Hydrological Research Letters **19**(4), 223–230 (2025)
Published online in J-STAGE (www.jstage.jst.go.jp/browse/hrl). DOI: 10.3178/hrl.24-00018

Original Research Letter

Unique drought tendency of an understudied region in the Mekong Delta, Vietnam

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Abstract:

Water resource vulnerability due to uneven precipitation and water allocations is a significant issue in many regions of the world, including the Mekong Delta. Although numerous studies have already evaluated drought tendencies in many parts of the Mekong Delta, some areas have been excluded. This study targeted these excluded areas, including one inland, one coastal area, and two islands, which are defined as “understudied regions.” The meteorological drought intensity, frequency, and duration in the study areas in the Mekong Delta were evaluated using different time scales of the Standardized Precipitation Index (SPI) between 1994–2020. Unique contrasts in drought features were found between the study areas, indicating that severe drought events occupied the highest percentages inland from 2011 onward, while the most extreme drought events occurred in the coastal areas. Furthermore, trends in drought intensity, tendency, frequency, and duration were identified within the same delta region, demonstrating that combining SPI with other indicators can detect drought patterns in the Mekong Delta. These findings emphasize the importance of comprehensive evaluation of drought tendencies, including in understudied regions, for a better understanding of the features and future of water resources management.

KEYWORDS drought index; drought trend; water resource variability; inland area; island area

INTRODUCTION

Freshwater is one of the most essential and vulnerable resources for inland areas and islands (Jiménez *et al.*, 2014). Areas with limited or no access to water resources, such as from rivers and reservoirs, face significant challenges. Sporadic precipitation, restricted surface water access, and limited groundwater storage capacity render these regions’ water resources unstable and unreliable (Jiménez *et al.*, 2014; World Bank, 2020). Despite geographic differences, inland areas and islands often share similar water-related problems, particularly during dry seasons (Hophmayer-Tokich and Kadiman, 2006). Unlike regions with abundant water resources, inland areas far from water sources typically suffer from insufficient water allocations (Finlayson and D’Cruz, 2005). Islands, more sensitive to environmental impacts, face significant water sustainability challenges due to limited precipitation (Hophmayer-Tokich and Kadiman, 2006; Huong *et al.*, 2019). These areas are often overlooked due to inconvenient accessibility and low population densities.

In order to evaluate water resources, researchers often investigate the precipitation and drought tendencies of an area. Drought, a key indicator of water scarcity, can be classified into meteorological, hydrological, agricultural, and socio-economic (Heim Jr, 2002). Meteorological drought, caused by an imbalance between precipitation and evaporation, can be analyzed using precipitation data (Chang, 1991; Eltahir, 1992; Food and Agriculture Organization (FAO), 2016). Bayissa *et al.* (2018) highlighted drought as a primary natural hazard linked to El-Niño phenomena. Indices such as the Palmer Drought Severity Index (PDSI), Soil Moisture Deficit Index (SMDI), Standardized Precipitation Evapotranspiration Index (SPEI), and Standardized Precipitation Index (SPI) are used globally to monitor drought events (Palmer, 1965; McKee *et al.*, 1993; Narasimhan and Srinivasan, 2005; Vicente-Serrano *et al.*, 2010).

However, the highly uneven seasonal distribution of precipitation leads to temporal droughts, particularly in the central and eastern delta (Ministry of Natural Resources and Environment (MONRE), 2013). In recent years, the Ministry of Agriculture and Rural Development of Vietnam (MARD) reported two significant drought events in 2015–2016 and 2019–2020, which prompted five local governments out of thirteen provinces to declare an emergency on drought (United Nations Viet Nam (UNVN), 2016; MARD, 2016; 2020). No severe drought events have been reported since 2020. Over the past two decades, the government of Vietnam has attempted to address environmental issues related to Mekong Delta droughts. MONRE and MARD issued the Mekong Delta Plan in 2013, and the National Action Plan to implement Government Resolution No. 120/NQ-CP, signed in November 2017, focuses on sustainable, climate-resilient development (Socialist Republic of Vietnam, 2017). The Prime Minister’s Decision No. 417/QD-TTg, signed in April 2019, endorses this plan by providing knowledge, informing policies, and guiding invest-

