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Space-time characterization of droughts in the Mae Klong River Basin, Thailand, using rainfall anomaly index

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ABSTRACT

Drought is a slow-onset natural hazard that has major social, economic, and environmental consequences. This study examined the temporal and spatial characteristics of meteorological droughts in the Mae Klong River Basin, Thailand, during 1971–2015. The rainfall anomaly index (RAI) was calculated for 3, 6, and 12 months using monthly observed rainfall data from eight stations. The RAI results showed the presence of multiple drought events ranging from moderate to severe conditions over the study period. Trend analysis was carried out for the drought duration, magnitude, and intensity using the Mann-Kendall test and the Sen's slope method. Increasing trends were found for drought intensity for both the 6- and 12-month time scales. The performance of RAI was assessed by comparison with the standardized precipitation index (SPI). In general, a high correlation (Pearson's coefficient $r>0.93$) was found between RAI and SPI. Cohen's Kappa test indicated fair agreement between the results of the two drought indices. The findings of this study are expected to help decision-makers better manage the basin's water resources.

Key words: drought, Mae Klong River Basin, rainfall, rainfall anomaly index

HIGHLIGHTS

- Spatial and temporal characteristics of meteorological droughts in the Mae Klong River Basin were examined by using the rainfall anomaly index (RAI).
- Results of RAI were compared with the standardized precipitation index (SPI). In general, high correlation (Pearson's correlation $r>0.93$) was found. However, Cohen's Kappa indicated a fair agreement between the results of the two indices.

1. INTRODUCTION

Drought is defined as a period when there is less rainfall than usual. Low rainfall can result in less runoff, which can contribute to a hydrological drought. River levels are dropping, water storage is decreasing, and soils are becoming drier. People and their chances of survival may be harmed because of the shortage of water. Drought in agriculture entails lower output, lower revenue, and a strain on communities. The effects of the socioeconomic drought are spreading throughout the community. During a drought, our entire environment is susceptible. In some circumstances, it may take several wet months for the landscape, waterways, and communities to recover.

Thailand is situated in a tropical region where rainfall provides adequate water throughout the rainy season (May to October). Droughts are more likely to occur during the dry season, which runs from November to April. In recent decades, Thailand has seen numerous floods and droughts. Thailand is one of the world's largest rice exporters. In 2015, Thailand faced its worst drought in over a decade, which had a severe impact on the agriculture sector. Drought directly impacted 8 out of 76 provinces, while 31 others remained at high risk. The off-season rice crop was reduced by more than 30%. The off-season crop requires irrigation water since it is grown during the dry season. Around 1.3% of the total rice farmland in Thailand was affected by drought (Reuters 2015). In 2019, the monsoon arrived two weeks later than expected and departed three weeks earlier. Insufficient rainfall along with high temperatures and evapotranspiration due to an El Niño event resulted in a drought situation (Mekong River Commission 2019). Approximately half of Thailand's largest reservoirs were operating at less than 50% of

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their capacity. Low river water levels promoted saltwater intrusion, posing a threat to the local water supply. In a country where 11 million people work in agriculture, the dry period posed a threat to crop production and the economy (AsiaNews 2020).

Many research studies have used the rainfall anomaly index (RAI) for the assessment of meteorological droughts. In Chahal *et al.* (2021), they studied spatio-temporal drought over the Sahibi river basin in Rajasthan, India using RAI on two time scales, i.e., annual and monsoon season. Run theory analysis was used to analyze drought characteristics (magnitude, duration, and intensity). During the study period 1961–2017, drought episodes were more common during the monsoon season. Ndlovu & Demlie (2020) used percent of normal precipitation index (PNPI) and RAI for meteorological drought assessment in KwaZulu-Natal Province, South Africa. Results indicated that RAI was more robust compared with PNPI for drought assessment. Goswami (2018) studied the intensity and frequency of wet and dry years using RAI for selected districts in the sub-Himalayan region of West Bengal, India. Results showed that the number of dry years was more than the wet years for all the districts in the study area from 1901 to 2010.

Drought indices are used by researchers to assess the consequences of drought in any given region, which may aid in the optimal distribution of water resources for various water use sectors. The main objectives of this research study were (i) to assess the spatio-temporal distribution of droughts using the RAI in the Mae Klong River Basin and (ii) to evaluate the effectiveness of the rainfall anomaly index by comparing it with the standardized precipitation index (SPI).

2. STUDY AREA

The Mae Klong River Basin lies in the domain of 13 °8′–16 °23′ N in latitude and 98 °11′–100 °13′ E in longitude with a total area of 30,167 km^2 as shown in Figure 1. The Mae Klong River, which feeds into the Gulf of Thailand, is formed by the confluence of two major tributaries, Khwae Yai (with a total length of 450 km) and Khwae Noi (with a total length of about 320 km). The Lam Thaphoen River empties into the Khwae Yai River, whereas the Lampachi River empties into the Khwae Noi River. Two major reservoirs, Srinagarind Dam on the Khwae Yai River and Vajiralongkorn Dam on the Khwae Noi River, have been built to regulate downstream flows. The Tha Thung Na Dam, which is downstream of the Srinagarind Dam, and the Mae Klong Dam, which is on the Mae Klong River, are two diversion dams. The water from the Mae Klong Dam is redirected for irrigation to the Greater Mae Klong Irrigation Project (GMKIP), which consists of eight sub-irrigation projects in the lower area of the basin: two on the right side and six on the left side of the Mae Klong River. Land use in the basin consists of forest (68.13%), agriculture (22.90%), urban (3.40%), miscellaneous areas (2.47%), and water (3.10%). Water is used for municipal and industrial uses, irrigation, salinity control, and hydropower inside the basin, while outside the basin, water is delivered to the Bangkok Metropolitan Waterworks Authority and diverted to the neighboring Tha Chin Basin during the dry season (Khalil *et al.* 2018).

3. MATERIALS AND METHODS

3.1. Data

In this study, monthly rainfall data from 1971 to 2015 were used. For calculation of the RAI, rainfall data from eight stations were provided by Royal Irrigation Department (RID) and Thai Meteorological Department (TMD). The spatial distribution of the eight stations is shown in Figure 2(a). The inverse distance weighting (IDW) technique was used to interpolate the mean annual rainfall in a GIS as shown in Figure 2(b). It shows that the western side of the basin received more rainfall than the eastern side. The annual time series of the rainfall for the eight stations is shown in Figure 3. Table 1 shows the statistical features of annual rainfall. The mean annual rainfall ranges from 840.73 mm (Stn130042) to 1,767.93 mm (Stn130053).

3.2. Methodology

3.2.1. RAI

The rainfall anomaly index was developed by Van Rooy (1965). The RAI considers two anomalies, i.e., positive anomaly and negative anomaly. First, the precipitation data are arranged in descending order. The ten highest values are averaged to form a threshold for positive anomaly and the ten lowest values are averaged to form a threshold for negative anomaly. The thresholds are calculated by Equations (1) and (2), respectively (Salehnia *et al.* 2017). Table 2 shows the rainfall anomaly

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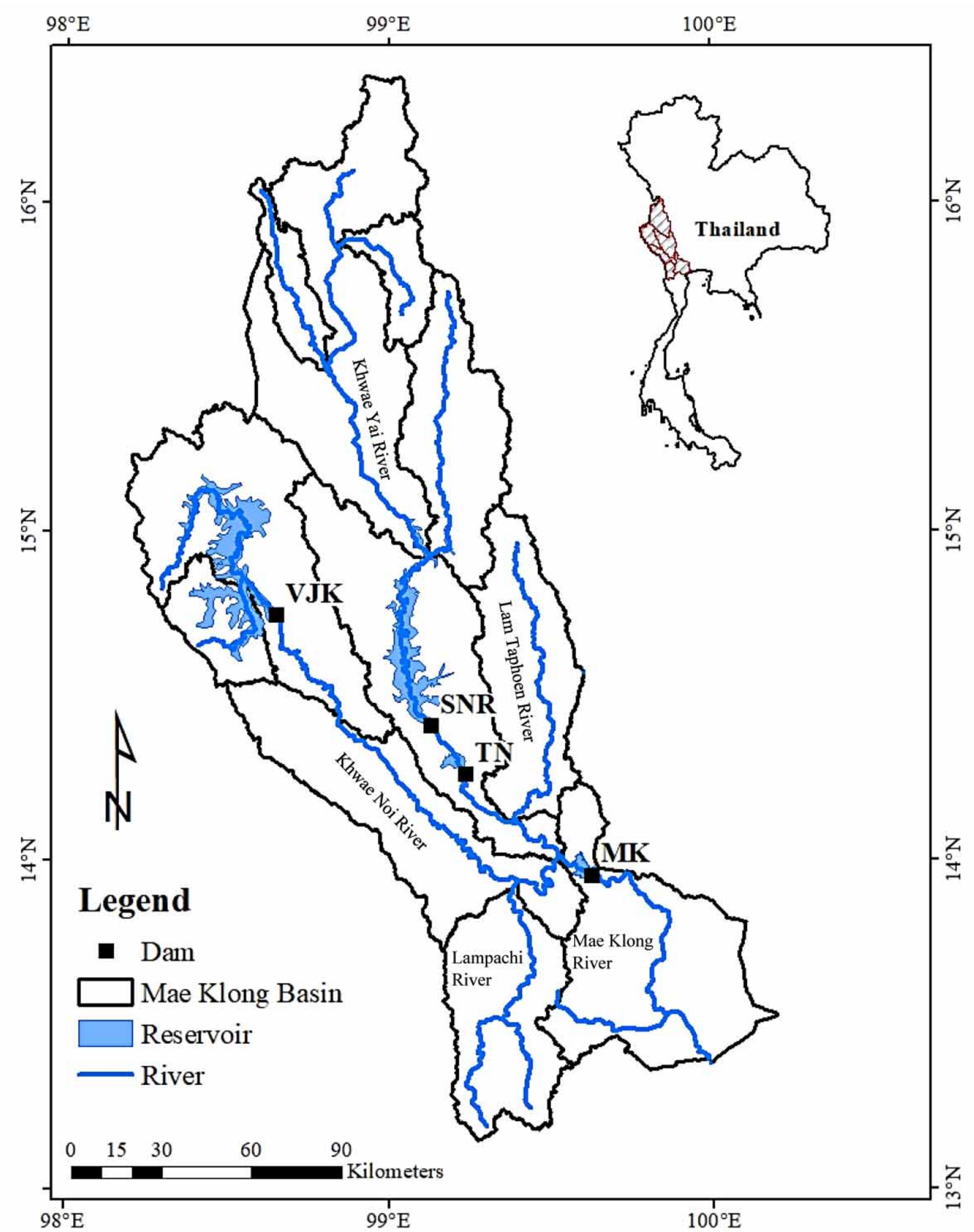

Figure 1 | The Mae Klong River Basin.

index classification used in the present study (Fluixá-Sanmartín *et al.* 2018).

$$RAI = 3 \times \left[\frac{p - \bar{p}}{\bar{m} - \bar{p}}\right] \tag{1}$$

$$RAI = -3 \times \left[\frac{p - \bar{p}}{\bar{m} - \bar{p}}\right] \tag{2}$$

where

p = the actual precipitation for each year (mm)

$\bar{p}$ = the long-term average precipitation (mm)

$\bar{m}$ = the mean of the ten highest values of p for the positive anomaly and the mean of the ten lowest values of p for the negative anomaly.

