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Assessment of annual high-discharge patterns in Kapuas River using information and complexity measures

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Abstract: A recent study revealed that the amount of rainfall on the Kapuas River has increased over the last 30 years. The increase in rainfall increases the possibility of high discharge events, which might lead to destructive flooding of the Kapuas River and its tributaries. Hence, the ability to characterise the pattern of high discharge events is compulsory for the development and management of the Kapuas River watershed. The main objective of this study was to assess and characterise flood patterns in the Kapuas River watershed. To achieve this objective, we utilised information and complexity measures that consisted of mean information gain (*MIG*), effective measure complexity (*EMC*) and fluctuation complexity (*FC*) in daily water level records from 2002 to 2011 from a gauging station in Sanggau, West Kalimantan Province. The results revealed that flood events in the Kapuas River were mainly generated by the Indo-Australian monsoon, which occurred from December to March. The anomaly in 2010, when intense flood events were observed during the dry season, can be identified as the effect of a strong negative El Niño-Southern Oscillation (ENSO). Additionally, the analysis of the information and complexity measures indicates that: (i) *EMC*, which reflects the length of flood events, tends to increase along with greater discharge, and (ii) *MIG* and *FC*, which denote the degree of randomness and fluctuation of flood events, respectively, tended to have higher values when the number of months without high discharge was less.

Keywords: El Niño-Southern Oscillation, flood pattern, information and complexity measures, Kapuas River, tropical monsoon

INTRODUCTION

The unique geographical location of Indonesia, which lies at the equator as well as between two continents and two oceans, makes this country associated with distinct climatic phenomena. These phenomena strongly affect the amount of water flowing through the rivers in this tropical country. One of the most notable rivers in Indonesia is the Kapuas River, which is also the longest river in Indonesia and flows through West Kalimantan Province to the Karimata Strait. Specifically, the regional climate of West Kalimantan Province is predominantly affected by the Indo-Australian monsoon and the El Niño-Southern Oscillation (ENSO) (Hidayat *et al.*, 2017).

The Kapuas River has a total length of approximately 1,140 km and a watershed area as large as 100,000 km^2 (Herawati, Suripin and Suharyanto, 2017). The vast area encompassed by the Kapuas River watershed makes the Kapuas River economically, ecologically, and hydrologically important, not only to sustain local communities but also to society on the island of Kalimantan, Indonesia. The statistical analysis performed on one of the

Kapuas River tributaries revealed that although the rainfall intensity has been decreasing over the period of 30 years, the rainfall amount has increased by 4.3% (Herawati, Suripin and Suharyanto, 2015; Herawati, Suripin and Suharyanto, 2017). The increase in rainfall raises the possibility of high discharge events, which could generate destructive flooding that affects the settlement areas and cities around the Kapuas River. At the same time, the Kapuas River stream has yet to be obstructed by man-made flow control structures (Kästner and Hoitink, 2019) and is still poorly gauged. Additionally, satellite image interpretation during the period from 1990 until 2012 also showed that significant changes in land use have occurred in Kapuas River Basin (Herawati *et al*., 2018). These changes were mainly inflicted by the increasing land use for open land and plantations and decreasing areas of swamp forest and primary dry forest. Subsequently, the changes in land use enlarged the value of the runoff coefficient in Kapuas River Basin which led to the larger river stream during months with high amounts of precipitation. Therefore, it is important to characterise the pattern of high discharge events for the better development and management of the Kapuas River watershed.

