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Asymmetric ENSO Modulation on Hidden Drying Trends in the Vietnamese Mekong Delta: Implications for Rice Security and Scarcity-based Adaptation

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ABSTRACT

Background: The long xuyen quadrangle (LXQ) serves as a critical cornerstone of rice production within the Vietnamese Mekong Delta, yet a paradox currently exists where traditional monotonic statistical tests classify the region's rainfall as "stable," contradicting farmers' reports of intensifying water scarcity due to climate change.

Methods: This study resolves this discrepancy by investigating the spatiotemporal evolution of rainfall (1984-2022) using the advanced innovative trend analysis (ITA) method, contrasted with the standard Mann-Kendall (MK) test and analyzing teleconnections to identify asymmetric ENSO modulation on local hydrology.

Result: While MK tests showed no significant trends for inland stations (p>0.05), ITA successfully unmasked a critical "hidden" drying trend in the lower rainfall quantiles, implying that "dry years are becoming drier" Spatially, coastal stations (Ha Tien, Rach Gia) exhibit accelerated drying trends driven by weakening Southwest Monsoon circulation. Teleconnection analysis reveals a robust, asymmetric ENSO modulation: El-Niño phases reduce dry-season rainfall by up to 41.2%, whereas La-Niña phases fail to provide an equivalent compensatory surplus (increasing only by 20.1%).

Key words: Climate adaptation, ENSO asymmetry, Innovative trend analysis, Long xuyen quadrangle, Meteorological drought.

INTRODUCTION

Global climate change is unequivocally altering the hydrological cycle, intensifying the frequency, duration and magnitude of extreme weather events such as catastrophic floods and prolonged droughts (IPCC, 2023; Lee and Dang, 2020). In recent decades, the Southeast Asian monsoon region has emerged as a hotspot for hydro-climatic volatility (Shahid *et al*., 2024; Li *et al*., 2021). Evidence indicates that anthropogenic forcing has significantly increased drought risk over this region, primarily through thermal forcing mechanisms and shifts in large-scale atmospheric circulation (Zhang *et al*., 2021; Loo *et al*., 2015). Within this context, hydrological alterations are deeply intertwined with planetary-scale atmospheric circulation patterns, particularly the El Niño-Southern Oscillation (ENSO), which acts as the dominant driver of interannual climate variability in the tropics (Dinh and Dang, 2023; Lee *et al*., 2023). Crucially, emerging research suggests that global warming is enhancing the amplitude of ENSO events, triggering "super El Niños" that result in unprecedented precipitation deficits (Hong *et al*., 2025; Shin *et al*., 2022).

The Vietnamese Mekong Delta (VMD), contributing over 50% of Vietnam's national rice production and 90% of its rice exports, is identified as one of the world's most vulnerable mega-deltas to climate change and sea-level rise (Bui and Dang, 2025; Nguyen *et al*., 2025). Within the VMD, the Long Xuyen Quadrangle (LXQ) represents a unique and complex hydrological zone. Historically functioning as a flood retention basin to protect downstream urban centers, the LXQ has been transformed into a primary triple-cropping rice cultivation area through intensive hydraulic engineering (Dang, 2018; Dinh and Dang, 2022). However, the historic droughts of 2015-2016 and 2019-2020 have signaled a fundamental shift in the regional hydro-climatic regime toward erratic water availability (Cong *et al*., 2025; Lee and Dang, 2019). These events caused massive saline intrusion, damaging hundreds of thousands of hectares of crops and threatening the livelihoods of millions.

Despite the urgency, a critical methodological gap persists in current hydro-climatic assessments of the region. The majority of existing studies rely heavily on linear trend detection methods, such as the Mann-Kendall

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(MK) test and Sen's slope estimator. While these non-parametric tests are robust against outliers, they assume a monotonic trend across the entire data distribution. This assumption is increasingly problematic in the context of climate change, where trends often manifest in the extremes rather than the mean. The MK approach potentially fails to capture "sub-trends"-for instance, a scenario where extreme rainfall increases while light rainfall decreases, resulting in a statistically "no trend" mean. For the LXQ, understanding the behavior of the "tails" of the distribution-specifically, whether dry years are intensifying-is far more vital for salinity intrusion management than knowing the long-term average rainfall.

