIS Division III from 2018 to 2022 from WaPOR Data

2.2.3. Soil and Percolation Data

Soil texture distribution across UPRIS Division III was identified using soil maps from the Bureau of Soils and Water Management (BSWM). As shown in Figure 4, the division exhibits considerable spatial variability. The western portion is dominated by clay, the eastern portion by silty loam, and the central area by clay loam.

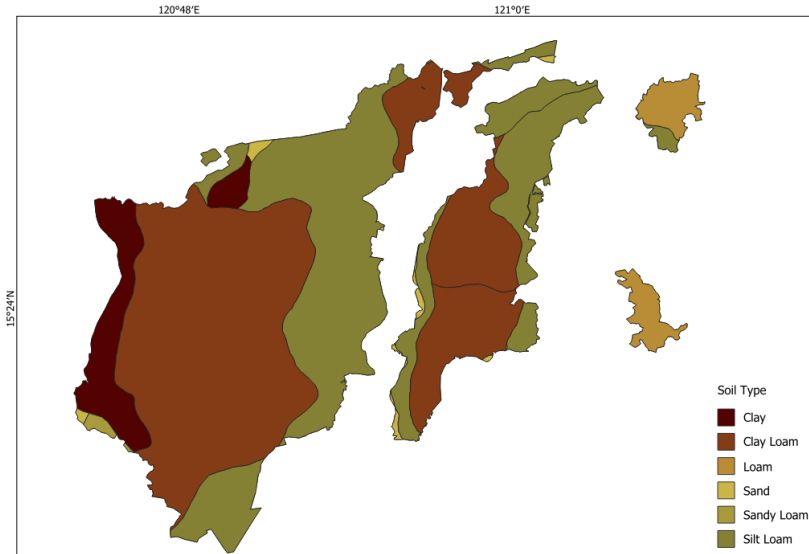


Figure 4. Soil Map of UPRIIS Division III

Percolation rates were assigned based on values reported by Luyun et al. (2021). Daily percolation values (mm/day) were aggregated to monthly rates (mm/month) for seasonal analysis. The calculated percolation rates for UPRIIS Division III are summarized in Table 1.

Table 1. Percolation rate of different soil textures in Division III [12].

SOIL TEXTURE	MEASURED AVERAGE PERCOLATION RATE (mm/day)
Sandy Loam	7.26
Loam	3.78
Silt Loam	2.49
Clay Loam	2.50
Clay	1.98

The observed spatial variability indicates that water demand across the division is not uniform. Areas dominated by coarse-textured soils exhibit percolation rates (7.26 mm/day) that are almost four times higher than those in clay-dominated zones (1.98 mm/day). As a result, these areas require higher irrigation inputs to sustain the target ponding depth, which may increase reliance on groundwater abstraction.

For this steady-state water balance approach, it is assumed that net changes in soil moisture storage are negligible over the annual study period. Furthermore, it is acknowledged that actual percolation may fluctuate during growth-stage-specific drainage or terminal drainage. However, given the predominantly flooded conditions of lowland rice in the study area, these constant rates provide a representative estimate of the total water requirement.

2.2.4. Irrigation Water Delivery

Records of the water delivery volumes of the main canal in Division III, as monitored by the Irrigation Management Office (IMO), were used to obtain the amount of water supplied through irrigation. Total daily flow (m^3/s) was converted into water depth in millimeters (mm) over the cropped area. To estimate the volume of water effectively used by the crops from the main canal deliveries, a total system efficiency of 32% was adopted (Luyun et al., 2021).

2.3. WATER BALANCE COMPUTATION

To estimate groundwater abstraction, a simplified steady-state water-balance approach was applied. All water balance components were expressed in millimeters (mm). The root zone and the ponded water layer typical of lowland rice cultivation define the system boundary as presented in Figure 5.

