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Long-term assessment of flood and drought phenomena in the Long Xuyen Quadrangle, Vietnamese Mekong Delta

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ABSTRACT: Floods and droughts are considered extreme climatic phenomena that significantly negatively impact human life and socio-economic activities. Using trend determination methods combined with statistical data, this study evaluates the evolution of floods and droughts over the past 45 years (1979-2023) in the Long Xuyen Quadrangle (LXQ) of the Vietnamese Mekong Delta (VMD). The results indicate that large and medium floods have become less frequent, while small floods have increased significantly. Flood levels have fluctuated over time and tend to decrease. However, contrary to the decreasing trend of peak flood levels in the upstream (Chau Doc) and inland areas (Tri Ton), the downstream area (Long Xuyen) shows an increasing trend in peak flood levels. Additionally, by calculating the Standardized Precipitation Index (SPI) and Rainfall Anomaly Index (RAI), the study has assessed the characteristics, frequency, and trends of meteorological droughts in the LXQ. The results indicate that from 1979 to 2023, the study area experienced fairly severe droughts; however, the severity has decreased gradually in recent years. The frequency and expression of droughts vary over time and space, with some periods experiencing prolonged droughts. The findings of this study can provide a critical basis and understanding to help managers propose policies and solutions to mitigate and respond to the increasing natural disasters in the LXQ region in recent times.
Keywords: meteorological drought; SPI; RAI; disaster risk; water management.

Avaliação de longo prazo dos fenômenos de inundação e seca no Quadrilátero Long Xuyen, Delta do Mekong vietnamita

RESUMO: Inundações e secas são consideradas fenômenos climáticos extremos que impactam significativamente a vida humana e as atividades socioeconômicas. Usando métodos de determinação de tendências combinados com dados estatísticos, este estudo avaliou a evolução de inundações e secas nos últimos 45 anos (1979-2023) no Quadrilátero Long Xuyen (LXQ), do Delta do Mekong Vietnamita (VMD). Os resultados mostram que inundações grandes e médias se tornaram menos frequentes, enquanto pequenas inundações aumentaram significativamente. Os níveis de inundação flutuaram ao longo do tempo e tendem a diminuir. No entanto, ao contrário da tendência decrescente dos níveis máximos de inundação nas áreas a montante (Chau Doc) e no interior (Tri Ton), a área a jusante (Long Xuyen) mostra uma tendência crescente nos níveis máximos de inundação. Além disso, ao calcular o Índice de Precipitação Padronizado (SPI) e o Índice de Anomalia de Chuva (RAI), o estudo avaliou as características, frequência e tendências de secas meteorológicas no LXQ. Os resultados indicam que de 1979 a 2023, a área de estudo sofreu secas bastante severas, mas a severidade diminuiu lentamente nos últimos anos. A frequência e a expressão das secas variam ao longo do tempo e do espaço, com alguns períodos sofrendo secas prolongadas. As descobertas deste estudo podem fornecer uma base crítica e compreensão para ajudar os gestores a propor políticas e soluções para mitigar e responder aos crescentes desastres naturais na região LXQ nos últimos tempos.
Palavras-chave: seca meteorológica; SPI; RAI; risco de desastre.

1. INTRODUCTION

Climate change is one of the global environmental issues that significantly impacts nature, economy, and society, which humanity is currently facing (PATE et al., 2011; SAOUTER; GIBON, 2024). Climate change can lead to extreme weather phenomena such as floods, droughts, storms, and other natural disasters (PANTALEONI et al., 2007). In this context, the spatial and temporal changes in floods and droughts have recently attracted the attention of scientists (Scheuer et al., 2011; Nedelea et al., 2013) because these factors are sensitive to climate change (KHAN et al., 2011). Floods are one of the most severe and destructive natural disasters (DASH et al., 2007; SMITH; ALEXANDER, 2018), often causing significant damage to agricultural production and infrastructure and severe economic and social disruptions (DOUGLAS, 2009; BLÖSCHL et al., 2019). Floods influence land-use/cover changes (AHMAD et al., 2017,2020; SMITH; ALEXANDER, 2018).

Droughts are also considered one of the most extreme weather events that are directly and strongly impacted by climate change (COOK et al., 2014). Recent studies indicate that droughts have become more severe due to climate change (MUNDETIA; SHARMA, 2015) and are one of the primary causes of reduced agricultural land area (STRZEPEK et al., 2010). The frequency and intensity of floods and droughts have increased over the past few decades due to climate change and global warming (TRENBERTH, 2005; LEHNER et al., 2006; DAI, 2011). Therefore, studying and understanding the patterns and dynamics of floods, droughts, and their spatial and temporal variations is essential.

The Vietnamese Mekong Delta (VMD) is situated in the monsoon climate zone of Southeast Asia, characterized by a distinctly seasonal climate influenced by the northeast and southwest monsoons. As a result, the dry season lasts from December to April, while the rainy season lasts from May to November. This seasonal climate division results in a corresponding seasonal division of floods and droughts. Annually, during the rainy season (from May to November), the delta receives a large amount of floodwater from the Mekong River system, inundating about 12 to 19 million hectares of the region's natural area (MARD, 2012).

Floods often bring numerous benefits to the fields, such as enriching the soil with alluvium, creating conditions for aquaculture and fishing for farmers in flood-prone areas. Rice yields are higher after each flood season due to the nutrients brought by the water (HUU, 2011; NGUYEN & JAMES, 2013). However, excessive floods have negative impacts, causing severe damage to crops, property, infrastructure, and even the lives of people in flood-affected areas (FAO, 1999).

For instance, the 2000 flood in the VMD affected more than 300,000 households, damaged 2,900 houses, and impacted 13 million people, resulting in 280 deaths; the economic loss was estimated at over $ 400 million (TUAN et al., 2007). Conversely, during the dry season (from December to April of the following year), the delta frequently faces drought and saltwater intrusion, significantly affecting the lives and production of the people. In recent years, climate change has made the weather more extreme, with prolonged dry seasons, reduced rainfall, increased temperatures, and reduced water flow from the Mekong River due to the construction of upstream hydropower dams, further exacerbating the drought situation in the region (HUNG, 2017; KEOVILIGNAVONG et al., 2023).

The Long Xuyen Quadrangle (LXQ) is one of the two low-lying areas in the VMD and faces numerous challenges due to climate change (HANINGTON et al., 2017; LEE; DANG, 2018b; HUNG; DINH, 2020). Research by Diep and colleagues shows that this area experienced severe flooding from August to December, with 47.6% of the total natural area submerged in October and 28.2% submerged in August 2015 (DIEP et al., 2019). Climate change has made the intensity and frequency of floods increasingly unpredictable, affecting the physical and mental well-being of residents (DIEP et al., 2019; DINH et al., 2012).

