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Propagation Characteristics of Hydrological Drought Based on Variable and Fixed Threshold Methods in Snowmelt and Rainfall Driven Catchments

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Abstract: Based on long-term (>30 years) monthly streamflow data from two catchments with different hydrological features, i.e., snowmelt-driven in Harp Lake, south-central, Canada and rainfall-driven in Dongjiang river, south China, the differences in the hydrological drought (*HD*) propagation characteristics identified by fixed (*FDT*) and variable drought thresholds (*VDT*) were explored. The results showed that (i) despite both *FDT* and *VDT* methods being able to describe *HD* propagation patterns well (i.e., slow intensification but quick recovery), the onset time, peak intensity time, and termination time of *HD* within a year were significantly different between the two methods, due to the different drought conceptual backgrounds of the methods. (ii) The *HD* months identified by *VDT* were close to evenly distributed in each month of the year, while the *HD* months identified by *FDT* were mainly concentrated in the dry season. (iii) The onset, peak intensity, and termination time of *HD* identified by *FDT* were in good agreement with the dryness/wetness attributes of the two study basins and can be recommended in the study case. (iv) More methods for monitoring and predicting *HD*, and for revealing the driving mechanisms for *HD* propagation, are needed.

Keywords: hydrological drought; propagation; fixed drought threshold; variable drought threshold; intensification and recovery

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1. Introduction

Droughts develop slowly, and persistent droughts cause serious pressure on water resources and ecosystems [1–3]. Typically, droughts can be broadly classified into meteorological, agricultural, hydrological, and socio-economic droughts [3]; these four drought types refer to deficits of precipitation, soil moisture, runoff or river discharge, and social water supply, respectively. Hydrological droughts (*HD*), characterized by surface runoff or streamflow shortages, are caused by continuation of meteorological drought [4]. *HD* has a serious impact on the water quantity and water quality [5,6], causing water shortages, worsening water pollution, and affecting industrial and agricultural production [1,7]. Thus, effective monitoring and prediction of *HD* is beneficial for managing water resources, especially during droughts.

Commonly, drought propagation refers to the period or process from meteorological drought to other types of droughts (e.g., agricultural and hydrological) [8,9]. Some kind of threshold is applied to identify a drought and its propagation. The issues concerning the drought propagation threshold and propagation processes have been explored previously, providing many interesting results [10–12]. In general, drought propagation can be described as follows: following the *HD* onset, the lifecycle of a *HD* includes an intensification stage and a recovery stage [13,14]. The intensification stage is the period from the *HD* onset to the time when the peak intensity (maximum water shortage during *HD*) is realized, while the recovery stage refers to the period from the peak intensity to the complete termination of the drought. In recent years, research on the *HD* propagation processes, including the formation threshold (e.g., formation from meteorological drought to *HD*) [10–12], intensification and recovery patterns [13,14], the water required for recovery [3], and the impacts of climate change and human regulation activities on these processes [15–18] have received widespread attention. Monitoring or evaluation methods (e.g., drought index) for *HD* based on in situ observation and/or remote sensing data have also been developed [19–21].

Due to the complexity of the drivers and hydrologic responses to hydrological drought, previous studies have recommended multiple methods and multiple drought thresholds for identifying *HD*, because no single method or threshold is commonly applicable to all water users or managers [22,23]. Commonly, either a variable drought threshold or a fixed drought threshold is used to identify *HD* events and then analyze the propagation characteristics [23]. The variable drought threshold (*VDT*) method usually defaults the occurrence frequency of drought in a certain period (e.g., a month) of a year to be the same, and thus, multiple and variable thresholds are required for extracting *HD* events for different months. The threshold for identifying a *HD* for a month or season that is usually wet is quite different the threshold for a month or season which is usually dry. A fixed drought threshold (*FDT*) considers the entire time series of streamflow as a whole for a year or multiple years, and adopts only one threshold with special meaning, such as the ecological security flow, to identify a *HD*. The *VDT* and *FDT* have different concepts and principles, and thus, may reveal different results for *HD* events and their propagation processes. A recent study from Hammond et al. (2022) [24] found that, despite the spatial patterns of *HD* in the U.S. being consistent between *VDT* and *FDT*, the average *HD* duration identified from *FDT* was longer than that of *VDT*. Although previous studies have provided valuable information for monitoring and predicting *HD* under changing environments, using different methods separately [15,25], studies considering both *VDT* and *FDT* for extracting *HD* characteristics from a propagation perspective (i.e., timing of onset, peak intensity, and termination), and revealing the differences caused by the two threshold methods in basins with different hydrological features, are lacking, and this necessitates more in-depth research work.

Therefore, our study aimed to understand the differences between *VDT* and *FDT* for identifying the *HD* propagation characteristics in two selected catchments with different hydrological features (i.e., snowmelt- and rainfall-driven basins). We focused on three main tasks:

(i) Reveal the difference in the *HD* distribution pattern within a year;
(ii) Demonstrate the difference in the propagation characteristics of *HD* events;
(iii) Determine/explain the possible reasons for these differences.

The results of this study may provide a reference for selecting reasonable *HD* assessment methods for a certain catchment, so as to further enrich drought theories.