Methods to characterise streamflow patterns and classify the flow regimes have been proposed throughout the years, such as principal component analysis (Detenbeck *et al*., 2005; Sanborn and Bledsoe, 2006; Matteau, Assani and Mesfioui, 2009), Fourier analysis (Kahya and Dracup, 1993), and wavelet decompositions (Anctil and Coulibaly, 2004). However, in recent years, a method known as information and complexity measures have caught the attention among hydrologists for its effectiveness to assess the variability within hydrological datasets (Engelhardt, Matyssek and Huwe, 2009; Pan *et al*., 2012). This method, which was proposed by Lange (1999), utilised strings of symbols which are derived from binary hydrographs coding before, then, analysed by information theory methods. Furthermore, recent studies (Al Sawaf and Kawanisi, 2020; Al Sawaf, Kawanisi and Xiao, 2022) have advanced the applicability of information and complexity measures by assessing the annual flood pattern in the subtropical environment of Gono River, Japan, which is strongly affected by the East Asian monsoon and tropical cyclones (Al Sawaf, Kawanisi and Xiao, 2022). However, this newly developed approach has not been used to assess flood patterns in tropical rivers affected by different climatic phenomena. Thus, the main objective of this study was to assess and characterise the annual high discharge patterns, particularly flood events, in the Kapuas River watershed by implementing an information and complexity measurement approach. In addition, we present the versatility of this approach for applications in various types of climatic environments.

MATERIALS AND METHODS

We utilised daily water level data from 2002 to 2011 from the gauging station in Sanggau (Fig. 1), which is located 285 km upstream of the river mouth. The dataset was obtained from the public river basin management organisation Balai Wilayah Sungai Kalimantan I Pontianak. First, the water level data were converted into discharge data by using the local rating curve equation. We then defined the threshold value of water depth at the Sanggau gauging station. This threshold value can be used as a reference for evaluating the river conditions during floods. However, because the official flood disaster warning scale is nonexistent for the Kapuas River, we used a proxy to specify the threshold water depth. We established this proxy from a recent flood event that occurred on November 12th 2021, on the Kapuas River. During this flood event, the water depth at the Sanggau gauging station was 9.356 m with a corresponding discharge of 5,431 m^3. Simultaneously, the effect of flooding was observed not only in Sanggau but also in Sintang (Photo 1), which is located approximately 100 km upstream of Sanggau. Hence, we used the observed water depth with its corresponding discharge on November 12th 2021, as a proxy for the threshold value to define

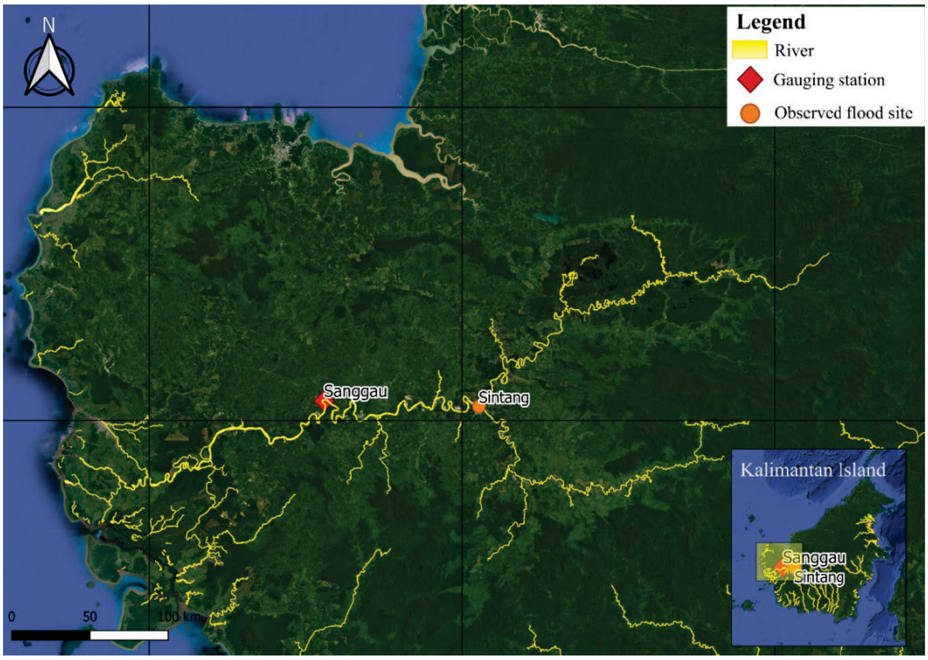

Fig. 1. The site of the Kapuas River watershed, the gauging station in Sanggau, and Sintang – the flood location (November 12th 2021); source: own elaboration based on Google Earth

