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ORIGINAL RESEARCH ARTICLE

Emergence of wet-season hydrological droughts and the development of a "brittle" river system in the Vietnamese Mekong Delta

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Abstract: River regulation works (RRWs) are a globally implemented strategy to enhance water security, primarily by increasing dry-season flows. However, this intervention can trigger unintended and often paradoxical consequences, fundamentally altering the nature of hydrological risk. This study investigates the profound impact of RRW development on drought characteristics in the Vietnamese Mekong Delta, a region of immense agricultural importance and ecological sensitivity. Building upon the established understanding of the Mekong's altered flow regimen, we analyze how this engineered shift has transformed drought dynamics. Using the standardized precipitation index-3 and standardized streamflow index (SSI-3) from 2000 to 2024, we uncover a critical paradigm shift. While the frequency of traditional dry-season hydrological droughts has significantly decreased as intended, the system's vulnerability to severe, prolonged wet-season droughts has increased dramatically. Correlation analysis reveals a significant "decoupling" between regional rainfall and streamflow in the current mega-dam era (2010–2024). The most alarming finding is the emergence of wet-season hydrological droughts, with the 2019–2020 event being the most extreme in the 25-year record, during which SSI values dropped to below −2.0 despite only a moderate meteorological drought. We introduce and define the concept of a "brittle" river system: By dampening the natural flood pulse, intensive regulation has removed the river's inherent buffering capacity against monsoon rainfall deficits, making the delta extremely vulnerable to climatic shocks. These findings challenge the conventional understanding of drought in the Vietnamese Mekong Delta and have urgent implications for water management, emphasizing the need for strategies that enhance wet-season resilience while addressing growing risks.

Keywords: Drought paradigm; Hydrological drought; River regulation; Standardized streamflow index; Brittle river system

1. Introduction

Globally, the construction of large-scale river regulation works (RRWs) and the strategic operation of reservoirs constitute primary tools for modern water resources management, intended to mitigate devastating floods and augment water supply during periods of scarcity.[1,2] While the intended benefits of flow regulation, such as enhanced hydropower generation[3-5] and reliable irrigation water,[5,6] are often realized, these profound interventions can lead to complex, and sometimes paradoxical, consequences for downstream ecosystems[7,8] and the societies that depend on them.[9-11] The alteration of natural flow regimens can disrupt sediment transport, degrade floodplain habitats, and fundamentally reshape the hydrological risk landscape.[12-14] The Mekong River Basin, which has undergone one of the most rapid and intensive periods of hydropower development in recent history, provides a critical natural laboratory for understanding these far-reaching and often unintended impacts.[15-17]

Historically, the Mekong's natural hydrological regimen was characterized by a powerful annual monsoon flood pulse, a defining event that shaped the delta's landscape and sustained its extraordinary agricultural and fisheries productivity through the delivery of water, sediment, and nutrients.[18-20] This flood pulse created a highly resilient system capable of buffering climatic variability.[21-23] However, previous research has firmly established that the seasonal flow regimen of the Lower Mekong Basin has been fundamentally altered by the cascade of RRWs, particularly those constructed in the Upper Mekong Basin.[24,25] The annual hydrograph has been systematically "flattened," a phenomenon characterized by a significant, managed increase in dry-season discharge and a corresponding decrease in the magnitude and duration of the wet-season flood pulse.[26-28] While previous studies have documented these hydrological alterations and their direct impacts on sediment transport and channel morphology,[27-29] a critical knowledge gap persists in understanding how this re-engineered flow regimen influences the nature, timing, and severity of hydrological drought. This study aims to fill that gap by examining the shifting drought paradigm as a direct consequence of flow regulation.

This emerging paradox motivates the central scientific question of our study: How has the anthropogenic alteration of the Mekong River's flow regimen affected the frequency, severity, and timing of hydrological droughts in the Vietnamese Mekong Delta (VMD)? We hypothesize that by systematically dampening the wet-season flood pulse, upstream reservoir operations have critically diminished the river's natural resilience, transforming it into a "brittle" system vulnerable to even moderate meteorological rainfall deficits. This study, therefore, aims to test the hypothesis of an emergent, regulation-induced "brittleness" in the Mekong's hydrological regimen. To test this hypothesis and explore its implications, this study has three specific objectives (i) to utilize standardized precipitation index (SPI) and standardized streamflow index (SSI) to quantitatively characterize and compare drought conditions across two distinct dam development eras: A "growth-dam" period (2000–2009) and the current "mega-dam" period (2010–2024); (ii) to quantify the changing relationship between rainfall and streamflow to demonstrate the "decoupling" effect of intensive regulation; and (iii) to conduct a detailed case study of the severe 2019–2020 drought to illustrate the mechanics of this emerging wet-season drought paradigm.