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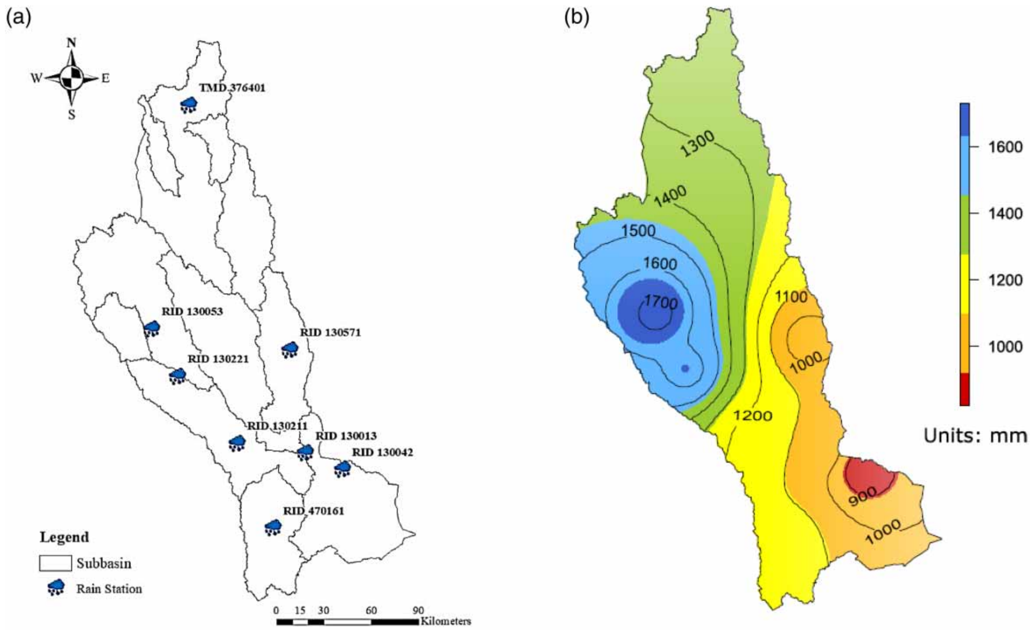

Figure 2 | Spatial distribution of (a) rainfall stations (b) mean annual rainfall in millimeter for the period 1971–2015 in the Mae Klong River Basin.

Details about the methodology and drought severity classification for the SPI can be found in Khalil (2020).

3.2.2. Pearson's correlation coefficient

It measures the strength of the linear relationship between the two variables. It ranges between −1 and +1. A value close to −1 indicates a very strong negative correlation, and a value close to +1 indicates a very strong positive correlation. It can be calculated by Equation (3)

$$r = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} (y_i - \bar{y})^2}} \quad (3)$$

where n is the sample size, $\bar{x}$ and $\bar{y}$ are the means of the x_i and y_i data sets, respectively.

3.2.3. Cohen's Kappa test

In this test the similarity between the drought indices can be quantified by their degree of agreement. This test is often applied to evaluate the degree of agreement between two raters, methods, or classifiers, mainly in medical sciences. The Kappa test is based on the following coefficient of agreement K, corrected for chance (Vergni *et al.* 2021):

$$K = \frac{P_0 - P_e}{1 - P_e} \quad (4)$$

where P_0 is the total observed frequency of agreement and P_e is the proportion of agreement expected by chance. In practice, K indicates how much the observational frequency of agreement is in excess of the frequency of agreement P_e, expected under a random classification. More details about the test can be found in Vergni *et al.* (2021). One way to interpret Kappa is given in Table 3 (Landis & Koch 1977).

The calculations above only consider exact matches between two drought indices. If the categories (Wet, Normal, Moderate drought, Severe drought, and Extreme drought) are ordered, we may wish to consider close matches. In other words, if

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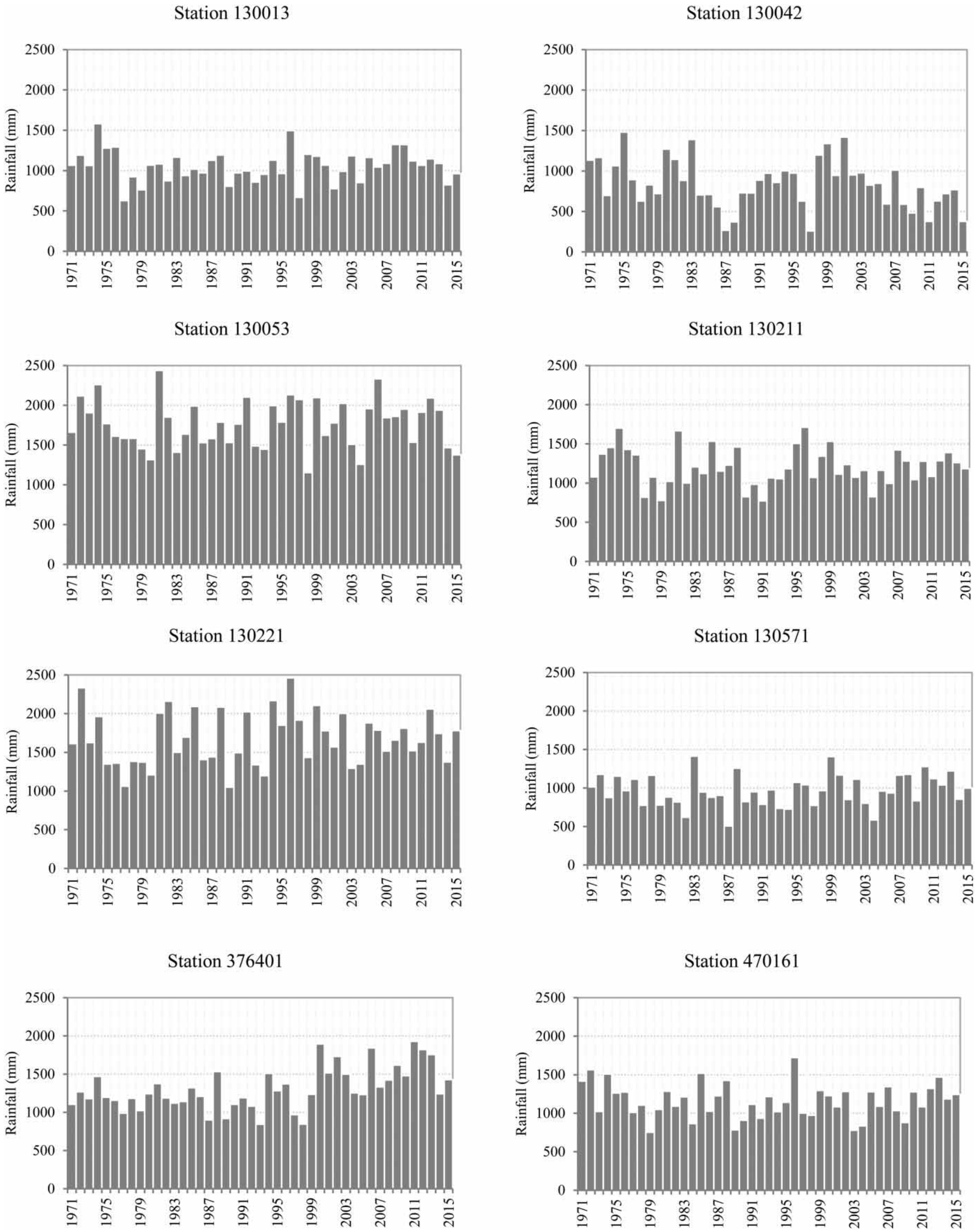

Figure 3 | Annual rainfall of 8 stations in the Mae Klong River Basin during 1971–2015.

one drought index classifies a subject into group 'Normal' and the other into group 'Moderate drought', this is closer than if one classifies into 'Wet' and the other into 'Severe drought'. The calculation of weighted Kappa assumes the categories are ordered and accounts for how far apart the two drought indices are. This calculation used linear weights.