Drought is also a concern in the region due to factors such as changes in temperature and precipitation (VAN et al., 2021). Meteorological droughts of varying frequencies occurred in the LXQ from 1984 to 2015, with moderate droughts occurring 31.5 times/32 years (98.4%), severe droughts 14.16 times/32 years (44.25%), and extreme droughts 7.5 times/32 years (23.43%) (LEE; DANG, 2018a). The combination of floods and droughts poses significant challenges to agricultural production in the LXQ (DINH et al., 2023). This necessitates comprehensive studies on the long-term dynamics of floods and droughts to assist local managers in making decisions to respond to and mitigate their impacts.

Therefore, to better understand the characteristics and dynamics of floods in the LXQ, this study employs trend determination methods and statistical data analysis to monitor changes in flood levels at hydrological stations in the region over the past 45 years (1979-2023). Global studies have categorized drought into four types: meteorological, hydrological, agricultural, and socioeconomic (WILHITE; GLANTZ, 1985; TSAKIRIS et al., 2007; SAHA et al., 2023).

This study applies the meteorological drought index to the LXQ region. Two indices used to study drought include the Standardized Precipitation Index (SPI) and the Rainfall Anomaly Index (RAI). These indices enable the assessment of the characteristics, frequency, and trends of meteorological drought in the LXQ over a 45-year period (1979-2023).

2. DATA AND METHODS

2.1. Study Area

The LXQ is situated in the southwestern part of the VMD, bordered by the Mekong River (Hau River), the Cai San Canal, the West Sea (Gulf of Thailand), and the Vietnam - Cambodia border. This region has a total natural area of 4,996.28 km², including parts of two provinces: An Giang (occupying 49.11% of the area) and Kien Giang (47.76%), and a small part of Can Tho city (3.13%) (DINH et al., 2012; HANINGTON et al., 2017).

The LXQ is a low-lying region and is considered one of the two “natural water reservoirs” of the VMD. Currently, the region plays a vital role in the agricultural development strategy of the Mekong Delta, regularly contributing approximately 20% of the region's rice production and being one of the largest aquaculture areas in the Delta (NGOC; HONTI, 2018; DINH et al., 2023). However, the LXQ region has experienced significant land-use changes in recent years, primarily due to agricultural development and the increasing demand for cultivation areas (NGUYEN et al., 2022; NGUYEN; NGUYEN, 2022).

This has led to the construction of numerous irrigation systems, dykes, and artificial surfaces aimed at water control and agricultural production (CHANH; LINH, 2021). However, these constructions have significantly altered the region's natural hydrological system, causing fluctuations in water regimes. Moreover, upstream factors from the Mekong River, such as dams and hydropower reservoirs, have also contributed to increasing irregularities in the water regime in the LXQ (KUENZER et al., 2013; POKHREL et al., 2018; SOUKHAPHON et al., 2021). These changes have made agricultural production more challenging and directly impacted the livelihoods of local people amidst the increasingly severe impacts of climate change (TRI et al., 2012; DINH et al., 2023).

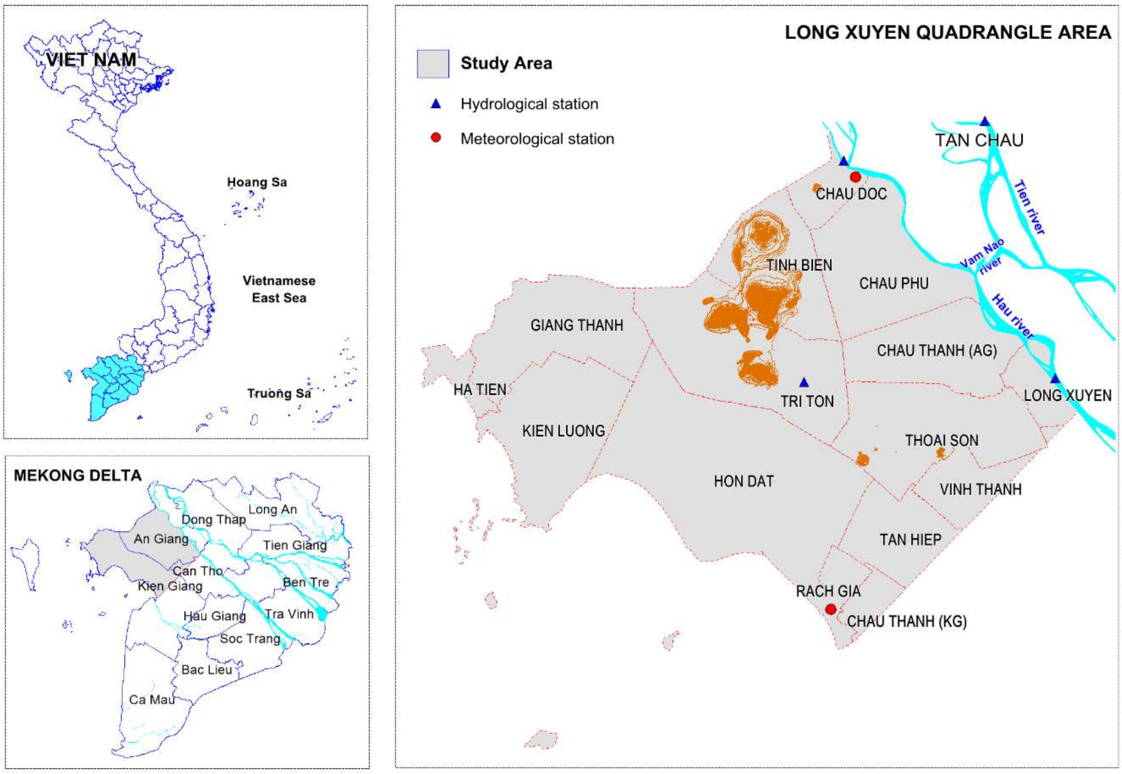

Figure 1. The geographic location of the Long Xuyen Quadrangle and the positions of meteorological and hydrological stations in the study area.
Figura 1. Localização geográfica do Quadrilátero Long Xuyen e posições das estações meteorológicas e hidrológicas na área de estudo.

2.2. Data

The Mekong River, one of the largest rivers in Asia, flows through several countries before entering Vietnam and splitting into two main branches: the Tien River and the Hau River (ADAMSON et al., 2009; ZALINGE et al., 2004). Both branches provide water, alluvium, and other resources to the VMD. Although the Tien River does not directly border the LXQ region, it has a significant impact on its flood regime and water resources. Water from the Tien River flows through the Vam Nao River into the Hau River and then spreads to the LXQ region via a dense canal system (Figure 1). Therefore, flood levels measured at the Tan Chau station reflect the flood regime in the LXQ region (NGUYEN et al., 2007). To assess flood levels (large, medium, and small floods), this study analyzed flood level data at the Tan Chau hydrological station (Tien River, upstream station) over a period of more than four decades (1979-2023).