2. Materials and methods

2.1. Study area and data collection

The study focused on the VMD, the low-lying terminal part of the Mekong River Basin. The VMD is located in the southwestern part of Vietnam and covers an area of approximately 40,000 km^2 (Figure 1). It is a geographically unique region, characterized by a low-lying, flat plain with average elevations ranging from 0.7 to 1.2 m above mean sea level.[11] Upon entering the VMD from Cambodia, the Mekong River bifurcates into two main tributaries—namely the Tien River (or the Mekong River) and Hau River (Bassac River). This study specifically analyzed data from two primary hydrological stations: Tan Chau (on the Tien River) and Chau Doc (on the Hau River) (Figure 1).

To conduct our analysis, we utilized daily discharge data for Tan Chau and Chau Doc, and daily rainfall data

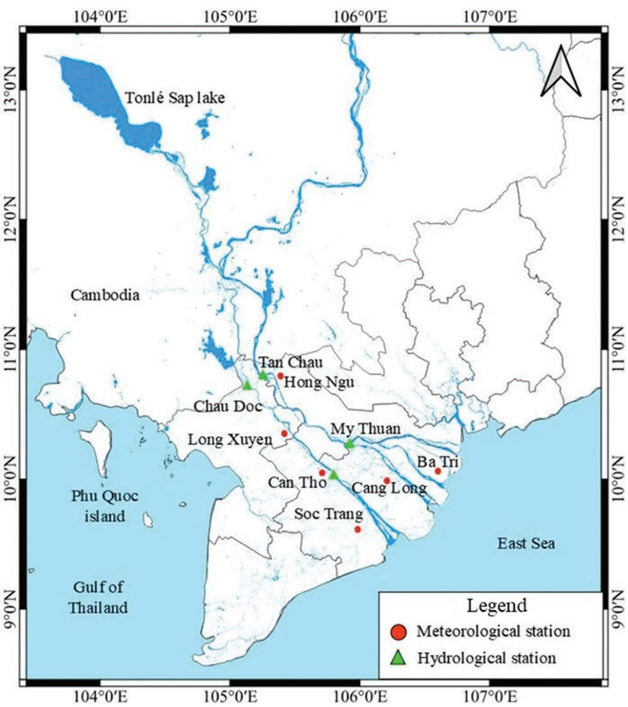

Figure 1. Mekong River Basin showing the locations of national precipitation, flow discharge, and water level monitoring stations

from the nearby Hong Ngu station, for the continuous period from January 1, 2000, to April 30, 2024 (Table 1). These long-term, high-quality datasets were obtained from the Mekong River Commission data portal and the Southern Regional Hydro–Meteorological Center, both of which provide quality-controlled and publicly available hydro–meteorological time-series. The obtained daily discharge and rainfall data underwent rigorous quality control to identify and handle any inconsistencies or missing values. Data gaps, which were minimal (<1% of the total record), were filled using linear interpolation from adjacent days, a standard procedure for high-frequency time-series data, deemed appropriate given the low percentage of missing values and the need to maintain a continuous record for time-series analysis.

To isolate the impacts of intensified dam operations, we divided the study period into two distinct eras based on the timeline of major RRWs in the Upper Mekong Basin:

(i) The "growth-dam" period (2000–2009): This period represents the initial phase of major dam construction, including the commissioning of the Dachaoshan Dam in 2003 and the Jinghong Dam in 2009.

(ii) The "mega-dam" period (2010–2024): This period begins with the operation of the Xiaowan Dam in 2010, which has a large storage capacity of 15 km^3, followed by the even larger Nuozhadu Dam in 2014, with a storage capacity of 23.7 km^3.

2.2. Standardized drought indices

To analyze meteorological and hydrological droughts on a comparable, standardized scale, we employed the widely used SPI and SSI.[28,30,31] These indices allow for the robust comparison of drought severity across different time periods and locations.[32,33] The SPI-3 was calculated to quantify meteorological drought based on 3-month precipitation deficits, while the SSI-3 was calculated using 3-month streamflow data to capture seasonal hydrological drought conditions. Following the standard procedure established by McKee *et al*.,[30] we fitted a Gamma probability distribution to the long-term, 3-month aggregation precipitation record from all stations across the VMD.[30,34,35] The probability density function of a Gamma distribution is given by Equation 1:

$$G(x) = \frac{x^{\alpha-1} e^{-\frac{x}{\beta}}}{\beta^{\alpha}\, \Gamma(\alpha)};(x > 0) \qquad (1)$$

where α and β are the shape and scale parameters, respectively, x is the precipitation amount, and Γ(α) is the Gamma function.