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Received 18 July, 2024
Accepted 31 January, 2025
Published online 21 October, 2025

ments (Socialist Republic of Vietnam, 2019). Despite these efforts, some inland areas and islands in the Mekong Delta, attractive tourist destinations, are excluded from development plans. Economic development, including tourism, increases water demand (Hophmayer-Tokich and Kadiman, 2006; Huong *et al.*, 2019). While numerous studies have examined precipitation trends and drought tendencies in the Mekong Delta (Thuong, 2016; Lee and Dang, 2018; Tran *et al.*, 2020; Dang *et al.*, 2020; Quang *et al.*, 2021), the World Bank (2020) has expressly indicated some concerns towards the lack of studies in some areas, including inland areas and islands, which have inadequate water resources management policies to achieve economic development.

Monitoring, managing, and mitigating droughts are essential for water governance in the Mekong Delta. Thus, investigating water resource availability in inland areas and island regions is crucial, as highlighted by the Japan International Cooperation Agency (JICA, 2013) and the World Bank (2020). These regions, often overlooked in previous studies, require attention in terms of precipitation trends and drought tendencies. This study identifies these understudied locations and aims to provide information that can support policy development for improved water resource management. This study defined those overlooked locations as "understudied regions" to help provide information that may support policy development for better water resources management in the understudied regions; it aims to understand current water resources availability and tendency in the areas for future comprehensive evaluation of the resources in the Mekong Delta. The specific objectives are as follows: 1) to evaluate the intensity, frequency, and duration of meteorological drought using different temporal scales and 2) to understand the historical drought features by comparing patterns in the understudied regions.

MATERIALS AND METHODS

Study area

The Mekong Delta in Vietnam is particularly vulnerable to the effects of climate change (Khoi *et al.*, 2020; World Bank, 2022). The Mekong River, an international river flowing through several countries, forms the Mekong Delta, which provides water for an area of 40,000 km^2 and supports nearly 20 million people as of 2019 (General Statistics Office (GSO), 2020).

This study focuses on Long An Province (one station) and Kien Giang Province (three stations) in the Mekong Delta, which represent one inland area (Moc Hoa), one coastal area (Rach Gia), and two islands (Phu Quoc and Tho Chu), as shown in Figure 1. Both provinces do not have direct flow from the Mekong River and have previously declared a state of emergency due to drought. There are four meteorological stations located in the study area. Between 2011 and 2022, the populations of Long An Province and Kien Giang Province increased by 13.93% and 2.03%, respectively (GSO, 2023).

Long An Province, with a population of 1.5 million and an area of 4,494 km^2, shares a border with Cambodia to the north and Ho Chi Minh City to the east. Long An Province's primary income sources are rice production, aquaculture (shrimp), and manufacturing. Kien Giang Province, located in the southern part of the Mekong Delta, is known for fishing, rice farming, and tourism. In 2010, the mainland produced 3.5 million tons of rice, making it the second-largest producer in the Mekong Delta (JICA, 2013). However, the local government is currently seeking ways to reduce groundwater use for irrigation to prevent land subsidence by constructing a pipeline system (Project office for Sustainable Development Vietnam (PSDV),

