REMOTE SENSING - BASED WATER DEMAND INDEX MAPPING: INSIGHTS FROM KHANH HOA PROVINCE, VIET NAM

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Received: 8/7/2025; Accepted: 28/8/2025

Abstract: *Located on the South-Central Coast of Viet Nam, the former Ninh Thuan (now is Khanh Hoa province) is one of the driest areas in Viet Nam and frequently experiences severe water shortages during the dry season. This study aims to develop spatial maps of the Water Demand Index (WDI) for Ninh Thuan area during the dry months from March to August in the representative drought year of 2020. The methodology integrates big Earth data and GIS data to compute WDI using key influencing first-order variables, namely soil moisture (SM), vegetative growth (NDVI), and heat factor (growing degree day, GDD). WDI reflects the spatial imbalance between vegetation water demand and the available soil water in areas with condensed agricultural activity at each pixel level. The WDI maps developed for the agricultural areas of Ninh Thuan reveal substantial spatial and temporal variability. Agricultural zones located in former Ninh Son, Thuan Bac, and Ninh Phuoc districts generally exhibit high WDI values (above 250), indicating considerable water stress. In contrast, certain regions such as the former Thuan Nam and Ninh Hai districts show comparatively lower WDI values. The WDI values peaked in April and May, coinciding with the most intense drought period and the critical crop development stage. This study provides a practical and spatially explicit tool for monitoring drought conditions and support effective water allocation planning amid the growing challenges of climate change and increasing water scarcity in the South-Central Coast of Viet Nam.*

Keywords: *Water Demand Index, Ninh Thuan area, remote sensing.*

1. Introduction

Drought, characterized as a recurrent and severe climatic hazard, has far-reaching implications for economic activities and the environment, with agriculture being the most adversely affected sector [1], [2]. Under the influence of climate change, this extreme event is projected to become more frequent and severe, driven by rising global temperatures, altered precipitation patterns, and heightened evapotranspiration [3], [4], [5]. Since agriculture is highly dependent on sufficient and timely water supply, increasing drought intensity not only heightens crop water requirements but also exacerbates irrigation demand and threatens food security. This growing imbalance between water availability and agricultural demand highlights the urgent need for more efficient water resource management and adaptive strategies to ensure sustainable agricultural production under changing climatic conditions. Accurately quantifying crop water requirements is therefore crucial for improving irrigation planning and mitigating drought impacts. Accurately quantifying crop water requirements is therefore crucial for improving irrigation planning and mitigating drought impacts.

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Conventionally, drought assessment and monitoring have been carried out using drought indices. These indices are generally categorized into two groups: Site-based indices, which rely on ground meteorological and hydrological data, and remote sensing-based indices, which are derived from satellite observations [6]. Site-based indices such as the standardized precipitation index (SPI) [7], Palmer drought severity index (PDSI) [8], and crop moisture index (CMI) [9] have been widely applied and remain fundamental tools for characterizing meteorological and hydrological drought. However, they are constrained by several limitations, including restricted spatial coverage due to sparse or unevenly distributed observation networks, and the fact that they provide only indirect representations of agricultural drought without explicitly capturing vegetation responses or crop water demand [10]. Given these limitations, remote sensing-based techniques have emerged as effective alternatives for assessing agricultural drought, as they provide spatially continuous observations and are closely linked to soil moisture dynamics and vegetation conditions. In this context, the Water Demand Index (WDI) developed by Singh and Das (2022) represents a significant advancement [18]. Unlike conventional indices, WDI explicitly incorporates crop water demand by integrating soil moisture (SM), vegetative growth (NDVI), and heat unit (growing degree day, GDD), thereby providing a more realistic representation of agricultural drought. By categorizing water demand into generalized classes included in Low, Moderate, High, and Extreme, WDI not only captures spatial and temporal variability in agricultural drought but also offers practical insights for irrigation management and climate adaptation planning.