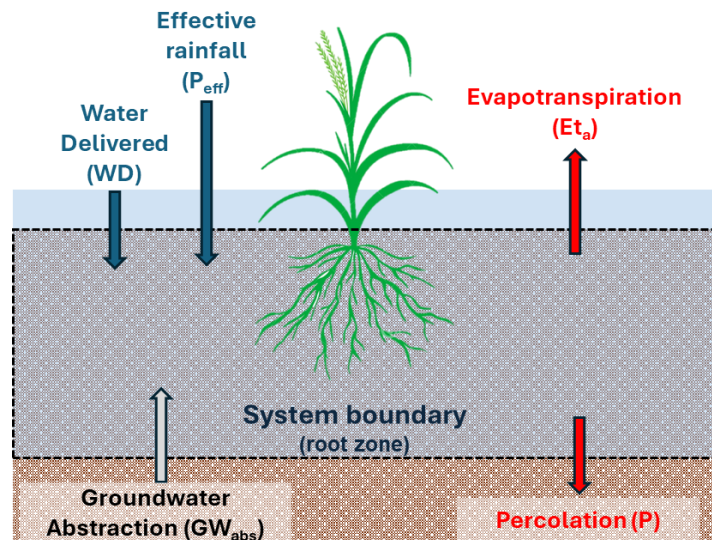


Figure 5. Conceptual framework of the root-zone water balance for UPRIS Division III

Water inputs include effective rainfall (P_{eff}) and water delivered through irrigation (WD), while water outputs or losses consist of actual evapotranspiration (ET_a) and percolation (P). Therefore, the water balance equation can be expressed as:

$$GW_{abs} = (ET_a + P) - (P_{eff} + WD)$$

Positive values of GW_{abs} indicate groundwater abstraction, while negative values are interpreted as potential groundwater recharge.

2.4. ANNUAL AND SEASONAL ANALYSIS

Potential groundwater abstraction was analyzed from 2018 to 2022. For seasonal analysis, monthly totals and monthly averages were used to capture temporal variations in groundwater abstraction between wet (June–September) and dry (November–April) seasons. For spatial analysis, annual totals (mm/year) were used and mapped in Quantum Geographic Information System (QGIS) to identify areas with high groundwater abstraction (hotspots).

3. RESULTS AND DISCUSSION

The hydrological regime of UPRIS Division III is strongly influenced by seasonal variations in water inflow and outflow components. The water gap, defined as the difference between total inflow (rainfall + irrigation) and outflow (ETa + percolation), necessitates inferred supplemental groundwater abstraction (GWabs) to meet the water requirements for rice production. As shown in Figure 6, the seasonal variability of each component is presented, highlighting the fluctuations in water flux over the five years.