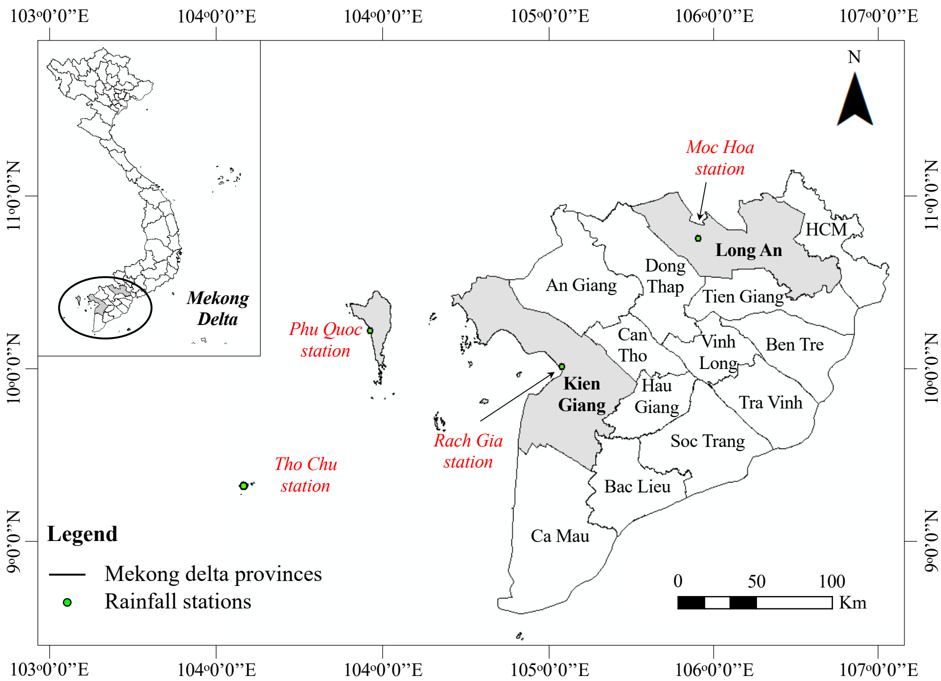

Figure 1. Location of the study area

2021).

Phu Quoc Island (574 km^2) and Tho Chu Island (13.95 km^2) belong to Kien Giang Province. Phu Quoc Island is defined as the largest island in Vietnam. During the dry season, the water supply is unstable. Since tourism is Phu Quoc Island's primary industry, hotels often use groundwater during water shortages (JICA, 2013). Tho Chu Island is located approximately 100 km from the center of Phu Quoc Island and 192 km southeast of Rach Gia, the provincial capital of Kien Giang Province. Established in 1992 by the local government as a strategic and economic zone, Tho Chu Island is the only inhabited island among the seven other islets of the Tho Chu archipelago. Detailed information on precipitation trends is provided in Text S1 and Figure S1.

Methodology

Meteorological droughts in the study area were analyzed using daily precipitation data from the Moc Hoa, Rach Gia, Phu Quoc, and Tho Chu stations over 27 years from 1994 to 2020. This timeframe closely aligns with the preferred 30-year period (McKee *et al.*, 1993). We compared trends and tendencies between the first 17 years (1994–2010) and the most recent 10 years (2011–2020). The data were collected by the Southern Regional Hydrometeorological Center of Vietnam (SRHCV). For Tho Chu station, incomplete daily precipitation data in 1994 and 1999 forced us to eliminate those years from the analysis. Because of limited data availability, SPI was employed.

Standardized Precipitation Index (SPI)

The Gamma Distribution (GAM) described in Text S2 was used to fit the data for SPI. SPI has been applied widely in drought studies in the Mekong Delta (Guo *et al.*, 2017). The temporal trends, intensity duration, and frequency of droughts are assessed with different temporal scales of 3-month (SPI-3) for basic drought monitoring, 6-month (SPI-6) for agricultural impact, and 12-month (SPI-12) for hydrological impact (McKee *et al.*, 1993; Guttman, 1998; Hayes *et al.*, 2011). The SPI is calculated by the Equation (1):

$$SPI = \frac{\left(P - \overline{P}\right)}{\sigma_p} \tag{1}$$

where P: precipitation (mm); $\overline{P}$: mean precipitation (mm); σ_p: standard deviation.

In this study, those three temporal scales were utilized to evaluate drought features. The drought categories were classified according to McKee *et al.* (1993) as shown in Table I. SPI-3, SPI-6, and SPI-12 were utilized to analyze precipitation trends and examine the drought characteristics in Moc Hoa (inland), Rach Gia (coastal), Phu Quoc, and Tho Chu islands.

