

RAPID-ONSET DROUGHTS AND IRRIGATION BUFFERING: ASSESSING WATER STRESS AND RICE YIELDS RESPONSES IN SOUTH KOREA

SÉCHERESSES À APPARITION RAPIDE ET EFFET TAMPON DE L'IRRIGATION : ÉVALUATION DU STRESS HYDRIQUE ET DES RÉPONSES DES RENDEMENTS RIZICOLES EN CORÉE DU SUD

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ABSTRACT

Rapid-onset droughts can intensify agricultural water stress before conventional drought indicators become fully established. In irrigated agricultural watersheds, however, the impacts of rapid soil moisture depletion may be partially buffered by reservoirs, river networks, and managed irrigation systems. This study evaluated the temporal relationships among rapid-onset drought intensity, river-network water-surface deficit, and vegetation stress in the Anseongcheon mid-watershed, South Korea, during 2017–2024. Rapid-onset drought intensity was represented using the Flash Drought Intensity Index (FDII), derived from soil moisture percentile dynamics. River-network water-surface deficit was assessed using WSA_spread, a satellite-based indicator derived from reservoir and river water-surface variability. Vegetation response was evaluated using Normalized Difference Vegetation Index (NDVI) anomalies. Weekly FDII, monthly WSA_spread, and 16-day NDVI datasets were harmonized to monthly time steps, and correlation, lag-correlation, event-centered composite, and compound stress analyses were conducted. The results showed that FDII exhibited a stronger relationship with WSA_spread than with NDVI anomalies. The strongest relationship occurred at a one-month lag between FDII and WSA_spread, indicating delayed hydrological response following rapid-onset drought development. In contrast, NDVI anomalies showed weak direct relationships with both FDII and WSA_spread, suggesting that vegetation stress responses may be buffered or delayed within managed irrigation systems. Compound stress conditions characterized by high FDII, high WSA_spread, and negative NDVI anomalies occurred intermittently during the irrigation season. These findings suggest that river-network water-surface deficit indicators can provide useful information for monitoring hydrological drought propagation in irrigated agricultural watersheds and highlight the importance of irrigation buffering effects when interpreting vegetation-based drought responses.

Keywords: Rapid-onset drought; Flash Drought Intensity Index; Irrigation buffering; Water-surface deficit; Vegetation stress; Lag analysis.

RESUME

Les sécheresses à apparition rapide peuvent aggraver le stress hydrique agricole même avant l'établissement plein des indicateurs de sécheresse classiques. Dans les bassins versants agricoles irrigués, cependant, les effets d'une réduction rapide de l'humidité du sol peuvent être partiellement atténués à l'aide des réservoirs, des réseaux hydrographiques et des systèmes d'irrigation gérés. Cette étude a évalué les relations temporelles entre l'intensité des sécheresses à apparition rapide, le déficit de surface d'eau du réseau fluvial et le stress de la végétation dans la partie centrale du bassin versant de l'Anseongcheon, en Corée du Sud, entre la période 2017 et 2024. L'intensité de la sécheresse à apparition rapide a été représentée à l'aide de l'indice FDII (Flash Drought Intensity Index), dérivé de la