Analogous to the SPI, the SSI was developed to characterize hydrological droughts. It applies the same statistical procedure but uses monthly streamflow data instead of precipitation. The SSI is particularly useful for assessing the impacts of river regulation, as it directly reflects water availability in the river channel. The SSI can be calculated using Equation 2:

$$SSI = W - \frac{C_0 + C_1W + C_2W}{q + d_1W + d_2W^2 + +d_3W^3} \qquad (2)$$

Where $W = \sqrt{-2\ln(p)}$ with $p \leq 0.5$; p is the probability of exceeding a determined x value, and $p=1 - F(x)$. If $p>0.5$, p is replaced by $1-p$, and the sign of the resultant SSI is reversed. $C_0 = 2.515517$; $C_1 = 0.802853$; $C_2 = 0.010328$; $d_1 = 1.432788$; $d_2 = 0.189269$; and $d_3 = 0.001308$ are constants. If the probability density function, F(x), is suitable for fitting the monthly

Table 1. Basic information on precipitation gauges and water level monitoring stations across the Vietnamese Mekong Delta

Station	Latitude (N)	Longitude (E)	Altitude (m)	Flow discharge	Rainfall	Duration (year)
Tan Chau	10°48'02"	105°14'52"	3.2	X	-	2000–2024
Chau Doc	10°42'19"	105°08'01"	3.4	X	X	2000–2024
Hong Ngu	10°47'45"	105°22'36"	1.64	-	X	2000–2024
Long Xuyen	10°21'10"	105°24'25"	1.11	-	X	2000–2023
Cao Lanh	10°33'24"	105°39'48"	1.02	-	X	2000–2021
Can Tho	10°01'40"	105°44'06"	0.8	-	X	2000–2024
Soc Trang	9°36'03"	105°58'22"	0.85	-	X	2000–2024
Vinh Long	10°14'02"	105°57'54"	1.08	-	X	2000–2024

Note: "X" indicates monitoring stations.

streamflow series, the average value of the SSI and the standard deviation must equal 0 and 1, respectively. SPI and SSI values were classified according to standard thresholds to define drought severity, as detailed in Table 2.

2.3. Analysis of hydro–meteorological linkages

To quantitatively assess the hydro–meteorological decoupling, we calculated Pearson's correlation coefficient (r) between the monthly SPI-3 and SSI-3 time series. This analysis was conducted separately for the two defined eras: The "growth-dam" (2000–2009) and "mega-dam" (2010–2024). A statistically significant decrease in the correlation coefficient between the two periods was used as a key indicator of decoupling, demonstrating that the river's flow is no longer driven primarily by natural precipitation patterns but by regulated reservoir operations.

2.4. Case study analysis of the 2019–2020 drought

The severe drought of 2019–2020 was selected as a detailed case study to illustrate the mechanics of the new drought paradigm. For this period, we analyzed the concurrent SPI-3 and SSI-3 values to compare the meteorological driver with the hydrological response. Furthermore, to quantify the severity of the flow deficit during this event, we calculated the percentage reduction in monthly discharge relative to the long-term average of a pre-drought baseline period (2000–2018). This approach provides a clear measure of the hydrological impact and allows for an examination of the amplification effect, whereby a moderate meteorological event can trigger a severe hydrological response in the regulated system.

Table 2. Drought classification based on the SPI or SSI values

SPI/SSI value	Drought classification
≥2.00	Extremely wet
1.50–1.99	Severely wet
1.00–1.49	Moderately wet
0.00–0.99	Mildly wet
0.00–−0.99	Mild drought
−1.00–−1.49	Moderate drought
−1.5–−1.99	Severe drought
≤−2.00	Extreme drought

Abbreviations: SPI: Standardized precipitation index; SSI: Standardized streamflow index.

3. Results and discussion

3.1. Re-engineering the river: Hydro–meteorological decoupling

The long-term SPI-3 and SSI-3 time-series analysis revealed a fundamental and visibly significant shift in the drought dynamics of the VMD between the two operational periods (Figure 2). During the growth-dam period (2000–2009), the SSI-3 at both Tan Chau and Chau Doc stations closely tracked the regional SPI-3. The two indices exhibited synchronous fluctuations, indicating a tightly coupled hydro–meteorological system. This relationship changed dramatically in the mega-dam period (2010–2024). A significant divergence between meteorological conditions and hydrological response emerged, creating two distinct seasonal patterns.

During the dry season (January–May), even when the SPI-3 indicates moderate to severe meteorological drought (e.g., in 2016 and 2020), the SSI-3 often remains near neutral or even positive. This is a direct and intended consequence of augmented dry-season releases from the massive upstream reservoirs. Conversely, during the wet season (August–October), a new and alarming pattern emerges. In years such as 2015, 2016, and particularly 2019, the SSI-3 plummets to values far more negative than the corresponding SPI-3. This hydrological "flattening" of the annual hydrograph is clearly illustrated by the altered discharge patterns in Figure 3.