Based on flood level data measured at the Tan Chau hydrological station, three flood levels can be distinguished: (1) Large floods when water levels > 450 cm, (2) Medium floods when water levels are 400 - 450 cm, and (3) Small floods when water levels < 400 cm (TUAN, 2020; TUAN et al., 2007).

To assess flood variability and trends in the LXQ, this study used statistical flood level data from three hydrological stations: Chau Doc (Hau River - upstream station in the LXQ), Tri Ton (Tri Ton canal - inland station in the LXQ), and Long Xuyen (Hau River - downstream station in the LXQ) (Table 1).

To evaluate drought levels in the LXQ, the study utilized the Standardized Precipitation Index (SPI) and the Rainfall Anomaly Index (RAI), based on rainfall data from two meteorological stations, Chau Doc and Rach Gia, spanning the period from 1979 to 2023 (Table 1).

Table 1. The location of meteorological and hydrological stations in the Long Xuyen Quadrangle.
Tabela 1. Localização das estações meteorológicas e hidrológicas no Quadrilátero Long Xuyen.

Station Type	Station Name	Latitude (North)	Longitude (East)	Location
Meteorological	Chau Doc	11° 51' 33.5507"	105° 14' 8.7152"	Chau Phu B, Chau Doc City
	Rach Gia	10° 41' 30.829"	105° 8' 24.455"	Vinh Thanh, Rach Gia City
Hydrological	Chau Doc	11° 51' 50.6861"	105° 14' 14.779"	Hau River (Vinh My, Chau Doc City)
	Tri Ton	11° 32' 55.7516"	105° 5' 33.266"	Tri Ton Canal (Ta Danh, Tri Ton District)
	Long Xuyen	11° 28' 55.799"	105° 47' 48.987"	Hau River (Binh Khanh, Long Xuyen City)

2.3. Methods

2.3.1. Assessing the variability of flood factors

Through the calculation of mean values, standard deviation, and relative variability (coefficient of variation) of the hydrological data series (x_i) over the study period (n), the study identified the variability of flood factors in the LXQ. If the standard deviation and relative variability are large, the flood factors fluctuate significantly around the mean value. This suggests the irregularity of the flood regime in the LXQ. The values were calculated as follows (LOI; HUNG, 2016):

Mean value: $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$ (01)

Standard deviation: : $SD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$ (02)

Coefficient of variation: $CV = \frac{SD}{\bar{x}} * 100$ (03)

2.3.2. Identifying flood level trends

To identify flood level trends over time, the study used a linear regression equation (LOI; HUNG, 2016):

$$y = at + b \quad (04)$$

where: y is the water level (dependent variable); t is the time (independent variable); a and b are coefficients determined by the formula:

$$a = \frac{\sum_{t=1}^{n}(y-\bar{y})(t-\bar{t})}{\sum_{t=1}^{n}(t-\bar{t})^2}; \qquad b = \bar{y} - a\bar{t} \quad (05)$$

The equation's coefficient a is the slope of the trend line, indicating the rate of change of the flood factors over a unit of time t.

2.3.3. Assessing drought based on the Standardized Precipitation Index (SPI)

McKee, Doesken, and Kleist (1993) developed the Standardized Precipitation Index (SPI) to quantify rainfall deficits over specific periods compared to previous periods. SPI is determined based on the distribution of precipitation and is calculated for different time scales (1, 3, 6, 9, 12, 24, and 48 months) (ROOY, 1965).

This study used SPI to represent the rainfall deficit and drought conditions in the LXQ region based on rainfall data from two stations (Chau Doc and Rach Gia) with three-time scales: 3 months (short-term), 6 months (medium-term), and 12 months (long-term) to meet the requirements for drought warning over different periods.

SPI is calculated using the following formula (MCKEE et al., 1993):

$$SPI = \frac{Ri - \bar{R}}{SD} \quad (06)$$

where: Ri is the precipitation during the period I; R is the average precipitation during the period I over many years; SD is the standard deviation of precipitation during period iii over many years.

Table 2. Classification of drought according to the value of the Standardized Precipitation Index (MCKEE et al., 1993).
Tabela 2. Classificação da seca segundo o valor do Índice Padronizado de Precipitação (MCKEE et al., 1993)

SPI Values	Category
> 0	Non-drought
0 to -0.99	Near normal/Mild drought
-1.49 to -1.0	Moderate drought
-1.99 to -1.5	Severe drought
-2.0 or less	Extreme drought

Negative SPI values indicate a rainfall deficit at the time of calculation compared to the average level, indicating that the period is at risk of drought. Positive SPI values indicate excess moisture, meaning rainfall at the calculation time is greater than the multi-year average.

2.3.4. Assessing drought based on the Rainfall Anomaly Index (RAI)

The Rainfall Anomaly Index (RAI) was introduced by Van Rooy (1965) as a simple and effective method for assessing rainfall anomalies, enabling researchers and resource managers to analyze and predict rainfall, floods, and droughts.

The Rainfall Anomaly Index (RAI) is calculated based on the deviation of actual rainfall from the long-term average precipitation using the following formula (ROOY, 1965):

$$RAI = 3 \times \frac{(P - P_i)}{(M - P_i)} \text{ if } P > P_i \quad (06)$$

$$RAI = -3 \times \frac{(P - P_i)}{(N - P_i)} \text{ if } P < P_i \quad (07)$$

where: P is the actual rainfall; P_i is the long-term average precipitation; M is the average of the ten highest values of P; N is the average of the ten lowest values of P.

Based on the calculation of the RAI, meteorological drought in an area is classified as Table 3:

Table 3. Classification of drought according to the value of the rainfall anomaly index (ROOY, 1965; DAFOUF et al., 2022).
Tabela 3. Classificação da seca segundo o valor do índice de anomalia pluviométrica (ROOY, 1965; DAFOUF et al., 2022).

RAI values	Drought category
≥ 3.0	Extremely wet
2.0 to 2.99	Very wet
1.0 to 1.99	Moderately wet
0.5 to 0.99	Slightly wet
0.49 to -0.49	Near Normal
-0.5 to -0.99	Slightly dry
-1.0 to -1.99	Moderately dry
-2.0 to -2.99	Very dry
≤ -3.0	Extremely dry

3. RESULTS

3.1. Flood Levels and Trends

3.1.1. Flood Levels and Frequency

Table 4 shows that over the past 45 years, there have been nine large floods, 17 medium floods, and 19 small floods. The distribution of floods has fluctuated significantly over time. Large floods occurred frequently during the first 30 years, with eight large floods, but there has been a sharp decline in the last 15 years, with only one large flood (in 2011). In contrast, small floods have shown an opposite trend. The frequency of floods from 1979 to 2008 was 26.7% large floods, 46.6% medium floods, and 26.7% small floods. From 2009 to 2023, these proportions changed to 6.7%, 20%, and 73.3%, respectively. This indicates a trend where large and medium floods are becoming less frequent, and small floods are increasingly common in the LXQ region (Table 4).