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dynamique des centiles d'humidité du sol. Le déficit de surface d'eau du réseau fluvial a été évalué à l'aide de WSA_spread, un indicateur satellitaire dérivé de la variabilité de la surface d'eau des réservoirs et des cours d'eau. La réponse de la végétation a été évaluée à l'aide des anomalies de l'Indice de végétation par différence normalisée (NDVI). Les séries de données hebdomadaires du FDII, mensuelles du WSA_spread et de 16 jours du NDVI ont été harmonisées à une échelle mensuelle, et des analyses de corrélation, de corrélation avec décalage temporel, de composite centré sur les événements et de contraintes composées ont été menées. Les résultats ont démontré que le FDII présentait une corrélation plus forte avec le WSA_spread par rapport aux anomalies du NDVI. La corrélation la plus forte a été observée avec un décalage d'un mois entre le FDII et le WSA_spread, ce qui indique une réponse hydrologique retardée suite à l'apparition rapide d'une sécheresse. [Au contraire](#), les anomalies du NDVI ont montré de faibles corrélations directes tant avec le FDII qu'avec le WSA_spread, proposant ainsi que les réponses de la végétation au stress peuvent être atténuées ou retardées au sein des systèmes d'irrigation gérés. Des conditions de contraintes composées, caractérisées par un FDII élevé, un WSA_spread élevé et des anomalies négatives du NDVI, se sont produites de manière intermittente pendant la saison d'irrigation. Ces résultats proposent que les indicateurs de déficit de surface d'eau du réseau hydrographique puissent fournir des informations utiles pour surveiller la propagation de la sécheresse hydrologique dans les bassins versants agricoles irrigués et soulignent l'importance d'effet tampon de l'irrigation lors de l'interprétation des réponses de la végétation à la sécheresse.

Mots-clés : Sécheresse à apparition rapide; Indice d'intensité des sécheresses rapides (FDII); Effet tampon de l'irrigation; Déficit de surface d'eau; Stress de la végétation; Analyse de décalage.

INTRODUCTION

Drought is a major hydroclimatic hazard for irrigated agriculture, but not all droughts develop in the same way. Conventional droughts often evolve gradually through accumulated precipitation deficits and persistent water shortages. In contrast, rapid-onset droughts, often referred to as flash droughts, develop within a much shorter time scale as soil moisture decreases rapidly under the combined effects of rainfall deficit, high evaporative demand, and land-atmosphere feedbacks (Otkin et al., 2018; Christian et al., 2021). Because these events can emerge quickly during the growing season, they may reduce the time available for water managers and farmers to respond. This rapid development is particularly important in agricultural watersheds where irrigation demand can increase abruptly when soil moisture and atmospheric conditions deteriorate simultaneously.

The agricultural impact of rapid-onset drought is not determined by meteorological or soil moisture conditions alone. In managed irrigation systems, reservoirs, canals, rivers, pumping stations, drainage networks, and operational decisions modify the way drought signals propagate from climate to crop stress. A rapid decline in soil moisture may increase irrigation demand, but crop stress may remain limited if sufficient stored water is available and if delivery systems can supply water at the required time. Conversely, when the available surface water is already reduced, even a short period of rapid drought development may contribute to hydrological stress and vegetation decline. Therefore, understanding drought impact in irrigated watersheds requires not only identifying the drought event, but also examining whether the event is reflected in water availability and vegetation condition.

Rice paddy systems are especially relevant for this issue. Rice production depends strongly on managed water supply, and paddy fields are often connected to reservoirs, stream networks, and drainage systems. In such environments, vegetation indices do not always respond linearly to drought intensity because irrigation can maintain canopy greenness even when soil moisture drought is detected at a broader scale. This means that the absence of a strong vegetation anomaly does not necessarily imply the absence of drought stress; it may instead indicate buffering by irrigation, delayed vegetation response, or spatial averaging over heterogeneous land cover. At the same time, surface-water changes in reservoirs and river-connected areas may provide an earlier or more sensitive indication of hydrological stress than vegetation response alone.

Remote sensing provides a practical basis for evaluating this propagation pathway. Soil moisture products can be used to detect rapid drought development, water-surface observations can capture changes in reservoirs and river-connected water bodies, and vegetation indices can represent the condition of crops and surrounding vegetation (Tucker, 1979; Huete et al., 2002). These data sources are particularly useful where direct measurements of irrigation withdrawals, field-level water delivery, and crop management decisions are limited. Rather than attempting to infer unobserved irrigation decisions directly, an observation-driven framework can evaluate whether rapid drought signals are followed by changes in water-surface deficit and vegetation anomaly.