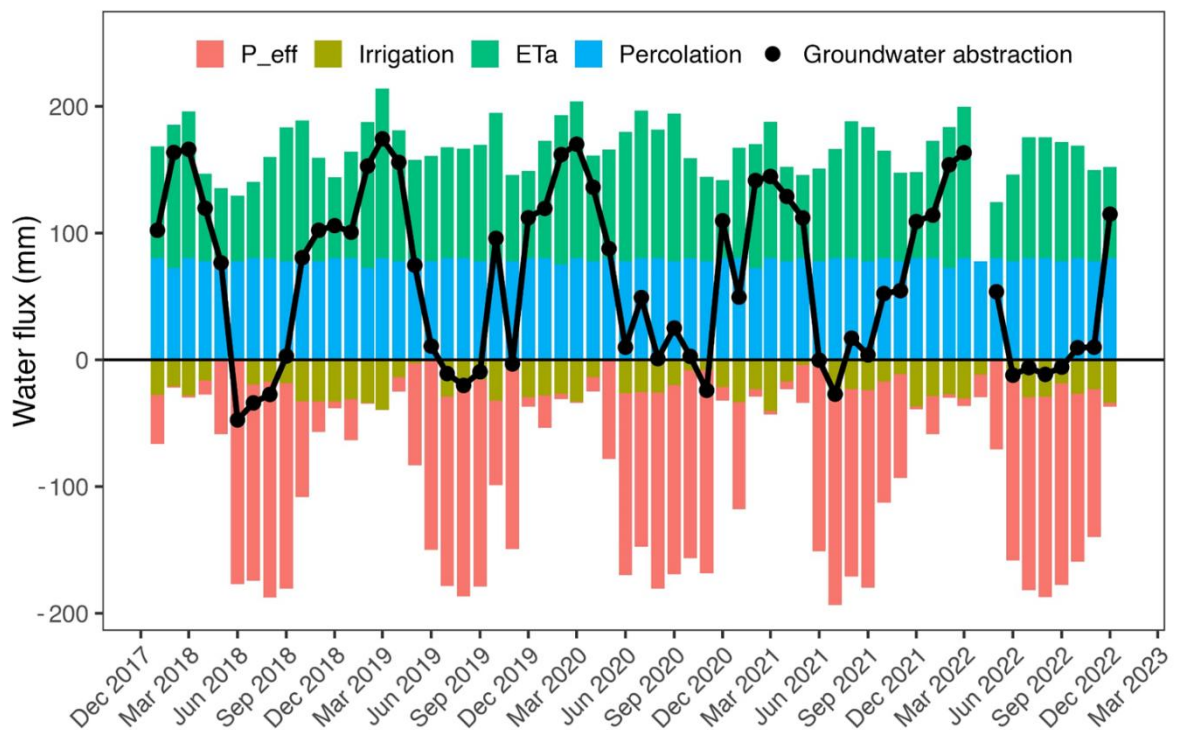


Figure 6. Water Balance Time Series of UPRIS Division III from 2018 to 2022.

The water balance analysis shows a consistent seasonal pattern in the climatic components. ETa peaks during the dry season when rainfall declines significantly. During the wet season, rainfall increases substantially while ETa slightly decreases. Other components, such as percolation, was

treated as seasonally constant since it is primarily governed by soil hydraulic properties under flooded conditions. Similarly, irrigation delivery remains generally consistent throughout the years, except during periods of extreme rainfall or fallow months (e.g., June 2018 and 2019; May 2022).

Comparing the total inflow and outflow shows that the “water gap” becomes pronounced during the dry season (November to April). This deficit corresponds to high inferred groundwater abstraction (GWabs), which can reach up to 170 mm during the peak summer month of March. During the wet season, a potential window for groundwater recharge is observed. However, the recharge amount remains minimal compared to the abstraction during the dry months, indicating that the seasonal deficit is not fully compensated within the year. This finding suggests a potential cumulative groundwater deficit over time.

The total annual inferred groundwater abstraction across the study area was also analyzed to identify potential hotspots of groundwater abstraction. Mapping these hotspots is important for informing groundwater planning and management strategies. Figure 7 presents the spatio-temporal variation in inferred groundwater abstraction over the five-year period.