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Table 1 | Statistical properties of annual rainfall data from 1971 to 2015

Rainfall Stations		Min. Rainfall (mm)	Max. Rainfall (mm)	Avg. Rainfall (mm)	Standard Deviation (mm)	CV	Skewness
Name	Code						
A. Mueang, Kanchanaburi	Station 130013	627.70	1,581.70	1,055.87	194.72	0.18	0.228
A. Tha Maka, Kanchanaburi	Station 130042	260.30	1,481.20	840.73	300.72	0.36	0.144
A. Thong Pha Phum, Kanchanaburi	Station 130053	1,155	2,438.70	1,767.93	298.08	0.17	0.124
Ban Lum Sum, Kanchanaburi	Station 130211	774.20	1,713.50	1,207.41	239.39	0.20	0.202
Huai Mae Nam Noi, Kanchanaburi	Station 130221	1,049.80	2,462.10	1,677.58	342.86	0.20	0.271
Ban Thong Pong, Kanchanaburi	Station 130571	508.88	1,414.41	970.49	204.80	0.21	0.037
Umphang, Tak	Station 376401	844.57	1,928.90	1,310.84	277.50	0.21	0.530
Ban Bo, Ratchaburi	Station 470161	754.00	1,722.20	1,159.71	222.40	0.19	0.315

Table 2 | RAI classification

RAI classes	Drought category
≥3.0	Extremely wet
2.0 to 2.99	Very wet
1.0 to 1.99	Moderately wet
0.50 to 0.99	Slightly wet
−0.49 to 0.49	Near normal
−0.99 to −0.50	Slightly dry
−1.99 to −1.0	Moderately dry
−2.99 to −2.0	Severely dry
≤−3.0	Extremely dry

Table 3 | Ranges of the Kappa statistic K and corresponding strength of agreement

Kappa statistic	Strength of agreement
<0.00	Poor
0.00–0.20	Slight
0.21–0.40	Fair
0.41–0.60	Moderate
0.61–0.80	Substantial
0.81–1.00	Almost perfect

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3.2.4. Mann–Kendall (MK) trend test

The Mann-Kendall test statistic S (Mann 1945; Kendall 1975) is calculated as;

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{Sgn}(x_j - x_k) \tag{5}$$

where

$$\mathrm{Sgn}(x_j - x_k) = \begin{bmatrix} 1 & \text{if } (x_j - x_k) > 0 \\ 0 & \text{if } (x_j - x_k) = 0 \\ -1 & \text{if } (x_j - x_k) < 0 \end{bmatrix} \tag{6}$$

x_j and x_k are sequential values of the time series data, and n is the length of the dataset. A positive value of S indicates an increasing trend, and a negative value indicates a decreasing trend. If the dataset length is more than 10, then the test is done using the normal distribution with expectation (E) and variance (var);

$$\mathrm{var}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5)\right] \tag{7}$$

where q is the number of tied groups, and t_p denotes the number of ties of extent p. A tied group is a set of sample data having the same value. The standard test statistic (Z_{MK}) is given by;

$$Z_{MK} = \begin{bmatrix} \dfrac{S-1}{\sqrt{\mathrm{var}(S)}} & \text{if } S > 0 \\ \dfrac{S+1}{\sqrt{\mathrm{var}(S)}} & \text{if } S < 0 \\ 0 & \text{if } S = 0 \end{bmatrix} \tag{8}$$

The value of Z_{MK} is the Mann-Kendall test statistic that follows a normal distribution with mean 0 and variance 1. Testing trend is done at the specific α significance level. When $|Z_{MK}| > Z_{1-\alpha/2}$, the null hypothesis is rejected and a significant trend exists in the time series. $Z_{1-\alpha/2}$ is obtained from the standard normal distribution table. In this analysis, the MK test is applied to detect if a trend in the time series data is statistically significant at significance level, α=0.05 (or 95% confidence intervals).

3.2.5. Sen's slope method

This non-parametric method (Sen 1968) is used to determine the magnitude of trend in hydro-meteorological data. The method involves computing slopes for all the pairs of ordinal time points and then using the median of these slopes as the estimate of the overall slope. This method is not sensitive to outliers and can be effectively used for quantification of trend in a time series data. The estimate of the trend slope Q is given by:

$$Q = \mathrm{median}\left[\frac{x_j - x_k}{j - k}\right] \quad \forall\, k < j \tag{9}$$

where For i=1, 2, …, N, x_j is the data value at time j, x_k is the data value at time k and j is the time after k (j>k) and N is a number of all pairs x_j and x_k.

4. RESULTS

4.1. Temporal and spatial analysis of meteorological droughts

For temporal analysis of droughts, the RAI was calculated on a time scale of 3, and 12 months from 1971 to 2015. For the analysis of the results, three representative rainfall stations were selected in the basin, one each in the upper region (Station 376401), the middle region (Station 130221), and the lower region (Station 130042). The temporal variation of the RAI for the selected stations on different time scales is shown in Figure 4. A drought event occurs when the RAI value is negative, and the intensity

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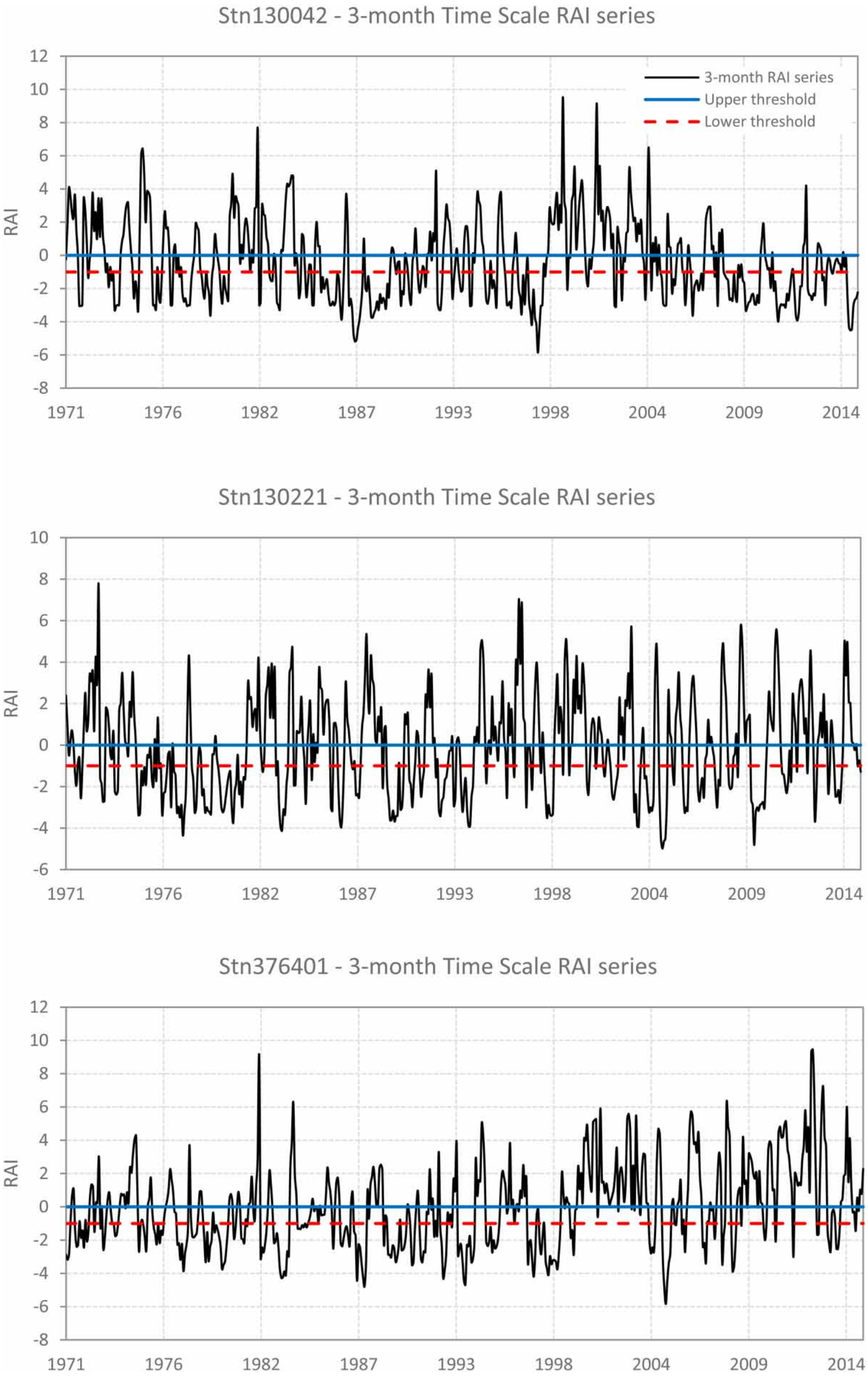

Figure 4 | RAI (3, 6, and 12) for the selected stations in the Mae Klong River Basin. *(continued.)*.