2. Methods

2.1. Fixed and Variable Drought Threshold

A Q_{20} value (the 20% discharge on the cumulative frequency curve of historical streamflow from low to high) was commonly used to identify *HD* events in previous studies [15,23–25]. If a streamflow (Q) under a certain timescale (usually a few months) is below the Q_{20} threshold, i.e., the monthly streamflow in a river minus the Q_{20} threshold is negative ($Q - Q_{20}$), it is regarded as a *HD*. The duration (D), severity (S), and intensity (I) are three basic characteristics of *HD* [2]. D is defined as the time span from the onset to the termination of the *HD* (i.e., the period from t_1 to t_2 in Figure 1), and the S is the absolute value for the sum of a negative drought index ($Q - Q_{20}$) during the D. Similarly to reference [26], we created an *HD* index time series $Q_x(t)$ (i.e., $Q - Q_{20}$) that specifies for each monthly time step 't' if the streamflow variable $Q(t)$ is at or below the threshold

Q_{20} (Q_{20}), and thus a streamflow anomaly below the threshold is identified, as defined in (Equation (1)):

$$Q_x(t) = Q - Q_{20} \tag{1}$$

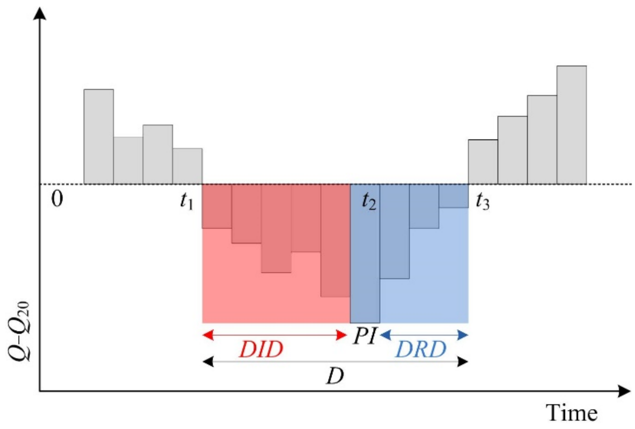

Figure 1. Propagation characteristics of hydrological drought. *D* is the drought duration; *DID* and *DRD* represent drought intensification and recovery durations; and *PI* is the peak intensity. Red and blue shaded represent intensification and recovery stages of hydrological drought, respectively [13].

One month or a few continuous months whose $Q_x(t) \le 0$ indicate a *HD* event. Then, the accumulated months from the onset to termination of a certain *HD* is regarded as *D*. Thus, the severity *S* (Equation (2)) and intensity I (Equation (3)) for the *HD* event are:

$$S = \sum_{t_{onset}}^{t_{termination}} [Q_x(t) \le 0] \tag{2}$$

$$I = \frac{S}{D} \tag{3}$$

The units of *D*, *S*, and *I* are month, m^3/s, and m^3/s, because the same timescale for the streamflow (e.g., monthly streamflow (unit: m^3/s)) was used. When a separate Q_{20} for each month within a year (thus twelve thresholds for a year) are determined to extract the *HD* events, this is called the variable drought threshold (*VDT*) method. If there is just one Q_{20} threshold for all months to extract *HD* events, this is the fixed drought threshold (*FDT*) method.

2.2. Identification of Hydrological Propagation Characteristics

According to the definition of previous studies [13,14], the duration *D* can be further divided into a drought intensification duration (*DID*) and drought recovery duration (*DRD*), based on the location of the time point of peak intensity (*PI*) (i.e., the t_2 in Figure 1). The *DID* period is regarded as from the drought onset (i.e., t_1 in Figure 1) to its *PI* (i.e., t_2 in Figure 1), and the *DRD* is defined as from the *PI* time point (i.e., t_2 in Figure 1) to the drought termination (i.e., t_3 in Figure 1). In this study, the time points of onset (t_1), *PI* (t_2), and termination (t_3) were extracted for analyzing the *HD* propagation characteristics of drought events. We chose the threshold of 0 as a preliminary criterion for the onset and termination time of a drought based on *HD* time series (i.e., S_x(t)). The reason for this was that when the Q_x(t) is lower (or larger) than 0, the streamflow is in a shortage (or surplus) condition [3]. It is noted that the termination time is the first month when the Q_x(t) > 0 after the drought end. Since the monthly streamflow was used to extract *DID* and *DRD* for a *HD* event in this study, the *HD* events longer than 3 months *D* were extracted for analyzing their propagation characteristics [13]. The linear trend and box-plot methods were also used to analyze the variation of the variables of interest in this study.

3. Study Case and Dataset

This study focuses on two catchments: the Harp Lake catchment, which is located in south-central Ontario, Canada, and has an area of 5.42 km^2 (Figure 2a); and Dongjiang River catchment, which is located in south China and has an area of 31,840 km^2. The Harp Lake catchment is a typical snowmelt-driven basin. Approximately one third of annual rainfall falls as snow in winter, with the majority of rain falling in autumn (accounting for 30% of the annual precipitation based on monthly records), and most runoff is from the spring snowmelt in the Harp Lake catchment. HP0, HP3, HP3a, HP4, HP5, and HP6 are the six drainage basins in the catchment, facilitated by long-term environmental monitoring of water quantity (Table 1). HP0 is the final controlling point of the catchment. Monthly streamflow was collected for these sites. The data were collected by the Inland Waters Unit, Environmental Monitoring and Reporting Branch, Ontario Ministry of Environment, Conservation and Parks, Canada.