The maximum water levels at the Tan Chau station from 1979 to 2023 also exhibit significant fluctuations in flood levels over different periods (Figure 2). From 1979 to 1988, flood levels remained high, with most years exceeding the 400 cm threshold, peaking in 1984 at around 480 cm. During 1989-1998, water levels fluctuated significantly, with some years falling below 350 cm, such as in 1992 and 1996, with 1996 being the lowest at around 300 cm. From 1999 to 2008, flood levels rose again, with many years exceeding 450 cm, with the highest peak in 2000 at 506 cm. The period from 2009 to 2018 witnessed fluctuations in water levels, albeit with a general downward trend, with the highest level recorded in 2011 at approximately 490 cm and the lowest in 2015 at around 255 cm. From 2019 to 2023, flood levels dropped below 400 cm in all years, with 2023 recording a low level of around 300 cm.

Large floods do not occur regularly, and years with large floods tend to cluster, such as in 1981, 1984, 1991, 1994, and 1996. Notably, large floods also occurred consecutively in 2000, 2001, and 2002. However, after this period, for 21 consecutive years (2003-2023), the LXQ experienced only moderate-to-small floods (except in 2011) and even extremely small floods in 2015.

3.1.2. Flood Level Trends

Figures 3a and 3b show that the peak water levels at the Chau Doc (upstream) and Tri Ton (inland) stations have a downward trend. The water level at Chau Doc has decreased by 1.82 cm/year, equivalent to about 82.1 cm over 45 years (1979 - 2023) (Figure 3a); the water level at Tri Ton has decreased by approximately 3.05 cm/year, equivalent to 103.9 cm over 34 years (1990 -2023) (Figure 3b). However, contrary to the downward trend in upstream and inland areas, the water level in Long Xuyen (downstream) exhibits an upward trend, increasing by 1.26 cm per year, equivalent to 56.91 cm over 45 years (Figure 3c).

Statistical analyses show that flood levels exhibit significant dispersion around the mean, with large standard deviations of 60.7 cm at Chau Doc and 72.2 cm at Tri Ton. Additionally, the difference between the largest flood year (2000) and the smallest flood year (2015) is substantial, reaching 255 cm at Chau Doc and 323 cm at Tri Ton (Table 5).

Table 4. Frequency of Floods at the Tan Chau Station (Tien River).
Tabela 4. Frequência de inundações na estação Tan Chau (rio Tien).

Period	Large Floods	Percentage (%)	Medium Floods	Percentage (%)	Small Floods	Percentage (%)
1979-2008	8	26.7%	14	46.6%	8	26.7%
2009-2023	1	6.7%	3	20.0%	11	73.3%
1979-2023	9	20.0%	17	37.8%	19	42.2%

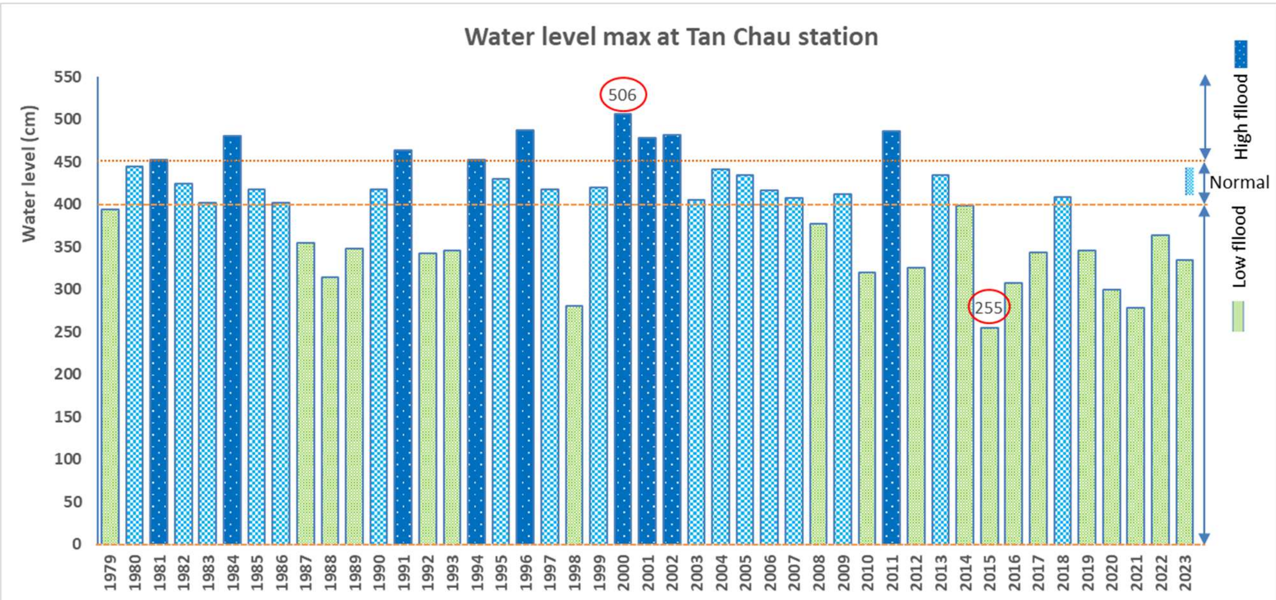

Figure 2. Evolution of flood levels from 1979 to 2023: the trend indicates a decrease in the number of years with large and medium floods, and an increase in years with small floods.
Figura 2. Evolução dos níveis de inundação de 1979 a 2023: a tendência mostra uma diminuição no número de anos com inundações grandes e médias e um aumento nos anos com inundações pequenas.

Table 5. Statistical indicators of floods at Chau Doc, Tri Ton, and Long Xuyen stations.
Tabela 5. Indicadores estatísticos de inundações nas estações Chau Doc, Tri Ton e Long Xuyen.

Station	Mean (cm)	Median (cm)	Standard Deviation (cm)	Coefficient of Variation (%)	Range (cm)	Minimum (cm)	Maximum (cm)	Count
Chau Doc	355.4	359	61.69	17.36	255	235	490	45
Tri Ton	230.79	238	52.46	22.73	180	128	308	34
Long Xuyen	232.31	234	24.10	10.37	102	178	280	45