For instance, at the peak of the 2019 monsoon season (September), the SSI-3 at Chau Doc reached −2.12 (extreme drought), while the SPI-3 was only −1.15 (moderate drought) (Table 3). This indicates a hydrological drought that is disproportionately severe compared to the meteorological event that triggered it. Such amplification of wet-season drought represents a new phenomenon, directly linked to the regulated regimen's suppression of the natural flood pulse.

3.2. Statistical confirmation of hydro–meteorological decoupling

The quantitative correlation analysis supports the visual evidence of a progressive hydro–meteorological decoupling (Table 4). In the growth-dam period, the correlation between regional rainfall (SPI-3) and river flow (SSI-3) was moderately strong and statistically significant, with Pearson's r values of 0.67 and 0.65 at Tan Chau and Chau Doc, respectively, considering a 1-month lag. In the mega-dam period, this correlation weakened significantly, dropping to 0.52 at both

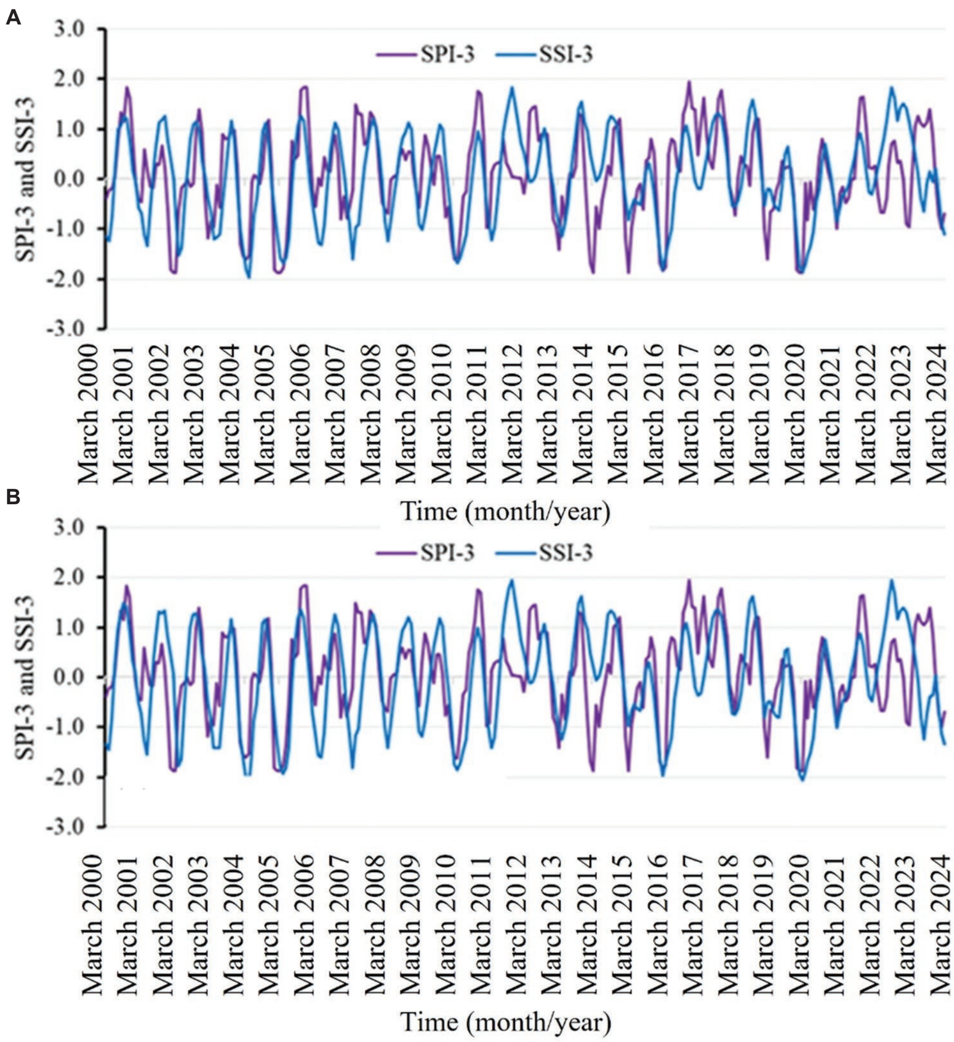

Figure 2. Time series of SPI-3 and SSI-3 at (A) Tan Chau station and (B) Chau Doc station from 2000 to 2024, illustrating the hydro–meteorological decoupling

Abbreviations: SPI-3: Standardized precipitation index (3-month timescale); SSI-3: Standardized streamflow index (3-month timescale).

stations. This demonstrates that upstream regulation has fundamentally altered the river's hydrological response.

