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Spatio-Temporal Analysis of Drought in the North-Eastern Coastal Region of Vietnam Using the Standardized Precipitation Index (SPI)

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Abstract

Spatio-temporal analysis of drought provides valuable information for drought management and damage mitigation. In this study, the Standardized Precipitation Index at the time scale of 6 months (SPI-6) is selected to reflect drought conditions in the North-Eastern coastal region of Vietnam. The drought events and their characteristics from 1981 to 2019 are detected at 9 meteorological stations and 10 Chirps rainfall stations. The spatio-temporal variation of drought in the study region is analyzed on the basis of the number, duration, severity, intensity, and peak of the detected drought events at the 19 stations. The results show that from 1981 to 2019 the drought events mainly occurred with 1-season duration and moderate intensity and peak. The number, duration, severity, and peak of the drought events were the greatest in the period 2001-2010 and were the smallest in the period 2011-2019. Among the 19 stations, the drought duration tends to decrease at 11 stations, increase at 7 stations, and has a slight variant at 1 station; the drought severity tends to decrease at 14 stations, increase at 4 stations, and has not a significant trend at 1 station; the drought intensity tends to decrease at 17 stations, increase at 1 station, and has a slight variant at 1 station; and the drought peak tends to decrease at 18 stations and increase at 1 station.

Keywords

Spatio-Temporal Analysis of Drought, Standardized Precipitation Index (SPI), Drought Characteristics

1. Introduction

Drought is a costly natural hazard, which caused huge economic, social, and environmental losses [1] [2]. In recent decades, numerous drought indices have been developed to quantify and characterize droughts [3] [4] [5]. Drought indices can be constructed by using drought variables [6] [7], the commonly used drought variables are precipitation, temperature, streamflow, soil moisture, snowpack, groundwater, and reservoir levels [8] [9] [10]. McKee *et al.* [11] proposed the Standardized Precipitation Index (SPI) using the standardized method for precipitation. The main advantage of SPI is that it can be calculated at different timescales from 1 month to 48 months or longer [8]. In 2009, WMO recommended using SPI as the main meteorological drought index to monitor drought conditions. Based on drought indices, the drought events are detected and characterized by their characteristics, such as drought duration, severity, intensity, frequency [12], and peak [13] [14].

Spatio-temporal analysis of drought provides valuable information for drought prevention and mitigation and for evaluating water resource systems under drought conditions [15]. There have been studies analyzing the spatial-temporal variation of drought characteristics, which are determined using drought indices. Zarei *et al.* [16] identified the changes in the spatial pattern of drought severity in the south of Iran from 1980 to 2010 using the Reconnaissance Drought Index (RDI) at 3-month and 12-month timescales. Brito *et al.* [17] used SPI at the time scale of 12 months and the vegetation health index to determine drought events in the semi-arid Northeast Brazil region from 1981 to 2016. Then, the frequency, duration, and severity of drought events were detected and applied to assess the spatio-temporal variation of drought in the study region. Ramkar and Yadav [18] investigated spatio-temporal drought in a semi-arid part of the middle Tapi River Basin, India in the period 1981-2013 using 4 drought characteristics including temporal coverage, spatial coverage, intensity, and duration. In this study, the rainfall decile (RD), standardized precipitation index (SPI), reconnaissance drought index (RDI), and Streamflow Drought Index (SDI) were employed to detect drought events and characteristics. Guo *et al.* [19] identified the spatial and temporal change in drought frequency, duration, severity, intensity, and preferred season in Central Asia during the period 1966-2015. These drought characteristics were determined using the Standardized Precipitation Evapotranspiration Index (SPEI) at 3-month, 6-month, and 12-month timescales. Alsafadi *et al.* [20] characterized drought trends, intensity, and duration in Hungary from 1961 to 2010 using SPI and SPEI at 12-month timescales. Sein *et al.* [21] analyzed the spatio-temporal variation of drought in Myanmar from 1986 to 2015 employing SPEI at 3, 6, and 12-month timescales. Yirga [22] used SPI to determine drought events and analyzed the spatio-temporal variation of drought in central Ethiopia from 1989 to 2017 based on the drought frequency and severity. The spatial and temporal change in the drought over the Kucuk Menderes River Basin in the western part of Turkey was investigated using SPI at the 3-month timescale [23]. Roushangar *et al.* [24] identified the spatio-temporal variation of drought frequency, duration, severity, and peak in Iran during the 1951-2016 period based on SPI with timescales of 3, 6, and 12 months. Waseem *et al.* [25] analyzed the spatio-temporal variation of drought frequency and severity in Punjab, Pakistan during 2001-2019 using SPI-12.

In general, the above-mentioned studies provided an overall picture to better understand drought in the research regions. Most of the studies used 2 drought characteristics for their analysis. There are several drought characteristics, hence the spatio-temporal variation analysis of drought is considered more reliable when more drought characteristics are used. To analyze the spatial variation of drought, the above studies used data collected from many ground stations [16] [18] [21] [24] [25] or satellite data [20] or both ground stations and satellite data [17] [23]. The results of spatio-temporal analysis of drought help constitute the scientific basis to analyze the impact of drought on crop production [21] [25], suggesting a cropping pattern for the drought-affected regions and implementing effective drought mitigation measures and water resource planning in drought areas [18].

Drought is ranked the third in socio-economic losses in Vietnam. The North-Eastern coastal region of Vietnam, including the provinces of Quang Ninh, Hai Phong and Thai Binh, is one of the regions affected by drought. Drought affects production activities such as industry, agriculture, etc. [26]. However, there are very few studies on drought characteristics as well as spatial and temporal variation of drought in this region. In Vietnam, SPI is used as the main drought index for drought monitoring. This study, therefore, analyzes the spatial and temporal variation of drought characteristics, including duration, severity, intensity, and peak from 1981-2019 using SPI. Since the uneven distribution of meteorological stations in the study area, this study uses satellite rainfall data to supplement rainfall data in areas where monthly rainfall data are not available. The results of this study are expected to form scientific basis for drought prevention and mitigation measures and water resources planning in the study region.

2. Materials and Methods

2.1. Study Area

The North-Eastern coastal region of Vietnam is located between the north latitude 20˚12'44" - 21˚44'1" and the east longitude 106˚25'21" - 108˚4'23" and covers an area of about 4407.69 km^2, including Quang Ninh, Hai Phong, and Thai Binh provinces (see **Figure 1**). In this region, the rainy season lasts from May to October, and the dry season from November to April. From 1981 to 2019, the rainfall in rainy seasons accounted for 85% of the annual total. Uneven distribution of rainfall between the rainy and the dry season is one of the causes of drought in this region [26].

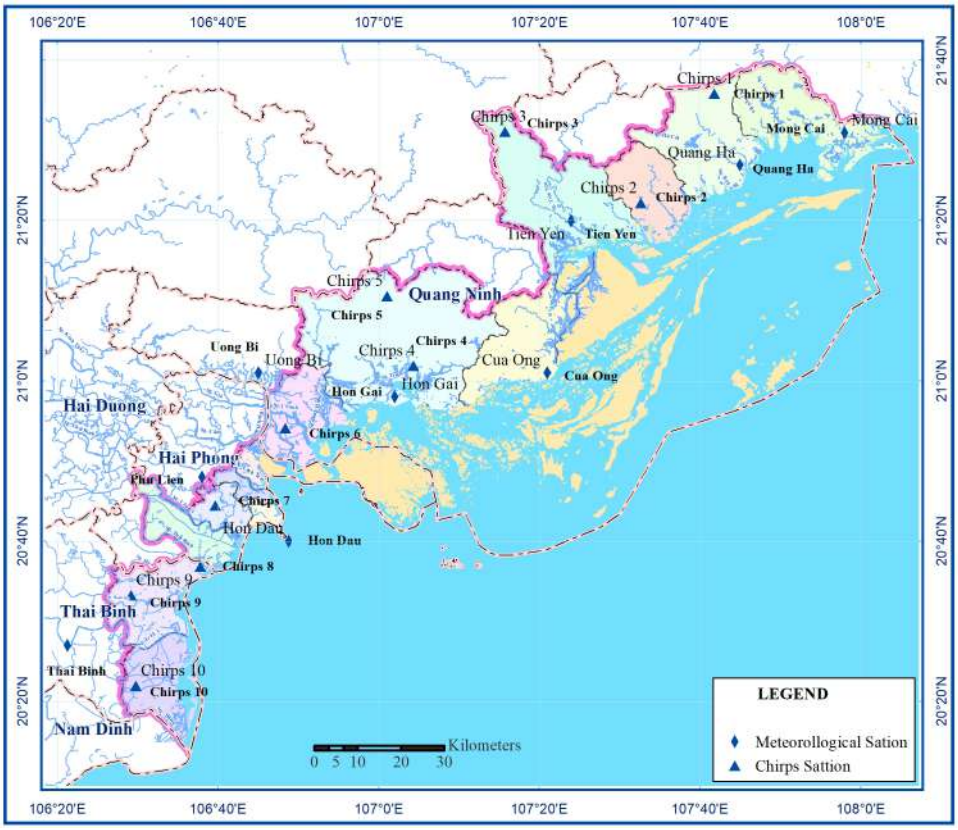


Figure 1. The North-Eastern coastal region of Vietnam.

2.2. Rainfall Data

There are 9 meteorological stations located in the North-Eastern coastal region (see Figure 1) and their data series of monthly rainfall observations from January 1981 to December 2019 obtained from the National Hydro-Meteorological Information and Data Center of the Vietnam Meteorological and Hydrological Administration are used in this study. The rainfall data is sufficient and reliable for calculations.

Due to the uneven distribution of meteorological stations in the study region, some areas are not covered by any rainfall gauging station there is hence not any rainfall data available. The study, therefore, uses satellite rainfall data to supplement rainfall data for those areas. In fact, Chirps rainfall has been used to supplement rainfall data for areas where rainfall data is not available in some river basins of Vietnam, such as Red River [27], Ca River [28], etc. In this study, the Nash–Sutcliffe Efficiency (NSE) [29], Kling-Goupta Efficiency (KGE) [30], and Percent Bias (PBIAS) [31] are used to evaluate the reliability and applicability of Chirps rainfall in the study region.

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n} \left(P_{oi} - P_{si}\right)^2}{\sum_{i=1}^{n} \left(P_{oi} - \bar{P}_o\right)^2} \quad (1)$$

$$\text{KGE} = 1 - \sqrt{\left(r-1\right)^2 + \left(\alpha-1\right)^2 + \left(\beta-1\right)^2} \quad (2)$$

$$\text{PBIAS} = \frac{\sum_{i=1}^{n}\left(P_i^{oi} - P_i^{si}\right)}{\sum_{i=1}^{n} P_i^{oi}} * 100 \tag{3}$$

where:

$$r = \frac{\sum_{i=1}^{n}\left(P_{oi} - \bar{P}_o\right)\left(P_{si} - \bar{P}_s\right)}{\sqrt{\sum_{i=1}^{n}\left(P_{oi} - \bar{P}_o\right)^2 \sum_{i=1}^{n}\left(P_{si} - \bar{P}_s\right)^2}} \tag{4}$$

$$\alpha = \frac{\sigma_s}{\sigma_o} \tag{5}$$

$$\beta = \frac{\mu_s}{\mu_o} \tag{6}$$

P_o is the monthly observed rainfall; P_s is the monthly Chirps rainfall; σ_o is the standard deviation of the monthly observed rainfall; σ_s is the standard deviation of the monthly Chirps rainfall; μ_o is the mean of the monthly observed rainfall; μ_s is the mean of the monthly Chirps rainfall.