In Viet Nam, where agriculture remains highly dependent on natural water availability, drought poses a persistent challenge to rural livelihoods and food security [11]. It directly undermines agricultural productivity by reducing soil moisture, limiting crop growth, and increasing irrigation demand beyond the capacity of local water supply systems. Prolonged dry spells not only lower yields of staple crops such as rice, maize, and coffee but also threaten high-value crops that are critical for farmers' incomes, including fruits and industrial crops. Recurrent drought events further exacerbate rural poverty by intensifying competition over limited water resources, leading to crop failures, income losses, and heightened vulnerability of farming households. However, its impacts are not evenly distributed across the country; different regions experience varying levels of severity depending on their climatic conditions, hydrological resources, and agricultural practices [12], [13]. The former Ninh Thuan area in the South-Central Coast stands out as one of the most drought-prone areas in Viet Nam [16]. Characterized by the lowest annual rainfall in the country and high interannual variability, the province frequently experiences severe water shortages during the dry season [14]. Its predominantly agricultural economy, which relies on crops such as grapes, maize, and rice, as well as livestock raising, is particularly vulnerable to recurrent droughts [15], [16]. Limited surface water resources, coupled with increasing irrigation demand, have intensified pressure on groundwater extraction, further exacerbating the risks of water scarcity [16], [17]. These challenges make Ninh Thuan a critical case study for assessing the imbalance between water demand and availability under changing climatic conditions.

Against this backdrop, the objective of this study is to develop spatially explicit maps of the Water Demand Index (WDI) to assess the spatial and temporal variations in crop water demand in Ninh Thuan area. By utilizing Earth observation and GIS data, the study constructs WDI maps that reveal water stress patterns across agricultural areas. These outputs are expected to provide valuable insights for irrigation planning, water allocation, and the design of adaptive strategies to strengthen agricultural resilience under conditions of increasing drought and water scarcity.

2. Methodology

2.1. Conceptual Framework

The Water Demand Index (WDI) is introduced by Singh and Das [18] to present a relative water demand of agricultural areas. The non-dimensional index provides a systematic approach to link crop water demand with available water resources. Unlike traditional drought indicators that are mainly based on precipitation or hydrological balance, WDI incorporates both supply- and demand-side factors of agricultural water use. The framework draws upon three core variables:

- Soil Moisture (SM): Representing the available water in the root zone that supports plant growth.
- Normalized Difference Vegetation Index (NDVI): Reflecting crop vigor and canopy activity, which drive evapotranspiration.
- Growing Degree Days (GDD): Quantifying cumulative heat units that regulate crop development and water requirements.

This relationship is expressed in a general form as:

$$WDI = f(SM, NDVI, GDD)$$

By combining these elements, WDI conceptualizes agricultural drought not simply as a lack of rainfall, but as a dynamic imbalance between crop water needs and available supply. This approach allows for spatially explicit monitoring of water demand using Earth observation data, thereby offering a valuable tool for supporting irrigation planning, water allocation, and climate adaptation in agriculture.

2.2. Data sources and preprocessing

Since the three input variables differ in their original units and scales, they were transformed into dimensionless indices prior to WDI computation. Soil moisture values were converted into a Soil Moisture Index (SM_{index}) using soil porosity as the reference, NDVI values were rescaled relative to their maximum and expressed as a Vegetation Index (Veg_{index}), and growing degree days were standardized against the optimum temperature growth range to produce a GDD Index (GDD_{index}). All indices were scaled uniformly from 0 to 10, ensuring comparability in their contribution to the WDI. To allow spatial consistency, all datasets were resampled to a 1 km resolution prior to calculation.

All datasets were downloaded for the period from March to August 2020 and subsequently processed in MATLAB. The specific computation methods and formulas for each variable are presented in the following subsections.

2.2.1. Soil Moisture

Soil moisture data were obtained from the SMAP-Sentinel Level-2 product at 3 km resolution, downscaled from the original SMAP (36 km) by integrating Sentinel-1 SAR backscatter [19]. This downscaled dataset is suitable for capturing field-scale heterogeneity in agricultural regions such as the former Ninh Thuan Province. Because availability depends on Sentinel-1 overpasses, observations were irregular; therefore, all images in each month were collected to maximize temporal coverage:

$$SM_{index}(t) = \left(1 - \frac{SM(t)}{SM_{max}}\right) \times 10 \qquad (1)$$

Where *SM(t)* is the soil moisture of grid cell (*i,j*) for day *t*, and SM_{max} is the saturated water content (soil porosity) of the grid cell (*i,j*). Soil porosity was estimated as:

$$SM_{max} = 1 - \frac{\rho_{bulk}}{\rho_{particle}} \qquad (2)$$

With ρ_{bulk} representing soil bulk density, which were extracted from the dataset of Hengl (2018) [22] and $\rho_{particle}$ the particle density, assumed to be 2.65 g/cm³ [18]. Lower soil moisture values correspond to higher SM_{index}, reflecting greater water stress conditions.