Furthermore, the relationship between local rainfall and ENSO is often treated as linear and symmetric in conventional studies (Hong *et al*., 2025; Hoang and Dang, 2025). However, recent physical modeling suggests that the atmospheric response to Sea Surface Temperature (SST) anomalies is inherently non-linear (Lin *et al*., 2024). The moisture divergence driven by El Niño (drying) may not be symmetric to the moisture convergence driven by La-Niña under a background warming signal (Bui and Dang, 2025). Ignoring this asymmetry can lead to dangerous underestimations of long-term water deficits, as agricultural planning often assumes that wet La-Niña years will compensate for dry El-Niño years.

To address these critical gaps and support evidence-based policy making, this study integrates updated ground-based observations with advanced statistical techniques. The specific objectives of this study are: (1) To investigate the spatiotemporal evolution of rainfall in the LXQ from 1984 to 2022 using the Advanced Innovative Trend Analysis (ITA) method; (2) To explicitly compare MK and ITA results to demonstrate the "masking" effect of traditional statistics on drought detection; (3) To identify the physical mechanisms responsible for the observed coastal-inland drying asymmetry by analyzing regional circulation patterns and (4) To quantify the asymmetric impact of ENSO phases on local hydrology. This study provides not only a local assessment for the VMD but also offers a methodological framework applicable to other tropical deltas facing similar "hidden" drying risks.

MATERIALS AND METHODS

Study area and ground-based data

The LXQ is situated in the northwestern region of the VMD, bounded by the Gulf of Thailand to the west, the border with Cambodia to the north, the Bassac River to the east and the Cai San canal to the south (Fig 1). The region is characterized by a complex hydraulic network designed to manage floodwaters from the Mekong River and facilitate irrigation (Lee and Dang, 2019). The climate is defined by a tropical monsoon regime with two distinct seasons: the rainy season (May to November), driven by the Southwest Monsoon and the dry season (December to April), dominated by the Northeast Monsoon (Lee and Dang, 2020).

To analyze the spatiotemporal variability of rainfall, daily rainfall data were collected from seven meteorological stations managed by the Vietnam Meteorological and Hydrological Administration. The stations were categorized based on their geographical characteristics: Coastal stations (Rach Gia, Ha Tien, Kien Luong), Inland-depression stations (Chau Doc, Long Xuyen, Tri Ton) and a Transitional station (Tan Hiep). The primary dataset covers a 39-year period from 1984 to 2022, which is sufficient for climatological trend analysis according to WMO standards. A specific note regarding data continuity is required for the Kien Luong station. This station was established and operated specifically for the period 1986-2016. Despite the gap, the 1986-2016 period encompasses critical climatic shifts and the record-breaking 2015-2016 drought, providing sufficient variance for the ITA method to detect structural changes in rainfall regimes. Quality control procedures, including the Pettitt test for homogeneity and outlier detection, were rigorously applied to all datasets