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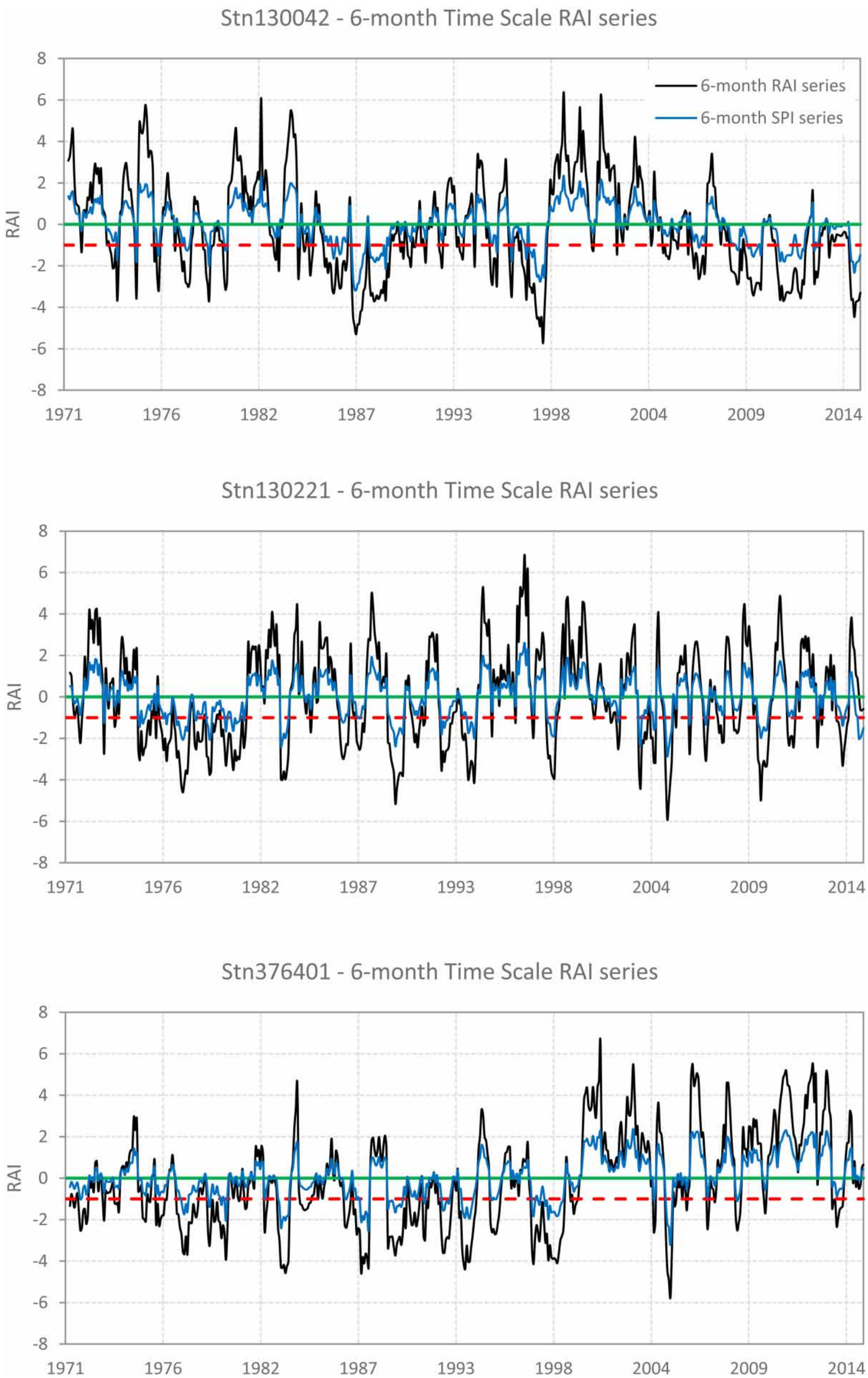

Figure 4 | Continued.

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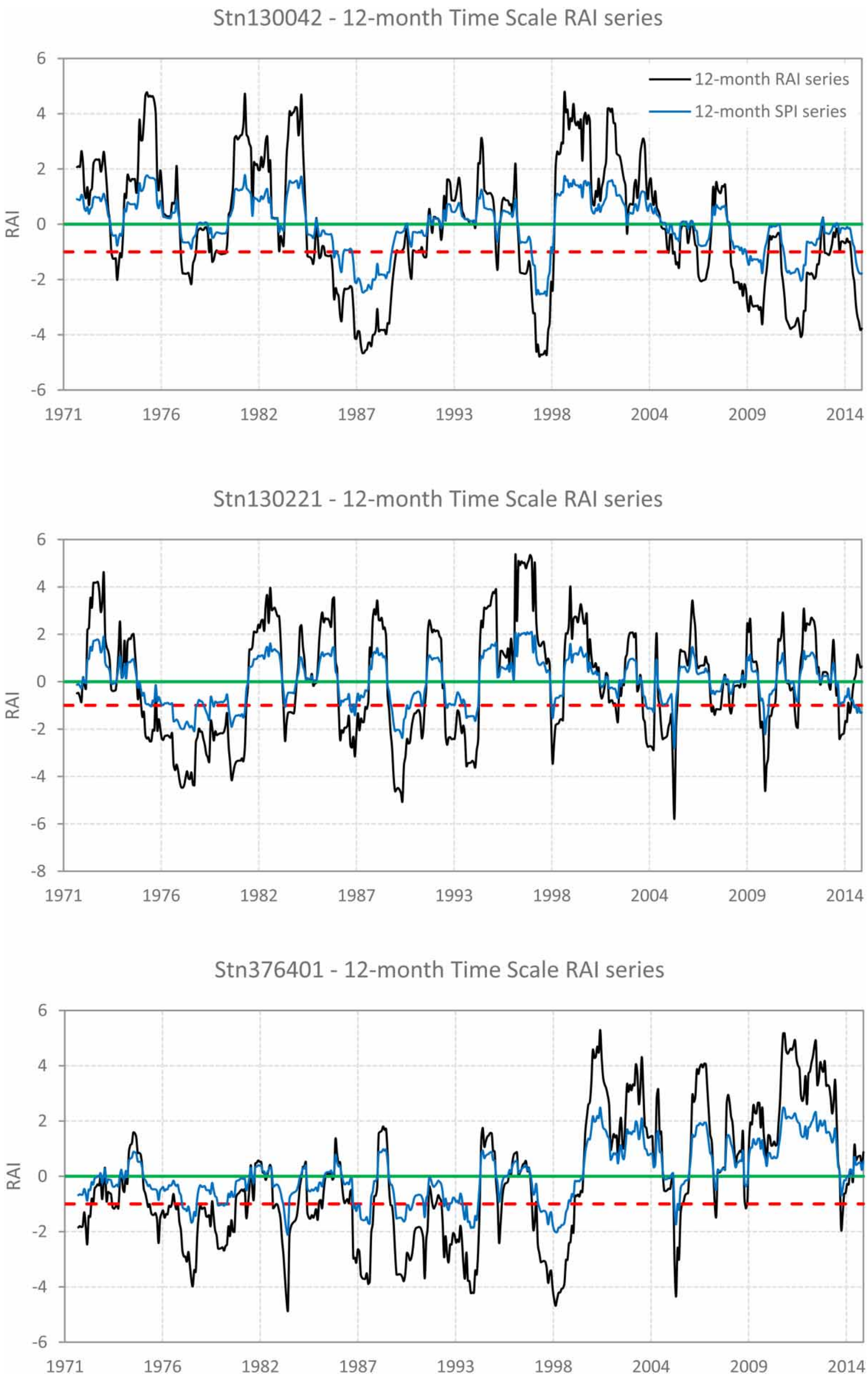

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is −1.0 or lower. The RAI values at various time frames represented changes in the basin's drought and wet conditions. Short-term rainfall has a significant impact on RAI values over a 3-month time range. Rainfall accumulation over long time scales becomes more essential, resulting in a decrease in the frequency of droughts and a clear separation between dryness and wetness.

Drought events with maximum intensities for RAI-6 and RAI-12 for the eight rainfall stations are presented in the Table 4. Contour plot for drought intensity and duration and multi variate plot for drought duration-intensity-density for selected stations based on RAI-6 and RAI-12 during 1971–2015 are shown in Figure 5. Considering the analysis for RAI-6, Station 130042, which is located in the lower region of the basin, had 30 drought events. A drought with a maximum intensity of 3.95 and a duration of 11 months occurred from 1987-May to 1988-Mar. Droughts with intensities between 1 and 2.6 associated with durations up to 14 months had higher density. Station 130221 (located in the middle part of the basin) showed a total of 30 drought events. A drought having a maximum intensity of 3.63 with a duration of 6 months occurred during 1983–Apr to 1983−Sep. Station 376401 (located in the upper part of the basin) had 26 drought events. The maximum intensity drought with an intensity of 3.19 was observed during 1987−May to 1988−Mar (11 months duration).

Considering the analysis for RAI-12, Station 130042 had a total of 10 drought events. The maximum intensity drought occurred from 1996−Sep to 1998−Sep (25 months duration) with an intensity of 2.90. Droughts with intensities between 1 and 2.4 associated with durations up to 12 months had higher density. A total of 14 drought events were indicated by the rainfall data for Station 130221. A drought with a maximum intensity of 2.68 and duration of 75 months occurred from 1975-May to 1981-Jul. For Station 376401, a total of 13 drought events were observed. The maximum intensity drought had a value of 2.60 and duration of 36 months from 1997−Apr to 2000−Mar.

The spatial distribution of RAI on a 6- and 12-month time scale for the selected stations is shown in Figure 6. RAI-6: Moderate to severe drought conditions prevailed in May 1977. Moderate droughts occurred in the upper and middle parts of the basin, while moderate droughts occurred in the lower part of the basin. Severe drought conditions were observed in almost the whole basin in August 2004. Slightly dry to severe drought-dry conditions were observed in May 2015. RAI-12: Moderate to severe dry conditions occurred in February 1977. A severely dry situation prevailed in the upper and middle parts of the basin in July 2004. In January 2015, RAI-12 results indicated near normal conditions. However, parts of the upper and lower regions had severe dry conditions. Khalil (2020) used the methodology suggested by Yoo (2006) and classified the years from 1971 to 2015 as dry, wet, and normal years. The years (1977, 1979, 1986, 1987, 1989, 1990, 1992, 1993, 1997, 2004, and 2015) were classified as dry years. The results of drought conditions indicated by RAI-6 and RAI-12 for the selected years in Figure 6 can be compared with the classified dry years.