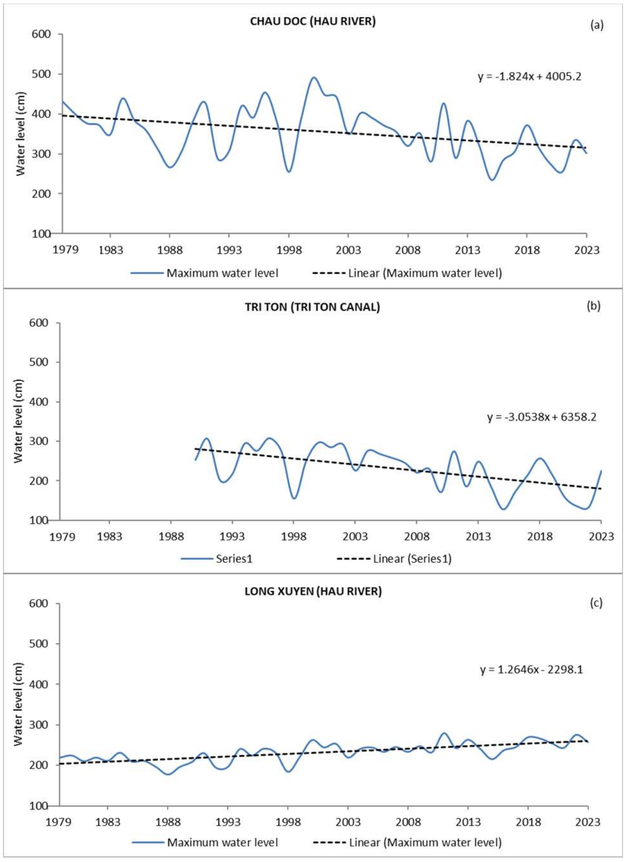

Figure 3. Evolution and trends in water levels at stations in the LXQ region.
Figura 3. Evolução e tendências dos níveis de água nas estações da região LXQ.

3.2. Drought Levels

3.2.1. Drought Assessment Based on the SPI

Meteorological drought levels in the LXQ region were assessed using the Standardized Precipitation Index (SPI), based on rainfall data from two stations, Chau Doc and Rach Gia, spanning a 45-year period (1979-2023). The SPI calculations for 3, 6, and 12-month periods at both stations indicate that drought in the LXQ occurs at various levels and frequencies:

In Rach Gia, the frequency of months experiencing drought from moderate to extreme levels is 17.4% (for the 3 months), 15% (for the 6 months), and 18.7% (for the 12 months). The frequency of extreme droughts is 2.04%, 1.3%, and 1.48%, respectively. Months with mild or near-normal drought conditions account for 33.33% of the 3-month period, 38.7% of the 6-month period, and 30.56% of the 12-month period (Table 6).

Similarly, at Chau Doc, the frequency of months experiencing drought from moderate to extreme levels is 17.04% (for the 3 months), 14.81% (for the 6 months), and 19.07% (for the 12 months). The frequency of extreme droughts is 2.04%, 1.30%, and 1.48%, respectively. Months with mild or near-normal drought conditions account for 32.78% of the 3-month period, 38.52% of the 6-month period, and 30% of the 12-month period (Table 7).

Overall, at both stations in the LXQ, the weather pattern from 1979 to 2023, across short, medium, and long periods, indicates that SPI values were predominantly in the non-drought (SPI > 0) and mild drought/near-normal range (0 < SPI < -1). Moderate to severe drought conditions occurred in 15-20% of the periods but were concentrated in specific years, such as 1990, 2012, 2016, and 2020, where extreme drought conditions appeared more frequently.

Table 6. SPI thresholds and drought levels from 1979 – 2023 at Rach Gia station.
Tabela 6. Limites do SPI e níveis de seca de 1979 a 2023 na estação de Rach Gia.

SPI value	Category	SPI3		SPI6		SPI12	
		Frequency	%	Frequency	%	Frequency	%
> 0	Non-drought	268	49.63	250	46.30	274	50.74
0 to -0.99	Near normal/ Mild	180	33.33	209	38.70	165	30.56
-1.49 to -1.0	Moderate drought	59	10.93	46	8.52	68	12.59
-1.99 to -1.5	Severe drought	22	4.07	28	5.19	25	4.63
-2.0 or less	Extreme drought	11	2.04	7	1.30	8	1.48

Table 7. SPI thresholds and drought levels from 1979 – 2023 at Chau Doc station.
Tabela 7. Limites do SPI e níveis de seca de 1979 a 2023 na estação Chau Doc.

SPI value	Category	SPI3		SPI6		SPI12	
		Frequency	%	Frequency	%	Frequency	%
> 0	Non-drought	271	50.19	252	46.67	275	50.93
0 to -0.99	Near normal/ Mild	177	32.78	208	38.52	162	30.00
-1.49 to -1.0	Moderate drought	58	10.74	44	8.15	70	12.96
-1.99 to -1.5	Severe drought	23	4.26	29	5.37	25	4.63
-2.0 or less	Extreme drought	11	2.04	7	1.30	8	1.48

The levels of drought and the timing of their occurrence for different periods are illustrated in Figure 4. For the 3-month SPI3 period, both Rach Gia and Chau Doc recorded 11 occurrences of extreme drought, mainly during the dry months (December to April) of the years 1984, 1985, 1987, 1990, 2002, 2003, 2004, 2012, 2015, and 2016. The lowest SPI3 values occurred from January to April 1990, specifically -2.65 in Rach Gia and -2.59 in Chau Doc. Severe drought also occurred 22 times in Rach Gia and 23 times in Chau Doc, with drought severity typically prevailing during the dry season, reflecting a high risk of water scarcity during this period in the LXQ.

For the 6-month SPI6 period, the study results also show that the frequency of droughts across categories, ranging from extreme to mild, varies between 1.3% and 38.52%. Moderate, severe, and extreme droughts occurred 81 times in Rach Gia and 80 times in Chau Doc, primarily during the first six months of the year. The most severe drought occurred from January to May 2002, with a SPI6 of -2.39 in Rach Gia and Chau Doc. Notably, some rainy season months also experienced rainfall deficits compared to the average (May 2004, July 1987, and August 2015 in both Rach Gia and Chau Doc), indicating the potential risk of water shortages not only during the dry season but also during the rainy season. In contrast, mild drought conditions mainly occurred in the middle and end of the year.

For the 12 months (SPI12), the results show that both Rach Gia and Chau Doc recorded 8 instances of extreme drought and 25 instances of severe drought. The overall trend indicates a decrease in the frequency of severe and mild droughts, but a significant increase in the number of moderate droughts.