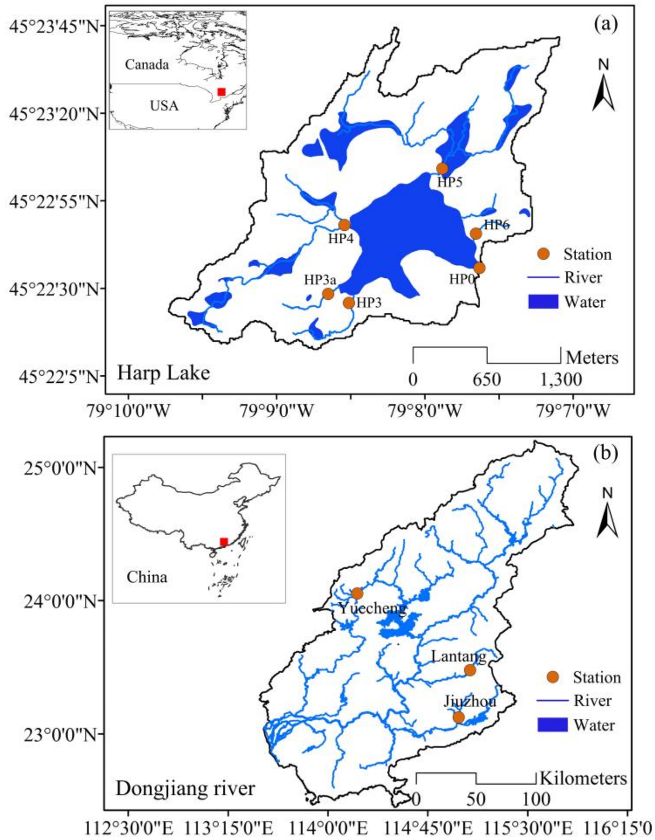

Figure 2. Location of the Harp Lake catchment (**a**) and Dongjiang River catchment (**b**), and their corresponding hydrological monitoring stations.

Table 1. The data for this study.

Catchment	Station	Timescale	Streamflow Records
Harp Lake	HP0	Monthly	1978–2019
	HP3	Monthly	1978–2019
	HP3a	Monthly	1978–2019
	HP4	Monthly	1978–2019
	HP5	Monthly	1978–2019
	HP6	Monthly	1978–2019
Dongjiang River	Yuecheng	Monthly	1960–2006
	Lantang	Monthly	1958–2015
	Jiuzhou	Monthly	1960–2006

Regarding the Dongjiang River catchment (Figure 2b), it is a typical rainfall-driven basin, where approximately 80% of the annual precipitation occurs in the warm season, from April to September [27,28]. Yuecheng, Lantang, and Jiuzhou are three branches of the Dongjiang River basin and have long-term streamflow records [27–29]. The monthly streamflows for Yuecheng, Lantang, and Jiuzhou were obtained from the water conservancy and electric power bureau of Guangdong Province, China (Table 1). All datasets have undergone strict quality control and have been used in previous studies [27–34].

4. Results and Discussion

4.1. Distribution Patterns of Streamflow within a Year

Figure 3 shows the variation of monthly streamflow within a year in the Harp Lake Figure 3a–f and Dongjiang River Figure 3g–i catchment. There are similar variation patterns of the monthly streamflow for the six stations of Harp Lake catchment and three stations of Dongjiang River catchment. For the two catchments, the monthly streamflow varies greatly between different months of the year.