2.2.2. Normalized Difference Vegetation Index (NDVI)

NDVI data were obtained from the MOD13A2 MODIS/Terra Vegetation Indices product, which provides 16-day composites at 1 km spatial resolution [20], [21]. As a 16-day composite, the temporal coverage is regular but limited to about two observations per month. To maximize information use, all available images within each month were collected.

The Vegetation Index (Veg_{index}) was computed as:

$$Veg_{index}(t) = \left(\frac{NDVI(t)}{NDVI_{max}}\right) \times 10 \qquad (3)$$

Where $NDVI(t)$ is the $NDVI$ value of grid cell (i,j) for day t, and $NDVI_{max}$ is the maximum $NDVI$ observed for that grid cell. Higher NDVI values indicate stronger vegetation vigor, leading to higher Veg_{index} values.

2.2.3. Growing Degree Days (GDD)

Temperature data for calculating GDD were obtained from the ERA5-Land reanalysis dataset (ECMWF), which provides hourly temperature fields at 0.1° (~9 km) spatial resolution [23]. Daily mean temperatures were derived from hourly values. The GDDIndex was then derived as:

$$GDD_{index}(t) = \left(\frac{GDD(t)}{Temperature\ growth\ range}\right) x\ 10 \quad (4)$$

Where $GDD(t)$ is the growing degree days of grid cell (i,j) on day t, and the Temperature growth range was defined as T_{base_upper} - T_{base}. For each day, the average temperature (T_{ave}) is calculated as the mean of the daily maximum and minimum air temperatures, and the $GDD(t)$ is then expressed as:

$$GDD(t) = \frac{Tmax+Tmin}{2} - T_{base} \quad (5)$$

T_{base} and $T_{base\text{-}upper}$ were used as 10°C and 30°C, respectively, for all types of crops and seasons. To minimize the influence of extreme temperature values on GDD calculation, several constraints were applied. When T_{min} was lower than Tbase, it was adjusted and set equal to T_{base}. Similarly, when the daily maximum temperature T_{max} exceeded the upper threshold temperature (T_{base_upper}), it was replaced by T_{base_upper}. In cases where both conditions occurred on the same day, the two adjustments were applied simultaneously.

2.2.4. Landuse

Land use/land cover (LULC) data were obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) product at a spatial resolution of 1 km. MODIS provides globally consistent and temporally continuous land cover classification, which is particularly useful for hydrological and climate-related studies. The MODIS LULC dataset captures major land cover categories such as croplands, forests, grasslands, urban areas, and water bodies, thereby enabling the assessment of spatial variability in land surface conditions. Its relatively coarse resolution compared to high-resolution remote sensing products is offset by the advantages of long-term temporal coverage and regular updates, making it well-suited for regional-scale applications such as water demand estimation, land-atmosphere interaction studies, and hydrological model parameterization.

2.3. Computation of Water Demand Index (WDI)

The WDI for each grid cell (i,j) at day t is expressed as [18]:

$$WDI(t) = SM_{index}(t)\ x\ Veg_{index}(t)\ x\ GDD_{index}(t) \quad (6)$$

Where $SM_{index}(t)$, $Veg_{index}(t)$, and $GDD_{index}(t)$ represent the *SM, NDVI*, and *GDD*, respectively. Higher *WDI* values indicate stronger agricultural water stress.

Because the three datasets differ in temporal availability, SM and NDVI were only available on specific satellite overpass dates, while GDD was derived daily. Accordingly, WDI was computed only for days with valid observations across all three indices. These daily estimates were then aggregated into weekly and monthly averages to facilitate temporal analysis.

2.4. Mapping and classification of WDI

After calculating the WDI values for each grid cell, the study applied the classification scheme proposed by Singh and Das (2022) [18]. This scheme divides WDI into four generalized water demand categories, as summarized in the Table 1.

The classified outputs were then processed and mapped using ArcGIS 10.1, allowing the spatial and temporal patterns of crop water stress in the former Ninh Thuan province to be clearly visualized.