Table I. SPI values and SPI category index (McKee *et al.*, 1993)

SPI Values	SPI Category
0 to –0.99	Mild drought
–1.00 to –1.49	Moderate drought
–1.50 to –1.99	Severe drought
≤–2.00	Extreme drought

RESULTS

Drought intensity

The temporal variation and intensity of droughts were analyzed, as illustrated in Figure 2. Results from the SPI-3 and SPI-6 calculations are discussed in Text S3. To evaluate hydrological impacts, SPI-12 was employed. This study identified drought events occurring in 2002, 2010–2011, and 2015–2016, which coincided with El Niño events, as reported by Lee and Dang (2018). At Moc Hoa station, the lowest SPI peak value of –2.2 was recorded in 2015, while Rach Gia experienced the highest drought intensity at –2.4 in 2010. Phu Quoc showed a peak SPI value of –1.6 in 2002, and Tho Chu also recorded –2.4 that same year. Severe and extreme droughts were observed at Moc Hoa in 2002 and during 2015–2016, with a notable rise in extreme drought frequency after 2015. Rach Gia faced extreme droughts in 2002, 2010, and 2015–2016, whereas Phu Quoc exhibited the lowest drought intensity across all stations. The linear regression line illustrated in Figure 2 shows a dramatic increase in drought intensity for Moc Hoa and Tho Chu and a noteworthy decline for Rach Gia, while Phu Quoc remained relatively stable.

Drought frequency

Severe and extreme drought events were evaluated using the SPI-12 index, as detailed in Table II. Among the four stations, Moc Hoa reported the highest total of 27 drought events, while Phu Quoc experienced only two months of severe drought throughout the study period. Beginning in 2011, the frequency of severe and extreme droughts in Moc Hoa rose significantly, with 8 severe droughts recorded from 1994 to 2010, increasing to 15 between 2011 and 2020. Additionally, extreme droughts surged threefold during the latter period, compared to just 1 extreme drought earlier. Rach Gia had 9 severe droughts from 1994 to 2010, followed by 8 after 2011, while extreme drought events increased from 4 to 5 post-2011. Phu Quoc did not encounter any extreme droughts throughout the study, having registered 2 severe drought events from 1994 to 2010, with none in subsequent years. Tho Chu saw an increase in severe droughts from 4 to 7 after 2011 but a decrease in extreme drought events from 5 to 2 during the same timeframe. In the earlier period, Rach Gia had the highest number of severe droughts, while Moc Hoa led after 2011. Tho Chu recorded the most extreme droughts before 2011, but Rach Gia had the highest count from 2011 to 2020.

The percentages of extreme, severe, and moderate droughts were assessed using SPI-12. The total number of drought months, spanning from moderate to extreme (index ≤–1), was calculated from the total dry months (index <0) over 27 years, and percentages for each drought classification were computed (Table III). Rach Gia exhibited the highest frequency of extreme droughts at 2.9%, while Moc Hoa had the highest severe droughts at 7.4%. Phu Quoc had the lowest percentages across all classifications and did not experience any extreme droughts. Although Tho Chu lacks