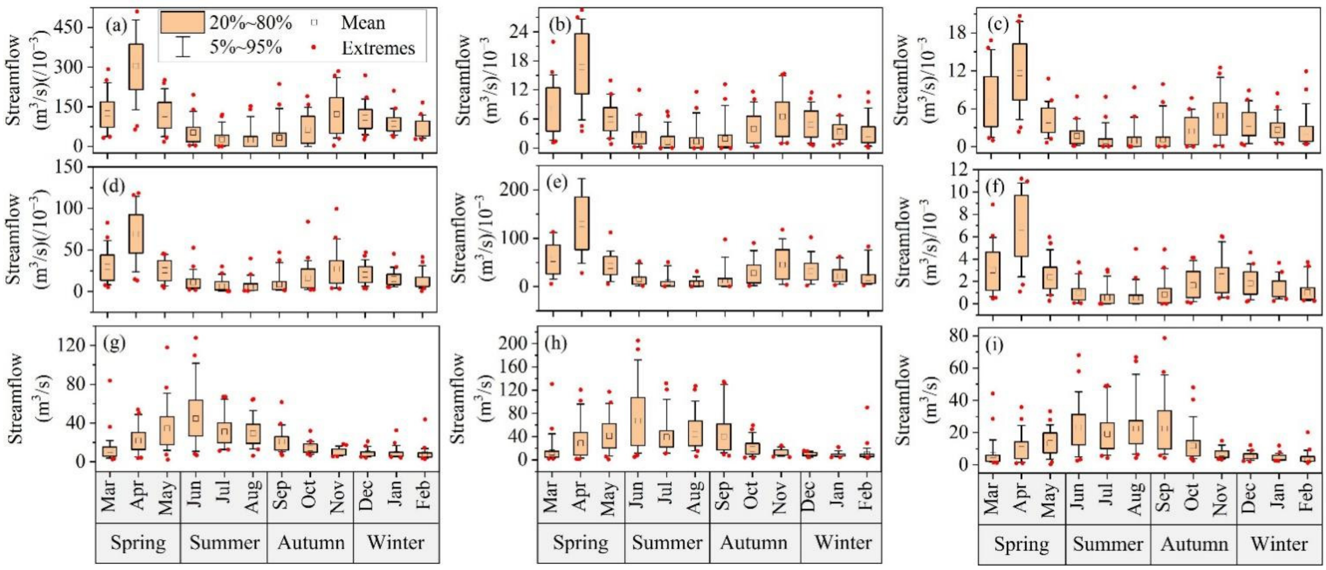

Figure 3. Box-plots for monthly streamflow in different months within a year in the Harp Lake (**a**–**f**) and Dongjiang River (**g**–**i**) catchment; (**a**) HP0, (**b**) HP3, (**c**) HP3a, (**d**) HP4, (**e**) HP5, (**f**) HP6, (**g**) Yuecheng, (**h**) Lantang, and (**i**) Jiuzhou.

For the Harp Lake catchment, the average of streamflow (i.e., the little square symbol in the box-plots) in April is the largest. For the Dongjiang River catchment, the average streamflow in August is the largest. Extreme streamflows (red circles), including extreme high (over the 95% quantile) and low streamflows (lower than the 5% quantile), occur in most months in the two selected catchments. The occurrence of samples for the extreme low streamflows were less frequent than extreme high streamflows (i.e., the boxplots of the tentacle extension for the extreme high flow are longer than that of extreme low flow). In other words, the frequency of extreme drought in the Harp Lake and Dongjiang River catchment was lower than the flooding frequency.

For the seasonal streamflow, the ratio of seasonal mean streamflow to the total annual streamflow was the largest in spring for the Harp Lake catchment and in summer for the Dongjiang River catchment (Figure 4). For the six stations of the Harp Lake catchment, the ratios of spring streamflow to the total annual flow were 48%, 51%, 53%, 50%, 55%, and 52%, at HP0, HP3, HP3a, HP4, HP5, and HP6, respectively. For the three stations of the Dongjiang River catchment, the ratios of summer streamflow to the total annual flow were 43%, 45%, and 43%, at Yuecheng, Lantang, and Jiuzhou, respectively.

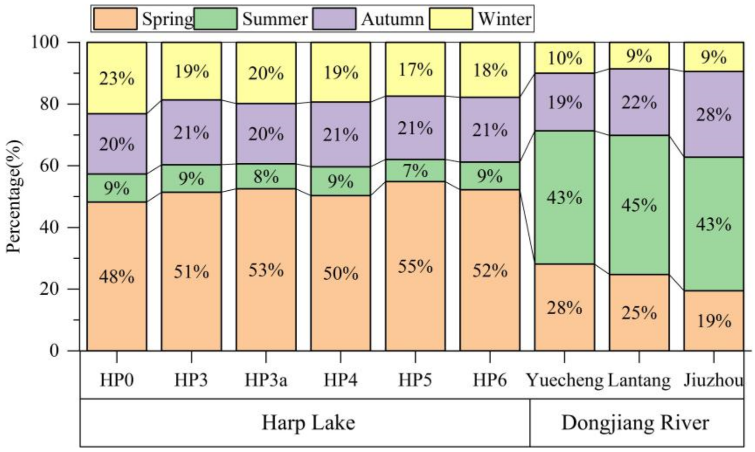

Figure 4. Ratio of seasonal streamflow to the total annual streamflow in the Harp Lake and Dongjiang River catchments.

4.2. Distribution Patterns of Hydrological Droughts within a Year

Since the HP0 site is the outlet control site for the Harp Lake catchment, and as Lantang has the longest streamflow records among the three stations of the Dongjiang River catchment, the *HD* at the HP0 site and Lantang station were identified and illustrated based on the methods developed in Section 2. The *HD* identified using the *FDT* and *VDT* methods were obviously different, both in the Harp Lake Figure 5a,b or Dongjiang River Figure 5c,d catchments.