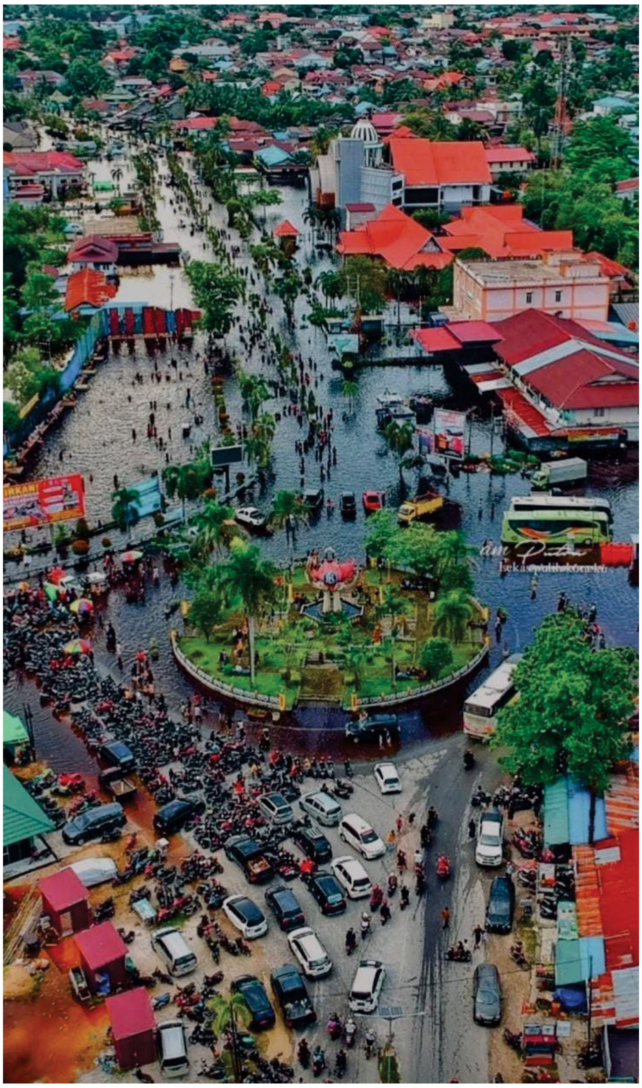

Photo 1. The inundation observed in Sintang on November 12th 2021 (phot.: *A.M. Putra*)

flood events in this study. This flood event was induced by heavy rain that occurred between November 11th and November 15th 2021. The inundation was observed to be around 100–300 cm that lasted for over 4 weeks. This flood affected as many as 123,936 people across 12 districts in Sintang Regency which makes it the greatest flood that occurred in the region since 1963 (Cipta, 2021; DetikNews, 2021).

After the threshold value was defined, the daily discharge value was converted into a binary sequence (i.e., 0 if below or at the threshold value, or 1 if above the threshold value). The binarised record of the daily discharge value was then arranged into two-character patterns with different possible words: 00, 01, 10, and 11. Each word denotes a different state of stream flow. The pattern 00 indicates that no significant flood occurred, 01 and 10 indicate that one significant flood occurred but lasted for less than one day, and 11 indicates a significant flood that occurred for more than one day.

The next step is to determine three sets of empirical probabilities (Lange, 1999) which consist of: a) state probability of the *i*th word to occur in a symbolic string ($p_{L,i}$), $i = 1, 2, ..., 2^L$, where: L = word length, L, = occurrence probability of the *i*th L word; b) probabilities of transition occurrence from the *i*th to the *j*th word ($p_{L,ij}$), $i = 1, 2, ..., 2^L$, $j = 1, 2, ..., 2^L$; and c) the conditional probability of *j*th word to occur, given that the *i*th word has occurred ($p_{L,i\to j}$), $i = 1, 2, ..., 2^L$, $j = 1, 2, ..., 2^L$. After all the empirical probabilities have been determined, finally, we utilised information and complexity measures using *MIG*, *EMC*, and *FC*. *MIG* depicts the degree of data randomness that includes the probabilities of state changes in the datasets (Pan *et al.*, 2012; Al Sawaf, Kawanisi and Xiao, 2022). *MIG* can be estimated by the following equation (Eq. 1):