3.3. The emergence of a new drought paradigm: The rise of wet-season risk

A detailed examination of major drought events across the 25-year period underscores the emergence of a novel and more dangerous drought paradigm (Table 5). The hydrological droughts of the growth-dam era, such as those in 2002–2003 and 2004–2005, were moderate in severity (approximately −1.5 peak SSI) and were direct and predictable consequences of preceding moderate-to-severe meteorological droughts.

In contrast, the major droughts of the mega-dam era are both more severe and paradoxically timed. The 2019–2020 drought represents the most severe and prolonged hydrological drought in the entire 25-year record. This amplification of drought severity during the wet season, in which a moderate rainfall deficit is transformed into an extreme flow deficit, is a novel phenomenon directly linked to the new regulated regimen.

3.4. Anatomy of a "brittle" system: The 2019–2020 drought case study

The 2019–2020 drought provides a powerful illustration of this new vulnerability (Figure 4). The 2019 monsoon was characterized by a regional rainfall deficit, linked to a moderate El Niño, resulting in persistently negative SPI values. In a natural, unregulated system,

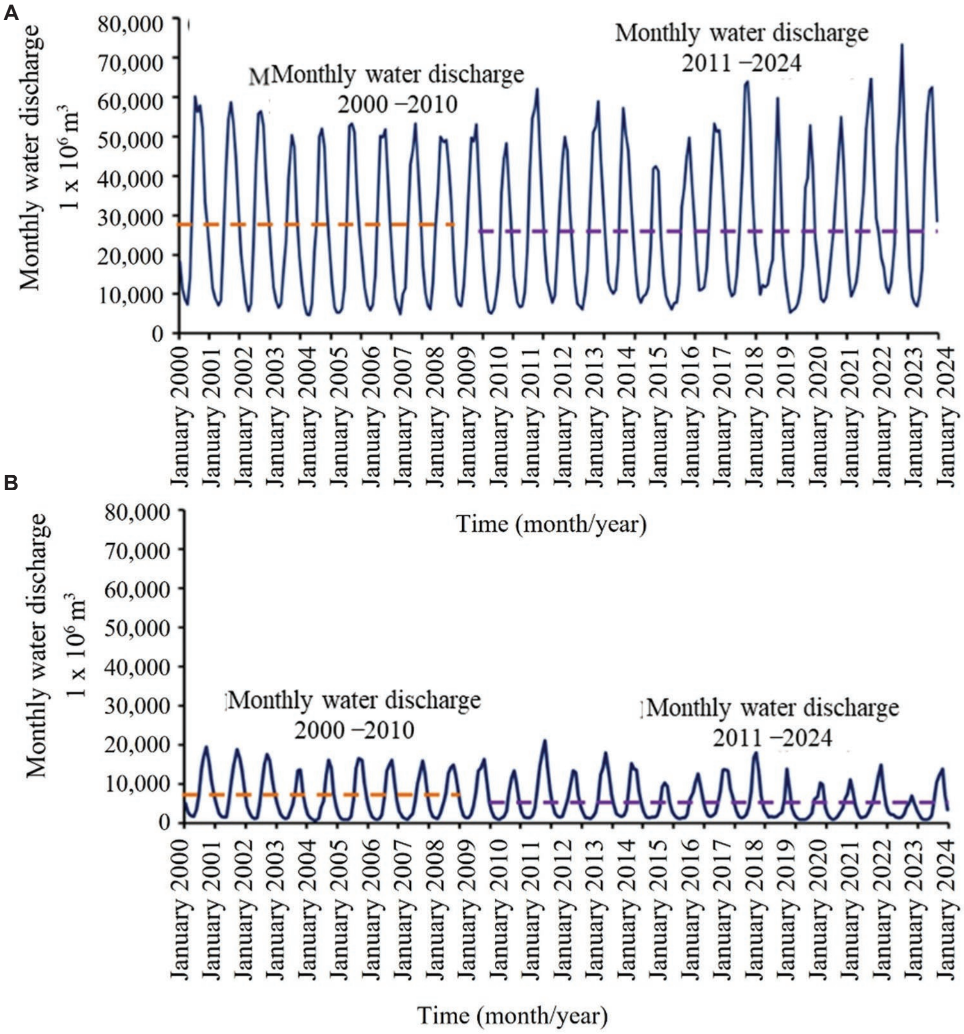

Figure 3. Change in mean monthly water discharge at (A) Tan Chau station and (B) Chau Doc station during the growth-dam period (2000–2009) and the mega-dam period (2010–2024)

the enormous volume of water delivered by the early and mid-monsoon flood pulse would act as a massive natural buffer, thereby mitigating the impact of a late-season rainfall deficit.[13]