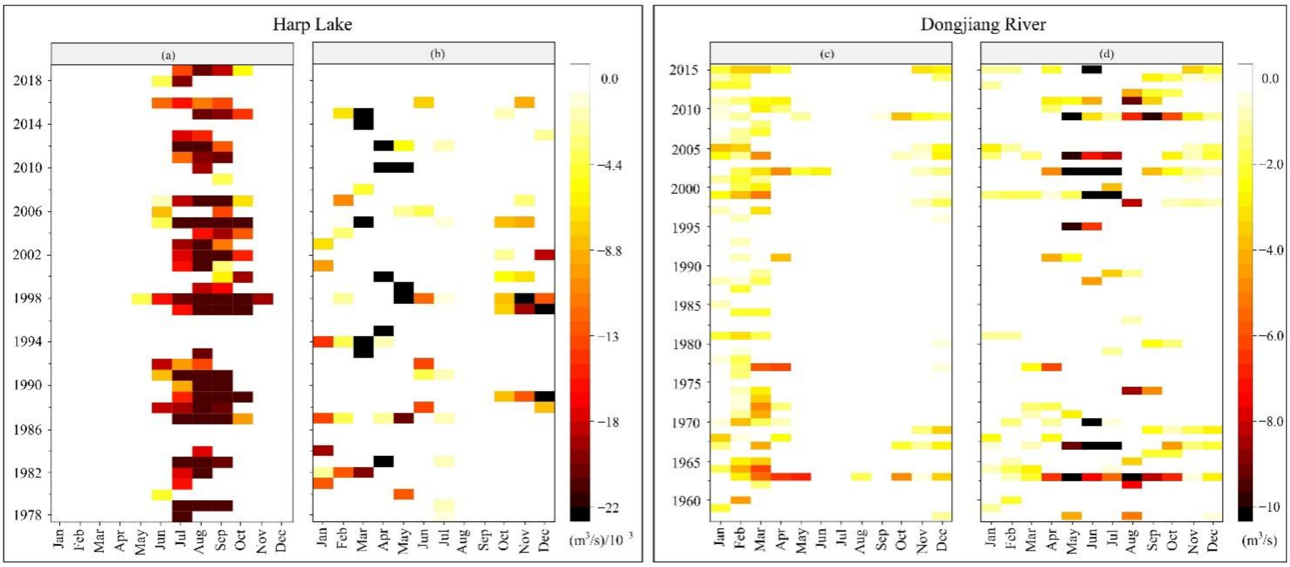

Figure 5. The distribution of streamflow deficit (i.e., the time series of $Q - Q_{20} \leq 0$) within a year, based on a fixed drought threshold (*FDT*) (**a**,**c**) and variable drought threshold (*VDT*) (**b**,**d**) at the HP0 station of Harp Lake catchment (**a**,**b**) and Dongjiang River catchment (**c**,**d**). The scaled legend bar on the right indicates the streamflow deficit in that month. The black grid in the figure shows that the streamflow deficit was lower than the minimum in the scaled legend.

For the HP0 station of the Harp Lake catchment, there were 35 and 50 *HD* events identified based on the *FDT* and *VDT* methods, in which 22 and 8 *HD* events have durations longer than 3 months, respectively. The most *HD* months extracted using the *FDT* method mainly occurred from June to October (dry season), especially from July to September (Figure 5a). However, the distribution of *HD* months identified using the *VDT* method occurred over all months (Figure 5b). The *HD* event with the longest duration occurred in 1998, with 7 months (from May to November in 1998) and a 0.12 m^3/s deficit based on the *FDT* method, and with 8 months (from May to December in 1998) and a 0.13 m^3/s deficit based on the *VDT* method. The year 1998 had one of the major droughts recorded in Canada [35]. The average *D* and *S* for the *HD* events with longer than 3 months identified by *FDT* (*VDT*) were 3.91 (4.67) months and 0.0634 (0.0421) m^3/s, respectively (Table 1). The average of *DID* was shorter than that of *DRD* for both *FDT* (2.64 vs. 1.27 months) and *VDT* (3.33 vs. 1.33 months) (Table 2).

Table 2. Averages for the propagation characteristics of hydrological drought (*HD*) events with a duration longer than 3 months at the HP0 station of Harp Lake and the Lantang station of the Dongjiang River catchment; *FDT* and *VDT* represent fixed and variable drought threshold methods, respectively; *D* and *S* are the duration and severity of *HD*; *DID* and *DRD* are the *HD* intensification and recovery duration.

Catchment	Methods	*D* (Month)	*S* (m^3/s)	*DID*	*DRD*
Harp Lake	*FDT*	3.91	0.054	2.64	1.27
	VDT	4.67	0.062	3.33	1.33
Dongjiang River	*FDT*	5.05	10.62	3.16	1.89
	VDT	5.47	23.58	2.6	2.87

For the Lantang station of the Dongjiang River catchment, there were 52 and 52 *HD* events identified based on the *FDT* and *VDT* methods, in which 19 and 15 *HD* events had a duration longer than 3 months, respectively. The majority of *HD* months identified using the *FDT* method occurred from October to March of the next year (dry season). However, the *HD* months extracted with the *VDT* method occurred over all months. The *HD* event with the longest duration occurred in 1963–1964, with 15 months (from January 1963 to March 1964) and a 44.59 m^3/s deficit based on the *FDT* method; and 14 months (from February 1963 to March 1964) and a 84.38 m^3/s deficit based on the *VDT* method. The major drought event in 1963–1964 was also identified by previous studies using standardized drought methods in south China [3,10]. The average *D* and *S* for the *HD* events longer than 3 months identified by *FDT* (*VDT*) were 5.05 (5.47) months and 10.62 (23.58) m^3/s, respectively (Table 1). The average of DID was shorter than that of DRD for both FDT (2.64 vs. 1.27 months) and *VDT* (3.33 vs. 1.33 months) (Table 2).

Generally, most *HD* months extracted using the *FDT* method occurred in the dry season for the two study catchments, but the *HD* months identified using the *VDT* method occurred over all months, because the Q_{20} threshold for each month was used, and there was about a 20% probability *HD* for every month. Moreover, the *HD* duration and severity identified using the *FDT* method was shorter and smaller than with *VDT*. By comparing Figure 5a,b and Figure 5c,d, the *HD* severity in the dry season identified with the *FDT* method was more severe than for the *VDT*; however, the *HD* severity in the wet season extracted using the *FDT* method was lesser than with *VDT*, because almost no *HD* was identified by *FDT* during the wet season.