2.3. Calculation of the Standardized Precipitation Index (SPI)

As proposed by Mckee [11], to calculate SPI, the Gamma distribution function was first chosen to fit a time-ordered series of precipitation data, and the SPI is then calculated as follows:

$$\text{SPI} = N^{-1}\left\{\Gamma(.)\right\} \tag{7}$$

where N^{-1} is the inverse standard normal distribution function, and $\Gamma(.)$ is the fitted Gamma distribution function. The classification of drought for SPI is shown in **Table 1**. In this study, to select the suitable timescale of SPI for reflecting drought conditions in the North-Eastern coastal region of Vietnam, SPI at 1-, 3-, 6-, 9-, 12-month timescales are calculated by using the SPI program of Santiago Beguería and Sergio M. Vicente-Serrano [32]. The classification of SPI follows the U.S. Drought Monitor classification for the standardized drought indices, as shown in **Table 1**.

2.4. Determination of Drought Events and Characteristics Based on SPI

In this study, to analyze spatio-temporal drought, drought events and characteristics are detected using SPI. Based on the drought classification of SPI, a

Table 1. Classification of drought for Standardized Precipitation Index (SPI).

Drought category	Classification	Value
D0	Abnormally dry	−0.5 to −0.7
D1	Moderate drought	−0.8 to −1.2
D2	Severe drought	−1.3 to −1.5
D3	Extreme drought	−1.6 to −1.9
D4	Exceptional drought	−2.0 or less

drought event starts when the SPI value is less than or equal to −0.5 and ends when the SPI value is greater than −0.5. Drought characteristics are used in this study, including drought duration (DD), drought severity (DS), drought intensity (DI), and drought peak (DP). Drought duration is the occurrence period of a drought event, which is determined by the number of months between the start month (included) and the end month (not included). Drought severity is the accumulated magnitude of a drought event, which is calculated by the absolute value of the sum of SPI values during a drought duration. Drought intensity is defined as drought severity divided by drought duration, meaning that drought intensity is also drought severity of a drought event when drought duration is equal to 1 month. Drought peak is the absolute value of the minimum value of SPI of a drought event. This study also uses the classification of drought duration [13] [33], shown in Table 2.

3. Results

3.1. The Reliability of Chirps Rainfall Data for Calculation

Table 3 shows the NSE, KGE, and PBIAS between the monthly observed rainfall and the monthly Chirps rainfall at 7 meteorological stations from 1981 to 2019. It can be seen that all NSE and KGE values were greater than 0.5, and all PBIAS values were below 25%, indicating that there is a good match of the monthly Chirps rainfall to the monthly observed rainfall in the study region. Thus, monthly Chirps rainfall data is reliable for calculations.

Table 2. Classification of drought duration.

Drought category	Drought duration (month)
1-month	1
1-season	2 to 3
Cross-quarter	4 to 6
Long-term	> 6

Table 3. The NSE, KGE, and PBIAS between the monthly observed rainfall data and the monthly Chirps rainfall data from 1981 to 2019 at the 7 meteorological stations.

Station	NSE	KGE	PBIAS (%)
Mong Cai	0.64	0.67	−24.27
Cua Ong	0.73	0.74	12.22
Tien Yen	0.77	0.89	−4.55
Uong Bi	0.74	0.80	−14.80
Co To	0.66	0.70	8.98
Quang Ha	0.69	0.83	6.71
Thai Binh	0.72	0.84	−9.13

3.2. The Best Suitable Timescale of SPI to Reflect Drought Conditions

The best suitable timescale of SPI for reflecting drought in the North-Eastern coastal region of Vietnam was selected based on the comparison between the actual drought and the drought detected using SPI-1/SPI-3/SPI-6/SPI-9/SPI-12. Table 4 shows the number of drought events, the percentage of months with severe or more intense drought occurred in the rainy season in the total number of drought months, and the percentage of severe or more intense drought peaks that occurred in the rainy season in the total number of drought events based on SPI-1/SPI-3/SPI-6/SPI-9/SPI-12 at the 9 meteorological stations and 10 Chirps stations from 1981 to 2019. It can be seen from Table 4 that from 1981 to 2019, the averages number of drought events based on SPI-1, SPI-3, SPI-6, SPI-9, and

Table 4. The number of drought events, the percentage of months with severe or more intense drought occurred in rainy season in the total number of drought months, and the percentage of severe or more intense drought peaks occurred in the dry season in the total number of drought events based on SPI-1/SPI-3/SPI-6/SPI-9/SPI-12 at the 9 meteorological stations and 10 Chirps stations from 1981 to 2019. (Where (1): Number of drought events; (2): The percentage of months with severe or more intense drought occurred in rainy season in the total number of drought months (%); (3): The percentage of severe or more intense drought peaks occurred in rainy season in the total number of drought events (%)).

Station	SPI-1			SPI-3			SPI-6			SPI-9			SPI-12		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
Mong Cai	94	21.7	74.5	61	20.6	77	43	17.3	81.4	37	15.2	75.7	21	9.9	76.2
Quang Ha	101	17.7	79.2	63	18.8	73	44	13.3	88.6	29	15.6	69	26	12.7	73.1
Tien Yen	95	19.7	76.8	61	19.5	77	44	17.5	81.8	29	18.9	75.9	25	15.4	76
Cua Ong	106	16.4	83	68	21.9	70.6	44	20.1	79.5	30	19.7	83.3	25	14.9	72
Hon Gai	110	17.3	80.9	66	21.4	80.3	45	22.2	82.2	38	20	81.6	33	16.2	81.8
Uong Bi	110	16.8	81.8	69	21.7	75.4	48	16.4	83.3	38	14.5	84.2	27	15.9	74.1
Phu Lien	102	18.6	78.4	77	15.9	84.4	46	16.8	73.9	32	18.1	75	23	14.8	73.9
Hon Dau	103	17.1	81.6	62	23	77.4	38	19.5	81.6	37	17.1	81.1	27	13.8	74.1
Thai Binh	112	16.5	81.2	68	17.6	80.9	45	14.3	80	32	16.2	71.9	16	15.6	62.5
Chirps 1	105	18.5	79	62	16.4	79	50	13.9	88	33	16.3	78.8	26	13.8	76.9
Chirps 2	103	16.3	78.6	71	9.9	83.1	54	14.4	88.9	35	20.1	74.3	26	17	65.4
Chirps 3	104	18.1	80.8	74	12.1	86.5	51	13.6	88.2	36	17.5	77.8	21	14.9	57.1
Chirps 4	106	18.8	81.1	68	13.8	80.9	50	12.7	86	41	15	80.5	28	16.7	78.6
Chirps 5	105	18.7	78.1	81	18.8	85.2	52	16.8	84.6	41	15.9	78	32	16.8	81.2
Chirps 6	101	19.4	75.2	68	15.3	82.4	52	20.4	86.5	37	20.3	81.1	27	13.5	74.1
Chirps 7	101	18.4	79.2	71	16.2	85.9	53	13.4	88.7	33	17.2	81.8	24	19	70.8
Chirps 8	99	21.1	77.8	78	14	80.8	49	15.4	87.8	35	13.7	74.3	21	19.2	71.4
Chirps 9	101	17.7	79.2	72	12.7	84.7	52	14.8	86.5	33	16.9	78.8	22	14.7	72.7
Chirps 10	100	15.9	78	65	12.8	83.1	49	15.3	79.6	35	14.5	71.4	22	14.8	77.3
Average	103	18.1	79.2	69	17.0	80.4	49	16.2	84.1	35	17.0	77.6	25	15.2	73.1

SPI-12 were 103, 69, 49, 35, and 25 events, respectively, indicating that the change of SPI-1 was the promptest while the change of SPI-12 was the slowest. In comparison with actual drought conditions, SPI-3, SPI-6, and SPI-9 were more suitable than SPI-1, and SPI-12 in reflecting the drought conditions of the study area. Furthermore, Table 4 also reveals that the percentage of severe or more intense drought peaks that occurred in the dry season in the total number of drought events corresponding to SPI-6 was the most, and the percentage of severe or more intense drought peaks that occurred in the dry season in the total number of drought events based on SPI-6 was smaller based on SPI-3 or SPI-9, indicating that SPI-6 was more suitable than SPI-3 and SPI-9. The above analysis shows that SPI-6 is selected as the best suitable for reflecting drought conditions in the North-Eastern coastal region of Vietnam.

3.3. The Spatio-Temporal Variation of Drought

To analyze the spatio-temporal variation of drought in the North-Eastern coastal region of Vietnam using SPI-6, the time from 1981 to 2019 is divided into 4 periods: 1981-1990, 1991-2000, 2001-2010, and 2011-2019. Figure 2 shows monthly SPI-6 from 1981 to 2019, Table 5 shows the number of drought events, the average values of drought duration, drought severity, drought intensity, and drought peak based on SPI-6, and Figures 3-7 respectively show the spatial variation of the number of drought events, drought duration, drought severity, drought intensity, and drought peak based on SPI-6 in the periods 1981-1990, 1991-2000, 2001-2010, and 2011-2019 at the 9 meteorological stations and 10 Chirps stations in the North-Eastern coastal region of Vietnam. It can be seen from Figures 2-7 and Table 5 that:

In the period 1981-1990: Severe or more intense droughts occurred throughout

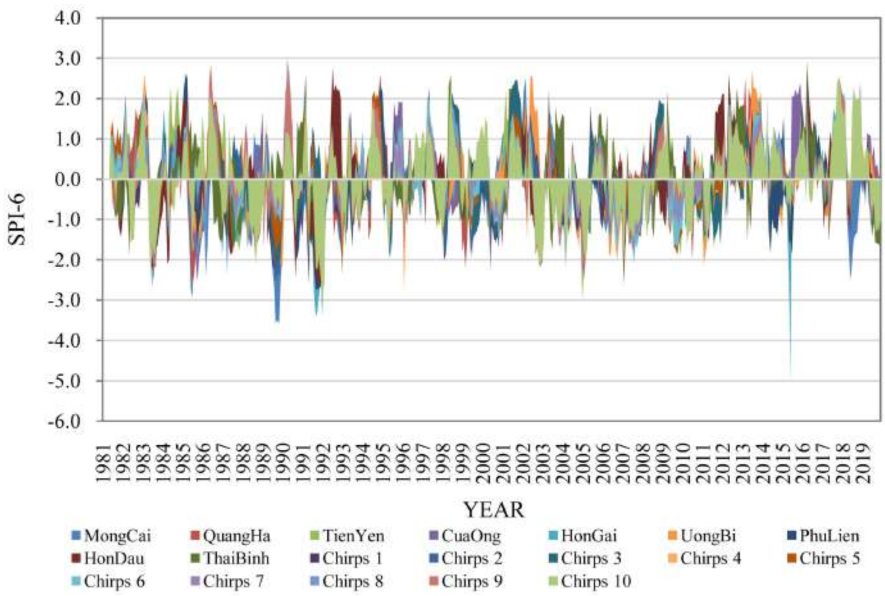


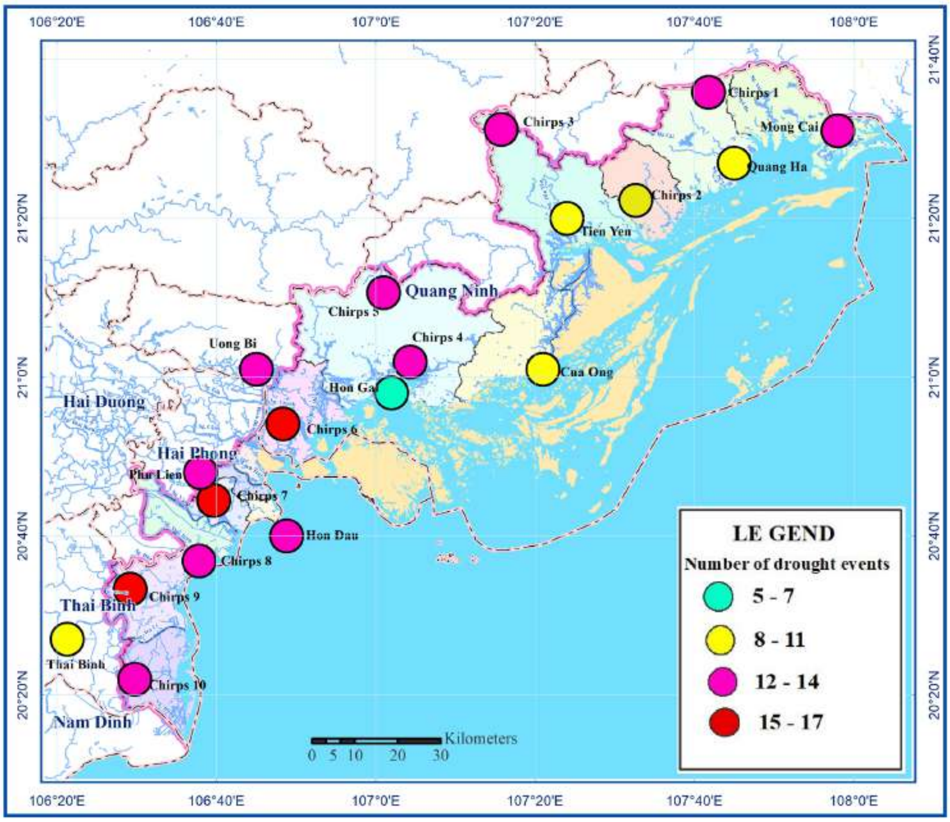
Figure 2. Monthly SPI-6 from 1981 to 2019 at the 9 meteorological station and 10 Chirps stations in the North-Eastern coastal region of Vietnam.

Table 5. The number of drought events, the averages of drought duration, drought severity, drought intensity, and drought peak based on SPI-6 at the 9 meteorological stations and 10 Chirps stations in the periods 1981-1990, 1991-2000, 2001-2010, and 2011-2019 (where N is the number of drought events).

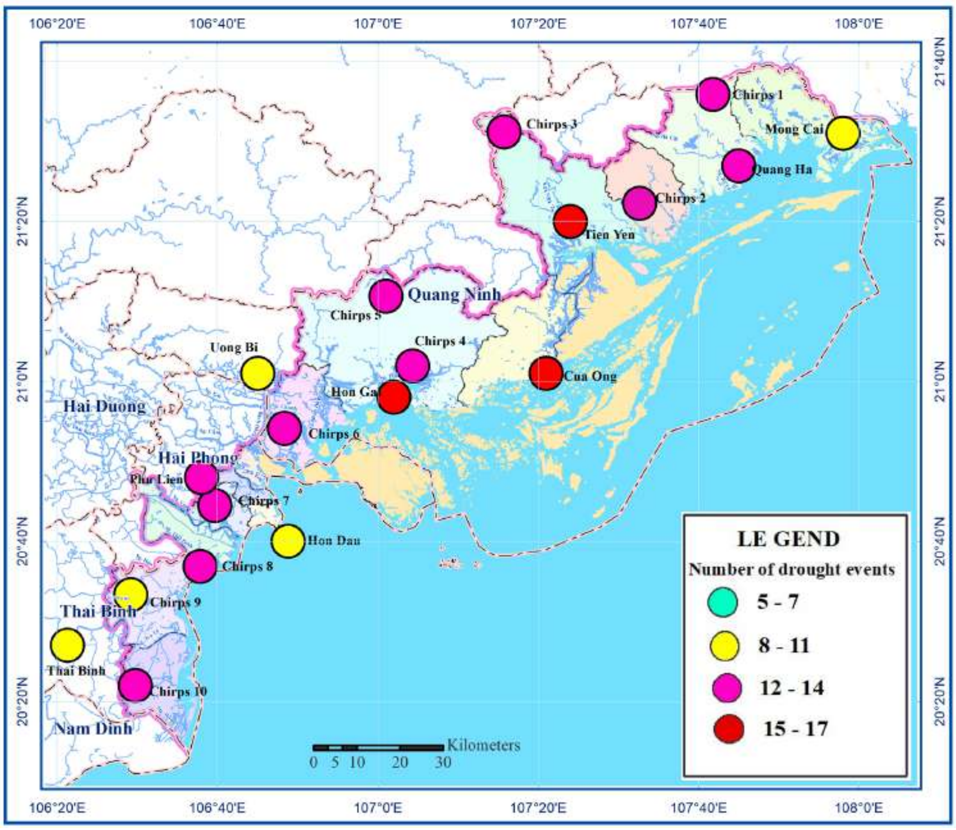
Station	1981-1990					1991-2000					2001-2010					2011-2019				
	N	DD	DS	DI	DP	N	DD	DS	DI	DP	N	DD	DS	DI	DP	N	DD	DS	DI	DP
MongCai	12	4	5	1.1	1.5	10	5	5.4	1.1	1.5	15	2	1.9	0.8	0.9	6	3	3.4	1.0	1.2
QuangHa	9	4	4.7	1.0	1.4	14	4	3.9	1.0	1.3	13	3	3.7	1.0	1.3	8	2	1.3	0.8	0.8
TienYen	9	4	4.8	1.1	1.3	15	2	2.4	1.0	1.1	11	4	4.9	1.1	1.6	9	3	3.2	0.8	0.9
CuaOng	9	5	6.8	1.2	1.6	17	2	2.4	0.9	1.1	12	4	3.9	1.0	1.3	6	2	1.7	0.9	1
HonGai	7	6	7	1.0	1.5	17	2	2.7	1.0	1.1	15	3	2.8	1.0	1.2	6	3	3.6	1.1	1.8
UongBi	14	3	3.2	1.0	1.2	10	4	4.3	1.0	1.4	16	3	2.9	1.0	1.2	8	3	2.7	0.9	1.1
PhuLien	12	4	3.5	0.9	1.2	13	3	3.6	1.1	1.2	13	3	3.5	1.0	1.2	8	3	3.3	1.0	1.2
HonDau	14	4	4.1	1.0	1.3	8	3	4.1	1.1	1.4	11	4	4.3	1.1	1.4	5	3	2.7	0.9	1.1
ThaiBinh	9	5	4.9	1.0	1.3	11	4	4.1	0.9	1.1	16	3	2.8	0.9	1	9	3	2.8	1.1	1.2
Chirps 1	12	4	3.9	0.9	1.1	14	3	3.3	1.0	1.3	15	3	3.3	0.9	1.2	9	2	1.9	0.8	0.9
Chirps 2	11	3	3	0.9	1.1	14	3	3.5	1.0	1.3	17	3	3.5	0.9	1.2	12	2	1.4	0.8	0.8
Chirps 3	12	3	2.9	1.0	1.1	13	3	3.1	1.0	1.2	15	4	4.1	0.9	1.3	11	2	2	0.8	0.9
Chirps 4	14	3	2.7	0.9	1.1	13	2	2.5	1.0	1.2	13	5	5.8	1.1	1.5	10	2	1.2	0.8	0.8
Chirps 5	12	2	2.5	0.9	1	13	3	3	0.9	1.3	16	4	4.5	1.0	1.4	11	2	1.3	0.8	0.9
Chirps 6	15	2	2.2	0.9	1.1	14	2	2	1.0	1.1	15	5	5.6	1.0	1.4	8	2	1.3	0.8	0.8
Chirps 7	17	2	2.1	0.9	1	13	2	2.4	1.0	1.3	15	5	5.1	1.0	1.3	8	2	1.7	0.8	0.9
Chirps 8	14	2	2.4	1.0	1.1	14	2	2.6	1.0	1.2	14	5	5.2	1.0	1.3	7	3	2.4	0.8	1
Chirps 9	15	2	2.7	1.0	1.1	11	3	3.2	1.1	1.3	16	4	4	1.0	1.3	10	2	1.5	0.7	0.8
Chirps 10	13	3	3.2	1.0	1.2	14	3	3.1	1.1	1.3	14	4	4.3	1.0	1.4	8	2	1.8	0.7	0.8
Average	12	3.4	3.8	1.0	1.2	13	2.9	3.2	1.0	1.2	14	3.7	4.0	1.0	1.3	8	2.4	2.2	0.9	1.0

the North-Eastern coastal region in 1983, and in Quang Ninh province in 1985 and 1989 (see **Figure 2**). The number of drought events was from 7 (at Hon Gai station) to 17 (at Chirps 7 station), making an average of 12 in this period. The average drought duration was 1-season at Uong Bi, Chirps 2, Chirps 3, Chirps 4, Chirps 5, Chirps 6, Chirps 7, Chirps 8, Chirps 9, and Chirps 10 stations, and cross-quarter at the remaining stations. At all the stations, the average drought intensity was moderate. The average drought peak was severe at Mong Cai, Cua Ong, and Hon Gai stations, and moderate at the remaining stations. The average drought severity was the most at Hon Gai station (DS = 7), and the least at Chirps 7 station (DS = 2.1). The average drought severity of the whole region was 3.8 in this period.

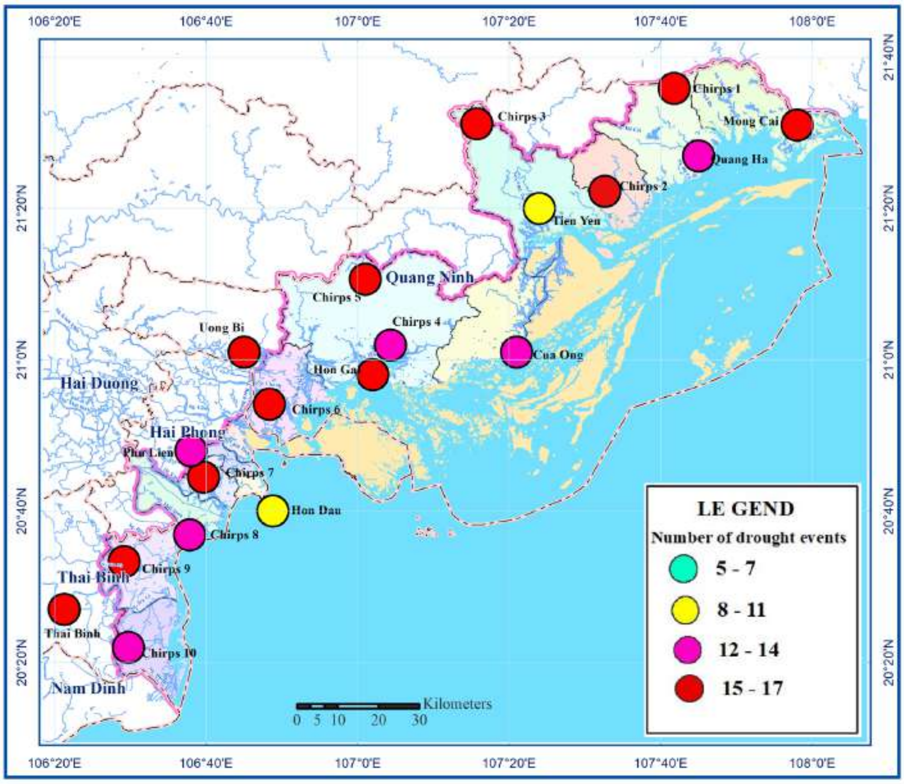
In the period 1991-2000: Severe or more intense droughts occurred in the whole study region in 1991, 1992, 1993, and 1995, and in Quang Ninh province in 1999 and 2000 (see **Figure 2**). The number of drought events was from 8 (at Hon Dau station) to 17 (at Cua Ong and Hon Gai stations), making an average