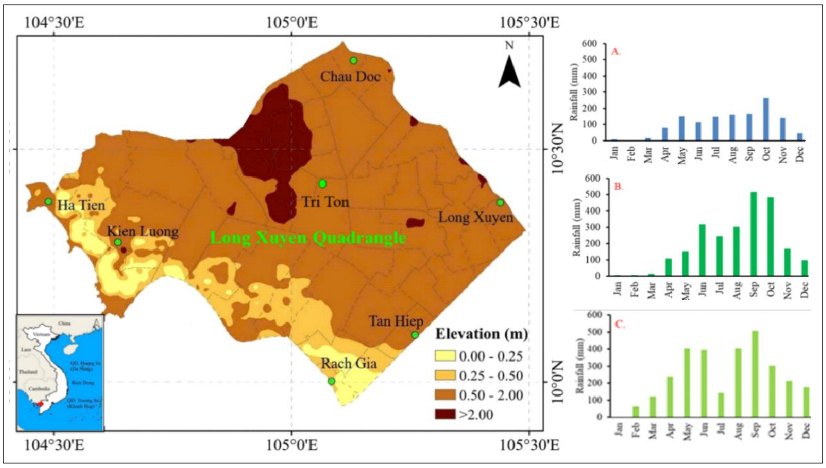


Fig 1: Geographical location of the long xuyen quadrangle and distribution of the seven ground-based rainfall observation stations with varying of rainfall distribution between A) the eastern region, B) mean rainfall and C) western regions.

prior to analysis. To analyze the atmospheric circulation patterns associated with drought years, synoptic charts of relative humidity at the 500 hPa level were retrieved from the Plymouth State Weather Center archive to visualize the convective environment during the monsoon onset period.

Standardized precipitation index (SPI)

To quantify meteorological drought severity and duration, we calculated the Standardized Precipitation Index (SPI) as proposed by McKee *et al.* (1993). The SPI is globally recognized for its flexibility in comparing precipitation anomalies across different climatic zones and timescales (Bayable *et al*., 2021). The long-term precipitation record for each station was fitted to a Gamma probability density function. We calculated SPI at four timescales to capture different drought impacts: SPI-3 (short-term moisture/agriculture), SPI-6 and SPI-9 (seasonal trends) and SPI-12 (long-term hydrological drought). Drought events are classified based on SPI values: Moderate drought (-1.0 to -1.49), severe drought (-1.5 to -1.99) and extreme drought (≤-2.0).

Advanced innovative trend analysis (ITA)

To overcome the limitations of monotonic tests, we employed the ITA method developed by Sen (2012). Unlike traditional methods that rely on a single statistic (*e.g*., Z-score), ITA visualizes trends across low, medium and high data values. The time series is divided into two equal halves (n/2) (Sen, 2017). The first half (X_i) is ordered and plotted on the x-axis, while the second half (Y_i) is plotted on the y-axis (Do *et al*., 2025). Data points clustering on the 1:1 (45°) line indicate no trend. Points falling below the line indicate a decreasing trend, while points above indicate an increasing trend. This method is particularly powerful for identifying "hidden" trends.

Mann-kendall test and sen's slope

For comparative purposes, the standard Mann-Kendall (MK) test and Sen's slope estimator were calculated (Lee and Dang, 2020). A positive Z_s indicates an upward trend, while a negative value indicates a downward trend. The null hypothesis of no trend is rejected if $|Z_s| > 1.96$ at the 95% confidence level.

ENSO teleconnection analysis

The relationship between rainfall anomalies and ENSO was evaluated using the Pearson correlation coefficient between SPI values and the Oceanic Niño Index (ONI) (Haile *et al*., 2021). The ONI tracks the 3-month running mean of SST anomalies in the Niño 3.4 region. Years were classified as El Niño (ONI ≥ +0.5), La Niña (ONI ≤ -0.5), or Neutral (Lee *et al*., 2023). We analyzed lag correlations (0 to 3 months) to determine the delayed atmospheric response of local precipitation to tropical pacific forcing.

RESULTS AND DISCUSSION

Spatiotemporal rainfall characteristics

Descriptive statistics reveal a pronounced spatial gradient in rainfall distribution from the coastal zone to the inland depression (Table 1). The coastal and transitional stations (Tan Hiep, Ha Tien) recorded the highest mean annual rainfall (>2300 mm), whereas the inland stations situated in the depression (Chau Doc) were significantly drier (~1290 mm). Crucially, the statistical moments of the distribution reveal underlying climatic differences. The standard deviation (SD) and skewness (S_k) are markedly higher at coastal stations (*e.g.*, Kien Luong: = 0.83; Ha Tien: SD = 689.6 mm) compared to inland stations (Chau Doc: = 0.14; SD = 295.9 mm). This high variability and skewness at the coast suggest that rainfall here is driven by erratic convective systems originating from the Gulf of Thailand, which are highly sensitive to local sea-surface interactions. In contrast, the inland rainfall is more stratiform and stable, governed by the large-scale monsoon flow.