4.3. Hydrological Drought Propagation Characteristics

The onset, *PI*, and termination time of *HD* events identified using the *FDT* method mainly occurred in June to November in the HP0 station of Harp Lake catchment (Figure 6a). Most of onset time of *HD* events occurred in June and July, the *PI* time mostly occurred from August to October, and the termination time was mostly focused in October and November. However, the onset, *PI*, and termination time of *HD* events extracted using the *VDT* method were distributed or scattered in all months (Figure 6b) at the HP0 station of the Harp Lake catchment. Relatively speaking, the most onset time of *HD* events identified using the *VDT* method occurred in January, April, and October, while the *PI* time of *HD* events mostly occurred in March and December, and the termination time of *HD* events mostly occurred in January and October. For the Lantang station of the Dongjiang River catchment, the times for the onset, *PI*, and termination of *HD* events identified using the

FDT method mainly occurred from October to May (mostly occurring in the dry season) Figure 6c. In addition, these key time points of *HD* events identified using the *VDT* method were distributed or scattered in all months within the year at the Lantang station of the Dongjiang River catchment Figure 6d. Overall, there were very different results for the onset, *PI*, and termination time of *HD* events extracted using the *FDT* and *VDT* methods.

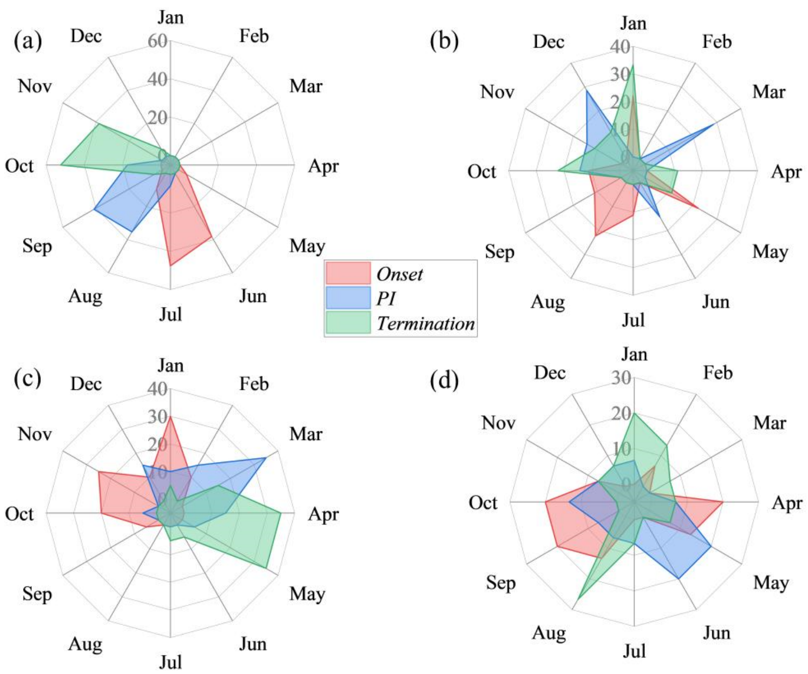

Figure 6. The onset, peak intensity (*PI*), and termination time of hydrological drought (*HD*) events within a year based on the fixed drought threshold (*FDT*) (**a**,**c**) and variable drought threshold (*VDT*) (**b**,**d**) at the HP0 station of the Harp Lake catchment (**a**,**b**) and Lantang station of the Dongjiang River catchment (**c**,**d**).

4.4. Variation of Hydrological Drought Characteristics

There is a regular and significant positive relationship between the duration and severity of *HD* both with the *FDT* (p = 0.00) and *VDT* (p = 0.00) methods for the HP0 station of Harp Lake (Figure 7a,b) and the Lantang station of Dongjiang River (Figure 7e,f) catchments; when the duration increases, the severity also increases. Conversely, the relationship between duration and severity under the *FDT* method was better than that under the *VDT* method (i.e., R^2 = 0.89 vs. R^2 = 0.43 at the HP0 station of Harp Lake catchment, and R^2 = 0.78 vs. R^2 = 0.68 in the Lantang station of the Dongjiang River catchment). An insignificantly decreasing trend for the *HD* intensity is seen for the *FDT* (*slope*= −0.1335, R^2 = 0.1, p = 0.06) and *VDT* (*slope*= −0.0351, R^2 = 0.00, p = 0.81) results identified in past few decades of the Harp Lake catchment (Figure 7c,d). In addition, for the Dongjiang catchment, a decreasing trend for *HD* intensity was identified with both the *FDT* and *VDT* methods, with an insignificant (*slope*= −0.0137, R^2 = 0.05, p = 0.13) decreasing trend for *HD* intensity extracted using the *FDT* method, and a significant (*slope*= −0.0658, R^2 = 0.12, p = 0.01) decreasing trend using the *VDT* method (Figure 7g,h).