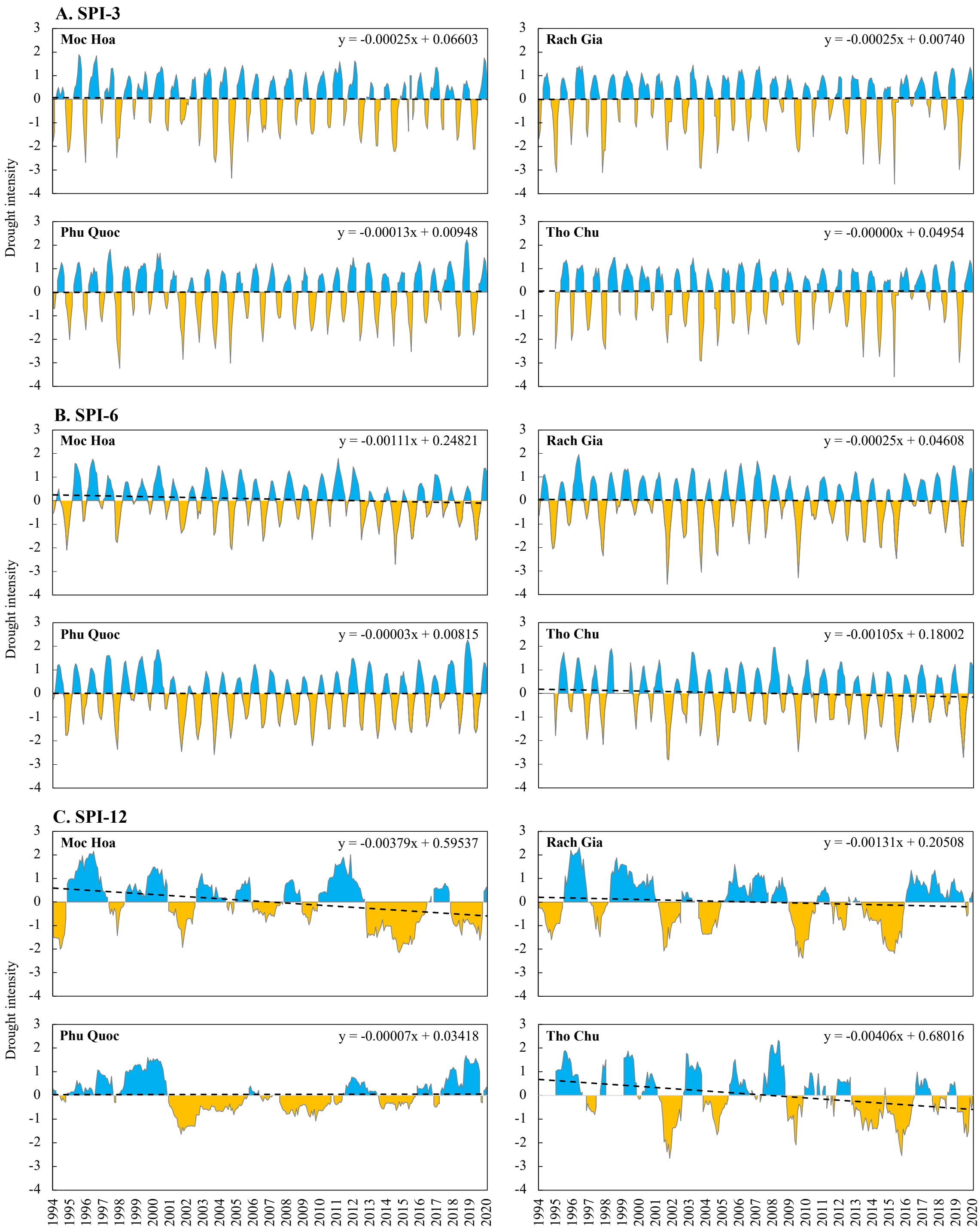

Figure 2. Drought intensity. (a): SPI-3, (b): SPI-6, and (c): SPI-12. The dotted line in each graph illustrates the regression line of each station

a few years of data (1994 and 1999), it had 2.4% of extreme drought and 10.4% of moderate drought.

Drought duration

Drought duration, defined as the period when the SPI index falls below zero, was analyzed and is depicted in Figure 3. The red line in the figure indicates the threshold for severe and extreme droughts (with SPI values below −1.5). The gray shading illustrates the lengths of these severe and extreme drought periods, defined as consecutive spans of negative SPI values that reach a minimum of –1.5 or less. When focusing on the SPI values below –1.5, Moc Hoa experienced a 7-month drought from December 1994 to July 1995, with its longest drought spanning 15 months from April 2015 to August 2016. During this latter period, extreme droughts persisted for three consecutive months,

Table II. Drought events between 1994–2020 using SPI-12. The data of 1994 and 1999 at Tho Chu station was excluded from calculation because of data availability

Station	1994–2010		2011–2020		1994–2020
	Severe	Extreme	Severe	Extreme	Total
Moc Hoa	8	1	15	3	27
Rach Gia	9	4	8	5	26
Phu Quoc	2	0	0	0	2
Tho Chu	4	5	7	2	18

Table III. Total months and percentages of extreme, severe, and moderate drought classification for each station. The data of 1994 and 1999 at Tho Chu station was excluded in calculation because of data availability

Station	Extreme (%)	Severe (%)	Moderate (%)	Total month (Months)
Moc Hoa	1.3	7.4	10.3	312
Rach Gia	2.9	5.4	9.3	312
Phu Quoc	0	0.6	3.8	312
Tho Chu	2.4	3.8	10.4	288