$$MIG = -\sum_{i,j-1}^{2^L} p_{L,ij} \log_2 p_{L,i\to j} \tag{1}$$

Datasets with *MIG* = 0 indicate uniform and predictable data, while *MIG* = 1 denotes a fully distributed random sequence with less predictability of datasets. *EMC* denotes the minimum amount of information that has to be stored to create the most optimum estimation of the subsequent symbol (Grassberger, 1986). Moreover, *EMC* also represents the length of flood events within the streamflow datasets, hence higher values of *EMC* indicate a longer duration of flood events. *EMC* can be calculated using Equation (2):

$$EMC = -\sum_{i,j-1}^{2^L} p_{L,ij} \log_2 \frac{p^L_{L,i\to j}}{p_{L,i}} \tag{2}$$

FC quantifies the fluctuations of transitions in the datasets from one system to another. Hence, *FC* denotes the fluctuation in the number of flood events and the high degree of fluctuation is represented by higher values of *FC* (Bates and Shepard, 1993). *FC* is calculated using Equation (3):

$$FC = -\sum_{i,j-1}^{2^L} p_{L,ij} \left(\log_2 \frac{p_{L,i}}{p_{L,j}}\right)^2 \tag{3}$$

RESULTS AND DISCUSSION

FLOOD ASSESMENT

Table 1 presents the number of different word patterns, the number of days with a discharge value greater than the threshold, and the number of each possible character pattern. From 2002 to 2011, almost all observed years had four different word patterns, indicating that the occurrence of maximum daily discharge that surpassed the threshold is commonly observed. Furthermore, while the average number of days with discharge values greater than the threshold was 25.7 days during the observed period, the number of days was significantly higher in 2010. During this year, the maximum daily discharge surpassed the threshold for more than 100 days, whereas most occurred for at least two days. In fact, the intense flooding observed in 2010 could have resulted from the influence of ENSO, which is elaborated on in a later subsection. In contrast, a one-word pattern was observed only in 2006, indicating that, during this year, the maximum daily discharge was below the specified threshold. This finding clearly indicates frequent flooding in the Kapuas River. However, because we only utilised a proxy to specify the threshold discharge, an official threshold to define flood events must be standardised by the local government or the river management bureau to improve river management and flood risk mitigation. Additionally, the construction of more gauging stations is also suggested because the number of gauging stations is very limited compared to the vast area covered by the Kapuas River watershed.

Table 1. The number of different word patterns in the Sanggau gauging station

Year	Number of different words	Days > 9.356 m (depth threshold)	Number of events				
			00	01	10	01	11
2002	4	31	332	1	1	1	30
2003	4	18	345	1	1	1	17
2004	4	14	350	1	1	1	13
2005	4	24	339	1	2	1	22
2006	1	0	364	0	0	0	0
2007	4	10	352	2	2	2	8
2008	4	21	341	3	3	3	18
2009	4	23	338	3	3	3	20
2010	4	108	242	14	14	14	94
2011	4	8	355	1	1	1	7

Source: own study.

In the case of the Sanggau gauging station during the observation period, the ranges of those scores were $0 \leq EMC \leq 0.53$, $0 \leq FC \leq 1.71$, and $0 \leq MIG \leq 0.36$ (Fig. 2). Figure 2a shows a comparison of the annual variation between *MIG* and *EMC*, whereas a similar comparison between *MIG* and *FC* is displayed in Figure 2b. Both comparisons are highly scattered,