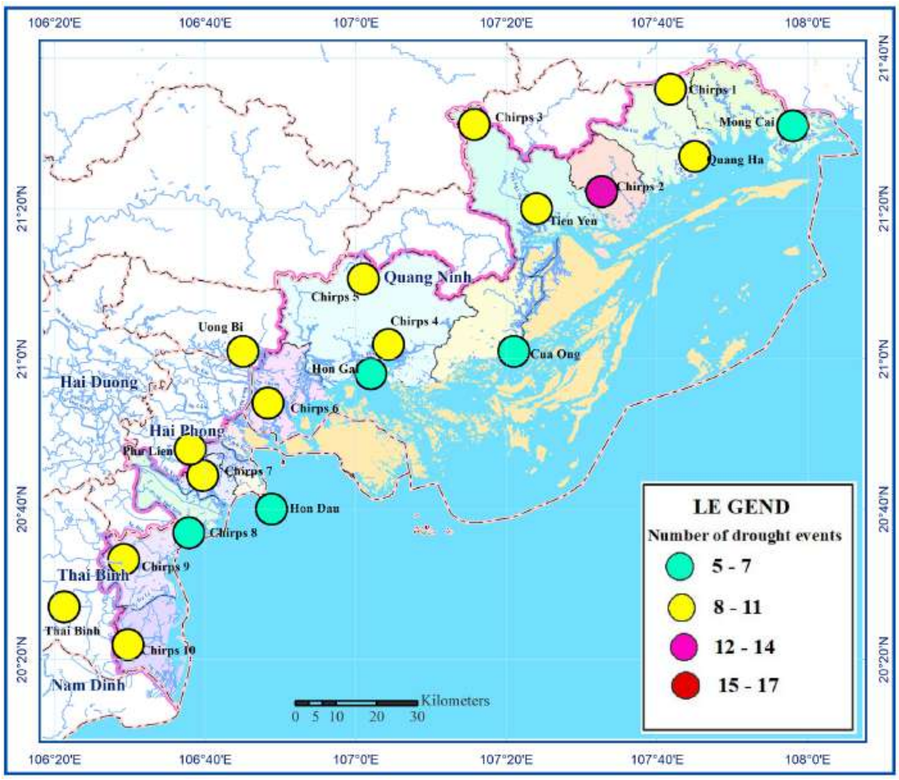
1981-1990



1991-2000

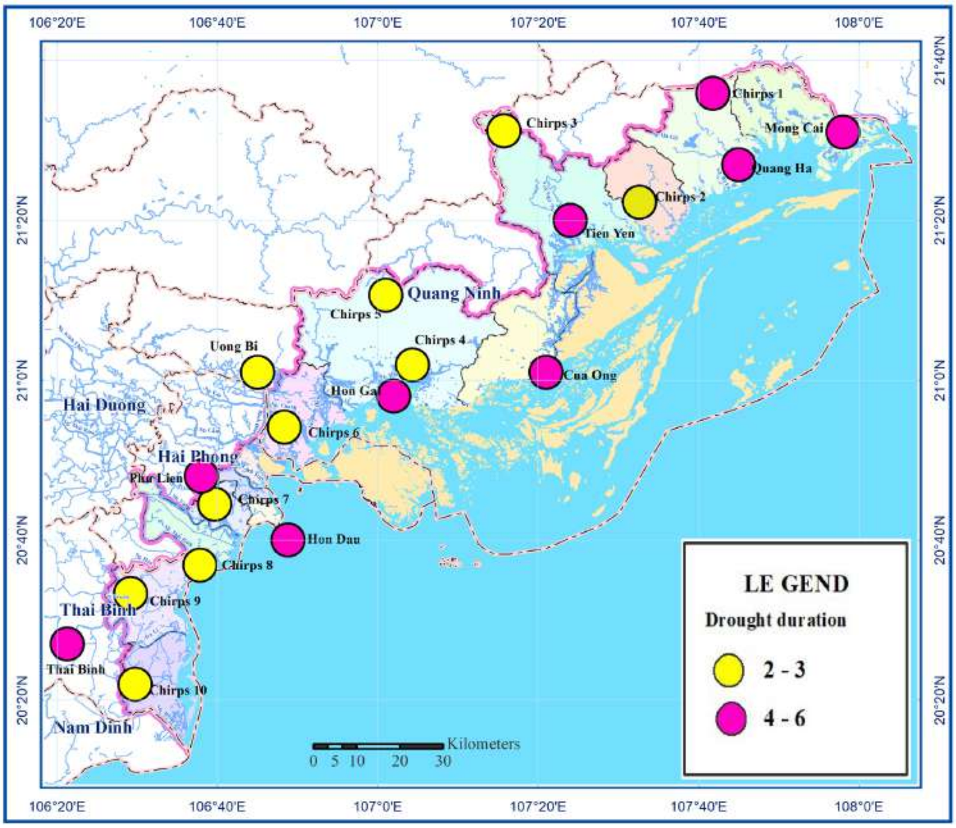


2001-2010

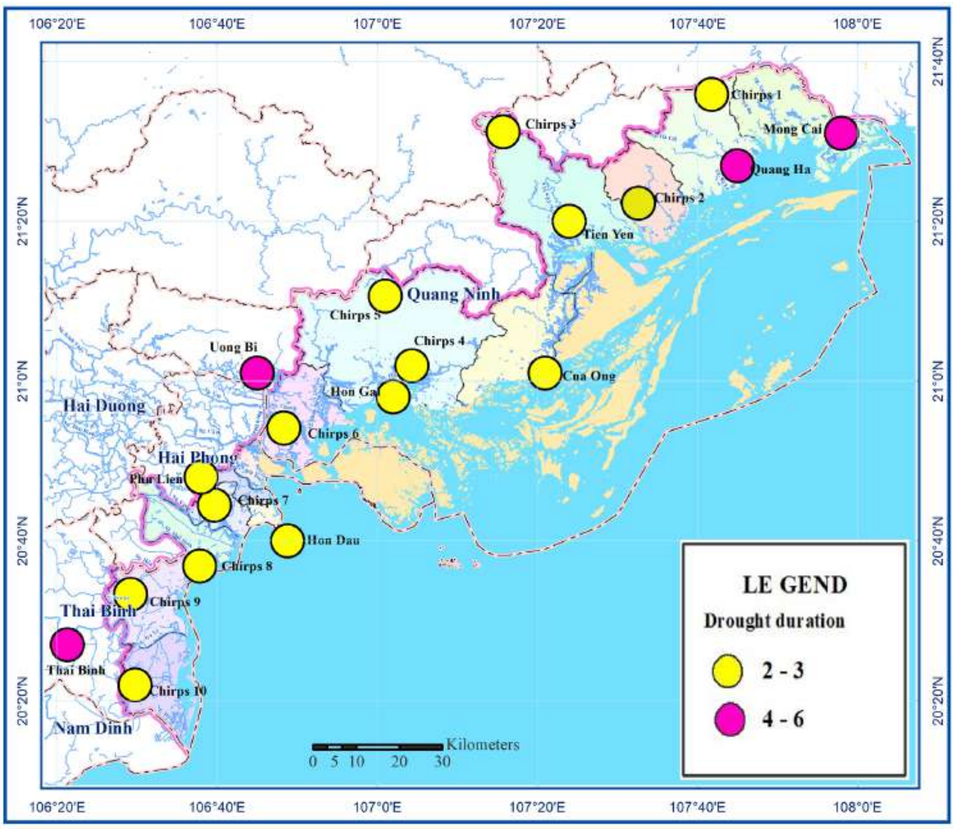


2011-2019

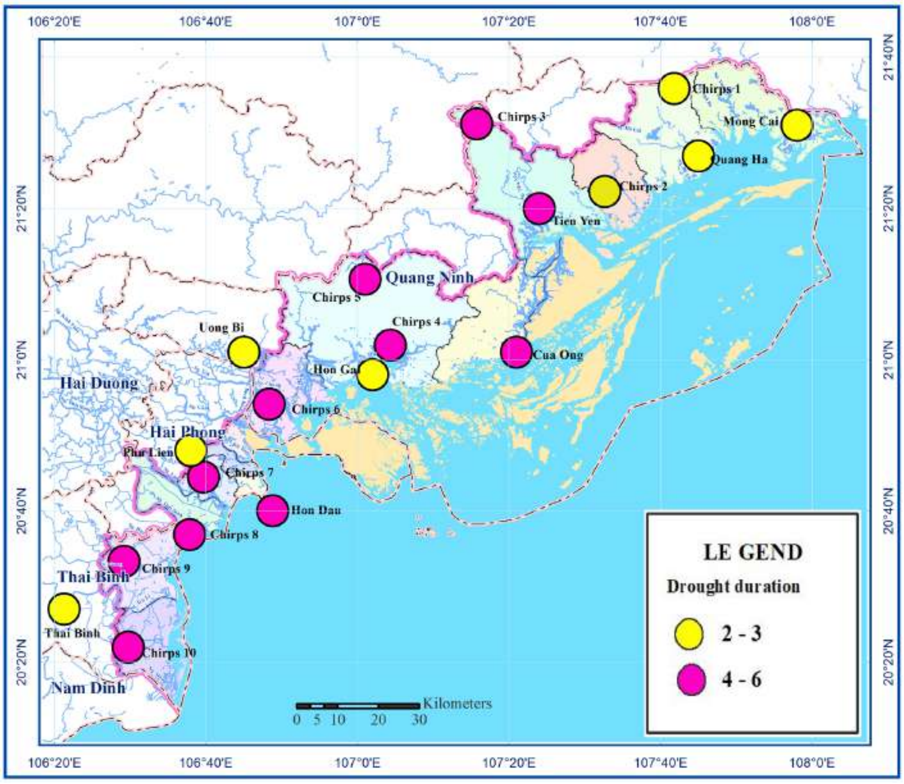
Figure 3. Spatial variation of the number of drought events in the North-Eastern coastal region of Vietnam from 1981 to 2019.