Table 1. Water Demand Index classification [18]

Class	WDI Range	Interpretation
Low	0 - 100	Minimal water stress
Moderate	100 - 250	Emerging irrigation demand
High	250 - 450	Severe water stress
Extreme	>450	Critical water deficit

3. Study area

The former Ninh Thuan province (now belongs to Khanh Hoa Province) is located in the South-Central Coast of Viet Nam, centered at approximately 11°33′56″N and 108°59′25″E, covering an area of about 3,358 km². Ninh Thuan's topography slopes from the Northwest to the Southeast, with mountains covering 63.2% of the province, midlands and hills 14.4%, and coastal plains 22.4% [25]. This configuration strongly shapes the local climate: The western mountains act as a barrier that blocks moist air masses, creating a rain-shadow effect over the lowlands and coastal plains (Figure 1).

As a result, the province experiences one of the driest climates in Viet Nam, with annual rainfall averaging less than 1,000 mm, and in the driest sub-regions only 300-500 mm [25]. Meanwhile, evaporation is much higher, ranging from 1,300 to 2,200 mm. The climate is distinctly divided into two seasons: A long dry season from January to August, and a short-wet season from September to December. Temperatures remain high year-round (24.6-27.2°C on average) and often exceed 35°C in the coastal plains, intensifying evapotranspiration and crop water requirements. Coupled with more than 2,400 sunshine hours per year and low relative humidity during the dry season, these conditions reinforce persistent agricultural water stress. Consequently, irrigation planning and water demand assessment are critical for sustaining agriculture under Ninh Thuan's harsh climatic regime.

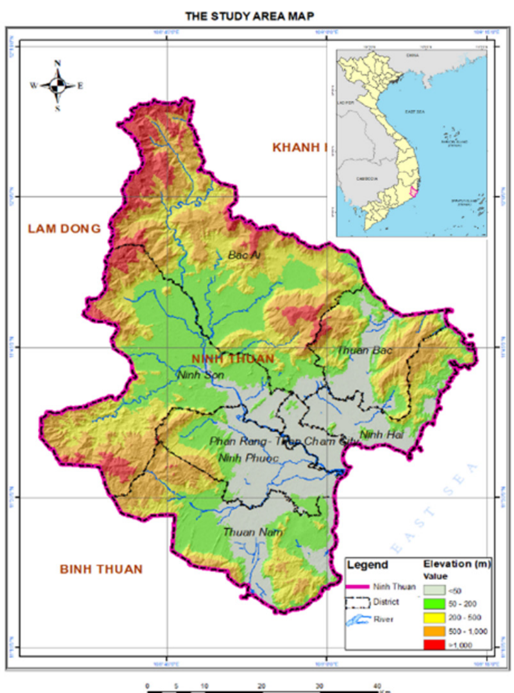

Figure 1. Map of former Ninh Thuan Province (now is the Southern part of Khanh Hoa province)

4. Results

4.1. Assessment of Agricultural Water Demand Based on WDI Maps

The WDI maps reveal that agricultural water demand in Ninh Thuan area fluctuates significantly by month during the dry-early rainy season, with considerable spatial heterogeneity among former districts (Figure 2). April was identified as the period of highest water demand throughout the year, reflecting the peak of the dry season when rainfall was almost absent and both temperature and evapotranspiration reached maximum levels (Figure 3).

In March, most agricultural areas were in the moderate range (100-250) (Figure 2a), consistent with the early dry season when crops had just entered their initial growth stages (see Figure 3b). However, the former Thuan Nam, Ninh Phuoc, and Ninh Hai districts already exhibited many high and some extreme values, concentrated in sandy coastal zones cultivating rice, grapes, and vegetables under intensive farming. Notably, parts of Ninh Phuoc still contained low areas adjacent to Phan Rang-Thap Cham, reflecting residual soil moisture from the previous season or access to favorable irrigation. Ninh Son and Thuan Bac were predominantly moderate, though localized high values were observed. Bac Ai remained largely moderate with few high points, while Phan Rang-Thap Cham showed only some moderate cells along its peri-urban agricultural fringe.