Unmasking hidden trends *via* ITA

The comparative analysis between the MK test and the ITA method confirms the primary hypothesis of this study: Traditional statistics are masking critical drying signals (Fig 2 and Table 2). The MK test results indicated "No Trend" for inland stations such as Chau Doc (= 0.515) and Tri Ton (= 0.787). Relying solely on this metric would lead policymakers to arguably conclude that the water supply is stable. However, the ITA scatter plots tell a different story. For these same stations, data points corresponding to the lowest 25th percentile (low rainfall years) consistently fall below the 1:1 line. The ITA slope for low values at Chau Doc is -0.12, indicating a "Hidden drying unmasked" phenomenon. This mathematically confirms that "dry years are becoming drier." The drying trend is even more severe

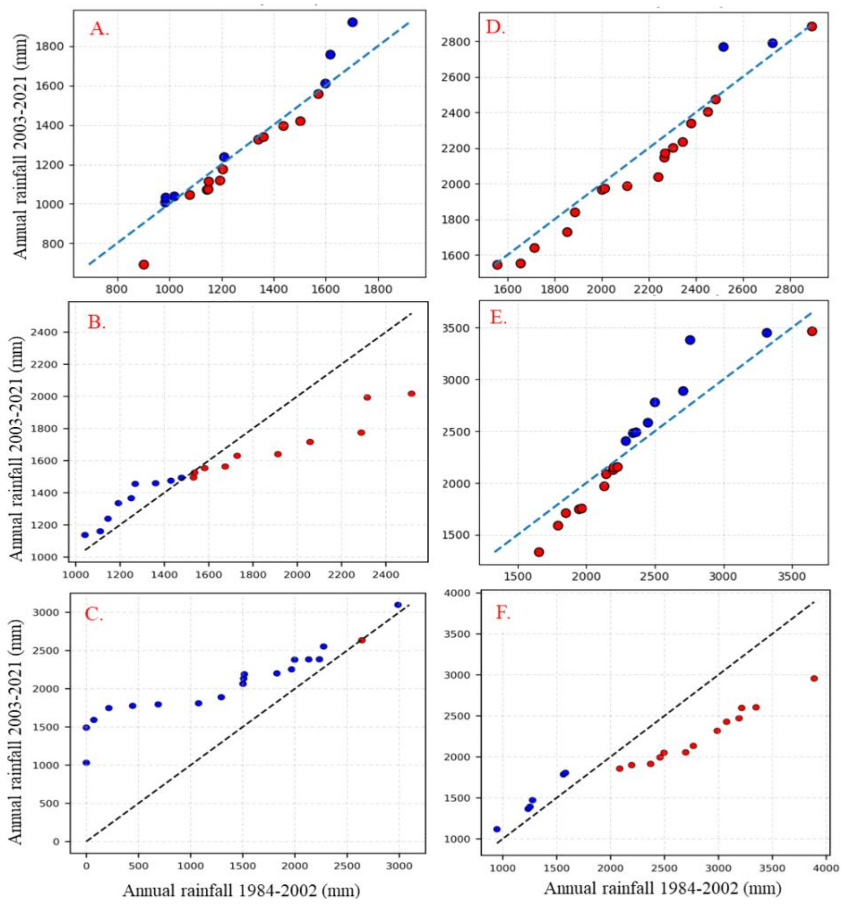
Table 1: Descriptive statistics of rainfall for the meteorological stations (1984-2022).