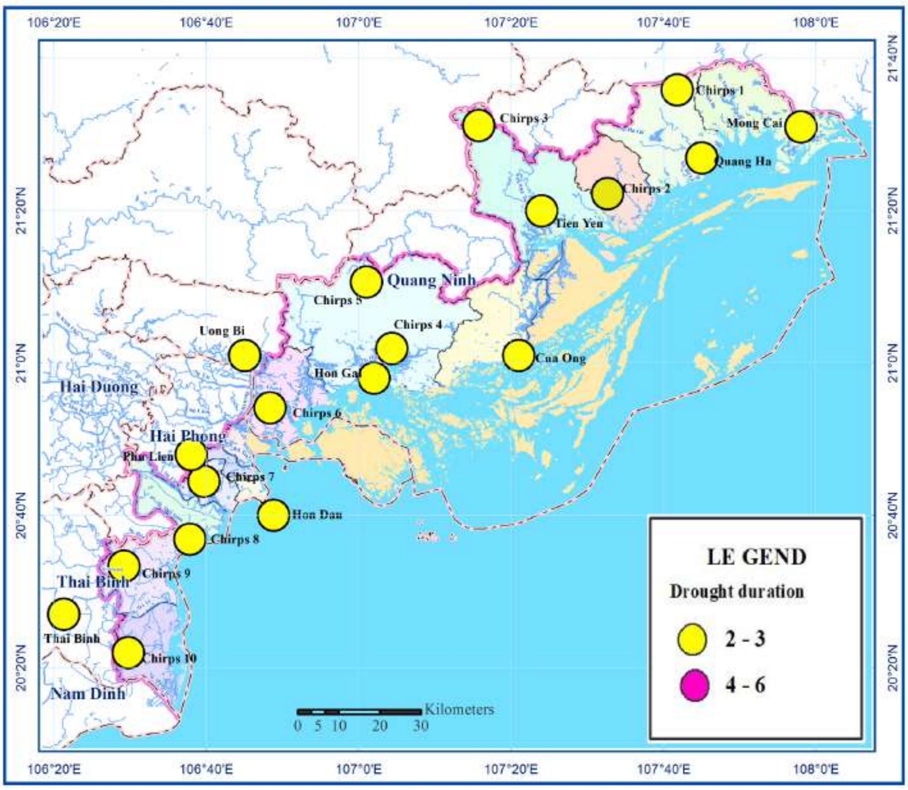
1981-1990



1991-2000

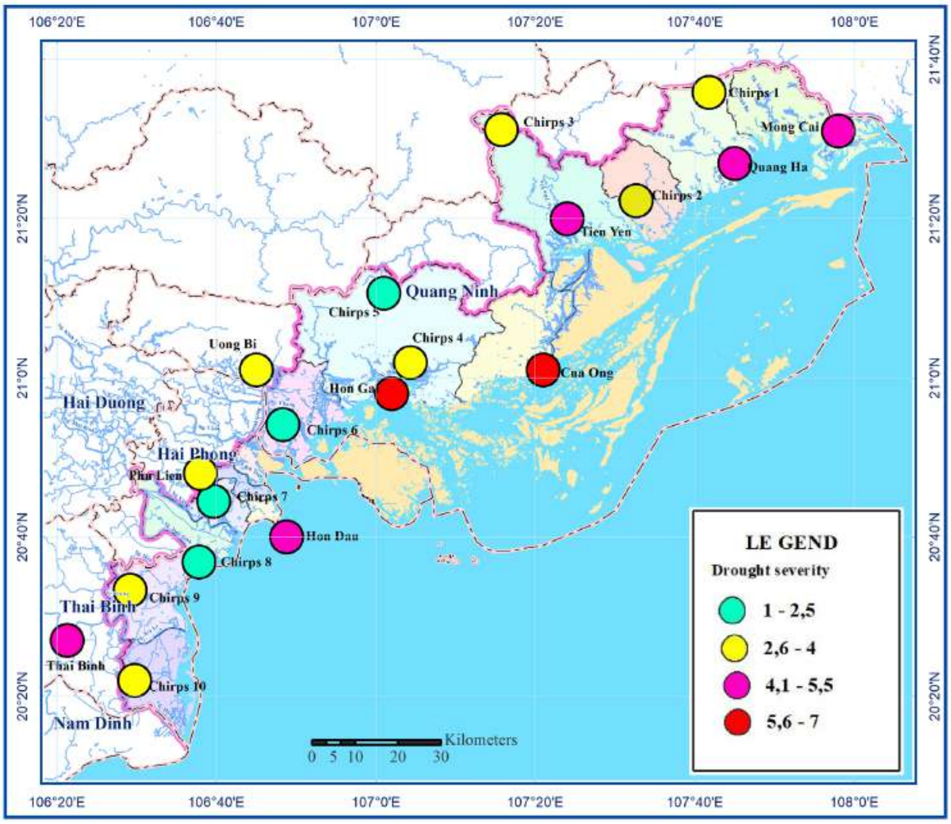


2001-2010

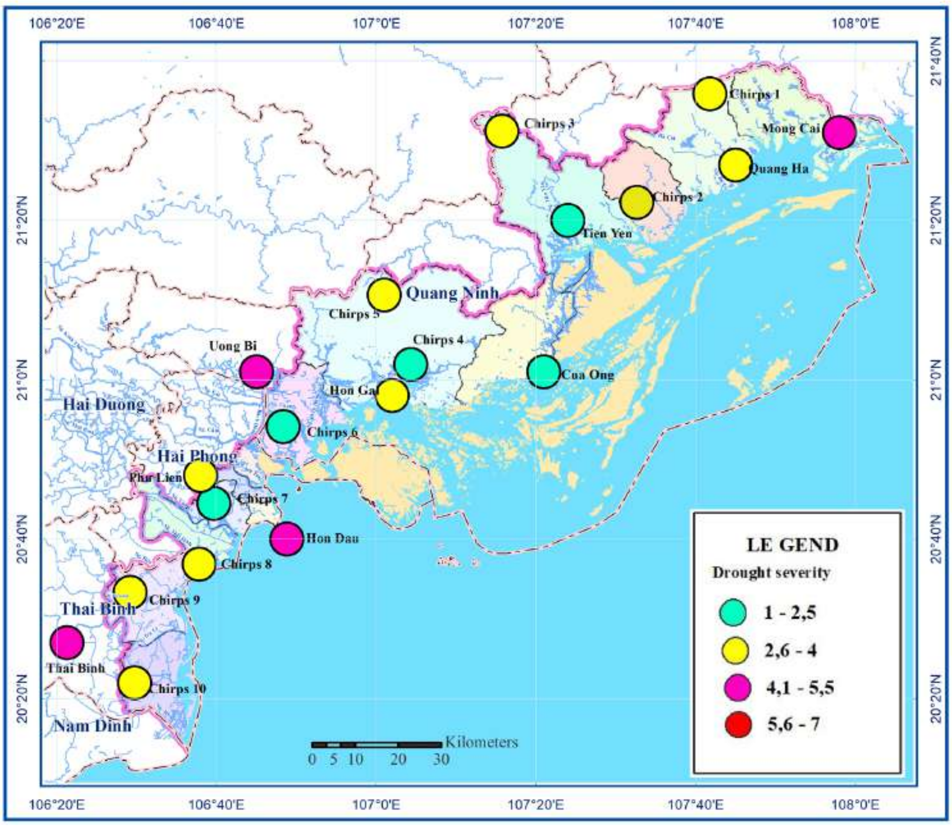


2011-2019

Figure 4. Spatial variation of drought duration in the North-Eastern coastal region of Vietnam from 1981 to 2019.



1981-1990



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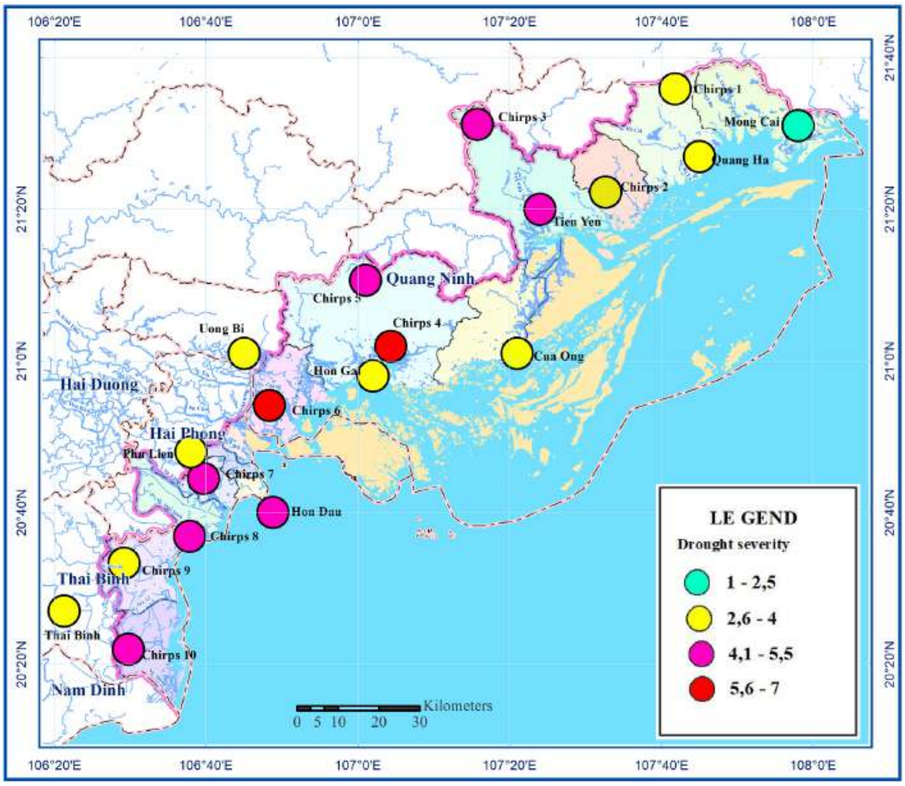
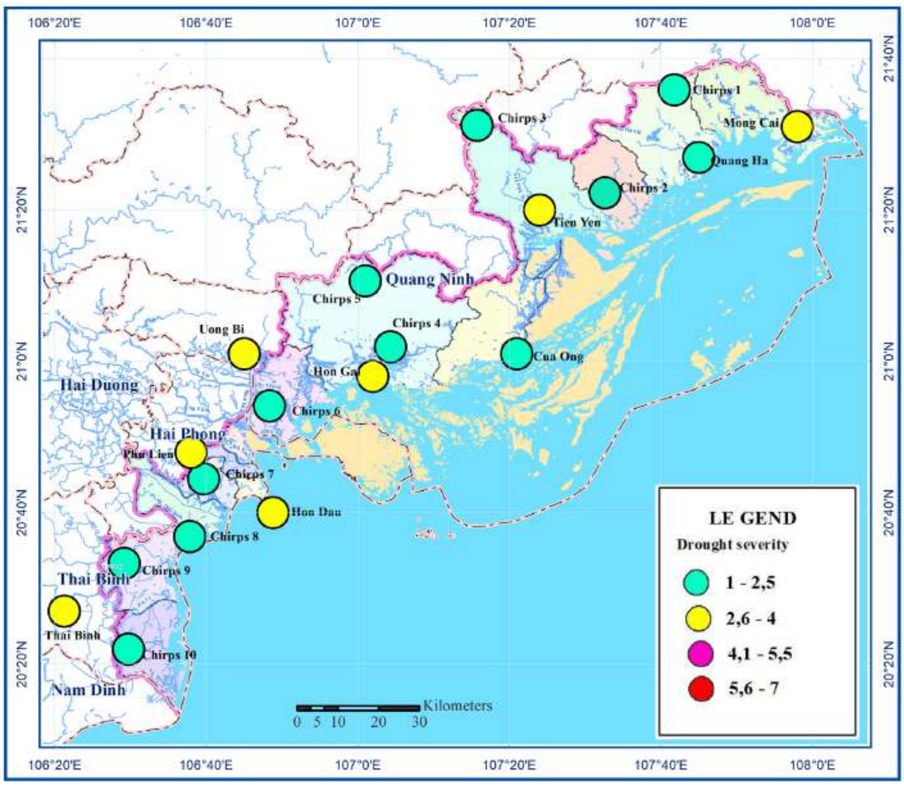
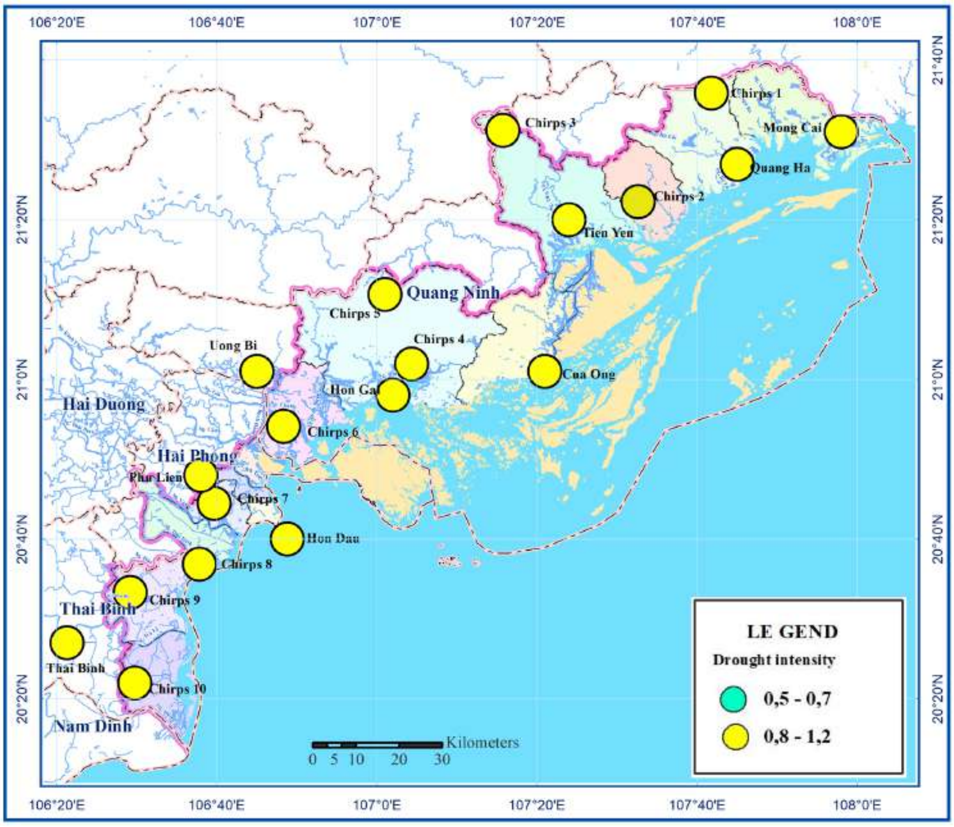