Table 4 | Maximum intensity droughts with durations for the rainfall stations

Station	RAI	Start_Date	End_Date	Duration (month)	Maximum Intensity
Station 130013	RAI-6	1982−Sep	1983−Aug	12	3.33
	RAI-12	1982−Nov	1983−Sep	11	3.34
Station 130042	RAI-6	1987−May	1988−Mar	11	3.95
	RAI-12	1996−Sep	1998−Sep	25	2.90
Station 130053	RAI-6	1998−Feb	1999−Jan	12	3.73
	RAI-12	1998−Jul	1999−Jul	13	3.88
Station 130211	RAI-6	1991−Apr	1991−Dec	9	4.42
	RAI-12	1989−May	1993−Mar	47	2.76
Station 130221	RAI-6	1983−Apr	1983−Sep	6	3.63
	RAI-12	1975−May	1981−Jul	75	2.64
Station 130571	RAI-6	1987−Apr	1988−Apr	13	3.60
	RAI-12	1993−Jul	1995−Aug	26	2.52
Station 376401	RAI-6	1987−May	1988−Mar	11	3.19
	RAI-12	1997−Apr	2000−Mar	36	2.60
Station 470161	RAI-6	2009−Sep	2010−Jul	11	3.98
	RAI-12	2009−Oct	2010−Sep	12	3.98

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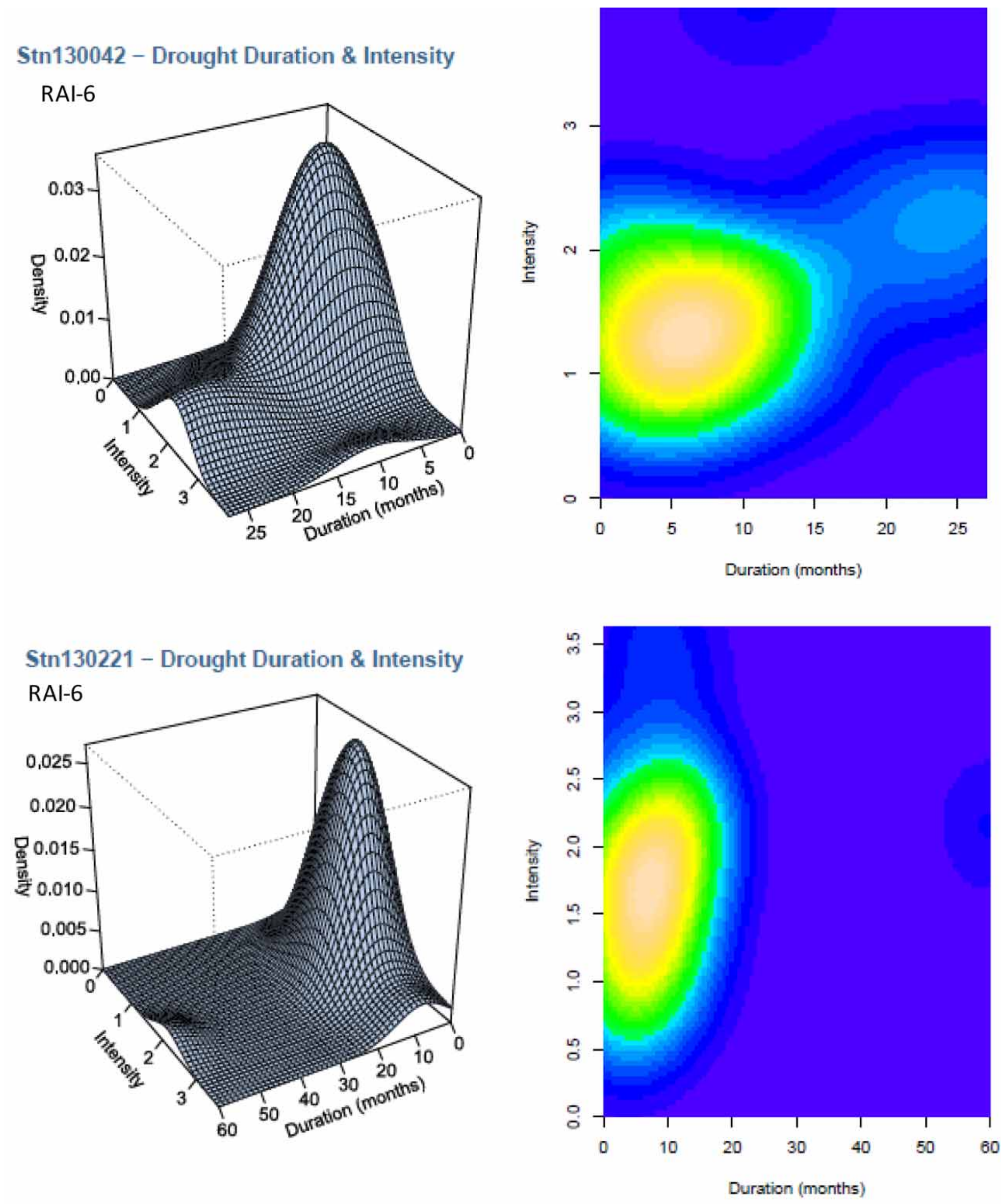

Figure 5 | Contour plot for drought intensity and duration and multi variate plot for drought duration-intensity-density for selected stations based on RAI-6 and RAI-12 during 1971–2015. (*continued.*).

4.2. Comparison of RAI results with SPI

The performance of RAI for the detection of droughts in the Mae Klong River Basin was assessed by comparing it with the SPI on 3, 6, and 12-month time scales. The scatter plots between RAI and SPI for the selected stations are shown in Figure 7. In order to compare the results of the two drought indices, Pearson's correlation coefficient r and Cohen's Kappa K were calculated for all the rainfall stations. The results are presented in Table 5. The values of the correlation coefficient r between RAI-3 and SPI-3 ranged from 0.938 to 0.980. In general, higher values for the correlation r were observed for the 6- and

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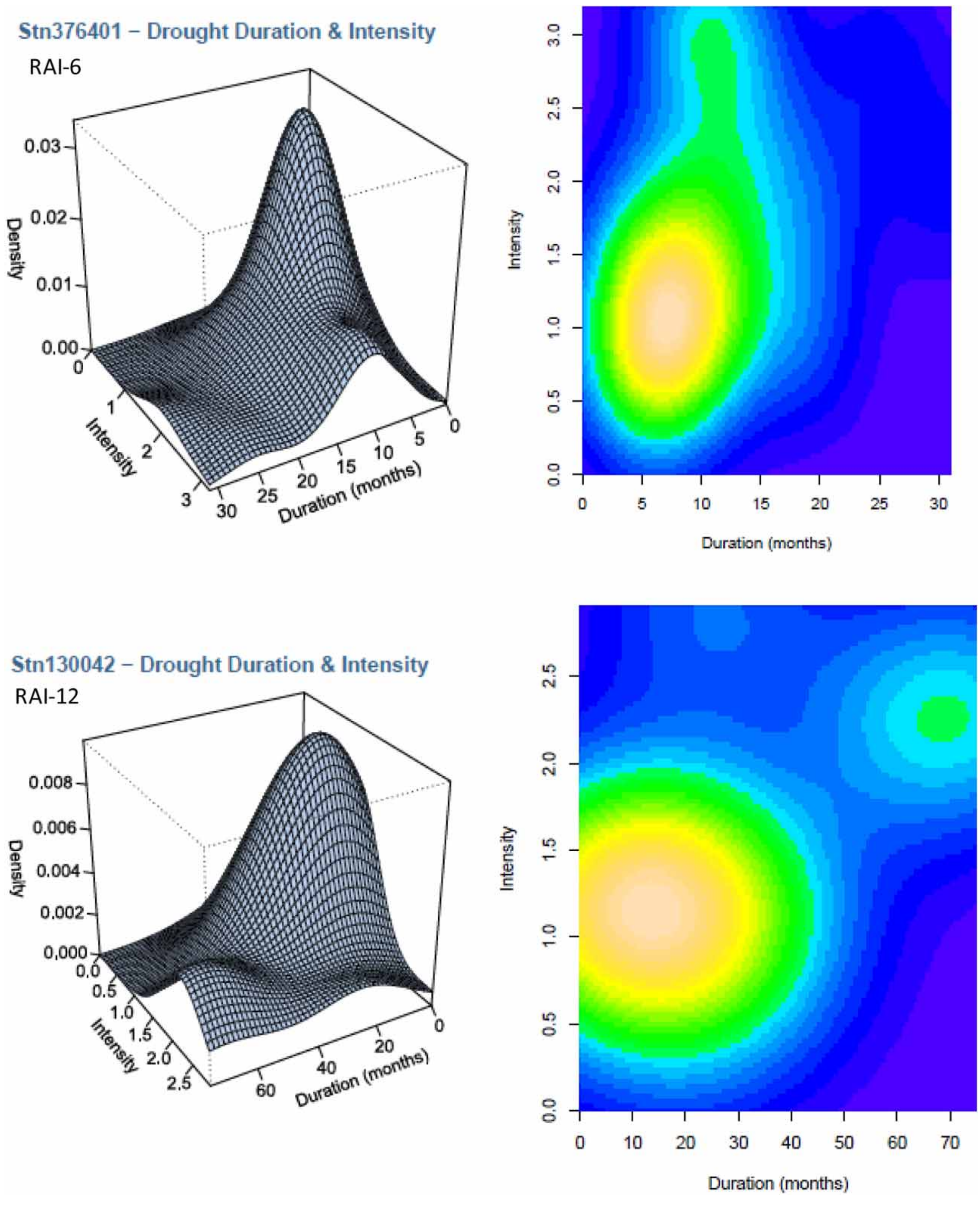

Figure 5 | Continued.

12-month time scales between RAI and SPI. In order to assess the strength of agreement between the two indices, The unweighted and weighted Cohen's Kappa were calculated. Unweighted Kappa ranged from 0.273 to 0.311 between RAI-3 and SPI-3, which shows a fair agreement (Table 3) between the two indices. Similarly, fair agreement was found between RAI and SPI for the 6- and 12-month time scales. The weighted Kappa showed moderate agreement between RAI-3 and SPI-3 for 7 (out of 8) rainfall stations. Station 130042 showed fair agreement between the two drought indices. For the 6- and 12-month periods, all the stations showed moderate agreement between the indices.