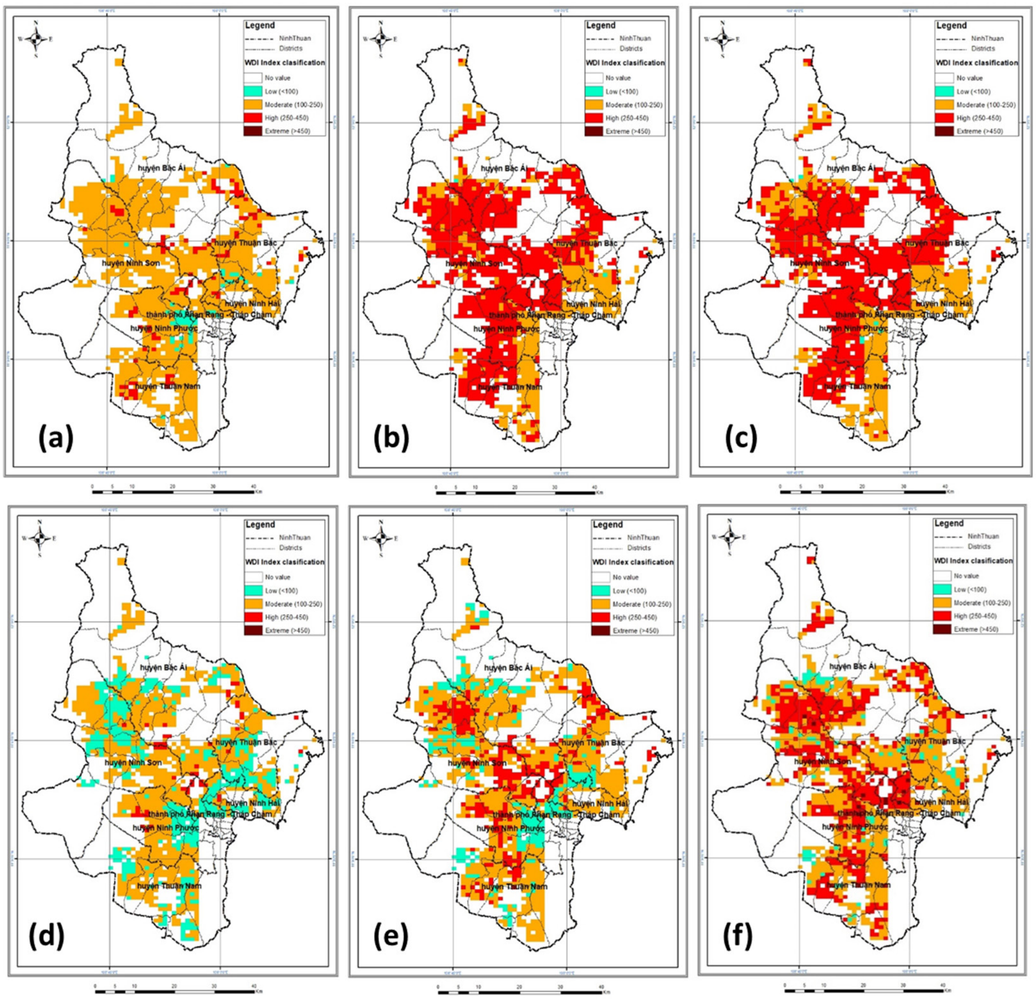

Figure 2. Agricultural Water Demand Index (WDI) maps of former Ninh Thuan Province for: (a) March, (b) April, (c) May, (d) June, (e) July, and (f) August 2020

By April, the combination of high GDDindex, Vegindex and SMindex (Figure 3) results annual maximum water demand index. Nearly all of Ninh Son, Thuan Nam, and Ninh Phuoc shifted into high and very high categories, reflecting extreme irrigation pressure (Figure 2b). Ninh Hai and Thuan Bac also recorded expanded high-value areas, particularly in sandy coastal farming zones. Even Bac Ai, typically less affected, registered additional high points. In Phan Rang-Thap Cham, peri-urban farmland also moves into high demand, indicating widespread water shortages.

In May, conditions remained largely unchanged compared to April (Figure 2c). The Ninh Thuan as a whole persisted under severe drought pressure, with high and extreme values dominating. Ninh Son, Thuan Nam, and Ninh Phuoc continued to face the most severe stress, while Ninh Hai remained mainly moderate with some scattered high values. Thuan Bac and Bac Ai showed further expansion of high demand areas. In Phan Rang-Thap Cham, peri-urban agricultural zones adjacent to Ninh Hai and Ninh Phuoc also remained under high water demand.