2001-2010

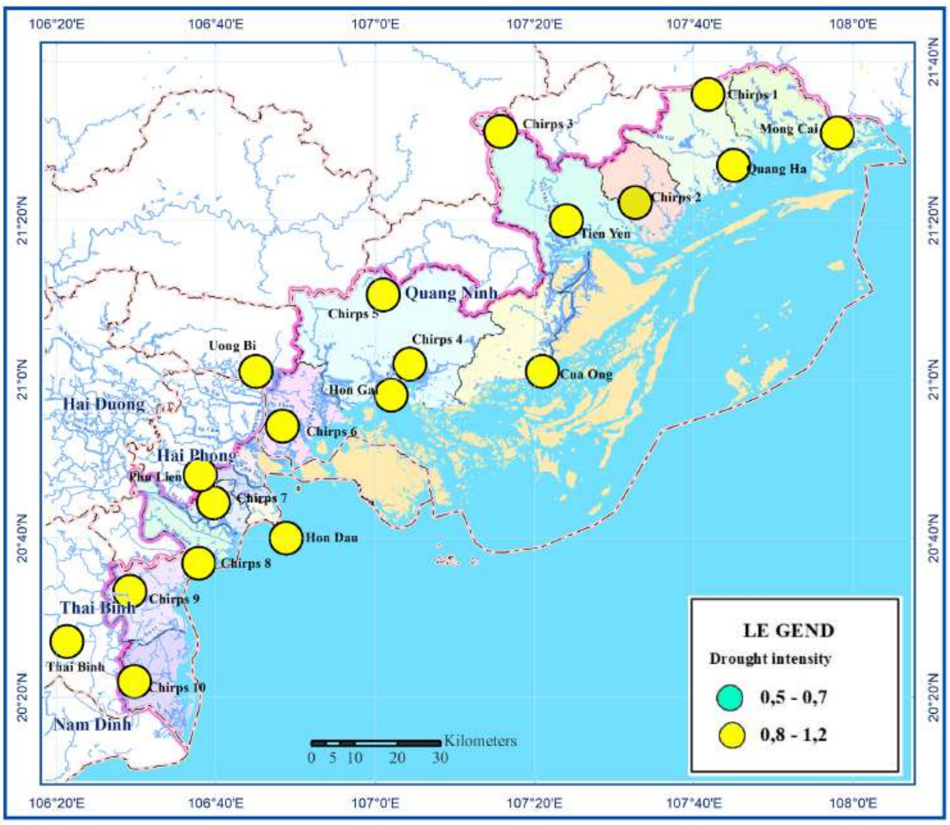


2011-2019

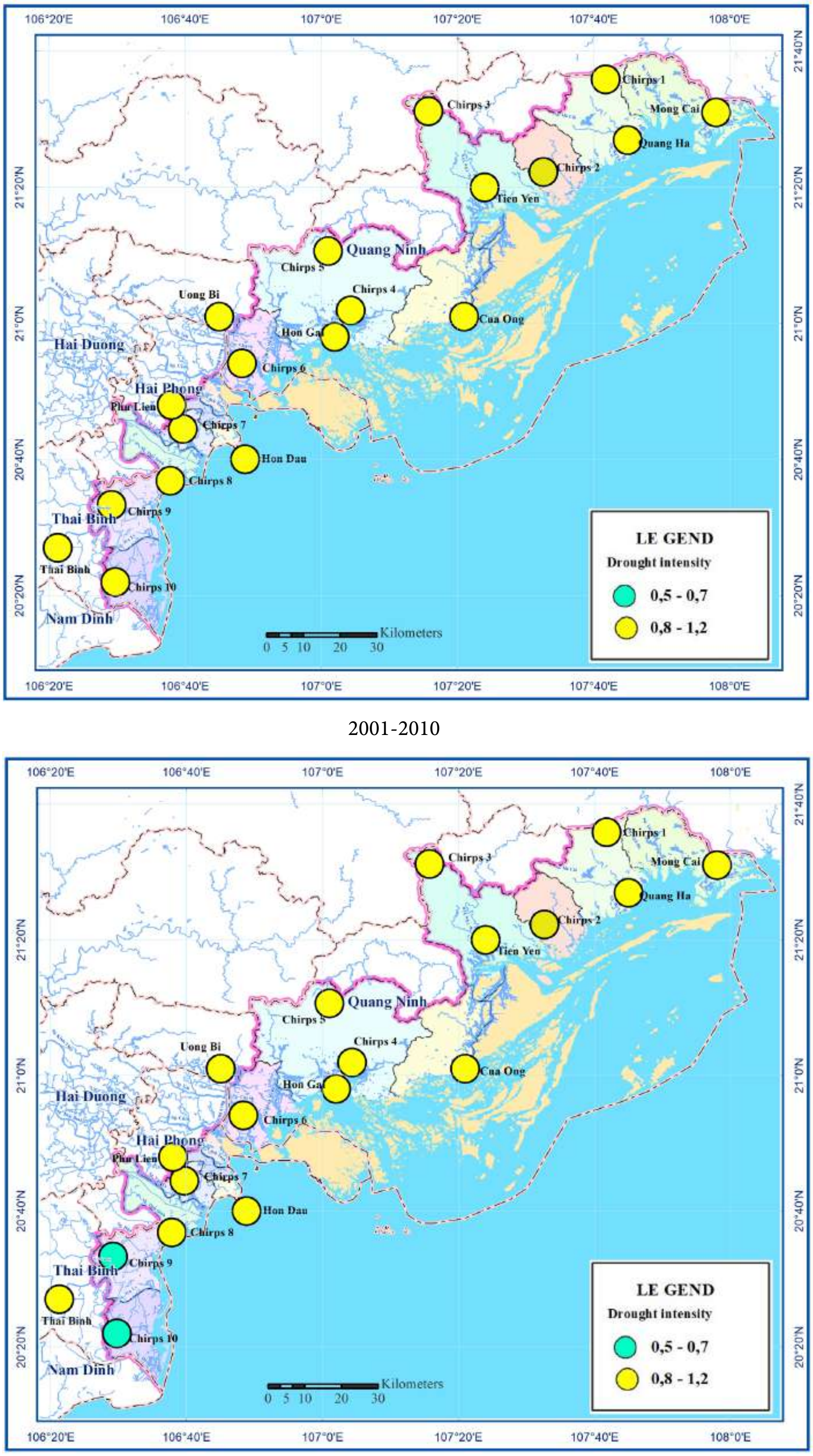
Figure 5. Spatial variation of drought severity in the North-Eastern coastal region of Vietnam from 1981 to 2019.