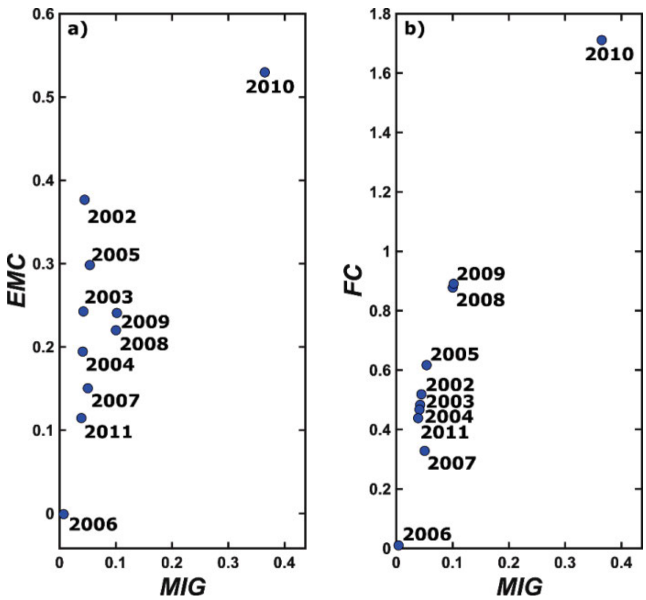

Fig. 2. Annual variations in the relationship between the information and complexity measure scores observed in Sanggau gauging station: a) *EMC* versus *MIG*, b) *FC* versus *MIG*; source: own study

which reflects the diverse flood patterns in the Kapuas River, with the furthest outliers being the annual variations in 2006 and 2010. The *EMC* reflects the duration of flood events, and the *MIG* denotes the degree of randomness of flood events (Al Sawaf, Kawanisi and Xiao, 2022). Thus, the observed outliers resulted from the absence of floods in 2006 and the long flood duration in 2010, as shown in Table 1. Additionally, the annual variations in 2008 and 2009 in Figure 2b were also scattered from the rest, although not as far as the annual variation in 2010. *FC* describes the number of flood occurrences; hence, the higher annual variation during 2008 and 2009 could be a result of the increase in both the number and randomness of flood events.

FLOOD PATTERNS

The relationships between the mean annual discharge and the information and complexity measures are shown in Figure 3. The trend lines in Figure 3 reveal that all information and complexity measures tended to have higher scores with greater mean annual discharge. The increase in *EMC* (Fig. 3b) indicates that the duration of the flood tended to be affected by the greater mean annual discharge flowing through the Kapuas River. However, an anomaly was observed in 2002 with a high *EMC* value when the Kapuas River experienced its second-lowest mean annual discharge during the study period. This high *EMC* value was observed because of the intense flooding that occurred for as many as 24 events in just one month (February), as illustrated in Figure 4. On the other hand, the increase in both *MIG* (Fig. 3a) and *FC* (Fig. 3c) reflects the influence of the mean annual discharge on the fluctuations of flood events. Higher discharge is more likely to increase the number of months that encountered high discharge events, such as in 2008 (three months), 2009 (three months), and 2010 (eight months), as shown in Figure 4. These findings demonstrate the strength of information and complexity measures for characterising flood patterns in tropical environments, where flood events are more prone to occur.

The distribution of flood events in each month during 2002–2011 is presented in Figure 4. The highest number of flooding events occurred in-between December and February. This three-month period indeed has a high chance of heavy rain

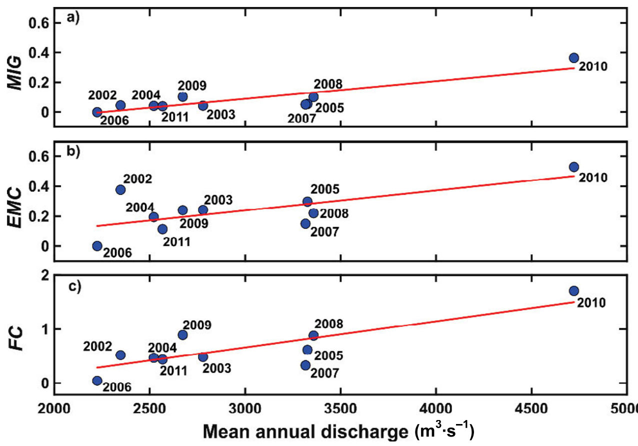

Fig. 3. Annual variations in the relationship between the information and complexity measure scores against mean annual discharge observed in Sanggau gauging station: a) *MIG*, b) *EMC*, c) *FC*; red lines = trendlines of each information and complexity measure with mean annual discharge; source: own study