Station	Latitude (N)	Longitude (E)	Mean (mm)	Min (mm)	Max (mm)	Standard deviation (mm)	Skewness	Interpretation
Chau Doc	10°41′24″	105°07′48″	1291.9	691.5	1920.9	295.9	0.14	Inland
Long Xuyen	10°23′08″	105°26′04″	1461.2	827.2	2360.1	293.6	0.46	Inland
Tri Ton	10°15′36″	105°01′48″	1385.6	407.0	1999.0	365.1	0.12	Inland
Tan Hiep	10°06′00″	105°16′00″	2357.1	1332.2	3986.2	762.1	0.46	Transitional
Ha Tien	10°23′01″	104°29′22″	2345.4	1332.2	3646.7	689.6	0.39	Coastal
Kien Luong	10°18′00″	104°37′60″	2125.0	1517.8	3275.7	380.3	0.83	Coastal
Rach Gia	10°00′00″	105°04′12″	2203.7	1528.6	2895.3	346.0	-0.05	Coastal

and explicit in coastal areas. Stations like Ha Tien and Rach Gia exhibit strong negative slopes across the distribution, particularly in the lower quantiles (ITA slope <-0.8).

Physical mechanism of coastal drying

The observed spatial gradient, where coastal areas exhibit accelerated drying compared to inland areas, requires a physical explanation rooted in regional atmospheric circulation. Since coastal rainfall in the LXQ (Rach Gia, Ha Tien) is largely orographic and convective-driven by moist westerlies originating from the Indian Ocean and Gulf of Thailand impacting the coastal boundary-any weakening of the monsoon wind speed results in insufficient orographic lift and moisture transport. To elucidate the



Note the deviation of low-rainfall points below the 1:1 line for coastal stations, indicating hidden drying trends.

Fig 2: Innovative trend analysis scatter plots for A) Chau Doc, B) Long Xuyen, C) Kien Luong, D) Rach Gia, E) Ha Tien and F) Tan Hiep station during the period of (1984-2022).

Table 2: Innovative trend analysis for annual rainfall showing slope and trend interpretation.

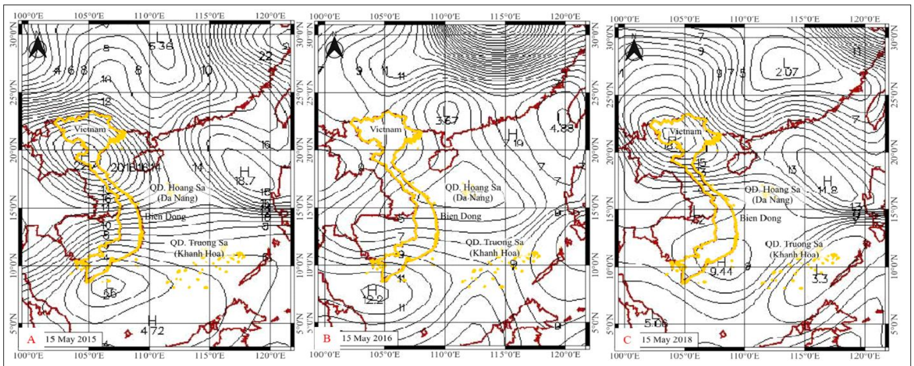
Station	Z_{MK}	*p*-value	ITA slope (S)	ITA interpretation (low values <25%)	Non-stationary drying signal
Chau Doc	0.021	0.515	-0.12	Decreasing	Hidden drying unmasked
Long Xuyen	0.063	0.046	+0.05	Stable	Wetting trend
Tri Ton	0.011	0.787	-0.08	Decreasing	Hidden drying unmasked
Tan Hiep	-0.091	0.004	+1.15	Stable	Wet years getting wetter
Ha Tien	-0.104	0.001	-0.85	Decreasing	Confirmed severe drying
Rach Gia	0.031	0.322	-0.92	Decreasing	Hidden drying unmasked
Kien Luong	-0.001	0.967	-0.44	Decreasing	General decline