1981-1990



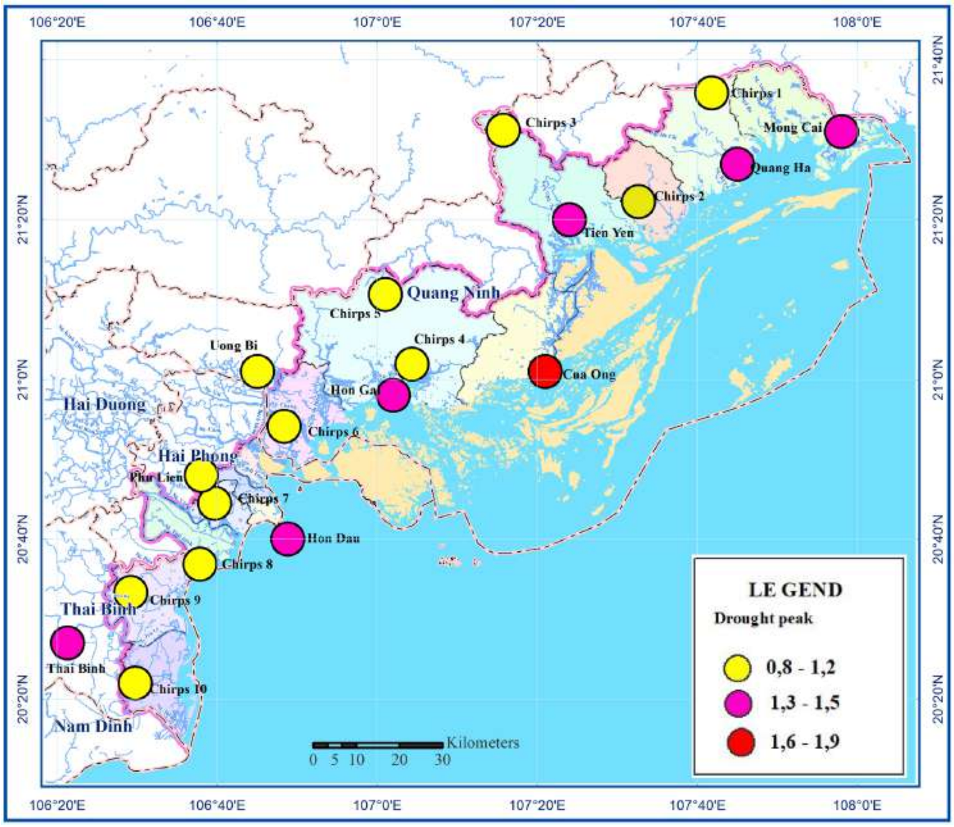
1991-2000



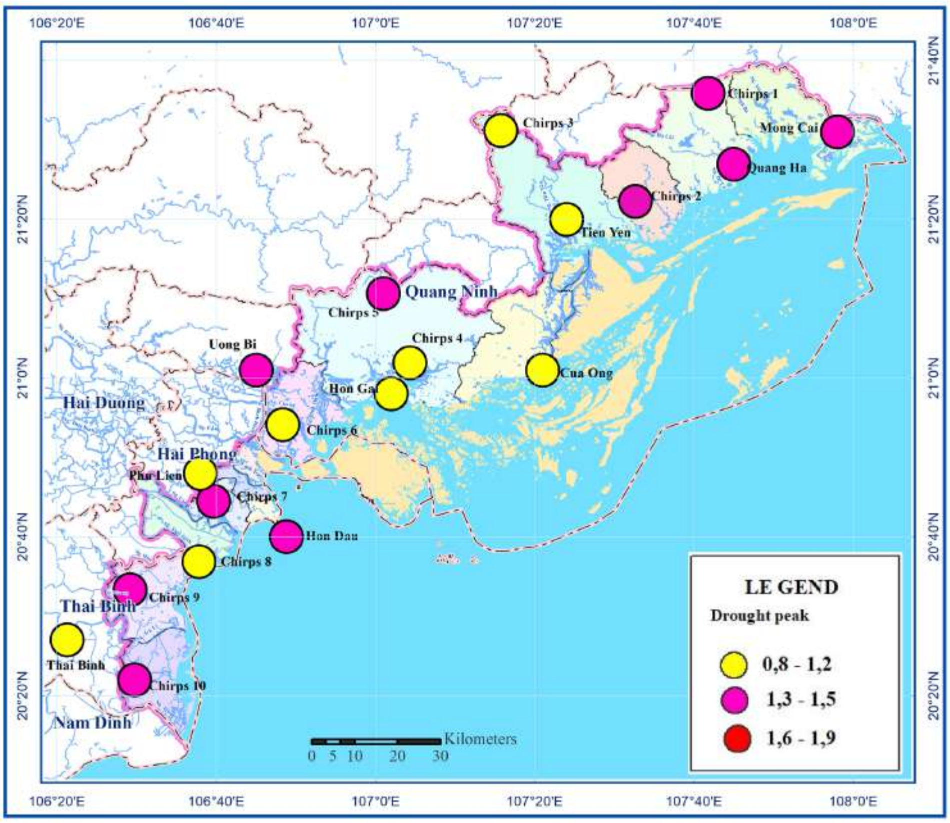
2001-2010

2011-2019

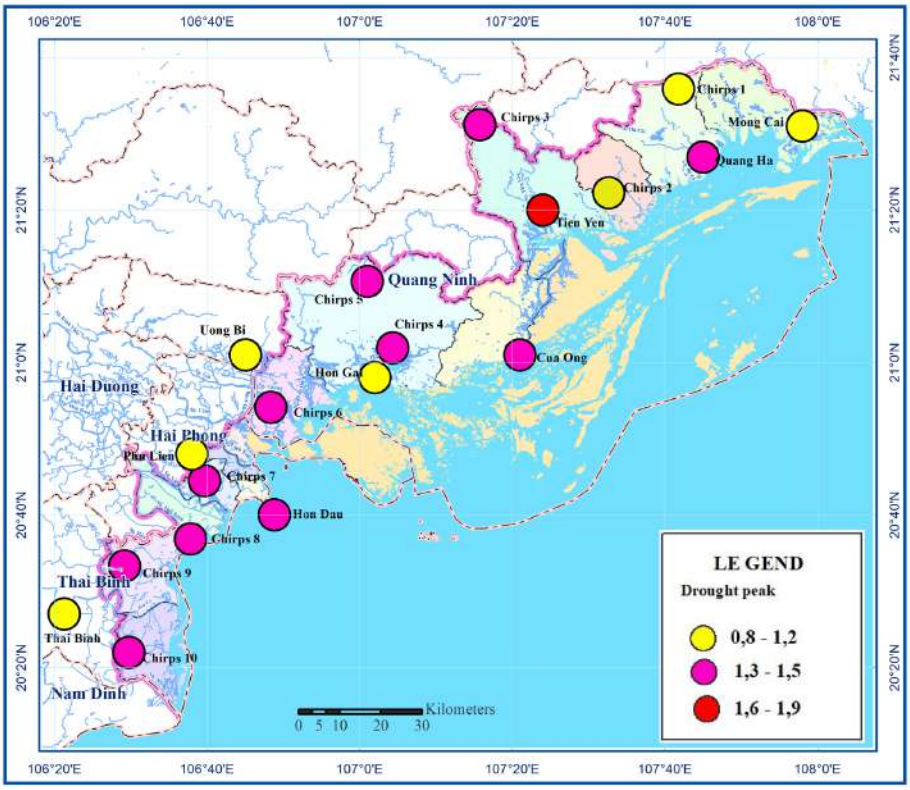
Figure 6. Spatial variation of drought intensity in the North-Eastern coastal region of Vietnam from 1981 to 2019.



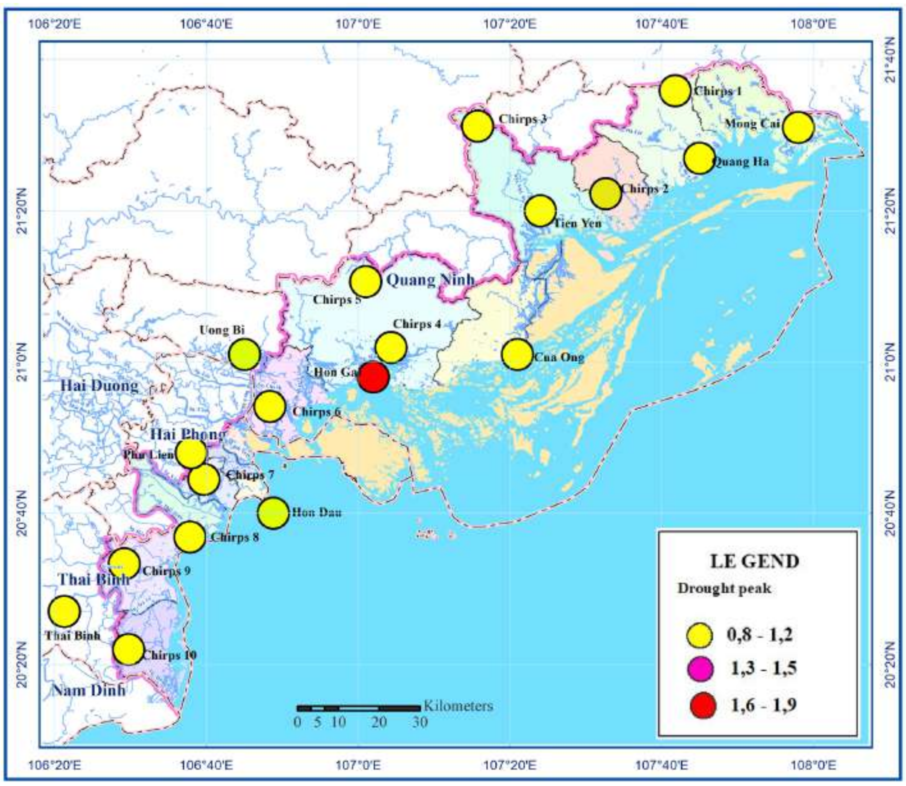
1981-1990



1991-2000



2001-2010



2011-2019

Figure 7. Spatial variation of drought peak in the North-Eastern coastal region of Vietnam from 1981 to 2019.

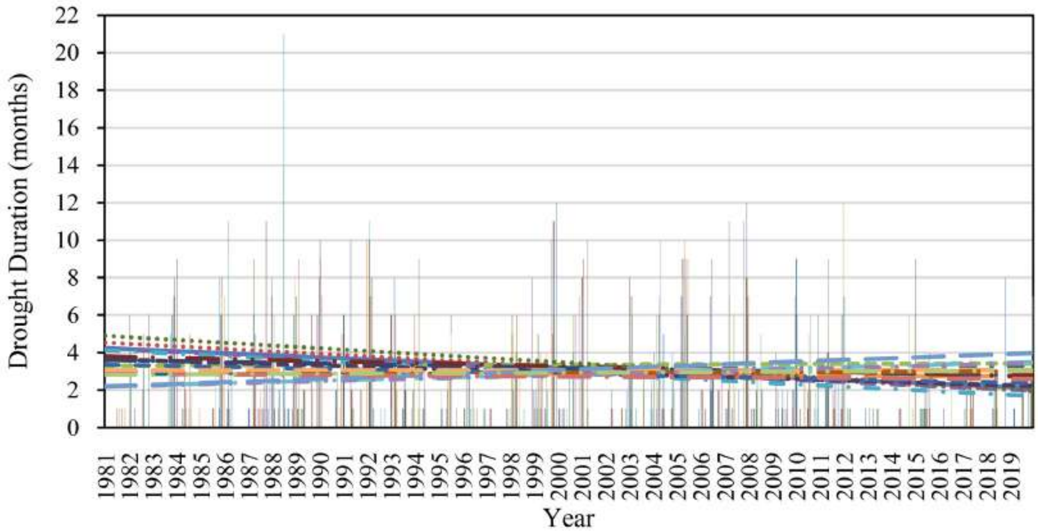
of 13. The average drought duration was cross-quarter at Mong Cai, Quang Ha, Uong Bi, and Thai Binh stations, and 1-season at the remaining stations. The average drought severity ranged from 2 (at Chirps 6 station) to 5.4 (at Mong Cai station), and the average drought severity was 3.2 of all the stations. The average drought intensity was moderate at all the stations. The average drought peak was severe at Mong Cai, Quang Ha, Uong Bi, Hon Dau, Chirps 1, Chirps 2, Chirps 5, Chirps 7, Chirps 9, and Chirps 10 stations, and was moderate at the remaining stations.

In the period 2001-2010: Severe or more intense droughts occurred throughout the study region in 2002, 2004, 2005, and 2007, and in Quang Ninh province in 2009 (see **Figure 2**). The number of drought events was from 11 (at Tien Yen, and Hon Dau stations) to 17 (at Chirps 2 station), making an average of 14 at all the stations. The average drought duration was 1-season at 8 stations, including Mong Cai, Quang Ha, Hon Gai, Uong Bi, Phu Lien, Thai Binh, Chirps 1, and Chirps 2 stations, and cross-quarter at the remaining 11 stations. The average drought severity was 4.0 of the whole study region, with the most of 5.8 at Chirps 4 station and the least of 1.9 at Mong Cai station. The average drought intensity was moderate at all the stations. The average drought peak was moderate at 7 stations (including Mong Cai, Hon Gai, Uong Bi, Phu Lien, Thai Binh, Chirps 1, and Chirps 2 stations), and severe at the remaining 12 stations (including Quang Ha, Tien Yen, Cua Ong, Hon Dau, Chirps 3, Chirps 4, Chirps 5, Chirps 6, Chirps 7, Chirps 8, Chirps 9, and Chirps 10 stations).