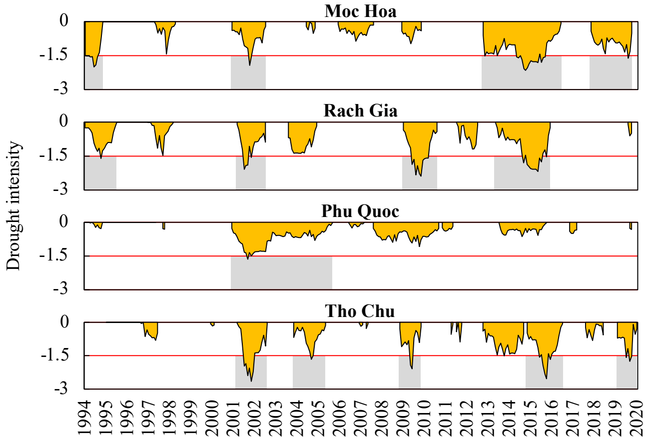

Figure 3. SPI-12 Drought duration. The red line in the figure indicates the threshold for severe and extreme droughts (with SPI values below –1.5). The gray shading illustrates the lengths of these severe and extreme drought periods, defined as consecutive spans of negative SPI values that reach a minimum of –1.5 or less

from August to October 2015. Rach Gia faced droughts lasting 10 months from May 2010 to February 2011 and 11 months from August 2015 to June 2016. The most significant extreme droughts were recorded from December 2015 to April 2016, lasting five consecutive months. At Tho Chu, 6 months of severe and extreme droughts were observed from June to November in 2002, with 4 of those months classified as extreme. Another event of severe and extreme drought occurred in 2016, lasting 7 months from May to November. Moc Hoa exhibited the most prolonged durations of severe and extreme droughts, while Phu Quoc had the fewest drought occurrences among the four stations. Additionally, long-term trends of severe and extreme droughts were noted at Moc Hoa, Rach Gia, and Tho Chu, whereas Phu Quoc showed no signs of long-term severe or extreme drought events during the study period.

DISCUSSION

SPI-3, 6, and 12 were used to analyze precipitation trends and investigate the drought features of Moc Hoa (inland), Rach Gia (coastal), and Phu Quoc and Tho Chu islands. SPI-12 was utilized to analyze drought intensity, duration, and frequency across the understudied regions, highlighting the unique phenomena present. We observed significant variations even within the same Mekong Delta region. In terms of Moc Hoa and Rach Gia, both regions showed similar SPI patterns from 1994 to 2003 and faced extreme droughts in 2002–2003 and 2015–2016. However, only Moc Hoa experienced severe to extreme droughts in 2019–2020, while Rach Gia did not encounter any drought events. Among all stations, Moc Hoa had the longest drought period, lasting 15 months during 2015–2016, which correlated with the drought events reported by the local government of Long An Province, mentioning overextraction of groundwater in the drought years (Long An People's Committee (LAPC), 2011). In the Vietnam Mekong Delta, rice cultivation primarily focuses on the upper zone, including Long An and Kien Giang provinces (Vu *et al.*, 2022). When examining the correlation between the drought events identified in this study and rice production rates in the Mekong Delta region, it was observed that production declined after the droughts of 2002, 2010–2011, and 2015–2016 (Vu *et al.*, 2022; GSO, 2023). The 2015–2016 drought event badly affected both provinces; 1.8% of Long An and 9.2% of Kien Giang's total rice area were damaged or lost (UNVN, 2016).