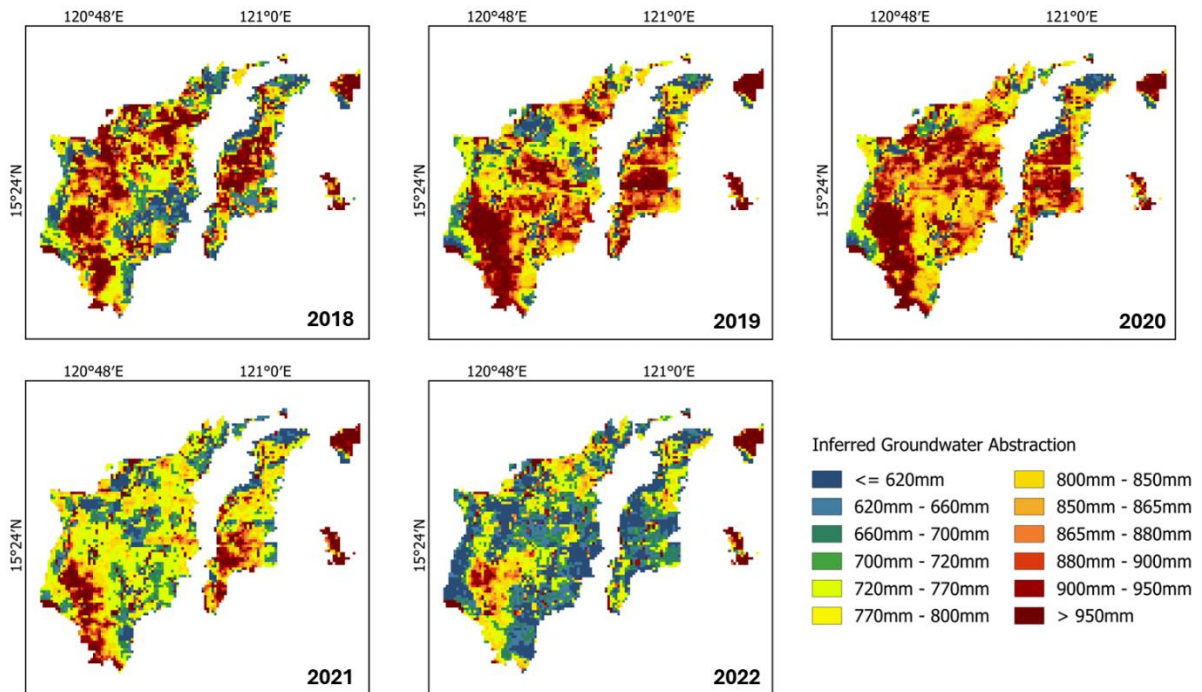


Figure 7. Spatio-temporal Analysis of Inferred Groundwater Abstraction.

As observed, the identified hotspots generally coincide with areas exhibiting high ETa. The bottom-left portion of Division III consistently shows elevated groundwater abstraction throughout the five-year period. Moreover, areas characterized by sand and sandy loam soils exhibit significantly higher abstraction rates, primarily due to their high percolation rates. This spatial pattern indicates that groundwater abstraction is strongly influenced by crop water demand and soil-controlled percolation losses. Considering that wet-season recharge remains minimal relative to dry-season deficits, these persistent hotspots may represent zones of increasing groundwater stress, which should be prioritized in management planning.

From Figure 7, annual inferred groundwater abstraction ranges from approximately 620 mm to 950 mm, with an average of about 780 mm per year. This indicates that a substantial portion of the water used for crop production in the study area is sourced from groundwater. Although large volumes of surface water are diverted into the system, the effective water delivered to farms is reduced due to the relatively low conveyance and application efficiency of UPRIIS. As a result, many farms continue to rely heavily on groundwater to compensate for system losses accumulated from canal conveyance to field application. This finding suggests that reducing groundwater abstraction will require significant improvements in overall system performance. Enhancing conveyance and on-farm efficiency could decrease supplemental pumping demand and improve water use efficiency across the irrigation system. In addition, integrating groundwater monitoring within irrigation districts in Central Luzon would allow better regulation of abstraction and support more sustainable use of surface water and groundwater resources.

4. CONCLUSION AND RECOMMENDATION

This study utilized readily available remote sensing and satellite data to analyze the water balance dynamics of UPRIIS Division III from 2018 to 2022 and infer the spatio-temporal patterns of potential groundwater abstraction in this data-scarce region. Analysis showed that UPRIIS Division III exhibits a clear seasonal water imbalance, with high groundwater abstraction required during the dry season to meet rice water demand. Hotspots of groundwater use are concentrated in areas with coarse-textured soils and high crop evapotranspiration, while inferred wet-season recharge remains minimal. Despite substantial surface water deliveries, low system efficiency forces farms to rely heavily on groundwater.