By June, early rainfall significantly alleviated water stress. Large areas shifted into low or moderate categories (Figure 2d). Ninh Hai exhibited the most significant change, with nearly all agricultural land falling into low demand, leaving almost no high values. Ninh Phuoc and Thuan Nam also saw reductions to mostly moderate and low demand, with only small clusters of high demand persisting inland. Ninh Son and Thuan Bac were mainly moderate, with isolated high points, while Bac Ai had almost no high demand. In Phan Rang-Thap Cham, peri-urban farmland fell into low to moderate levels. Compared with March, June had a similar spatial pattern dominated by moderate and low demand, though for different reasons. Particularly, March reflected early-season crop growth, while June was a result of rainfall-driven relief after the drought peak [26].

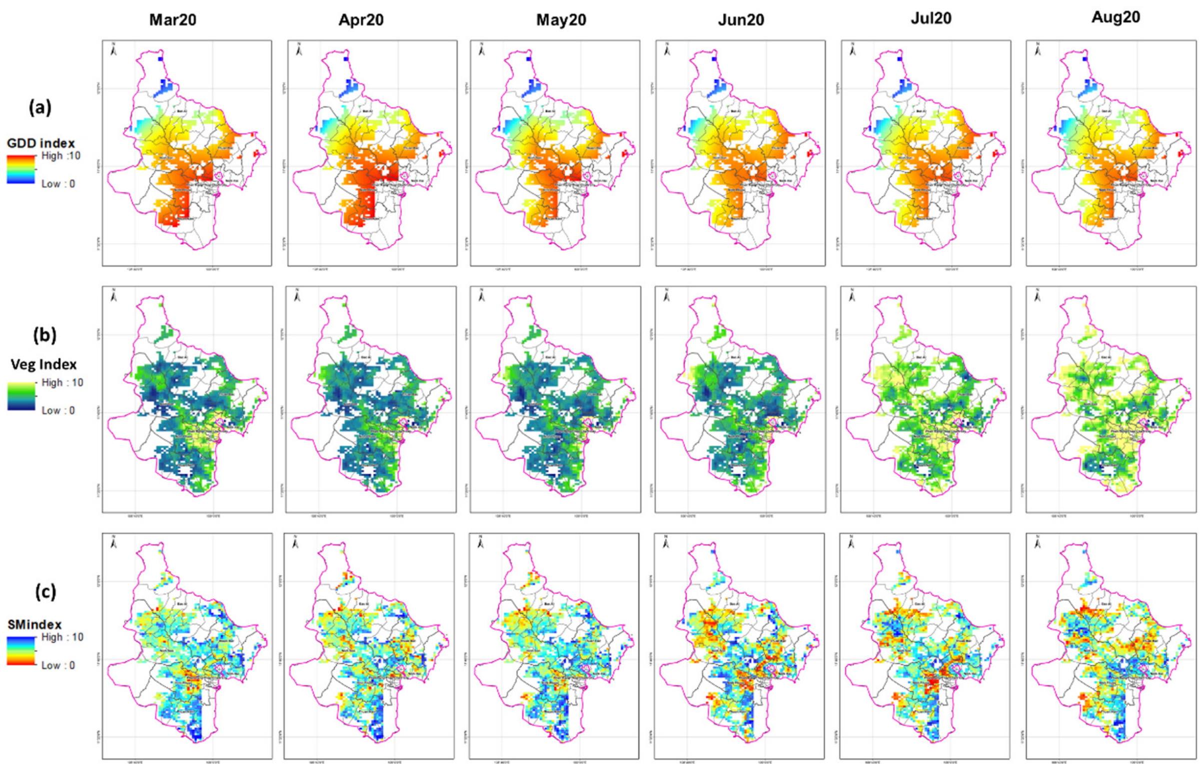

Figure 3. Maps of GDD, NDVI and SM Index of former Ninh Thuan Province

In July, agricultural water demand rose again as rainfall became unevenly distributed and crops entered reproductive stages (Figure 2e). High demand expanded across several districts. Ninh Son emerged as the most notable hotspot, with extensive high values concentrated in its central and western areas. Thuan Nam and Ninh Phuoc also recorded expanded high demand compared with June. Ninh Hai and Thuan Bac were mostly moderate, though scattered high values reappeared. Bac Ai registered more high cells than in June, indicating drought effects extending into upland areas. In Phan Rang-Thap Cham, additional moderate and high values emerged in peri-urban farmland, while the urban core consistently remained at low values.