Z_{MK}: Mann-kendall Z-value.

dynamic mechanism behind the "hidden drying" trends, we analyzed the synoptic patterns of the 850 hPa wind field, which represents the core layer of the Southwest Monsoon flow (Low-Level Jet). Coinciding with severe El-Niño phases (*e.g.*, 2015, 2016), the airflow over the Indochina Peninsula and the Gulf of Thailand is characterized by weak and disorganized wind vectors (Fig 3). The typical strong southwesterly flow (Somali Jet extension) is notably absent or replaced by weak variable winds or even easterly anomalies. Without the strong kinetic energy of the westerly wind burst, the coastal orographic effect is nullified (Fig 3).

Drought evolution and frequency analysis

The temporal evolution of SPI values highlights a regime shift post-2000, characterized by a transition toward more frequent and intense negative anomalies (Fig 4 and Fig 5). A clear spatial escalation of drought risk towards the coast is evident. Rach Gia experienced the highest number of total drought months (69 months), followed by Ha Tien (63 months) (Table 3). In contrast, inland stations like Chau Doc recorded significantly fewer drought months (47 months). Detailed event analysis for Kien Luong provides a forensic view of specific catastrophes (Table 4). The 2016 event stands out with an SPI-3 of -1.85 in April, coinciding



The dominance of low wind speeds (blue/green shading) and lack of organized southwesterly flow over the VMD indicate a weakened monsoon circulation and suppressed moisture transport. (Source: Modified from plymouth state weather center).

Fig 3: Synoptic charts of wind speed (knots) and streamlines at the 850 hPa pressure level over Southeast Asia during the monsoon onset period (May 15) for drought years: (A) 2015, (B) 2016 and (C) 2018.

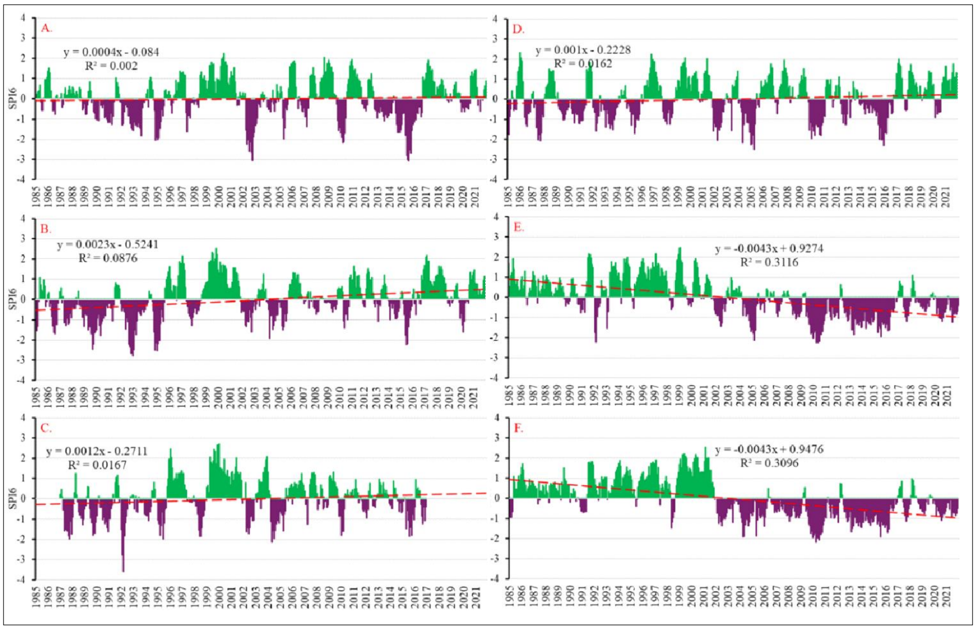


Fig 4: Temporal evolution of drought trends for 6-months drought timescale (SPI-6) at rainfall observation stations A) Chau Doc, B) Long Xuyen, C) Kien Luong, D) Rach Gia, E) Ha Tien and F) Tan Hiep during the period of (1984-2022).

with the peak dry season. This event was not merely a meteorological anomaly but propagated rapidly into a hydrological drought, facilitating the devastating salinity intrusion recorded that year.