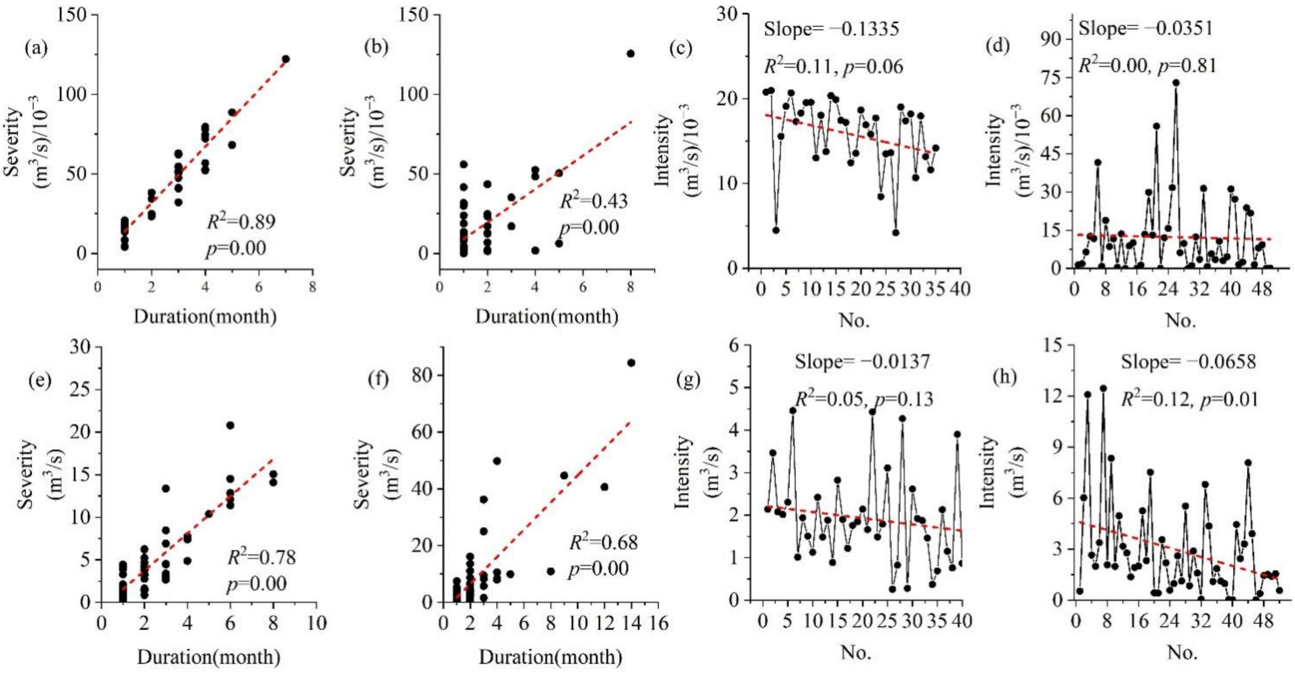

Figure 7. The relationship between the duration and severity of hydrological drought (*HD*) events at the HP0 station of the Harp Lake catchment (**a**–**d**) and Dongjiang River catchment (**e**–**h**) based on a fixed drought threshold (**a**) and (**e**) and variable drought threshold (**b**) and (**f**) methods; the linear change trend for the *HD* intensity identified using a fixed drought threshold (**c**) and (**g**) and variable drought threshold (**d**) and (**h**), respectively.

5. Discussion

There are obvious differences in the *HD* propagation processes identified using the *FDT* and *VDT* methods. The reasons for these differences are related to the differences in the background of the drought concepts of the *FDT* and *VDT* methods. For example, the principle of the *VDT* method is that a *HD* is judged based on a relative and time-sensitive concept; that is, the deficits of streamflow in a certain month relative to the historical streamflow in the same month. Thus, the *HD* frequency identified in different months is close to equivalent, which will cause a drought-free state in the wet season to be identified as a drought. In fact, similarly, the Standardized Runoff Index (*SRI*) [36] and the Standardized Streamflow Index (*SSI*) [37], commonly applied to identify the *HD*, are also based on the relative drought concept. Each drought level in a certain month is regarded as having an equal frequency for *SRI* and *SSI* [2]. The fixed drought threshold method regards the entire monthly streamflow series as a whole and just uses one fixed threshold for all months in a year to identify *HD* events [22]. The basic principle of the *FDT* method is to regard *HD* as an absolute concept, rather than a relative concept [22,23,38]. Thus, the *HD* identified using the *FDT* method mainly occurred in the actually dry season (from June to October in the Harp Lake catchment and from October to March in the Dongjiang River catchment) Figure 5a,c), and never allowed the wet season to be judged as an *HD* event.

For the Harp Lake catchment, the lowest flow occurred in the summer and pre-autumn, especially in summer (Figure 3a–f); and thus, when the *FDT* method was used, it inevitably determined that *HD* events were concentrated in the summer and pre-summer (i.e., dry season). For the Dongjiang River catchment, the lowest flow occurred from October to March of the next year, see Figure 3g–i; and thus, when the *FDT* method was used, it also inevitably determined that *HD* events were concentrated in autumn and winter (i.e., dry season). However, the *HD* occurrence month, as extracted by the *VDT* method, seems to be unreasonable and does not fit with the local climatic features, both in the Harp Lake and Dongjiang River catchments. For example, most of the *PI* time occurred in March, October, and December Figure 6b using the *VDT* method, but the average streamflows in these months were high, especially in March Figure 3a at the HP0 station of the Harp Lake catchment. Moreover, most of *PI* occurred in May and June Figure 6d using the *VDT* method, but the average streamflows in these two months were high Figure 3a in the Lantang station of Dongjiang River catchments.