Previous studies have improved the definition and detection of flash drought, including approaches based on rapid soil moisture decline and drought severity (Otkin et al., 2021). Other studies have demonstrated the usefulness of satellite-based water detection using optical and Synthetic Aperture Radar observations for monitoring reservoir dynamics and surface-water changes (McFeeters, 1996; Chan and Vese, 2001). However, relatively few studies have connected rapid-onset drought intensity, river-network water-surface deficit, and vegetation response in a single watershed-scale framework. This gap is important for irrigation and drainage management because drought impacts often occur through linked hydroclimatic and managed water pathways rather than through a single drought variable.

The objective of this study is to assess whether rapid-onset drought intensity is associated with subsequent water-surface deficit and vegetation stress in a managed agricultural watershed. Specifically, this study aims to: (1) construct monthly time series of drought intensity, water-surface deficit, and vegetation anomaly; (2) evaluate simultaneous and lagged relationships among these variables; (3) examine event-centered responses after high drought-intensity months; and (4) identify compound stress periods when drought intensity, water-surface deficit, and negative vegetation anomaly overlap. The study focuses on the Anseongcheon mid-watershed in South Korea, where reservoirs and river networks are important components of agricultural water management. The analysis is intended as a simple but interpretable framework for assessing drought propagation and irrigation-buffering conditions using remote sensing indicators.

DATA AND METHODS

Study Area and Datasets

The study area is the Anseongcheon mid-watershed, located in the central-western part of South Korea. The watershed includes agricultural land, urbanized areas, reservoirs, and river-connected water supply systems, making it suitable for evaluating drought propagation under managed hydrological conditions. The watershed is influenced by both reservoir-based and river-based water management, and therefore rapid drought signals may be modified by available surface water, stream connectivity, and irrigation infrastructure before they become visible as vegetation stress.

The Anseongcheon mid-watershed contains multiple rural water districts and a dense network of national and local rivers. In the upper and middle parts of the watershed, agricultural reservoirs contribute to local water supply, whereas the lower part is influenced by river-based pumping and broader water distribution systems. This combination of storage, river connectivity, and agricultural land use creates a complex environment in which the relationship between drought intensity and vegetation response may be delayed or buffered. The analysis period was set to 2017-2024 because the main satellite-based drought, water-surface, and vegetation datasets were consistently available for this period.

Remote Sensing-Based Drought and Water-Stress Indicators

Three primary time-series datasets were used in this study: Flash Drought Intensity Index, water-surface area deficit spread, and Normalized Difference Vegetation Index. Before each abbreviation is introduced, the full name is provided to maintain clarity. The Flash Drought Intensity Index (FDII) was used to represent rapid-onset drought intensity. water-surface area deficit spread (WSA_spread) was used as a river-network-based water-surface deficit indicator. The Normalized Difference Vegetation

Index (NDVI) was used as a vegetation condition indicator and a proxy for potential crop stress. All datasets were harmonized to a monthly temporal scale before analysis.

The FDII was derived from satellite-based soil moisture information. Advanced Microwave Scanning Radiometer 2 (AMSR2) soil moisture retrieved using the Land Parameter Retrieval Model (LPRM) has been widely used to represent surface soil moisture variability at regional to global scales (Owe et al., 2008; Kim et al., 2015). In this study, the soil moisture percentile approach was adopted because rapid-onset drought detection is more concerned with relative depletion and intensification than with absolute volumetric soil moisture values. The FDII combines the rate of intensification and drought severity, following the conceptual structure proposed by Otkin et al. (2021).

$$FDII = FD_INT \times DRO_SEV \quad (1)$$

where FDII is the flash drought intensity index, FD_INT is the rate of intensification, and DRO_SEV is drought severity. The rate of intensification represents how rapidly soil moisture percentiles decline toward the drought threshold, while drought severity represents the average deficit below the threshold during the event. Weekly FDII values were aggregated to monthly mean, maximum, and cumulative values. Monthly maximum FDII was selected as the main drought-intensity variable because rapid-onset droughts can be short and intense, and monthly averaging may weaken the signal.

$$FD_INT = (\Delta PER_BASE / \Delta T_BASE)^{(-1)} \times \max(\Delta PER_OBS / \Delta T_OBS) \quad (2)$$

$$DRO_SEV = (1 / np) \sum (DRO_BASE - DRO_OBS(n)) \quad (3)$$

Water-surface deficit was represented using WSA_spread. In this study, WSA_spread was not interpreted as direct irrigation withdrawal, reservoir release, or field-level water delivery. Instead, it was interpreted as a spatial indicator of water-surface deficit and weakened hydrological buffering capacity along the river-network-influenced area. A larger WSA_spread value indicates a greater degree of water-surface shortage. This interpretation is important because irrigation actions were not directly observed in this study.