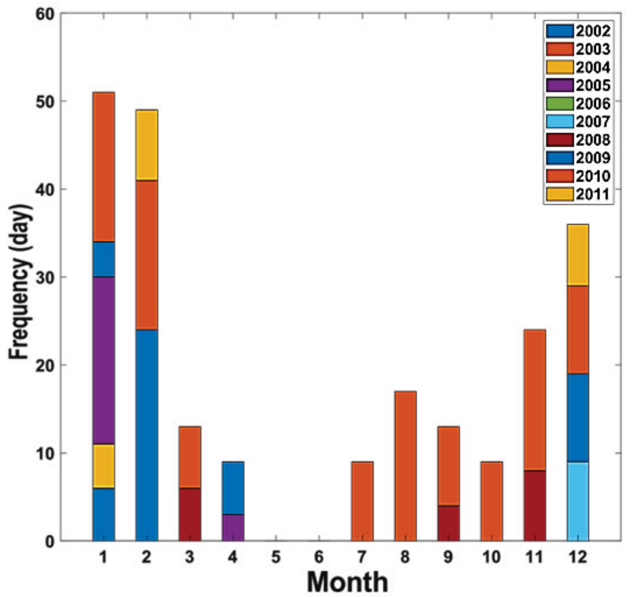

Fig. 4. Number of observed days that surpassed the threshold during 2002–2011 in Sanggau gauging station; source: own study

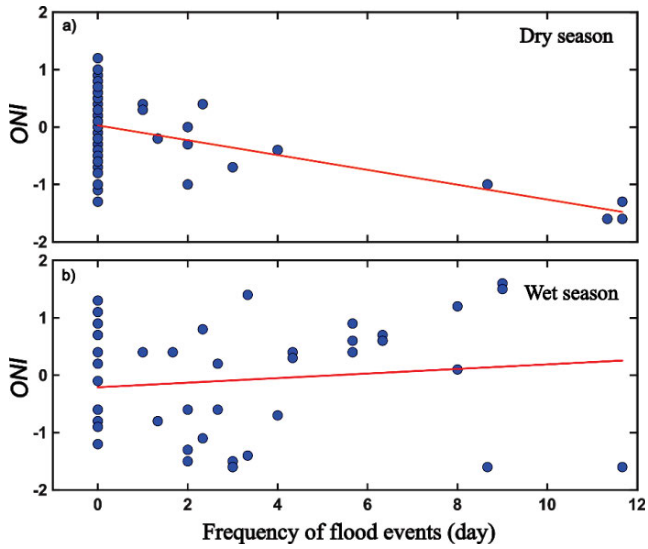

Fig. 5. Comparison between *ONI* with the number of observed days that surpassed the threshold during 2002–2011 (both were moving averaged with 3 months interval) on: a) dry season, b) wet season; red lines = trendlines of *ONI* with frequency of flood events; source: own study

which is induced by the Australian and Maritime Continent monsoon that takes place during the period of December–March every year (Aldrian and Susanto, 2003; Jourdain *et al.*, 2013). Interestingly, a notable number of flood events was observed during the dry season from July to October 2010. This anomaly can be attributed to the event of La Nina, which grew from weak (from –0.5 to –0.9) in MJJ (May–June–July) to strong (from –1.5 to –1.9) in ASO (August–September–October) that lasted until the turn of the year (Tab. 2, blue indices). In contrast, although another strong La Niña event also occurred during 2007–2008, it did not generate significant flood events. To determine the relationship between *ONI* and flood events, we compared the results in Figure 5. During the dry season, flood events tended to become more frequent along with a lower negative *ONI* value. This indicated the influence of La Niña on flood events during the dry season. Meanwhile, in the wet season, the relationship between the *ONI* and flood events is not clear. The patterns of *ONI* and flood events in both seasons are in agreement with a previous study by Hendon (2003). He mentioned that the rainfall anomalies in the dry season induced by La Niña do not persist in the wet season because of the cancellation effect of the local sea surface temperature in the Indonesian region. Hence, the La Niña event in 2007–2008 did not generate prominent flooding compared with La Niña in 2010 because its strongest period occurred during the wet season. On the other hand, Table 2 also presents several periods of El Niño (red indices) with most of them classified as moderate (from 1 to 1.4). El Niño is supposed to generate drought events whenever it occurs, however, flood events were still observed in 2004 and 2009–2010, during which El Niño occurred during both periods. However, because the scope of this study was more focused on the characterisation of flood events as end products of climatic phenomena rather than on the phenomena themselves, we did not elaborate on these anomalies further.