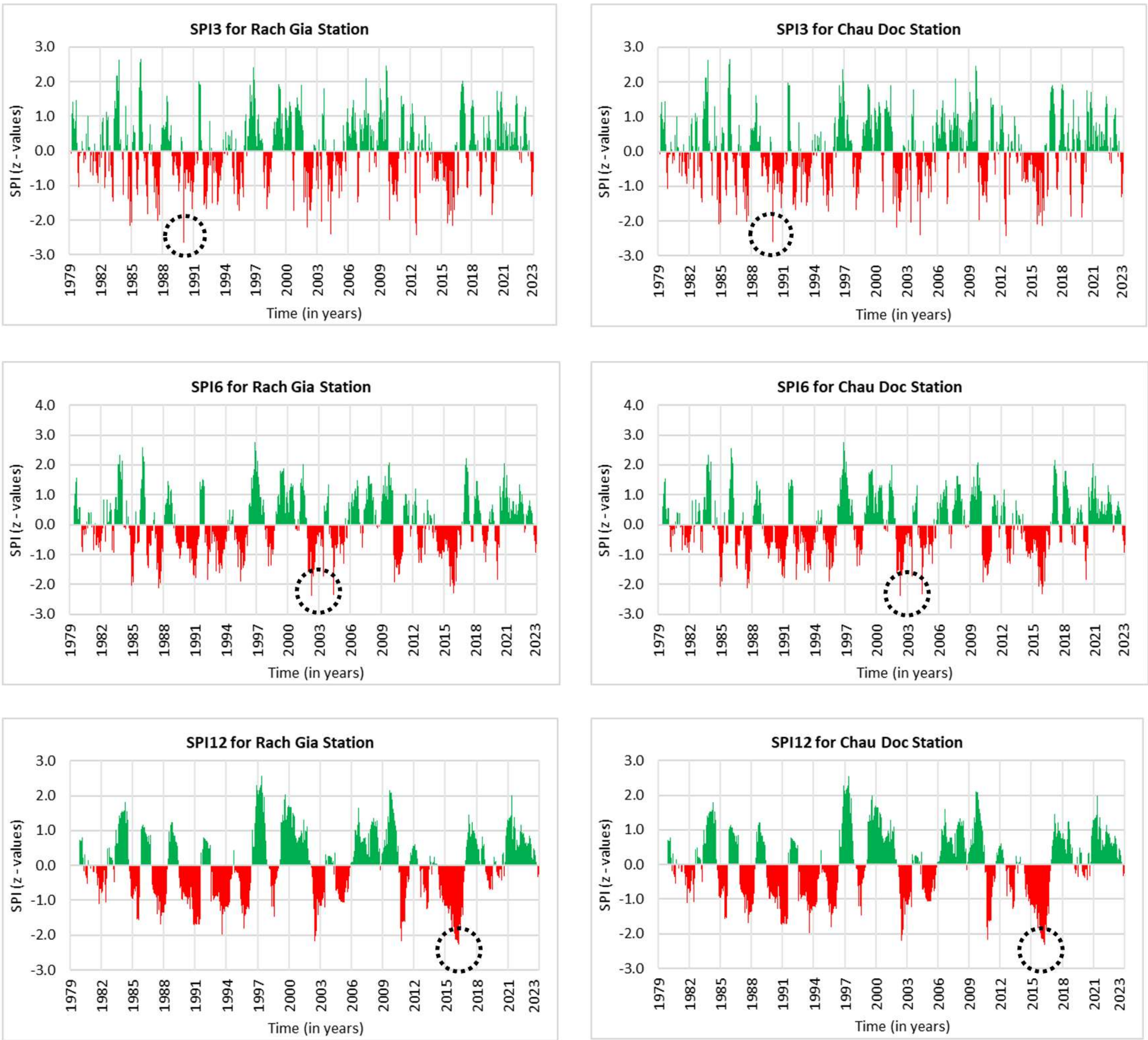

Figure 4. SPI Index for 3-month, 6-month, and 12-month periods at the Chau Doc and Rach Gia stations from 1979 to 2023.
Figura 4. Índice SPI para períodos de 3, 6 e 12 meses nas estações Chau Doc e Rach Gia, durante o período de 1979 a 2023.

In addition, to assess meteorological drought variations, the study calculated the number of drought months in a year (rainfall ≤10mm during the dry season and ≤50mm during the rainy season). The results show that in severe drought years, such as 1983, 1988, 1990, 1993, 2004, 2016, and 2020, the number of drought months was high, accompanied by very low monthly rainfall. At the Chau Doc station, dry season rainfall in 1983 was 80.4mm (4 months during the dry season had monthly rainfall ≤10mm), in 1988, it was 82.4mm (4 months during the dry season had monthly rainfall ≤10mm and 2 months during the rainy season had rainfall ≤50mm), in 1990 it was 49.1mm (4 months during the dry season had monthly rainfall ≤10mm and 2 months during the rainy season had rainfall ≤50mm), in 1993 it was 66.8mm (3 months during the dry season had monthly rainfall ≤10mm and 1 month during the rainy season had rainfall ≤50mm), in 2004 it was 9.4mm (5 months during the dry season had monthly rainfall ≤10mm), in 2016 it was 106.2mm (4 months during the dry season had monthly rainfall ≤10mm). In 2020, the average rainfall was 92.1. Specifically, 4 months during the dry season had monthly rainfall of ≤10 mm and 1 month during the rainy season had rainfall of ≤50 mm. Similarly, at the Rach Gia station, dry season rainfall in 1983, 1988, 1990, 1993, 2004, 2016, and 2020 was 39.5mm (4 months during the dry season had monthly rainfall ≤10mm), 70.4mm (3 months during the dry season had monthly rainfall ≤10mm), 29.7mm (3 months during the dry season had monthly rainfall ≤10mm), 32.8mm (4 months during the dry season had monthly rainfall ≤10mm), 35.9mm (4 months during the dry season had monthly rainfall ≤10mm), 36.3mm (4 months during the dry season had monthly rainfall ≤10mm), and 116.1mm (3 months during the dry season had monthly rainfall ≤10mm), respectively.

3.2.2. Drought Assessment Based on the RAI

The calculation results of the RAI show that from 1979 to 2023, Rach Gia experienced drought in 19 years with RAI values < -0.5, including 4 instances of mild drought (frequency 8.89%), 4 instances of moderate drought (8.89%), 7 instances of severe drought (15.56%), and 4 instances of extreme drought (8.89%) (Figure 5a). In Chau Doc, 21 instances of drought were recorded, including 4 instances of mild drought (8.89%), 7 instances of moderate drought (15.56%), 6 instances of severe drought (13.33%), and 4 instances of extreme drought (8.89%) (Figure 5b). Periods of extreme drought with RAI values ≤ -3.0 in Rach Gia occurred in 2015 (-4.41), 1990 (-3.68), 2010 (-3.52), and 1987 (-3.03). In Chau Doc, extreme droughts occurred in 2002 (-4.92), 1992 (-3.45), 2014 (-3.35), and 2015 (-3.29).

From Figure 5, it can be seen that during the 1986-2016 period, Chau Doc experienced three prolonged drought periods: 1988-1995 (an 8-year consecutive drought), 2001-2004 (a 4-year consecutive drought), and 2011-2015 (a 5-year consecutive drought). Within these periods, severe and extreme droughts occurred consecutively, such as during 1992 - 1994 (RAI ranging from -2.05 to -3.45) and 2013 - 2015 (RAI ranging from -2.5 to -3.35). In Rach Gia, only one prolonged drought period was recorded, from 1992 - 1995 (4 consecutive years of drought), while other drought periods lasted for 2 years or were not continuous.