ENSO teleconnections and asymmetry

Correlation analysis confirms a strong negative relationship between ONI and SPI, with a 2-month lag being the most predictive predictor (Table 5). The most critical finding of this study is the asymmetric ENSO impact (Table 6). During El-Niño phases, rainfall across the LXQ collapses drastically. Rach Gia station recorded a deficit of -41.2% and Ha Tien recorded -38.4% compared to neutral years. Conversely, during La-Niña phases, while rainfall increases, the surplus is disproportionately smaller. Rach Gia only sees a +20.1% increase and Ha Tien +18.2%.

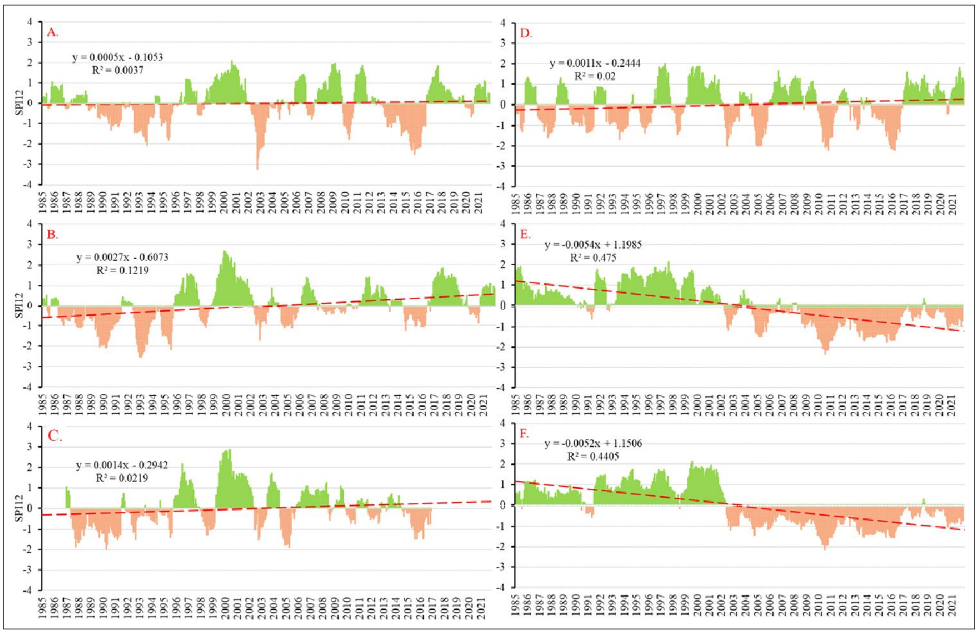


Fig 5: Temporal evolution of drought trends for 12-months drought timescale (SPI-12) at rainfall observation stations A) Chau Doc, B) Long Xuyen, C) Kien Luong, D) Rach Gia, E) Ha Tien and F) Tan Hiep during the period of (1984-2022).

Table 3: Frequency of drought events based on 6-month drought timescale (SPI-6) during the period of 1984-2022.

Station	Moderate drought (-1.0 to -1.49)	Severe drought (-1.5 to -1.99)	Extreme drought (≤-2.0)	Total drought months	Impact duration (% of time)
Chau Doc	28	14	5	47	10.1%
Long Xuyen	31	12	6	49	10.5%
Tri Ton	11	9	7	27	9.8%
Tan Hiep	25	18	9	52	11.1%
Ha Tien	34	21	8	63	13.5%
Kien Luong	30	19	12	61	14.1%
Rach Gia	36	22	11	69	14.7%

Table 4: Analysis of time scales for drought characteristics at Kien Luong station.