Table 2. Three months' moving average of Oceanic Niño Index (*ONI*) during 2002–2011

Year	Three months' moving average of *ONI*											
	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
2002	–0.1	0.0	0.1	0.2	0.4	0.7	0.8	0.9	1.0	1.2	1.3	1.1
2003	0.9	0.6	0.4	0.0	–0.3	–0.2	0.1	0.2	0.3	0.3	0.4	0.4
2004	0.4	0.3	0.2	0.2	0.2	0.3	0.5	0.6	0.7	0.7	0.7	0.7
2005	0.6	0.6	0.4	0.4	0.3	0.1	–0.1	–0.1	–0.1	–0.3	–0.6	–0.8
2006	–0.9	–0.8	–0.6	–0.4	–0.1	0.0	0.1	0.3	0.5	0.8	0.9	0.9
2007	0.7	0.2	–0.1	–0.3	–0.4	–0.5	–0.6	–0.8	–1.1	–1.3	–1.5	–1.6
2008	–1.6	–1.5	–1.3	–1.0	–0.8	–0.6	–0.4	–0.2	–0.2	–0.4	–0.6	–0.7
2009	–0.8	–0.8	–0.6	–0.3	0.0	0.3	0.5	0.6	0.7	1.0	1.4	1.6
2010	1.5	1.2	0.8	0.4	–0.2	–0.7	–1.0	–1.3	–1.6	–1.6	–1.6	–1.6
2011	–1.4	–1.2	–0.9	–0.7	–0.6	–0.4	–0.5	–0.6	–0.8	–1.0	–1.1	–1.0

Explanations: DJF, ..., NDJ = abbreviations of consecutive months' names, the first is D = December, red-coloured indices = warm periods, blue-coloured indices = cold periods.
Source: NOAA (2022).

CONCLUSIONS

The ability to comprehend flood events is necessary for improving river management and river-related disaster mitigation plans. Furthermore, the urgency of this ability becomes more prominent if the streamflow situation of a managed river is significantly affected by distinct climatic phenomena. This study focuses on flood event assessment and flood pattern characterisation in the Kapuas River, Indonesia. We utilised the information and complexity measures for the 10-year daily water level data, which were converted to discharge data previously obtained from the Sanggau gauging station located 285 km upstream from the sea. We utilised a proxy for threshold discharge to determine the word patterns. Furthermore, the information measure is determined by *MIG*, whereas the complexity measure is specified by *EMC* and *FC*. The results of the word pattern analysis showed that frequent flooding was often observed in the Kapuas River during the study period, with persistent floods happening for 2 consecutive days in 9 out of 10 years. Flood events mostly occur from December to January, which is the period when the Australian and Maritime Continent monsoon induce the rainy season in the Indonesian region. In contrast, flood events were also observed during the dry season in 2010 owing to the effects of strong La Niña events. In 2010, La Niña induced prolonged flood event duration and numbers as well as randomness, which were displayed by the quantified values of *EMC*, *MIG*, and *FC*. In fact, the analysis of the information and complexity measures indicates that (i) the flood duration tends to increase along with the greater mean annual discharge, and (ii) the degree of randomness and fluctuation of floods is also affected by higher discharge because it is more likely to increase the number of months in which flood events occur. In addition, this study reveals the versatility of the information and complexity measures used to capture flood patterns in a tropical river affected by various climatic phenomena. However, despite the encouraging prospects for information and complexity measures, the fact that rivers in tropical regions are not sufficiently gauged hinders the optimal utilisation of this approach. Therefore, for better Kapuas River watershed management, we recommend the following: (i) the number of gauging stations or streamflow datasets in this region must be increased and (ii) the standard of flood event definition must be officially established by the local government, river management bureau, or any other responsible institutions.

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