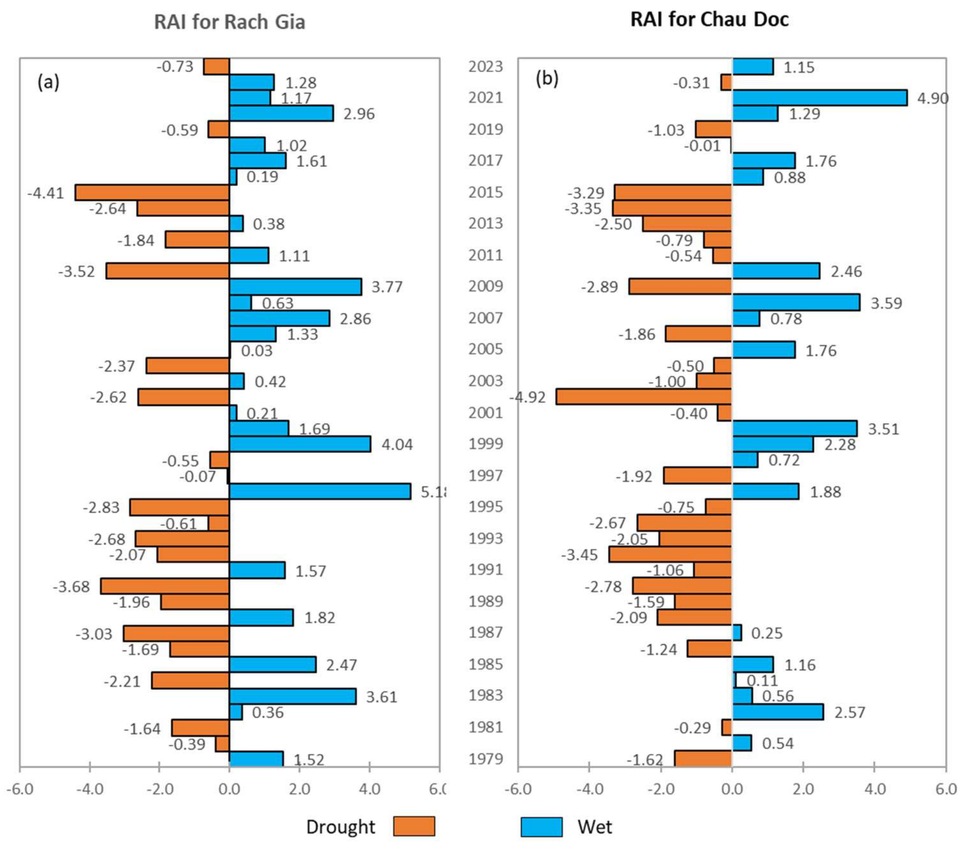

Figure 5. RAI at Rach Gia and Chau Doc stations from 1979 – 2023.
Figura 5. RAI nas estações Rach Gia e Chau Doc de 1979 a 2023.

The RAI from 1979 to 2023 shows an increasing trend in recent years, but the rate is slow, as reflected by the following linear regression equations:

- In Rach Gia: y = 0.0128x - 0.3138
- In Chau Doc: y = 0.0211x - 0.7687

This indicates that the meteorological drought, as measured by the RAI, in the LXQ region is trending downward, meaning recent rainfall is lower than the multi-year average.

The regression equations indicate a positive relationship between the RAI at Rach Gia and Chau Doc (Figure 6). However, the R^2 values are not high, suggesting this relationship is relatively weak. Although the RAI values at both locations fluctuate significantly, they do not have a clear linear relationship. This result reflects the spatial distribution differences in drought regimes between the northern (Chau Doc) and southern (Rach Gia) parts of the LXQ. This may be due to Rach Gia's coastal location, where rainfall is relatively high, and the annual variation is not large, with rainfall patterns primarily dependent on the southwest monsoon from the sea. In contrast, Chau Doc, located inland, experiences reduced rainfall, with rainfall patterns influenced by both the southwest monsoon and local convective activities.

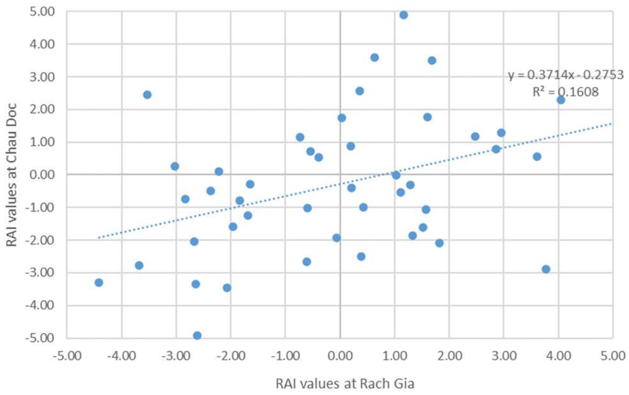

Figure 6. The relationship between the RAI at Rach Gia and Chau Doc.
Figura 6. A relação entre o RAI em Rach Gia e Chau Doc.

4. DISCUSSION

Over the course of more than four decades, flood levels in the LXQ have undergone significant fluctuations. Notably, in recent years, the frequency of large floods has decreased, while the frequency of small floods has increased markedly compared to previous decades. This result aligns with the findings of Le Anh Tuan (2020) regarding flooding in the Mekong Delta, which indicated that during the two recent decades (2000-2019), there were three very large floods in 2000, 2001, and 2002, and the next large flood did not occur until ten years later, in 2011. Small floods also exhibited unusual patterns, with seven small floods recorded during this period. From 2000 to 2009, there was only one small flood in 2008; however, in the following decade, from 2010 to 2019, six small floods occurred (TUAN, 2020).

This variability can be partially attributed to the region's increasingly severe impacts of climate change (DINH et al., 2012; SMAJGL et al., 2015; TY et al., 2022). Changes in land use and land cover, particularly the conversion of large areas of wetlands into agricultural land in recent decades, have led to a decline in certain wetland functions (FUNKENBERG et al., 2014; NGUYEN et al., 2022). Similarly, many flood-preventing dykes have been constructed to increase rice production areas, contributing to changes in the flood regime in the LXQ (DIEP et al., 2024; THIEN et al., 2013; TRAN et al., 2018). Additionally, the increasing number of upstream dams built on the Mekong River has significantly altered the flow and water regime in the lower Mekong River, particularly in the Mekong Delta (POKHREL et al., 2018; LU; CHUA, 2021).

The distribution of floodwaters within the LXQ region has also shown variability. Statistical correlation analysis of peak water levels between the hydrological stations of Chau Doc and Tri Ton shows a relatively high correlation (Figure 7a), with approximately 84.32% of the water level variability at Tri Ton being explained by the water level at Chau Doc.