Year	Month	SPI-3	SPI-6	SPI-9	SPI-12	Classification
1998	Apr	-0.13	-0.57	-0.59	-1.06	Moderate (Hydrological)
	May	-0.29	-0.45	-0.92	-1.20	Moderate
2002	Apr	-0.99	-1.62	-0.40	0.58	Severe (Seasonal)
2004	Dec	-2.17	-1.70	-1.38	-1.34	Extreme agri/severe hydro
2016	Feb	0.77	0.94	-0.59	-1.02	Moderate
	Mar	-0.39	0.45	-1.12	-1.05	Moderate
	Apr	-1.85	0.54	-0.99	-1.44	Severe (Agri/hydro)
	May	-0.17	0.13	0.57	-0.64	Recovery

Table 5: Pearson correlation coefficients between ONI and SPI at different lags.

Station	Lag 0	Lag 1	Lag 2	Lag 3
Chau Doc	-0.32	-0.41	-0.55	-0.48
Long Xuyen	-0.29	-0.38	-0.51	-0.44
Tri Ton	-0.31	-0.40	-0.53	-0.46
Tan Hiep	-0.35	-0.45	-0.58	-0.49
Ha Tien	-0.38	-0.49	-0.62	-0.53
Kien Luong	-0.36	-0.47	-0.60	-0.51
Rach Gia	-0.39	-0.50	-0.64	-0.55

Table 6: Rainfall deviation (%) during ENSO phases vs. neutral years showing asymmetric impacts.

Station	El-Niño phase (Rainfall deviation %)	La-Niña phase (Rainfall deviation %)
Chau Doc	-28.5%	+12.4%
Long Xuyen	-25.2%	+10.8%
Tri Ton	-23.6%	+14.5%
Tan Hiep	-32.1%	+15.6%
Ha Tien	-38.4%	+18.2%
Kien Luong	-35.6%	+16.5%
Rach Gia	-41.2%	+20.1%

This asymmetry supports the “non-linear response to warming” hypothesis (Lin *et al*., 2024). For the LXQ ecosystem, this implies a cumulative water deficit over time. The “wet” years are not wet enough to refill the aquifers and reservoirs depleted by the increasingly “dry” years. This creates a cumulative deficit regarding water storage that threatens the long-term sustainability of the triple-cropping rice model.

CONCLUSION

This study employed the Advanced Innovative Trend Analysis (ITA) to resolve the paradox of water scarcity in the Long Xuyen Quadrangle, yielding robust insights that traditional methods failed to detect. The key conclusions are: (1) Hidden drying trends: While annual means appear stable under Mann-Kendall tests, ITA reveals a statistically significant structural decline in rainfall during dry years (lower quantiles). The axiom for the region is “Dry years are getting drier.” (2) Coastal vulnerability: A distinct drying gradient exists, where coastal stations (Ha Tien, Rach Gia) exhibit accelerated drying trends, likely driven by the weakening of the Southwest Monsoon and suppressed coastal convection. (3) Asymmetric ENSO Risk: The hydro-climatic response to ENSO is highly asymmetric. The rainfall deficit during El Niño (-41.2%) is approximately double the magnitude of the surplus during La Niña (+20.1%). This creates a net long-term water deficit that threatens the region’s freshwater balance.

The findings advocate for an urgent paradigm shift in the Mekong Delta’s agricultural planning. The current strategy, which often relies on “average” conditions and flood control, is ill-equipped for the “hidden drying” reality. We recommend a transition to “scarcity-based adaptation,” prioritizing aggressive freshwater storage, dynamic crop scheduling utilizing the 2-month ENSO lag and zoning adjustments in the coastal fringe where triple-cropping rice may become unsustainable.

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Disclaimers

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Informed consent

Not applicable for this study.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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