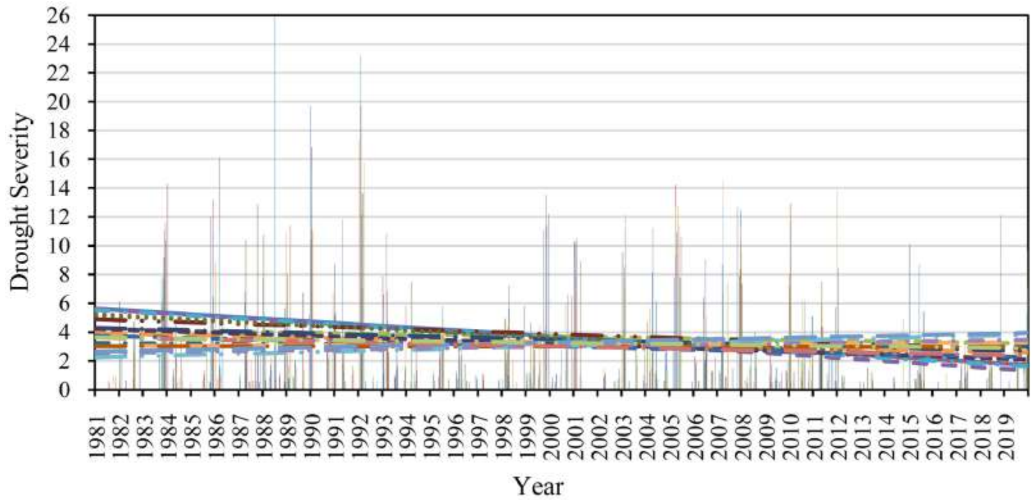
In the period 2011-2019: Severe or more intense droughts occurred over the North-Eastern coastal region in 2011 (see **Figure 2**). The number of drought events was from 5 (at Hon Dau station) to 12 (at Chirps 2 station), making an average of 8. The average drought duration was 1-season at all the stations. The average drought severity ranged from 1.2 (at Chirps 4 station) to 3.6 (at Hon Gai station), and the average drought severity of all stations was 2.2. The average drought intensity was moderate at all the stations. The average drought peak was extreme at Hon Gai station only and moderate at all the remaining stations.

In general, the rainfall data obtained from the Chirps rainfall stations that were added in areas where rainfall data are unavailable and from the ground rainfall stations, allowed a more detailed performance of the spatial and temporal distributions of the drought characteristics. Among the 5 drought characteristics considered, the spatio-temporal variant of drought number and severity was more significant, the variant of drought intensity was the slightest, and the spatial change of 5 drought characteristics was the smallest in the period 2011-2019. Drought events in the study region mainly occurred in 1-season duration and at moderate intensity and peak. In the 4 periods, the drought events occurred with the highest number, longest duration, most severity, and greatest peak in the period 2001-2010, while the drought events occurred with the least number, shortest duration, least severity, and smallest peak in the period 2011-2019.

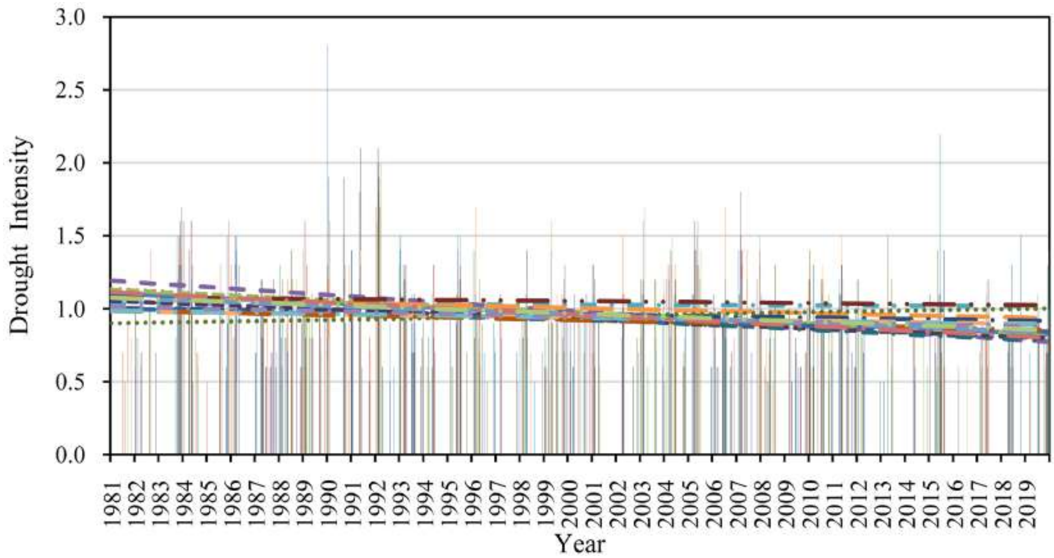
Figure 8 shows the temporal variation of drought characteristics (including drought duration, severity, intensity, and peak) based on SPI-6 from 1981 to


Drought Duration (months)
Year

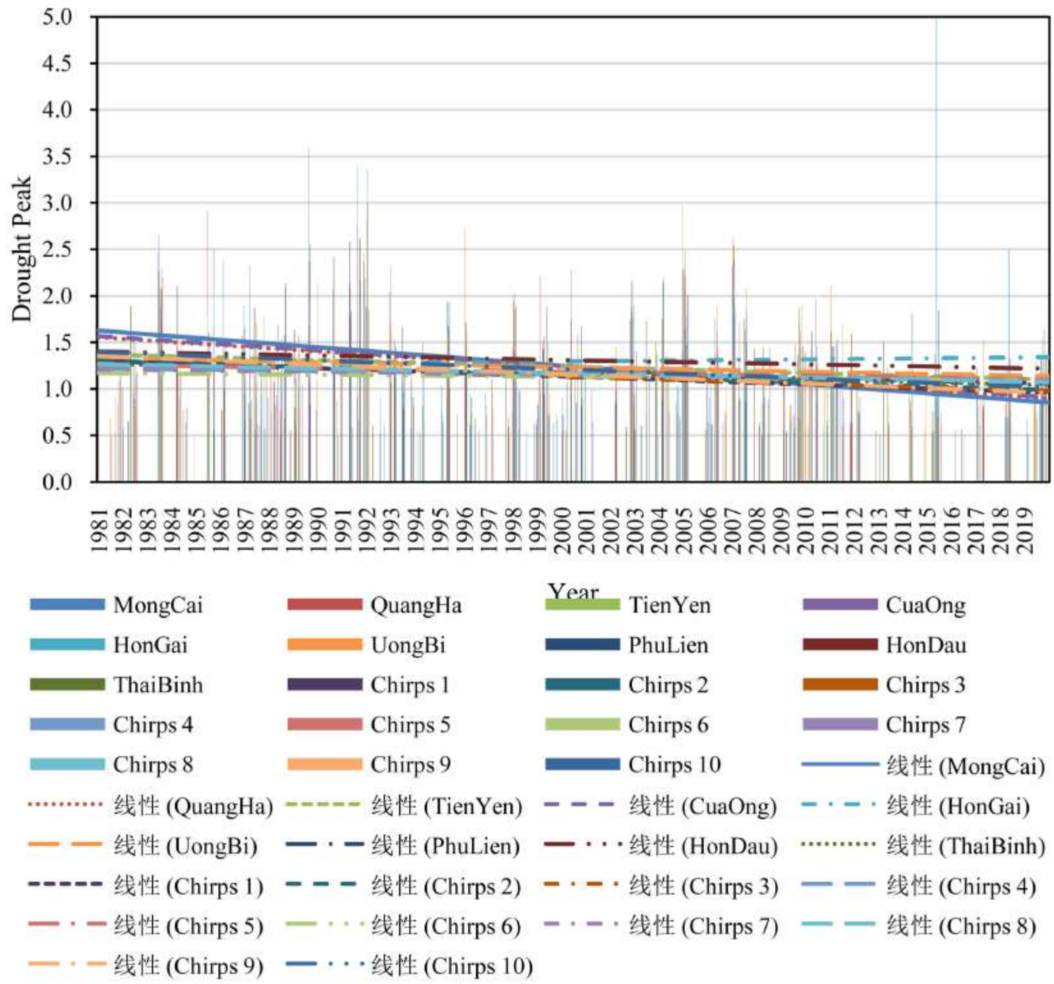
(a)


Drought Severity
Year

(b)


Drought Intensity
Year

(c)



(d)

Figure 8. Temporal variation of drought characteristics based on SPI-6 from 1981 to 2019 at the 9 meteorological station and 10 Chirps stations in the North-Eastern coastal region of Vietnam: (a) Drought duration; (b) Drought Severity; (c) Drought Intensity; (d) Drought peak.

2019 at the 9 meteorological station and 10 Chirps stations in the North-Eastern coastal region of Vietnam. It can be seen from **Figure 8** that:

Drought duration (see **Figure 8(a)**) tends to decrease at 11 stations, increase at 7 stations, and remain almost constant at 1 station, specifically, the drought duration tends to decrease gradually at Thai Binh, Quang Ha, Hon Gai, Cua Ong, Mong Cai, Hon Dau, Chirps 2, Chirps 1, Phu Lien, Chirps 9, Uong Bi stations; and tends to increase gradually at Chirps 8, Chirps 6, Chirps 7, Chirps 3, Chirps 10, Chirps 5, Tien Yen stations, and has not significant trend at Chirps 4 station.

Drought severity (see **Figure 8(b)**) tends to decrease at 14 stations, increase at 4 stations, and remain almost constant at 1 station, specifically, the drought severity tends to decrease gradually at Cua Ong, Mong Cai, Hon Gai, Quang Ha, Thai Binh, Chirps 1, Hon Dau, Phu Lien, Chirps 2, Uong Bi, Chirps 9, Tien Yen, Chirps 10, Chirps 3 stations; increase gradually at Chirps 6, Chirps 8, Chirps 7, Chirps 4 stations, and be almost the same at Chirps 5 station.

Drought intensity (see **Figure 8(c)**) tends to decrease at 17 stations, increase at 1 station, and does not change much at 1 station, specifically, it tends to decrease gradually at Cua Ong, Chirps 3, Quang Ha, Tien Yen, Chirps 9, Mong Cai, Chirps 1, Chirps 8, Chirps 10, Uong Bi, Chirps 2, Chirps 5, Chirps 7, Phu Lien, Chirps 4, Chirps 6, and Hon Dau stations; and increase gradually at Thai Binh station, and be almost the same at Hon Gai station.

Drought peak (see **Figure 8(d)**) tends to decrease at 18 stations and increase at 1 station, specifically, the drought peak tends to decrease gradually at Mong Cai, Quang Ha, Cua Ong, Chirps 9, Chirps 10, Chirps 1, Chirps 2, Tien Yen, Chirps 3, Phu Lien, Thai Binh, Uong Bi, Hon Dau, Chirps 8, Chirps 4, Chirps 5, Chirps 6, and Chirps 7 stations; and increase gradually at Hon Gai station.

4. Conclusions

In this study, satellite rain was examined to supplement rainfall data in areas without rain gauges, SPI with a suitable timescale was selected, and the spatio-temporal variation of drought characteristics was analyzed using SPI with the most suitable timescale. The results are as follows:

The Chirps' monthly rainfall is reliable to supplement the rainfall data for the study region.

SPI at the timescale of 6 months was the best for reflecting drought in the North-Eastern coastal region of Vietnam.

From 1981 to 2019, the drought events mainly occurred with 1-season duration and at moderate intensity and peak. The number, duration, severity, and peak of the drought events were the greatest in the period 2001-2010 and were the smallest in the period 2011-2019. Among the 19 meteorological stations, the stations with decreasing values of drought characteristics are more than those with increasing values of drought characteristics. Specifically, the drought duration tends to decrease at 11 stations, increase at 7 stations, and be almost the same at 1 station; the drought severity tends to decrease at 14 stations, increase at 4 stations, and has no significant trend at 1 station; the drought intensity tends to decrease at 17 stations, increase at 1 station, and has no significant trend at 1 station; and the drought peak tends to decrease at 18 stations and increase at 1 station.

This study can provide useful information to develop water supply management plans and improve water resources management under drought conditions. However, this study analyzed only the spatial and temporal variation of individual drought characteristics while exploring the spatial and temporal variation of the joint distributions and joint return periods of drought characteristics also provides valuable information for the management and mitigation of damage caused by drought. The results of this study are the basis for further studies on the spatio-temporal variant of the joint distribution of drought characteristics in the study region.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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