This indicates that the flood regime in the inland areas of the LXQ is closely tied to the upstream flood regime. In contrast, the correlation between water levels at Chau Doc and Long Xuyen is very weak ($R^2 = 0.0979$), suggesting that downstream flooding is not entirely dependent on upstream floods (Figure 7b). This can be explained by the fact that since 2000, a series of major irrigation projects developed by the Ministry of Agriculture and Rural Development have been implemented in accordance with the flood control plan for the LXQ and Dong Thap Muoi regions, which the government has approved. As a result, numerous comprehensive dykes and flood control sluices were constructed to support the policy of increasing the area for triple cropping of rice each year (MANH et al., 2014).

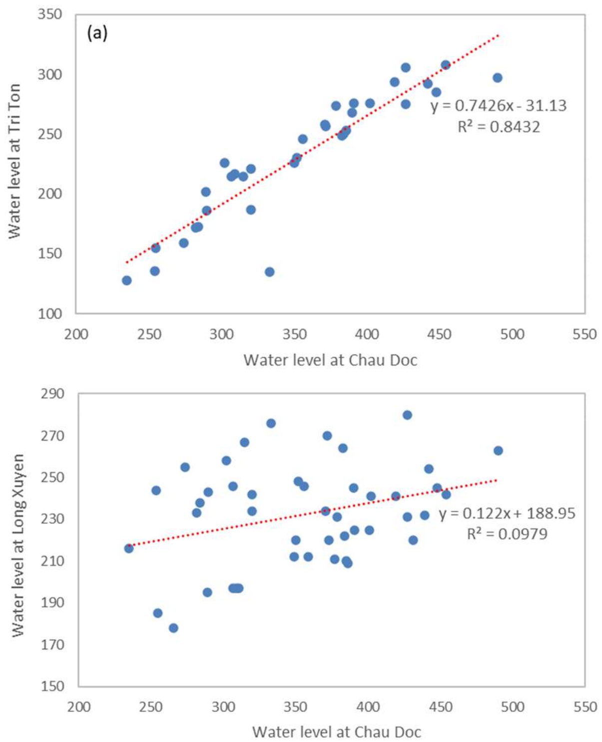

Figure 7. Correlation of peak flood levels between hydrological stations (a) Chau Doc and Tri Ton; (b) Chau Doc and Long Xuyen.
Figura 7. Correlação dos níveis máximos de cheia entre as estações hidrológicas (a) Chau Doc e Tri Ton; (b) Chau Doc e Long Xuyen.

The intensification and increase in cropping have reduced the flood retention space in the LXQ's low-lying areas, resulting in a decrease in flood absorption capacity from 9.2 billion m³ in 2000 to 4.5 billion m³ in 2011, a reduction of approximately 51.1% (ICEM, 2015). Due to the reduced flood absorption space, more floodwater has flowed downstream, increasing flood levels in the downstream areas of the LXQ and leading to a rising trend in flood inundation in these areas. For instance, in large flood years like 2011, the peak flood level at Chau Doc was 427 cm, 63 cm lower than the peak flood level in 2000, which was 490 cm. However, the flood level in Long Xuyen City in 2011 was 280 cm, 17 cm higher than the peak flood level recorded in 2000 (263 cm).

Like the flood regime, drought in the LXQ has also experienced significant variability over the past four decades. Analyzing the frequency of drought occurrences in the LXQ using the Standardized Precipitation Index (SPI) at 3-month, 6-month, and 12-month intervals, it was found that approximately 50% of the time, mild droughts were the most common, followed by moderate, severe, and then extreme droughts. This result aligns with the study on meteorological drought in the LXQ from 1982 to 2015 by Lee; Dang, which identified that the main levels of drought included moderate droughts occurring 31.5 times/32 years (98.4%), severe droughts 14.16 times/32 years (44.25%), and extreme droughts 7.5 times/32 years (23.43%) (LEE; DANG, 2018a). This trend is also highlighted in the findings of Ty et al. (2015), who examined the meteorological drought index at three stations: Can Tho, Chau Doc, and Bac Lieu in the VMD from 1980 to 2012. In that study, all four drought levels (mild, moderate, severe, and extreme) were observed over the past 33 years in the VMD, with a decreasing frequency from mild to extreme drought (TY et al., 2015). Thus, in the period from 1979 to 2023, drought occurrences consistently accounted for about 50%. Notably, the LXQ experienced multiple consecutive drought years, such as 1982–1983, 1987–1988, 1990–1991, 1993–1995, 2002–2004, 2014–2016, and 2019–2020. Particularly, 2016 and 2020 were considered the most severe drought years in recent times (PHAN et al., 2020; MINH et al., 2022; KEOVILIGNAVONG et al., 2023).

The frequency of droughts in the LXQ has decreased in recent years, but the severity of droughts has intensified. Analysis based on the RAI indicates that drought years have occurred frequently between 1979 and 2023 (Figure 5). This pattern is consistent with trends observed in other southern regions of Vietnam. For example, in Ninh Thuan Province, Nguyen; Canh (2022) reported regional drought developments using RAI from 1986 to 2016. The RAI calculations from their study showed that from 1986 to 2016, Ninh Thuan experienced 15 drought occurrences (RAI < -0.5), with severe and extreme droughts occurring 12.5% of the time (4 occurrences) and mild droughts 34.4% of the time (11 occurrences) (NGUYEN; CANH, 2022). These findings suggest that the RAI measures drought frequency and indicates the severity of drought events, reflecting the trends and characteristics of drought in a region amidst climate change.

5. CONCLUSIONS

This study has assessed the current status and trends of floods and droughts over more than four decades in the Long Xuyen Quadrangle (LXQ) within the context of climate change. Data collected from 1979 to 2023 show significant variations in floods and droughts. The analysis results indicate:

Floods:

The frequency of large and medium floods has decreased gradually over time, while the occurrence of small floods has increased. Peak flood levels have declined at the Chau Doc and Tri Ton hydrological stations, but there is an increasing trend at the Long Xuyen station. This can be attributed to changes in water infrastructure, particularly the construction of dykes and flood control sluices.

Large floods do not occur regularly but tend to follow a cyclical pattern, with consecutive large flood periods occurring in 1981, 1984, 1991, 1994, and 1996, and particularly in 2000, 2001, and 2002. In recent years, there have been fewer large floods, except for the notable exception of 2011.

Droughts:

Meteorological drought, assessed using the SPI and RAI indices, shows that drought severity has varied over time and space. The frequency of droughts has decreased, but the intensity of drought events has increased, especially in recent years, with droughts becoming more severe.

From 1979 to 2023, multiple consecutive drought events occurred. Meteorological droughts primarily occurred during the dry season, resulting in severe water shortages that significantly impacted human life and agricultural production. In certain years (1987, 2004, 2015), meteorological droughts even occurred during the rainy season, indicating a potential risk of water shortages in both the dry and rainy seasons in the LXQ.

The research results have provided an overall picture of the characteristics and changing trends of floods and droughts in the LXQ while also highlighting the challenges posed by climate change and the recent increase in human activities. These findings provide a crucial foundation for proposing effective water resource management solutions and promoting sustainable socio-economic development in the region.

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