The water-surface component used to construct WSA_spread was based on satellite water detection. Sentinel-1 Synthetic Aperture Radar (SAR) observations are useful for water-body monitoring because radar backscatter over smooth water surfaces is generally lower than over surrounding land surfaces. Ground Range Detected (GRD) data acquired in Interferometric Wide swath (IW) mode with Vertical transmit and Vertical receive (VV) polarization were used because this configuration is widely applied for hydrological monitoring and flood or water-body detection. Incidence-angle normalization and Refined Lee filtering were applied to reduce angular effects and speckle noise while preserving water-body boundaries (Lee, 1980). Chan-Vese (CV) segmentation was then used to delineate water surfaces from processed radar imagery because it can segment objects even when edges are not sharply defined (Chan and Vese, 2001).

$$WSA_ratio(r,t) = N_water(r,t) / N_poly(r) \quad (4)$$

$$WSA_deficit(r,t) = 1 - WSA_ratio(r,t) \quad (5)$$

$$WSA_spread(i,t) = \sum W_r(i) \times WSA_deficit(r,t) \quad (6)$$

where WSA_ratio is the detected water-surface ratio for reservoir r at time t , N_water is the number of detected water pixels, N_poly is the number of pixels within the reservoir polygon, WSA_deficit is the reservoir-level water-surface deficit, and $W_r(i)$ is the spatial influence weight from reservoir r to grid cell i . This formulation allows reservoir water-surface shortage to be spatially propagated along hydrologically relevant areas rather than being treated only as a reservoir polygon attribute.

Vegetation condition was represented using the NDVI. This Index has been widely used to represent canopy greenness and vegetation vigor (Tucker, 1979). Moderate Resolution Imaging Spectroradiometer (MODIS) vegetation index products provide consistent time-series information for monitoring regional vegetation dynamics (Huete et al., 2002). In this study, the NDVI was not used as a direct surrogate for rice yield. Rice yield is affected by cultivar, planting date, irrigation operation, fertilization, pest and disease occurrence, typhoon damage, and heat stress. Instead, negative NDVI anomalies were interpreted as below-normal vegetation condition and potential crop stress.

$$\text{NDVI_anom}(y,m) = \text{NDVI}(y,m) - \text{mean}[\text{NDVI}(m)] \quad (7)$$

$$\text{NDVI_stress}(y,m) = -\text{NDVI_anom}(y,m) \quad (8)$$

where NDVI_anom is the monthly NDVI anomaly, y is year, m is calendar month, and mean[NDVI(m)] is the multi-year monthly climatology. Positive anomalies indicate above-normal vegetation condition, whereas negative anomalies indicate below-normal vegetation condition. For event-centered analysis, the sign of anomaly was reversed to define NDVI_stress so that higher values consistently indicate stronger stress, similar to higher FDII and higher WSA_spread values.

Lagged Drought Propagation and Compound Stress Analysis

The framework was designed to test whether rapid-onset drought intensity propagates into water-surface deficit and vegetation stress. The analysis proceeded in five steps. First, weekly FDII and 16-day NDVI were aggregated to monthly values, while monthly WSA_spread was used directly. Second, monthly time-series plots were used to examine whether high drought-intensity periods coincided with or preceded changes in water-surface deficit and vegetation anomaly. Third, pairwise relationships were evaluated using Pearson correlation coefficients. These zero-lag relationships were considered diagnostic but not sufficient because hydrological and vegetation responses may occur with delay.