However, in the highly regulated system of 2019, this natural buffer was absent. Upstream reservoirs were in their "storage phase" during the wet season, capturing the already reduced inflow to ensure sufficient water for dry-season power generation and releases.[8,13,17] The result was a rapid and severe drop in river levels and discharge, leading to an extreme hydrological drought (SSI: <-2.0) that was amplified by, rather than buffered against, the existing river state. This dynamic leads us to define the regulated Mekong as a "brittle" system. This concept draws from ecological resilience theory, where the removal of natural variability (the flood pulse) reduces a system's ability to absorb external shocks (monsoon deficits), shifting it from a resilient to a brittle state.[36] By systematically removing the wet-season flood pulse—the river's primary source of natural storage and resilience[33]—upstream regulation has made the entire downstream system highly sensitive and vulnerable to meteorological anomalies during the monsoon. This phenomenon is not unique to the Mekong. Similar patterns of altered risk have been observed in other heavily regulated systems globally, such as the Colorado River in the United States[22] and the Nile River in Africa,[37] where flow management has fundamentally changed downstream ecological and hydrological dynamics.

3.5 Compounding risks in a brittle system: The intersection of drought, subsidence, and salinity

The emergence of this brittle state is not an isolated issue; it significantly interacts with and amplifies

Table 3. Meteorological and hydrological conditions during the 2019–2020 drought event

Month	Year	SSI-3			Discharge deviation from mean (%)	
		Region	Tan Chau	Chau Doc	Tan Chau	Chau Doc
January	2019	−0.65	−0.88	−0.95	−33.9	−42.8
February		−0.92	−1.15	−1.21	−45.1	−53.7
March		−1.08	−1.33	−1.40	−40.2	−48.8
April		−1.21	−1.48	−1.55	−44.1	−52.6
May		−1.13	−1.52	−1.60	−49.2	−58.3
June		−1.25	−1.65	−1.74	−58.1	−66.1
July		−1.30	−1.82	−1.91	−69.5	−76.8
August		−1.22	−1.98	−2.07	−65.9	−74.7
September		−1.15[a]	−2.05[a]	−2.12[a]	−48.7	−59.4
October		−0.89	−1.88	−1.96	−41.3	−55.8
November		−0.51	−1.67	−1.74	−49.6	−62.8
December		−0.74	−1.59	−1.66	−58.4	−69.2
January	2020	−1.34	−1.71	−1.79	−69.3	−76.8
February		−1.78	−1.85	−1.93	−81.0	−85.9
March		−1.95	−1.92	−2.01	−80.6	−87.0
April		−1.88	−1.90	−1.98	−78.3	−84.6
May		−1.62	−1.77	−1.84	−74.9	−82.6
June		−1.20	−1.55	−1.61	−66.7	−76.8
July		−0.85	−1.28	−1.33	−54.7	−67.3
August		−0.41	−0.99	−1.02	−30.0	−47.0
September		0.15	−0.76	−0.78	−22.3	−41.1
October		0.33	−0.42	−0.44	−4.4	−28.0

Note: [a]statistically significant.
Abbreviation: SSI-3: Standardized streamflow index (3-month timescale).

Table 4. Pearson's correlation coefficient between SPI-3 and SSI-3 for 2000–2009 versus 2010–2024 periods

Station	Development period	0-month lag (r)	1-month lag (r)	2-month lag (r)	3-month lag (r)	Highest correlation (r) and lag
Tan Chau	Growth-dam	0.53	0.67	0.62	0.49	0.67; 1-month lag
	Mega-dam	0.38	0.52	0.51	0.44	0.52; 1-month lag
Chau Doc	Growth-dam	0.51	0.65	0.61	0.50	0.65; 1-month lag
	Mega-dam	0.36	0.51	0.52	0.48	0.52; 2-month lag

Abbreviations: SPI-3: Standardized precipitation index (3-month timescale); SSI-3: Standardized streamflow index (3-month timescale).

other critical environmental stressors in the VMD. The suppression of the flood pulse and its associated sediment load—a direct consequence of upstream trapping by dams[12]—is a primary driver of delta subsidence. The recurrent, severe wet-season low flows identified in our study further exacerbate this problem by reducing the already diminished sediment distribution across the floodplain, accelerating the sinking of the delta relative to sea level.