Rach Gia, Phu Quoc, and Tho Chu islands are all part of Kien Giang Province and form a triangular geographic layout (Figure 1). During the specified period, Rach Gia and Tho Chu faced severe and extreme drought events in 2002–

2003, 2010–2011, and 2015–2016, while Phu Quoc did not experience any extreme droughts during that time. After 2016, Rach Gia showed no signs of drought, while Tho Chu faced severe drought in 2020, mirroring the situation in Moc Hoa as previously mentioned. It was interesting to discover a similar tendency in both stations in recent years. Although Moc Hoa and Tho Chu experienced severe and extreme droughts, the first drought event occurred in 1994–1995 for Moc Hoa, while Tho Chu did not show any sign of severe and extreme droughts until 2002. Tho Chu suffered from many drought events with insufficient volume of available surface water, leading most households to drill their own wells to extract groundwater (Huong *et al.*, 2019). In addition, as fish and squid processing as their primary industry and requires a high demand for freshwater, the local people tend to suffer from a lack of freshwater on the island (Huong *et al.*, 2019). Tho Chu thus had more frequent and intense drought tendencies in a shorter period.

Although Tho Chu and Moc Hoa exhibited similar drought patterns during the extreme drought periods of 2002–2003, 2015–2016, and 2019–2020, Phu Quoc experienced only severe drought conditions in August and October 2012. Phu Quoc exhibits diverse topography includes hills, mountains, caves, primary forests, and abundant freshwater resources, with a stream density of 0.42 km/km and shallow groundwater primarily concentrated in the southern region, sustained by the tropical monsoon climate (Quyet *et al.*, 2022). However, the lower intensity of droughts in Phu Quoc does not imply that the island is free from water resource issues. In 2013, JICA conducted an environmental assessment regarding the expansion of the tourism industry on Phu Quoc Island. The assessment revealed problems related to both the quality and quantity of water resources, primarily due to insufficient capacity, particularly during the dry season, and overextraction of groundwater. The island faces significant water shortages for its inhabitants and issues associated with saltwater intrusion (Vu and Ngo, 2019).

To the best of our knowledge, the distinctive precipitation patterns, drought tendencies, and phenomena observed in the inland and coastal areas, and islands of the Mekong Delta in Vietnam have yet to be analyzed simultaneously. While a few earlier studies have highlighted various water resource issues in these islands, they have primarily approached the topic from socioeconomic angles, neglecting precipitation trends and drought tendencies due to insufficient focus on these understudied regions.

Previous research on drought tendencies in the Mekong Delta has mainly concentrated on areas with significant development potential, such as the provinces along the Mekong River and coastal zones. Our findings indicate that assessing and comparing drought tendencies in understudied regions is essential, as different phenomena have emerged within the same delta region. This underscores the necessity for separate evaluations of each province, including islands, regardless of their size and proximity. Additional data collection and assessments are crucial for comprehending these discrepancies in the understudied regions and understanding the diverse phenomena affecting the Mekong Delta.

CONCLUSION

This study uncovered the commonalities and variations in drought features across the understudied regions by employing the SPI at various temporal scales and indices. The key findings are summarized as follows:

➢ Longer periods of severe drought occurred in an inland (Moc Hoa) than in the coastal area (Rach Gia).
➢ Inland (Moc Hoa) had double the number of severe drought events in recent 10 years (2011–2020) compared to the years from 1994 to 2010.
➢ The coastal area (Rach Gia) showed no signs of drought after 2016, while an island (Tho Chu) experienced severe drought conditions in 2020.
➢ An island (Phu Quoc) experienced the least drought conditions among the four stations; however, it has faced water shortages in recent years, particularly during the dry seasons.

While SPI is helpful in assessing drought conditions, it does not fully capture the actual impacts of drought. Thus, we have combined SPI with other indicators and assessments to understand drought conditions better. This study emphasizes the need to include understudied regions in evaluating drought characteristics in the Mekong Delta, especially considering the complex trends and phenomena observed in the inland and coastal regions and islands. Due to data availability, some missing data and a duration of less than 30 years limit direct comparisons of absolute numbers. Ongoing research and evaluation will be crucial for mitigating drought impacts and ensuring food and water security in the region moving forward.

ACKNOWLEDGMENTS

This work was partially supported by JSPS KAKENHI Grant Number 22KK0093.

SUPPLEMENTS

Text S1. Precipitation tendency
Text S2. Gamma Distribution (GAM)
Text S3. Drought intensity using SPI-3 and SPI-6
Figure S1. Annual variation of precipitation for the four stations from 1994–2020. The data of 1994 and 1999 at Tho Chu station were not shown because of large amounts of missing information

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