Fourth, lag-correlation analysis was performed to quantify delayed relationships. For two variables X and Y, the correlation between X at month t and Y at month t+k was calculated for lags from zero to three months. The main relationships evaluated were FDII(t) versus WSA_spread(t+k), FDII(t) versus NDVI anomaly(t+k), and WSA_spread(t) versus NDVI anomaly(t+k). Fifth, high-drought months were identified using the 75th percentile threshold of monthly maximum FDII, and event-centered composites were calculated from two months before to two months after each high-drought month.

Finally, compound stress months were classified by combining the three indicators. A compound stress month was defined when high FDII, high WSA_spread, and negative NDVI anomaly occurred simultaneously. High WSA_spread was also defined using the 75th percentile threshold of its monthly distribution. This classification was not intended to prove crop loss, but to identify months when rapid drought intensity, water-surface deficit, and below-normal vegetation condition overlapped.

$$r_k = \text{corr}(X_t, Y_{t+k}) \quad (9)$$

RESULTS AND DISCUSSION

Temporal Evolution of Drought Intensity, Water-Surface Deficit, and Vegetation Stress

The monthly time series show distinct but partially connected variations among FDII, WSA_spread, and NDVI anomaly (Figure 1). Several peaks in monthly maximum FDII appeared during the analysis period, including pronounced events in 2018, 2022, 2023, and 2024. WSA_spread also showed repeated increases, with particularly high values during months following or coinciding with high drought-intensity periods. This pattern suggests that rapid-onset drought intensity may be reflected in subsequent water-surface deficit conditions in the watershed.

The NDVI anomaly fluctuated around zero during most months, indicating that basin-average vegetation condition remained close to its monthly climatological value for much of the analysis period. A pronounced negative anomaly occurred in 2020, and smaller negative departures were observed in several other years. However, the vegetation signal was not as closely aligned with drought intensity as WSA_spread. This result implies that vegetation response may be weakened by irrigation buffering, delayed response, phenological differences, or spatial averaging across mixed land cover. Therefore, NDVI anomaly should be interpreted as a potential vegetation-stress indicator rather than a direct measure of rice yield loss.

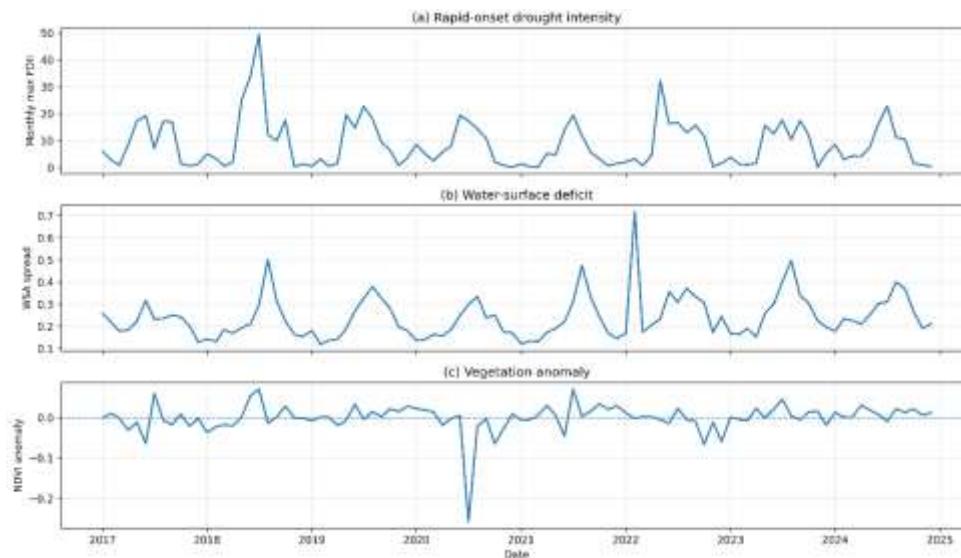


Figure 1. Temporal variations of rapid-onset drought intensity (FDII), river-network water-surface deficit (WSA_spread), and vegetation anomaly (NDVI anomaly) in the Anseongcheon mid-watershed during 2017–2024.