Furthermore, historically low river flows during the wet season create conditions favorable for deeper and more prolonged saltwater intrusion, a threat previously confined mainly to the dry season.[38] Specifically, during the wet season of a hydrological drought, the river's

Table 5. Comparison of major hydrological drought events at the Tan Chau and Chau Doc stations

Station	Period	Drought event (start–end)	Duration (months)	Severity (peak SSI)	Magnitude (cumulative SSI deficit)	Associated SPI-3 conditions
Tan Chau	Growth-dam (2000–2009)	November 2002–February 2003	4	−1.58	−5.1	Moderate-to-severe meteorological drought (SPI-3 peak: −1.8) preceded the event
		December 2004–February 2005	3	−1.33	−3.7	Triggered by a short yet sharp meteorological drought (SPI-3 peak: −1.4)
		January 2008–April 2008	4	−1.61	−5.3	Occurred following a period of consistently below-average rainfall
	Mega-dam (2010–2023)	December 2010–March 2011	4	−1.82	−5.9	Occurred despite relatively normal rainfall conditions (SPI-3 values were not strongly negative), likely linked to the initial filling phase of a major upstream dam
		January 2016–May 2016	5	−2.21	−8.9	The most severe event on record, coinciding with an extreme El Niño-driven meteorological drought (SPI-3 peak: −2.1) and further intensified by upstream flow retention
		December 2019–April 2020	5	−1.74	−6.8	A long-duration event during a period of moderate meteorological drought, suggesting upstream conditions were a major contributor
Chau Doc	Growth-dam (2000–2009)	December 2002–March 2003	4	−1.51	−5.0	Followed the same moderate-to-severe meteorological drought recorded at Tan Chau station
		January 2005 – March 2005	3	−1.29	−3.6	Represented a direct and rapid response to the short meteorological drought of late 2004
		February 2008–May 2008	4	−1.55	−5.2	Consistent with the 2008 event at Tan Chau station, driven primarily by below-average regional rainfall
	Mega-dam (2010–2023)	January 2011–April 2011	4	−1.90	−6.2	A severe event, closely mirroring the Tan Chau drought, not directly triggered by extreme local rainfall deficit, but rather associated with upstream dam filling
		January 2016–May 2016	5	−2.25[a]	−9.1[a]	The most severe and impactful event on record, with peak

(Cont'd...)

Table 5. ***(Continued)***

Station	Period	Drought event (start–end)	Duration (months)	Severity (peak SSI)	Magnitude (cumulative SSI deficit)	Associated SPI-3 conditions
						severity at Chau Doc station slightly exceeding that at Tan Chau station, confirming the extreme nature of this El Niño-exacerbated drought
		January 2020–May 2020	5	−1.88	−7.5	A prolonged and severe drought event, confirming the widespread impact observed at Tan Chau station, with a significant contribution from upstream flow conditions

Note: [a]statistically significant.
Abbreviations: SPI-3: Standardized precipitation index (3-month timescale); SSI: Standardized streamflow index.