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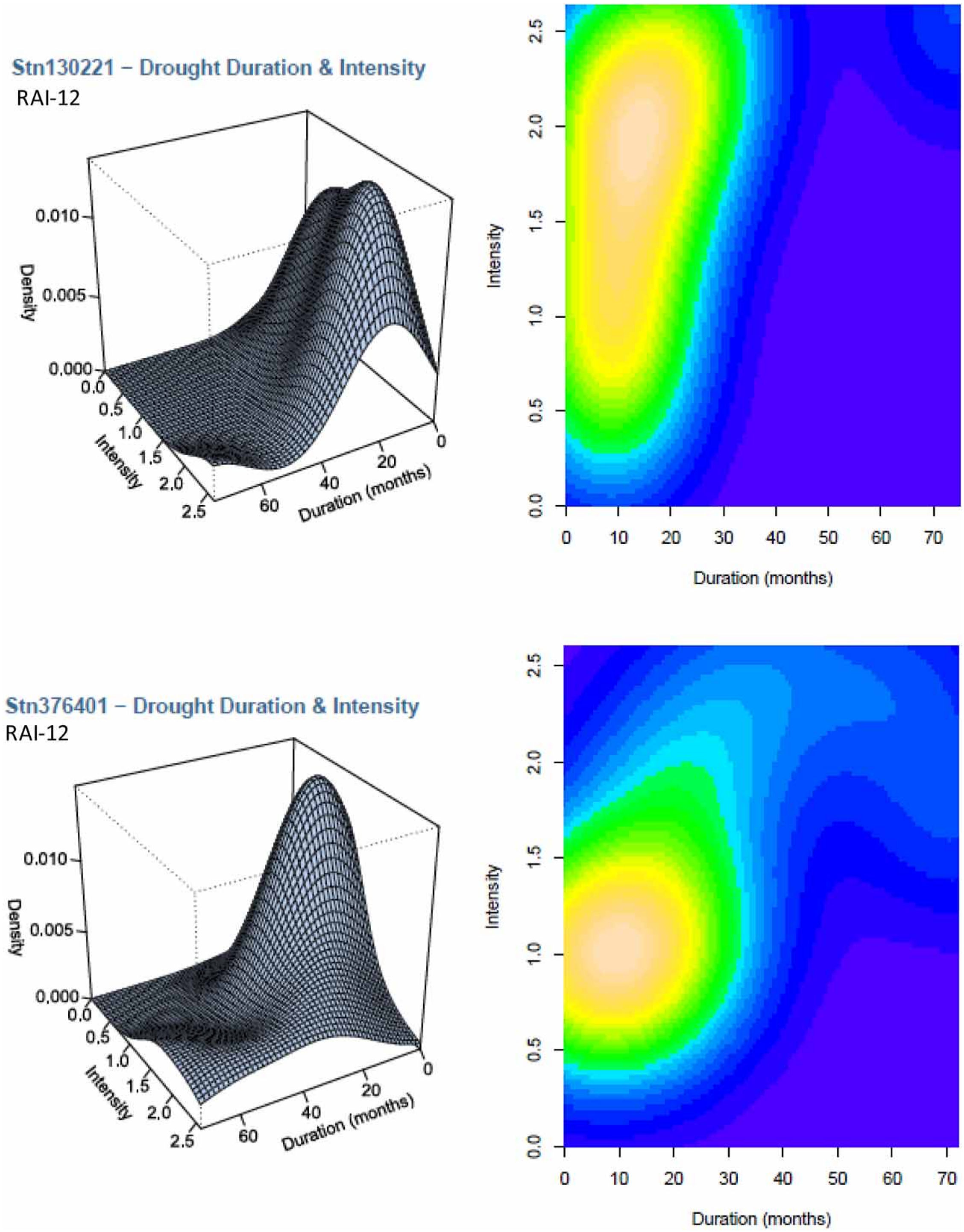

Figure 5 | Continued.

4.3. Trend analysis of droughts' characteristics

A trend analysis of drought features such as durations, magnitudes, and intensities was conducted for the years 1971–2015. The trend (increasing or decreasing) was calculated using the well-known Mann-Kendall test, while the magnitudes of the trends were estimated using Sen's slope method. These tests were conducted at a 5% significance level. The findings of

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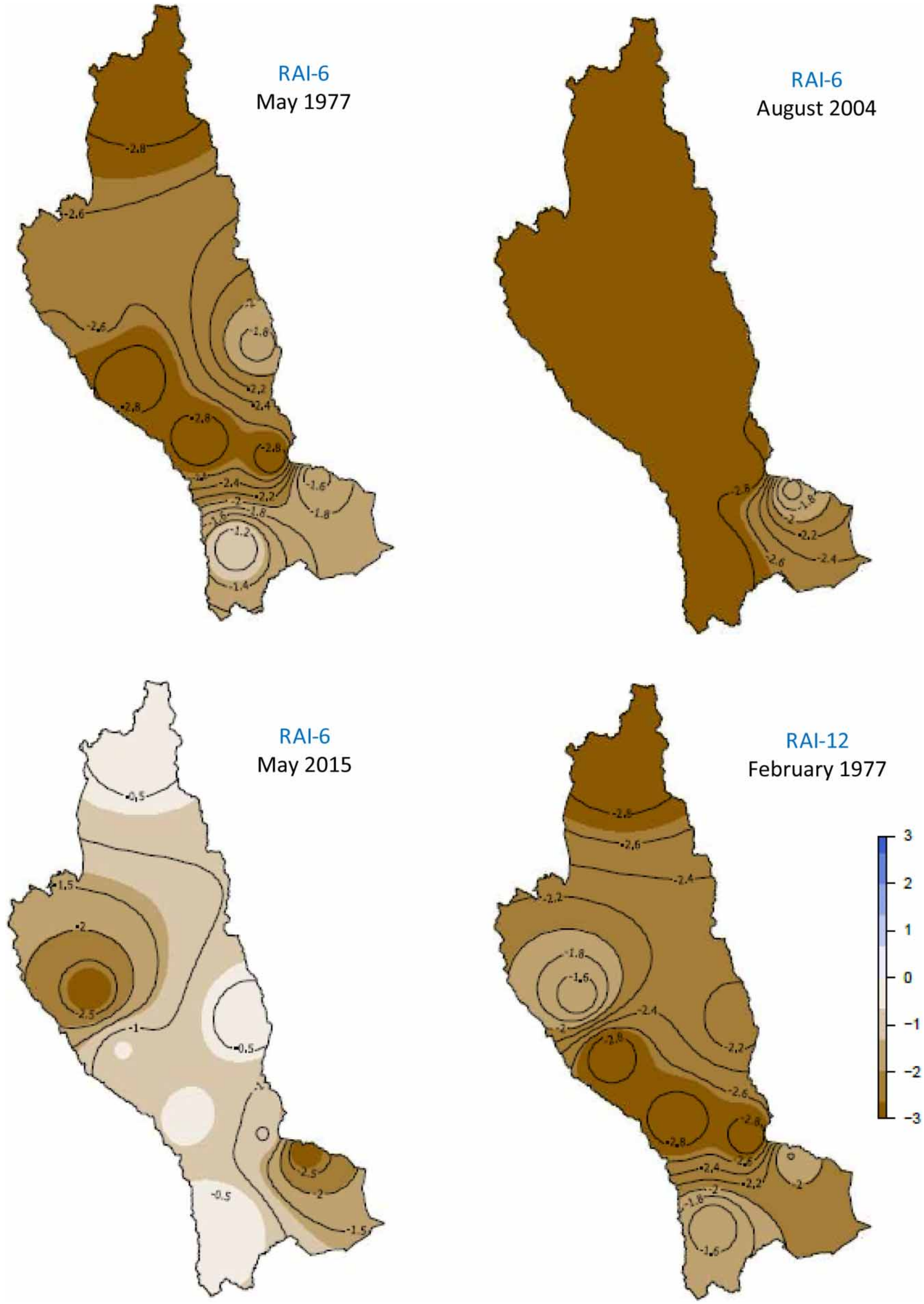

Figure 6 | Spatial distribution of droughts on 6-, 12-month RAI for selected months. *(continued.).*

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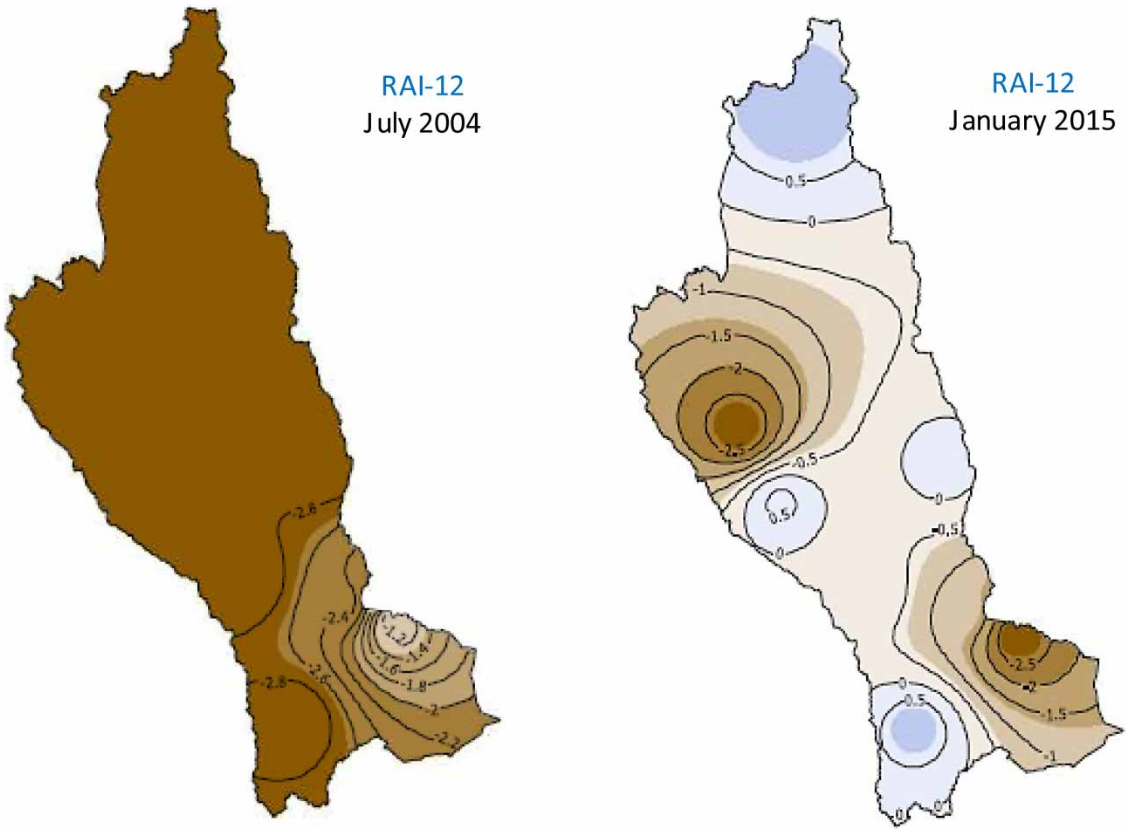