Pairwise Relationships among Drought, Water Deficit, and Vegetation Indicators

Pairwise scatter plots further clarify the different levels of association among the indicators (Figure 2). The relationship between FDII and WSA_spread was positive, with a Pearson correlation coefficient of approximately 0.39. This value indicates a moderate relationship at the monthly watershed scale. Although the relationship is not strong enough to imply direct causality, it suggests that months with stronger rapid-onset drought intensity tend to be associated with greater water-surface deficit.

In contrast, the direct relationship between FDII and NDVI anomaly was weak, with a correlation coefficient of approximately 0.07. The relationship between WSA_spread and NDVI anomaly was also weak, with a correlation coefficient close to zero. These weak relationships suggest that the vegetation response did not occur as a simple simultaneous function of either drought intensity or water-surface deficit. This finding is consistent with the characteristics of managed agricultural watersheds, where vegetation condition can be moderated by irrigation supply, management practices, and crop phenology.

Lagged Relationships between Drought Intensity and Hydrological Response

Lag-correlation analysis revealed that the strongest relationship occurred between FDII and WSA_spread at a one-month lag (Figure 3). The correlation between $FDII(t)$ and $WSA_spread(t+1)$ was approximately 0.61, which was higher than the zero-lag correlation of approximately 0.39. The correlation remained moderately positive at a two-month lag and declined at a three-month lag. This pattern indicates that water-surface deficit did not necessarily peak in the same month as rapid drought intensity. Instead, water-surface deficit tended to increase after high drought-intensity conditions.

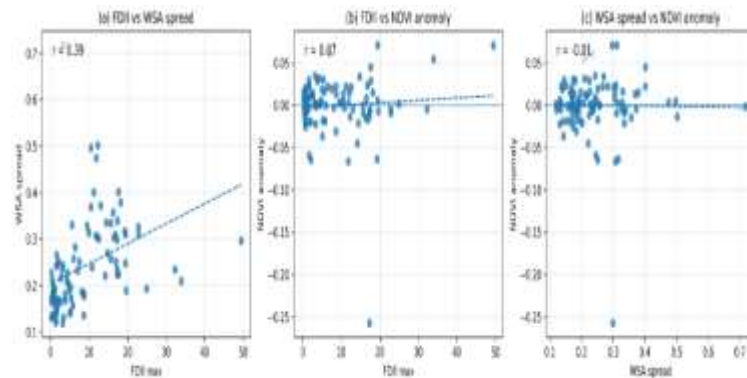


Figure 2. Pairwise relationships among monthly rapid-onset drought intensity (FDII), river-network water-surface deficit (WSA_spread), and vegetation anomaly (NDVI anomaly) during 2017–2024.

The lagged relationships involving NDVI anomaly were much weaker. Correlations between FDII and subsequent NDVI anomaly remained close to zero, and correlations between WSA_spread and subsequent NDVI anomaly were also small. These results suggest that vegetation response, at least at the basin-average monthly scale, was not strongly controlled by the drought and water-surface indicators used in this study. Nevertheless, the relatively clear lagged relationship between FDII and WSA_spread supports the interpretation that rapid-onset drought signals may propagate into hydrological water-surface deficit before becoming evident in vegetation metrics.

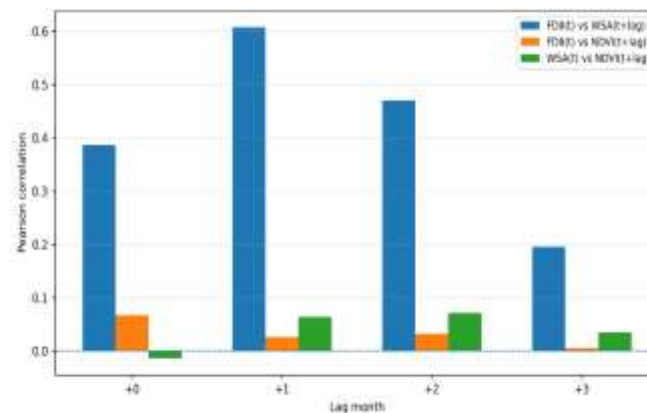


Figure 3. Lag-correlation analysis among FDII, WSA_spread, and NDVI anomaly showing delayed hydrological response to rapid-onset drought conditions.