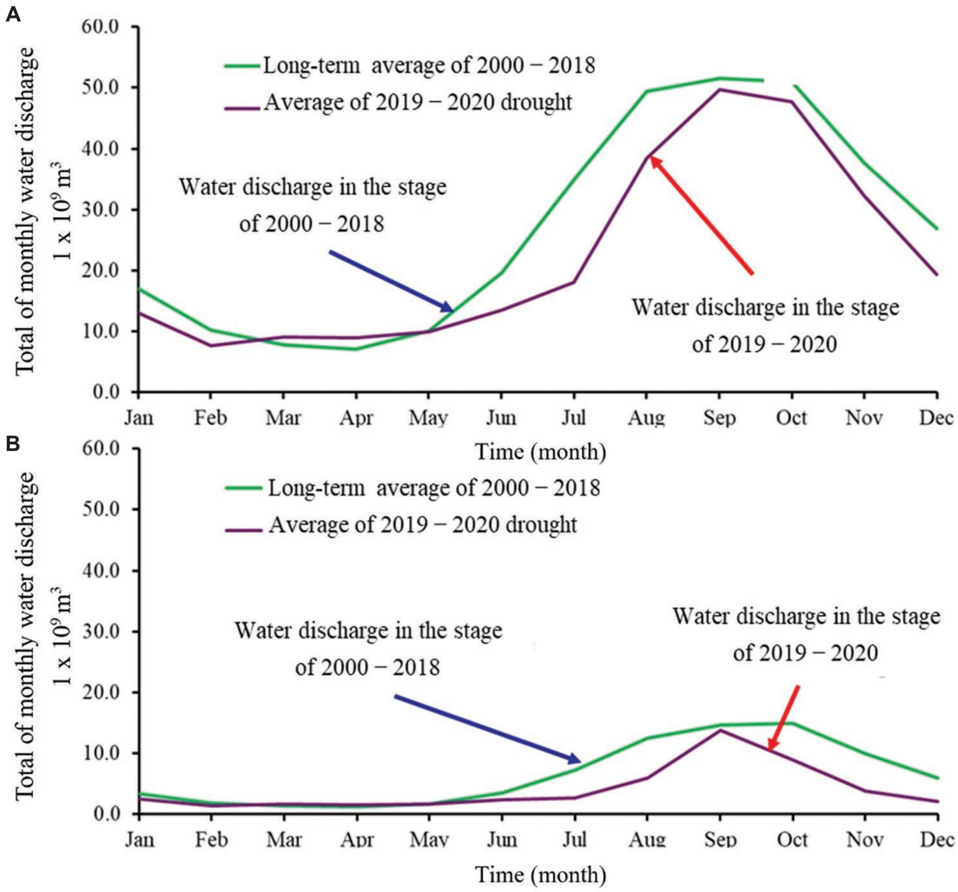

Figure 4. Discharge anomalies during the 2019–2020 drought at (A) Tan Chau station and (B) Chau Doc station, relative to the 2000–2019 long-term average, highlighting the extreme deficits in the wet season of 2019 and the subsequent dry season of 2020

freshwater plume, which normally extends far toward the river mouths or even open coastal waters and acts as a hydraulic barrier, is significantly weakened. This allows saline water from the East Sea to penetrate farther upstream and for longer durations into the delta's intricate network of canals, contaminating

Table 6. Specific flow discharge reductions during the 2019–2020 case study compared to the long-term average (2000–2018 baseline)

Year	Season	Reduction/increase (%)	
		Tan Chau	Chau Doc
2019	Dry season (January–May)	−42.5	−51.4
	Wet season (June–November)	−53.2	−61.9
2020	Dry season (January–May)	−76.0[a]	−81.8[a]
	Wet season (June–November)	−30.8[a]	−45.1[a]

Note: [a]statistically significant.

the surface and groundwater resources critical for the "rice bowl's" triple-cropping systems and aquaculture. The occurrence of a hydrological drought during the monsoon, therefore, presents a dual threat: a direct scarcity of fresh water and a heightened risk of its contamination.

3.6. Uncertainties and alternative explanations

While this study presents strong evidence suggesting upstream regulation as the primary driver of the VMD's emergent brittleness, we acknowledge that other factors, including the overarching influence of climate change on the intensity and timing of monsoon rainfall,[27] could also contribute to the observed changes. Additional factors include potential increases in local water abstraction for intensifying agriculture within the delta and land-use changes that alter local runoff patterns.[23]

However, the abrupt and systemic nature of the hydro–meteorological decoupling, which precisely coincides with the commissioning of the mega-dams (post-2010), strongly supports the evidence that intensive flow regulation is the dominant and overriding factor. The amplification effect, in which a moderate meteorological drought triggers a severe hydrological drought, is a clear signature of reservoir operations (storing water during the wet season), rather than a gradual change in local demand or climate, as quantified by the severe seasonal discharge reductions shown in Table 6.

4. Conclusion

This study reveals a fundamental and paradoxical shift in the nature of drought risk in the VMD, a direct and quantifiable consequence of intensive upstream hydropower development. Our primary finding is that, while flow regulation has successfully reduced the frequency and severity of traditional dry-season hydrological droughts, it has inadvertently created a new, systemic vulnerability by diminishing the river's natural resilience. The managed increase in dry-season flows has come at the cost of suppressing the wet-season flood pulse, a critical component of the basin's natural hydrological cycle.

The most critical consequence of this change is the emergence of a new drought paradigm, characterized by the occurrence of severe and prolonged wet-season hydrological droughts. We define this new state as a "brittle" river system, one that has lost its natural capacity to buffer against climatic shocks. The extreme 2019–2020 drought is not an anomaly but an indicator of this new, precarious state.

These findings carry urgent and significant implications for policy-making and water management. First, drought monitoring and early warning systems must be fundamentally adapted to recognize and forecast the risk of compound events, where wet-season drought intersects with heightened salinity intrusion and long-term subsidence. Second, regional adaptation strategies must evolve. Sole reliance on regulated dry-season flow is no longer a viable strategy for ensuring water security; it must be complemented by investments in local and regional water storage solutions, such as the restoration of natural retention areas and the development of small- and medium-scale reservoirs—designed to capture and manage water during the diminished wet periods.[5] Finally, our findings highlight the critical need for transparent, basin-wide water management agreements, where the downstream risks of an altered drought regimen are fully integrated into the operational strategies of upstream infrastructure, addressing the inherent trade-offs between hydropower, food security, and biodiversity.[39]

Future research should focus on developing integrated models that couple dam operation scenarios with climate projections to forecast the probability and severity of future wet-season droughts.[34] Furthermore, socioeconomic studies are needed to quantify the vulnerability of different agricultural sectors to this new drought paradigm and to assess the efficacy of various farm-level adaptation strategies through stakeholder-based assessments.[40]

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: All authors
Formal analysis: All authors
Investigation: All authors
Methodology: All authors
Writing–original draft: All authors
Writing–review & editing: All authors

Availability of data

Data are available from the corresponding author upon reasonable request.

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