To reduce groundwater dependence and improve system sustainability, irrigation performance should be enhanced through improved conveyance and on-farm application efficiency. Targeted management should prioritize the identified hotspots, focusing on reducing losses, optimizing water distribution, and advocating sustainable groundwater abstraction to avoid irreversible damage in the region's subsurface and surface water system.

Additionally, to further enhance the analysis of the study, the following recommendations are suggested:

1. The locations of groundwater pumps within the study area should be mapped to determine whether the identified hotspots correspond to actual well locations. This will help validate the inferred abstraction results and support more targeted planning and management strategies.
2. Fallow periods may be excluded from the analysis, assuming that groundwater abstraction is minimal due to the absence of crop water demand. This could improve the estimation of annual groundwater abstraction.
3. The integration of local groundwater monitoring data is recommended to validate the inferred abstraction values and improve groundwater management strategies in the area.

4. REFERENCES

- [1] Santiago FA. A Historical Evaluation of the Emergence of Nueva Ecija as the Rice Granary of the Philippines. Proceedings of the DLSU Research Congress 2015, Manila, Philippines: De La Salle University; 2015.
- [2] Tecson Z. Central Luzon remains PH's top palay producer in Q1. Philippine News Agency 2022. <https://www.pna.gov.ph/articles/1175948> (accessed February 6, 2026).
- [3] National Irrigation Administration. Upper Pampanga River Integrated Irrigation System (UPRIIS) System Profile [Internet]. Manila, Philippines: National Irrigation Administration; n.d. [cited 2026 Feb 6]. Available from: <https://upriis.nia.gov.ph/>
- [4] Peras RJJ, Pulhin JM, Lasco RD, Cruz RVO, Pulhin FB. Climate Variability and Extremes in the Pantabangan-Carranglan Watershed, Philippines: Assessment of Impacts and Adaptation Practices. *Journal of Environmental Science and Management* 2008;11:14–31.
- [5] National Irrigation Administration. P9.18-Million solar-powered pump irrigation project to benefit Novo Ecijano farmers. Manila, Philippines: National Irrigation Administration; 2024.
- [6] National Irrigation Administration. 82 completed solar irrigation projects in 2023 to aid in El Niño mitigation. Manila, Philippines: National Irrigation Administration; 2024.
- [7] Luyun RA, Fajardo AL, Elazegui DD. Managing Groundwater Resources for Sustainable Agriculture. *College of Public Affairs Policy Brief* 2018;3.
- [8] Elazegui DD. Policy and Institutional Landscape for Groundwater Management. Los Baños, Laguna; 2018.
- [9] International Water Management Institute. Integrated water-resources institutional strategies for improving the productivity of agricultural water management; 2001.
- [10] Resco JP, Cura AL, Torres AG, Doctor MaA, Cinco T, Basconcillo J, et al. State of the 2022 Philippine Climate. Metro Manila, Philippines; 2024. <https://doi.org/doi:10.18783/spc1.2022.101>.
- [11] Gutierrez MA, Paguirigan NM, Raviz J, Mabalay MR, Alosnos E, Villano L, et al. The Rice Planting Window in the Philippines: An Analysis Using Multi-Temporal Sar Imagery. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 2019;XLII-4/W19:241–8. <https://doi.org/10.5194/isprs-archives-XLII-4-W19-241-2019>.
- [12] Luyun JR, Galoso JRM, Delos Reyes RB, Duka MA. Assessment of the Water Use Efficiencies of Selected Laterals and Paddy Fields at the Upper Pampanga River Integrated Irrigation System (UPRIIS), Philippines. *Philippine Journal of Agricultural and Biosystems Engineering* 2021;17:3–18. <https://doi.org/10.48196/017.02.2021.01>.

- [13] Santos GDC. 2020 tropical cyclones in the Philippines: A review. *Tropical Cyclone Research and Review* 2021;10:191–9. <https://doi.org/10.1016/j.tcrr.2021.09.003>.