Event-Based Drought Propagation Responses

The event-centered composite analysis provides an additional perspective on drought propagation (Figure 4). High-FDII months were defined as months in which monthly maximum FDII exceeded the 75th percentile of the analysis-period distribution. By standardizing each variable and aligning all events to the event month, the composite shows the average response from two months before to two months after high-drought conditions.

The composite result shows that FDII peaked at the event month, as expected. WSA_spread increased before the event month and reached its highest standardized value one month after the high-FDII month. This result is consistent with the lag-correlation analysis and suggests a delayed hydrological response. Vegetation stress, defined as the negative of NDVI anomaly, increased only slightly around the event month and one month after the event, and then decreased two months after the event. This weak and short-lived vegetation response implies that basin-average vegetation condition did not respond strongly to high-FDII events, even when water-surface deficit increased after those events.

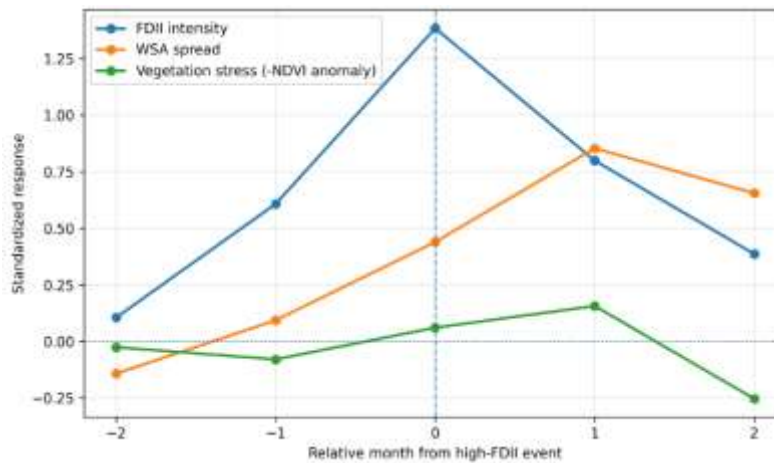


Figure 4. Composite temporal responses of FDII intensity, WSA_spread, and vegetation stress relative to high-FDII events.

Compound Stress Responses under Rapid-Onset Drought

Compound stress classification identified months when high FDII, high WSA_spread, and negative NDVI anomaly occurred simultaneously (Figure 5). These months were interpreted as periods when rapid drought intensity, water-surface deficit, and below-normal vegetation condition overlapped. Compound stress months appeared intermittently rather than continuously, and they were concentrated mainly during the growing-season months.

Several notable compound stress months were detected, including summer months in 2017, 2019, 2022, 2023, and 2024. In addition, some months were classified as drought-water deficit conditions, where high FDII and high WSA_spread occurred without a negative vegetation anomaly. This distinction is important because it indicates that hydrological stress did not always translate into basin-average vegetation decline. Conversely, water-vegetation stress conditions occurred in some months without high FDII, suggesting that vegetation anomalies may also be influenced by factors other than rapid-onset drought intensity.

Overall, the classification results support the main conclusion that the drought-water deficit linkage is more evident than the drought-vegetation linkage. The compound stress framework is useful not because it proves yield loss, but because it identifies potential high-risk periods that may deserve closer examination using field observations, crop-specific masks, irrigation operation records, or administrative yield statistics.