In August, conditions worsened further, marking the second demand peak of the year after April and May. High and extreme demand areas expanded across nearly all districts (Figure 2f). Ninh Son and Ninh Phuoc were almost entirely covered by high and extreme WDI values, indicating extreme irrigation stress. Thuan Nam also recorded extensive high demand, with only a few small low demand areas remaining. Ninh Hai and Thuan Bac experienced a resurgence of high values, though still intermixed with moderate and low cells in coastal areas. Bac Ai also showed more scattered high points. Phan Rang-Thap Cham expanded its peri-urban high-demand zones.

4.2. Validation

The fieldwork in Ninh Thuan area was carried out with the overarching goal of assessing the suitability and effectiveness of the Agricultural Water Demand Index (WDI) maps for water resource management. Validation focused on selected areas in the former Ninh Son, Ninh Hai, and Thuan Nam districts, where WDI values indicated high to extreme demand. The validation process relied on two sources of information: (i) The 1 km resolution WDI maps for former Ninh Thuan Province in 2020, which were previously presented in Section 4.1, and (ii) A questionnaire survey administered to two groups, including seven local water resource management officers and three farmers. The survey included five questions regarding the readability and clarity of the WDI maps, their appropriateness in the context of 2020, their accuracy in reflecting actual field conditions, discrepancies between WDI outputs and reality, and potential improvements if the maps were to be used in practice. Most respondents reported that the WDI maps were easy to read and interpret, and generally captured the timing and location of water shortages during 2020. However, 2 out of 10 respondents indicated discrepancies: In some locations the maps classified areas as water-stressed, while there is no water shortage in reality. These inconsistencies demonstrate that local irrigation system work effectively to supply water for the area in the dry periods. The validation results suggest that the WDI maps are a robust and useful decision-support tool, with strong potential applications in drought monitoring, irrigation planning, and crop pattern adjustment, thereby contributing to adaptive water resource management in formerly Ninh Thuan area.

5. Conclusion and Recommendation

The paper developed the WDI maps for the agricultural area of the former Ninh Thuan province in 2020, a critical drought year in the area. The zoning maps demonstrate that April 2020 is the most water-stress month for majority of agricultural land in the province, especially in Ninh Hai and Thuan Bac areas. The water-stress is less severe in June and Jul because of rain and crop schedule before increasing in August. A validation was implemented by field survey and stakeholder feedback that revealed promising applicability of the WDI maps in irrigation management.

Although WDI maps provide a fast and generalized way to assess water demand using remote sensing data, they still have some limitations. First, WDI is a dimensionless index that only shows the relative water demand of an area. It does not directly represent the actual water requirements of crops that cause difficulties for irrigation manager to decide the irrigation water amount. Second, the calculation of WDI depends strongly on the spatial and temporal resolution of the input data. Therefore, it requires high-quality and detailed datasets those might face challenges in data availability.

Several future recommendations can be made to strengthen the applicability of WDI maps for agricultural water management in the area. Firstly, the spatial resolution of WDI products should be improved to provide details in agricultural land and irrigation system as well. In addition, the reliability of soil moisture datasets and the thresholding methods used for WDI classification should be systematically verified and adjusted to suit specific local contexts. Finally, establishing a web-based information portal would enable provincial agencies and communities to conveniently access and download updated WDI maps, thereby facilitating their operational use in drought monitoring, irrigation planning, and agricultural adaptation.

Author contribution: *Ngo Thi Thuy designed the research and developed the WWDI maps; Luong Tuan Trung and Duong Hong Nhung wrote the manuscript and develop WDI maps; Vu Thi Thuy did validation; Narendra N. Das provide advices and validation.*

Acknowledgement: *This study is supported by the Seed Grant Project "Strengthening Food Security via Strategic Agricultural Water Management: A Case Study on Assessing Water Demand from High-Resolution SAR Remote Sensing for Enhanced Operational Plans in Water Works Systems of Viet Nam and Cambodia" No. CRRP2024-09SY-Ngo.*

Declarations: *All authors declare that they have no conflicts of interest. The authors confirm that our manuscript is original research and has not been published and is not under consideration for publication elsewhere.*

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