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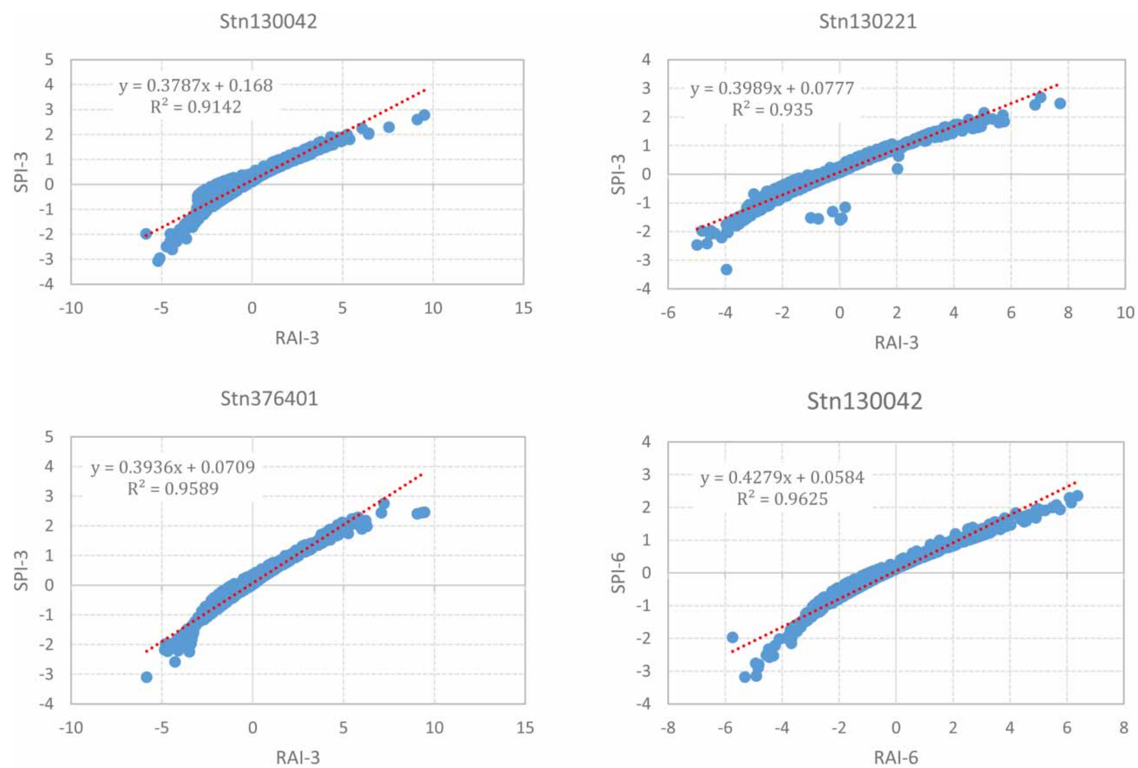

Figure 7 | Scatter plots between RAI and SPI (3, 6, and 12-month time scales). (*continued.*).

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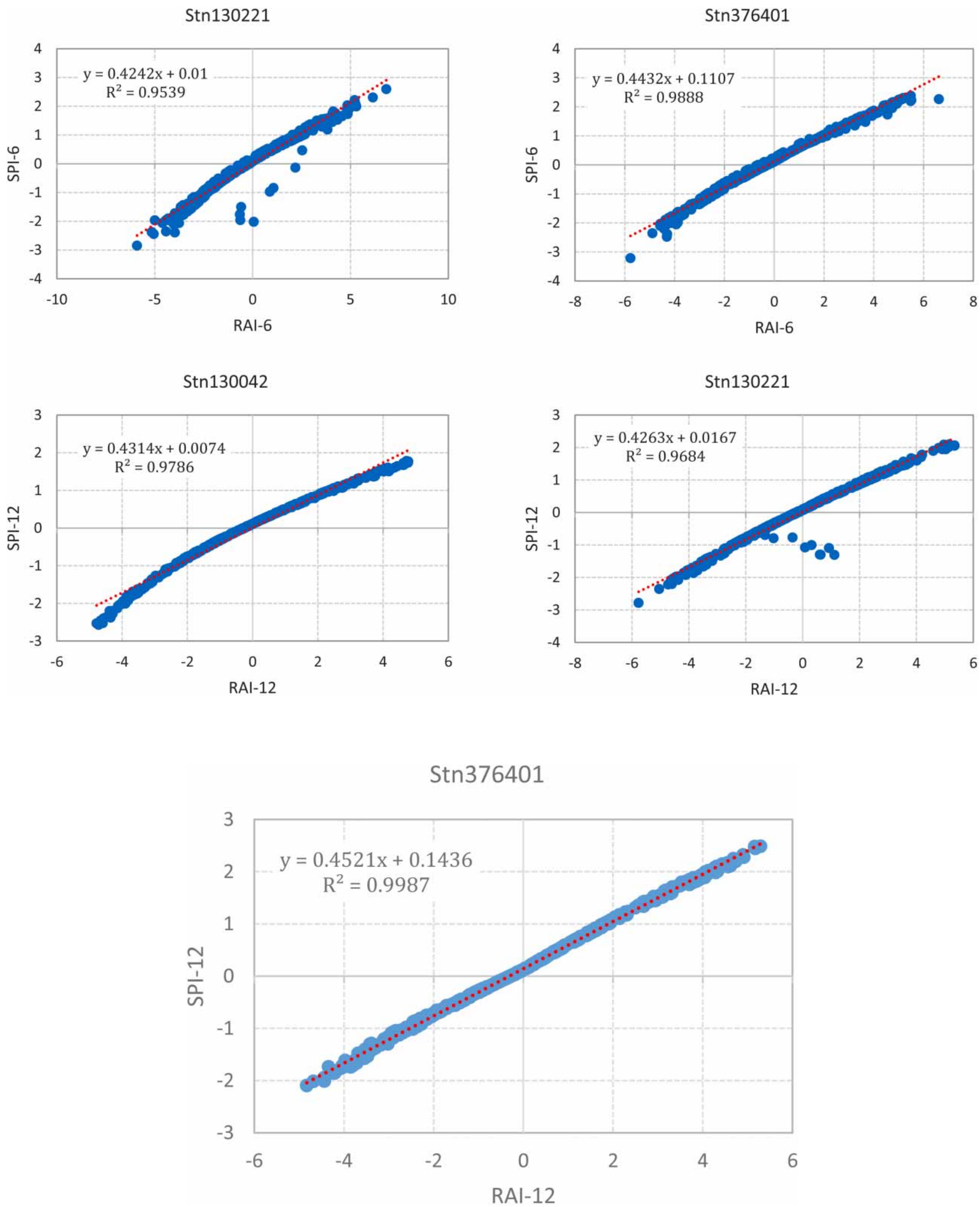

Figure 7 | Continued.

these tests were compared to those obtained using the linear trend method. The results of the trend analysis in the drought events based on RAI-6 and RAI-12 are presented in Tables 6 and 7, respectively. The spatial distribution of the trends in drought features is shown in Figure 8. For RAI-6, 50% of the stations (i.e., 4 stations) showed decreasing trends in drought durations. The decreasing trend for Station 376401 was statistically significant at a 5% significance level with a Sen's slope of −0.16 mm/year. The linear trend approach had a decreasing slope of −0.167 mm/year. For drought magnitude,

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Table 5 | Pearson's correlation r and Cohen's Kappa K between RAI and SPI for the rainfall stations during 1971–2015

Criteria	Stn130013	Stn130042	Stn130053	Stn130211	Stn130221	Stn130571	Stn376401	Stn470161
	Between RAI-3 and SPI-3							
Pearson's Correlation, r	0.967	0.956	0.980	0.938	0.967	0.955	0.979	0.970
Unweighted K	0.282	0.273	0.286	0.283	0.277	0.311	0.286	0.311
Weighted K	0.448	0.373	0.441	0.428	0.419	0.435	0.431	0.472
	Between RAI-6 and SPI-6							
Pearson's Correlation, r	0.991	0.981	0.992	0.933	0.977	0.962	0.994	0.976
Unweighted K	0.318	0.334	0.309	0.3	0.303	0.344	0.342	0.341
Weighted K	0.482	0.52	0.493	0.481	0.496	0.503	0.512	0.535
	Between RAI-12 and SPI-12							
Pearson's Correlation, r	0.995	0.989	0.997	0.971	0.984	0.975	0.999	0.990
Unweighted K	0.296	0.335	0.289	0.301	0.292	0.288	0.345	0.291
Weighted K	0.499	0.548	0.5	0.507	0.462	0.465	0.515	0.485

Table 6 | Trends in drought events' durations, magnitudes, and intensities for RAI-6

		Mann-Kendall test		
Rainfall Stations	Drought Events	Trend	Sen's slope (mm/yr)	Linear trend (mm/yr)
Station 130013	Duration	Decreasing	−0.025	−0.05
	Magnitude	Decreasing	−0.003	−0.089
	Intensity	Increasing	0.011	0.007
Station 130042	Duration	Increasing	0.104	0.188
	Magnitude	Increasing	0.089	0.372
	Intensity	Increasing	0.0001	−0.003
Station 130053	Duration	Increasing	0.067	0.030
	Magnitude	Increasing	0.101	0.112
	Intensity	Increasing	0.011	0.008
Station 130211	Duration	Decreasing	−0.083	−0.115
	Magnitude	Decreasing	−0.166	−0.33
	Intensity	Decreasing	−0.013	−0.009
Station 130221	Duration	Increasing	0.037	−0.141
	Magnitude	Increasing	0.048	−0.335
	Intensity	Decreasing	−0.005	−0.007
Station 130571	Duration	No trend	0.000	−0.058
	Magnitude	Increasing	0.096	0.057
	Intensity	Increasing	0.016	0.017
Station 376401	Duration	Decreasing	−0.160	−0.167
	Magnitude	Decreasing	−0.168	−0.195
	Intensity	Increasing	0.004	0.002
Station 470161	Duration	Decreasing	−0.034	−0.064
	Magnitude	Increasing	0.026	−0.005
	Intensity	Increasing	0.017	0.017

five stations showed increasing trends while three stations indicated decreasing trends. The intensity of the drought events was found to have increasing trends for 6 out of 8 stations.