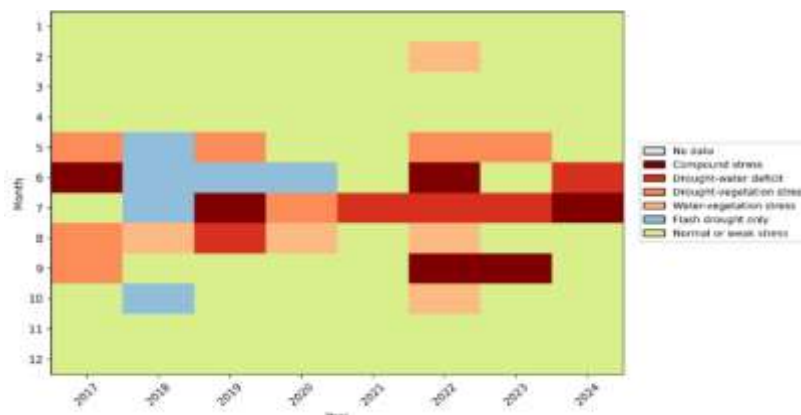


Figure 5. Temporal classification of compound drought stress conditions derived from FDII, WSA_spread, and NDVI L anomaly in the Anseongcheon mid-watershed.

CONCLUSIONS

This study evaluated the linkage among rapid-onset drought intensity, river-network water-surface deficit, and vegetation anomaly in the Anseongcheon mid-watershed of South Korea during 2017–2024. The analysis used the Flash Drought Intensity Index (FDII) as a drought-intensity indicator, WSA_spread as a river-network-based water-surface deficit indicator, and NDVI anomaly as a vegetation condition indicator. By harmonizing these datasets to a monthly temporal scale, the study assessed simultaneous relationships, lagged relationships, event-centered responses, and compound stress periods associated with rapid-onset drought development.

The results showed that FDII was more clearly associated with WSA_spread than with NDVI anomaly. The strongest relationship was observed between FDII and WSA_spread at a one-month lag, indicating that rapid-onset drought intensity was followed by delayed increases in water-surface deficit. Event-centered composite analysis confirmed this propagation pattern, showing that WSA_spread reached its maximum standardized response one month after high-FDII events. These results suggest that hydrological water-surface deficit may provide a clearer watershed-scale response signal to rapid-onset drought than vegetation condition indicators in managed irrigation systems.

In contrast, the direct relationships between drought intensity and NDVI anomaly were weak. This does not necessarily imply that vegetation or crops were unaffected by drought conditions. Rather, the results suggest that vegetation response in irrigated agricultural watersheds can be buffered, delayed, or spatially diluted by irrigation supply, reservoir operation, crop phenology, and mixed land-cover conditions. Consequently, NDVI anomaly should be interpreted as an indicator of potential vegetation stress rather than as a direct representation of rice yield reduction. The weak relationship between FDII and vegetation anomaly further highlights the importance of considering irrigation-buffering effects when interpreting vegetation-based drought responses in managed agricultural systems.

The compound stress classification identified months when rapid drought intensity, water-surface deficit, and below-normal vegetation condition occurred simultaneously. These periods represent potential high-risk conditions for agricultural water management because hydrological stress and vegetation stress may overlap during critical growing-season periods. At the same time, the classification also identified drought-water deficit conditions without strong vegetation anomaly, indicating that hydrological stress does not always translate directly into observable vegetation decline at the watershed scale. Overall, the study demonstrates that rapid-onset drought propagation in managed agricultural watersheds may occur more clearly through hydrological water-surface deficit pathways than through immediate vegetation response. The proposed framework is observation-driven, data-efficient, and transferable to other managed irrigation watersheds where direct observations of irrigation withdrawal, field-level water delivery, or operational reservoir releases are unavailable. By integrating drought intensity, water-surface deficit, and vegetation indicators within a unified analytical framework, the study provides a practical basis for assessing irrigation-buffering effects and drought propagation processes using remotely sensed observations.

Future research should incorporate crop-specific land-cover masks, irrigation command areas, reservoir operation records, groundwater supply information, and administrative rice yield anomalies to further clarify the pathways linking rapid-onset drought development, hydrological stress propagation, irrigation buffering, and agricultural impacts.

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