For RAI-12, five stations showed decreasing trends in drought duration. For drought magnitude, five stations indicated decreasing trends while three stations showed increasing trends. The decreasing trend of Station 130221 had a statistically

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Table 7 | Trends in drought events' durations, magnitudes, and intensities for RAI-12

Rainfall Stations	Drought Events	Mann-Kendall test		Linear trend (mm/yr)
		Trend	Sen's slope (mm/yr)	
Station 130013	Duration	Decreasing	−0.017	−0.182
	Magnitude	Decreasing	−0.170	−0.508
	Intensity	Decreasing	−0.016	−0.011
Station 130042	Duration	Increasing	0.357	0.150
	Magnitude	Increasing	0.602	0.337
	Intensity	Increasing	0.009	0.006
Station 130053	Duration	Decreasing	−0.290	−0.413
	Magnitude	Decreasing	−0.229	−0.525
	Intensity	Increasing	0.003	0.009
Station 130211	Duration	Increasing	0.076	−0.162
	Magnitude	Increasing	0.118	−0.547
	Intensity	Increasing	0.005	0.001
Station 130221	Duration	Decreasing	−0.353	−1.04
	Magnitude	Decreasing	−1.440	−2.980
	Intensity	Decreasing	−0.027	−0.033
Station 130571	Duration	Decreasing	−0.325	−0.397
	Magnitude	Decreasing	−0.469	−0.720
	Intensity	Increasing	0.012	−0.001
Station 376401	Duration	Decreasing	−0.405	−0.651
	Magnitude	Decreasing	−0.477	−1.040
	Intensity	Decreasing	−0.003	−0.007
Station 470161	Duration	No trend	0.000	−0.115
	Magnitude	Increasing	0.201	−0.022
	Intensity	Increasing	0.027	0.024

significant decreasing trend with a slope of −1.440 mm/year. The corresponding linear trend was found to be −2.980 mm/year. For drought intensity, five stations showed increasing trends.

5. DISCUSSION

The Mae Klong River Basin is one of Thailand's 25 major river basins. This basin contributes significantly to water resource availability and hydropower generation, both of which are critical to the national economy. The hydropower generation from the basin is 1,070 MW from the four dams (Srinagarind Dam (720 MW), Vajiralongkorn Dam (300 MW), Tha Thung Na Dam (38 MW) and Mae Klong Dam (12 MW). Thailand's electricity producing authority (EGAT) had also planned to build an 18 MW hydropower plant downstream of the Vajiralongkorn Dam (Khalil *et al.* 2018). Therefore, the amount of rainfall in the upper region of the basin is critical, which supplies water to the two main dams (Srinagarind and Vajiralongkorn dams). The water stored in these dams is not only used for hydropower generation but also regulates the flows in the rivers downstream to meet the water demands during the dry season. The GMKIP, located in the lower region of the basin, is the second-largest irrigation project in Thailand, after the greater Chao Phraya irrigation project. Water from the basin is also supplied to the Bangkok Metropolitan Waterworks Authority (MWA) and to the neighboring Tha Chin Basin during the dry season. Results of this study indicated that the basin had faced moderate-to-severe drought conditions. Khalil (2020) found increasing trends in the total rainfall on an annual scale for 5 out of 8 stations. Rainfall was found to be increasing in the upper region of the basin as compared with the lower parts of the basin. During the 2020s (2011–2040) and 2050s (2041–2070), rainfall is expected to increase in the wet season and decrease in the dry season, while it is expected to increase in both seasons during the 2080s (2071–2099) (Shrestha 2014; Deb *et al.* 2018). RAI-6, which reflected the seasonal drought conditions, had increasing trends for

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Figure 8 | Trends in drought (a) durations (b) magnitudes (c) intensities for the Mae Klong River Basin (based on RAI-6, RAI-12, and Mann-Kendall test). *(continued.)*.

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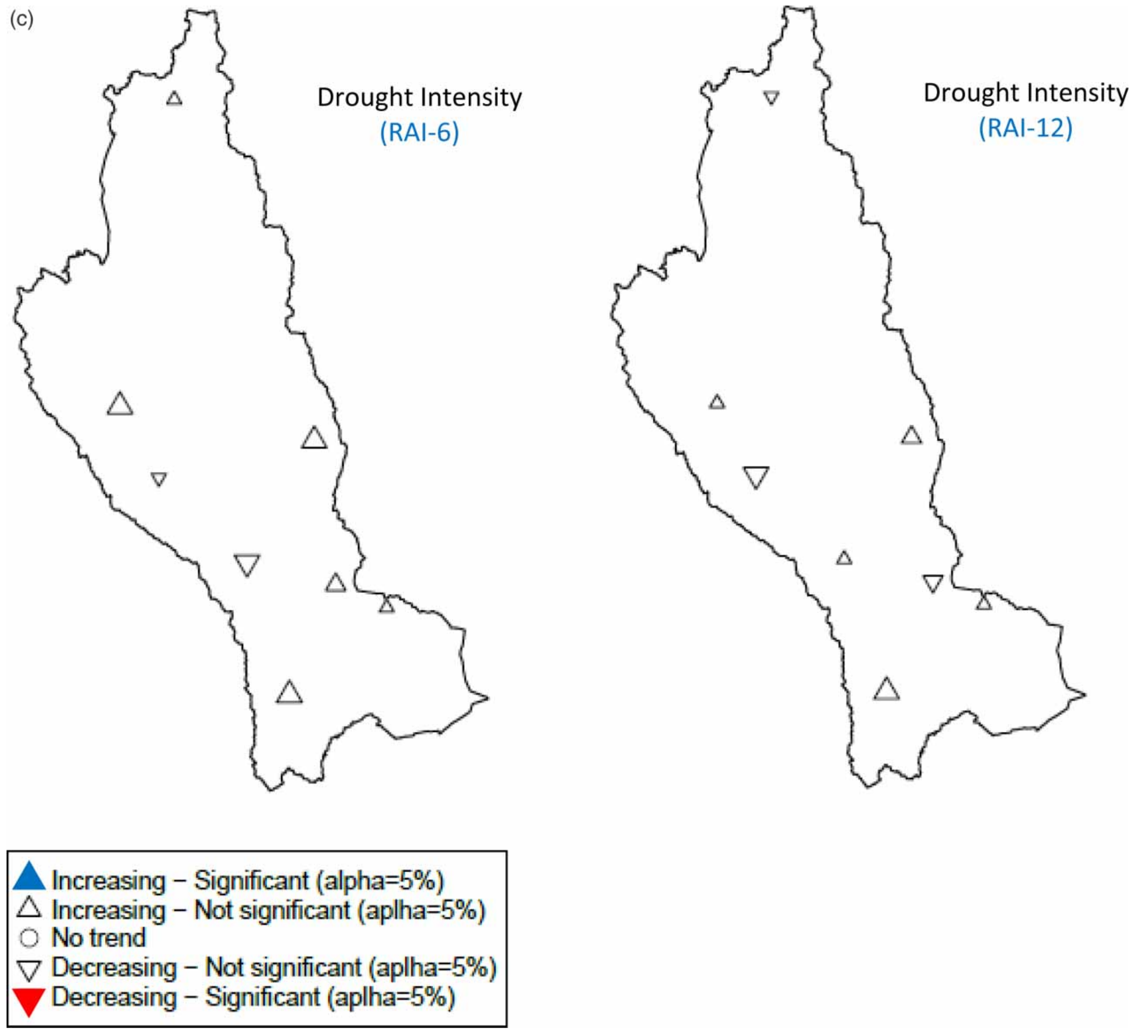

Figure 8 | Continued.

drought magnitude and intensity for the majority of the stations. However, RAI-12 results indicated decreasing trends for drought duration and magnitude but an increasing trend for drought intensity. The increasing trend in the drought intensity for both RAI-6 and RAI-12 suggests that there is a need for optimal operation of the dams in the basin to help offset the effects of droughts in the future. The operation of the three dams (Srinagarind, Vajiralongkorn, and Tha Thung Na dams) is controlled by EGAT, while RID operates the Mae Klong Dam. In the context of droughts in the basin, close coordination between the two organizations is critical for efficient planning and better management of water resources in the Mae Klong River Basin in the future.

6. CONCLUSIONS

The rainfall anomaly index was used to analyze the meteorological drought characteristics in the Mae Klong River Basin from 1971 to 2015. Calculations of trends in drought characteristics were made using Mann-Kendall and Sen's slope tests. According to an analysis of mean annual rainfall, the upper part of the basin received more rainfall than the lower basin. The performance of the RAI was evaluated by comparing it with SPI results using Pearson's correlation coefficient and Cohen's Kappa. The main findings of this research can be summarized as:

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1. For both the RAI-6 and the RAI-12, more drought events were observed in the lower and middle regions of the basin.
2. Increasing trends in the drought magnitude and intensity were found for RAI-6 results for the majority of the rainfall stations, while decreasing trends were observed in the drought durations. For RAI-12, drought duration and magnitude had decreasing trends, but drought intensity showed increasing trends. The increasing trend of drought intensity for both RAI-6 and RAI-12 could suggest that the dams in the basin need to be operated in an optimal manner to better cope with the severity of droughts in the future.
3. The Pearson's correlation coefficient between RAI-3 and SPI-3 varied from 0.938 to 0.980. For 6- and 12-month time scales, higher values of the correlation coefficient were observed between the two drought indices. The unweighted Kappa ranged from 0.273 to 0.311 between the RAI-3 and SPI-3, which shows a fair agreement between the two indices. Similarly, the results of the two indices showed fair agreement for the 6- and 12-month time scales. The weighted Kappa showed moderate agreement between RAI and SPI for all the time scales.

The results of this study are expected to provide a scientific foundation for policymakers to evaluate drought management policies such as climate change adaptation and mitigation initiatives, as well as drought preparedness plans.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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