The significant positive relationship between the duration and severity of *HD*, as shown in Figure 7a,b in the Harp Lake catchment and Dongjiang River catchment (Figure 7e,f) confirmed findings obtained from other catchments of other regions [9–11,16,39]. We also found that the relationship between the duration and severity identified using the *FDT* method was better than that of *VDT* method. The reason for this that the *HD* events identified using the *FDT* method were mainly concentrated in dry season (i.e., summer and pre-autumn in the Harp Lake catchment, autumn and winter in the Dongjiang River catchment), and the streamflow was lower than in the other seasons. However, the distribution of *HD* events identified by *VDT* was relatively scattered within the year, and the relationship between the duration and severity was inevitably worse. Therefore, if we use the relationship of drought characteristics to describe a related issue, care should be taken regarding the different results from the different methods.

The long-term change trends of annual streamflow in the Harp Lake and Dongjiang River catchments were further examined Figure 8a,b. The slope for the variation of annual streamflow in the HP0 station was positive (Figure 8a), indicating an increasing trend for the annual streamflow in general. The slope for the variation of annual streamflow at the Lantang station of Dongjiang River catchment was negative (Figure 8b), indicating a decreasing trend for the annual streamflow at the Lantang site of the Dongjiang River catchment. However, the change trend of annual streamflow, both in the HP0 and Lantang station, did not pass the significant test (i.e., $p > 0.05$). We assume that the different change trends of *HD* intensity between the *FDT* and *VDT* methods (as shown in Figure 7) are partly related to the change trends of annual streamflow. In other words, when the streamflow increases (decrease), the *HD* intensity may decrease (increase). For the HP0 station in the Harp Lake catchment, the change trend of *HD* intensity was insignificant decreased and was consistent with the change trend of annual streamflow in general. For the Lantang station of the Dongjiang River catchment, the change trend of *HD* intensity had an insignificant (*FDT* method) or significant (*VDT* method) decrease, but the change trend of the annual streamflow also showed an insignificant decrease (*slope*$= -0.0461$, $p = 0.57$). The possible reason for the decreasing trend of *HD* intensity in the Lantang station of Dongjiang River catchment may have been cascade reservoir regulation [40]. The variation of *HD* characteristics is very complex and related to many direct or indirect factors, which need to be further studied.

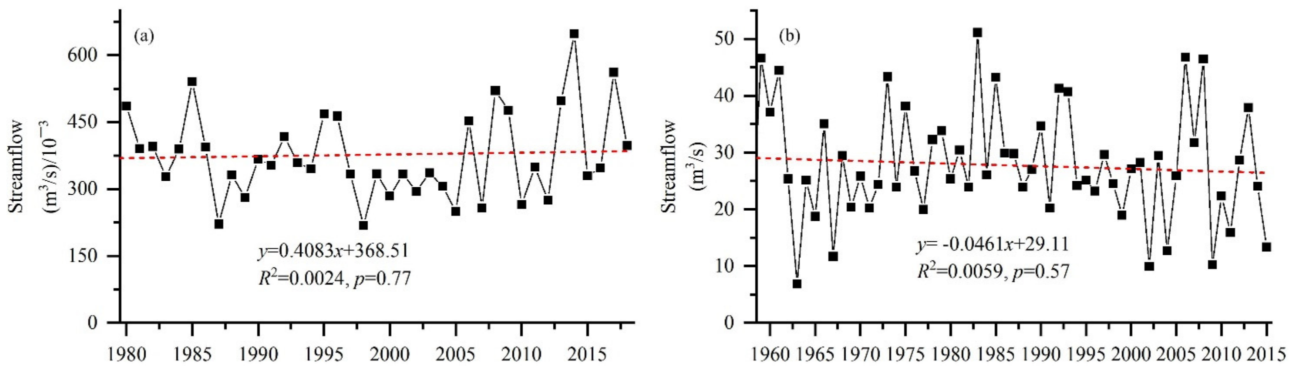

Figure 8. The change trend of annual streamflow in at the HP0 site of Harp Lake (**a**) and the Lantang station of the Dongjiang River (**b**) catchment.

It is not possible to give a reasonable answer or recommendation to address questions such as: which method of *FDT* and *VDT* is more reasonable, how to monitor and forecast

HD under the changing environment, and what are the basic criteria for using the two types of methods? More studies for these challenging issues are necessary. For the selected cases (i.e., Harp Lake and Dongjiang River catchments), the time of onset, *PI*, and termination of *HD* events identified using the *FDT* method were more consistent with the hydrological attributes than with the *VDT* method. Although previous studies [22,24] also explored the differences of *HD* characteristics between the *FDT* and *VDT* methods, the differences in *HD* propagation processes between these two methods were overlooked. Here, our suggestion would be that the implementation of drought prevention and disaster mitigation policies should be carried out scientifically, by selecting a reasonable identification method and corresponding threshold based on the regional needs of drought prevention and disaster reduction from a *HD* propagation perspective. More cases and trials in different climate zones are needed. We recommend employing more approaches to monitor and forecast *HD* propagation processes, to explain their propagation patterns and driving mechanisms from more perspectives.

6. Conclusions

The variable drought threshold method identified hydrological droughts which were scattered over 12 months in a year, whereas the droughts identified by the fixed drought threshold method occurred in the dry season. The variable drought threshold method may overestimate the drought severity for the wet season, which may lead to the failure of drought monitoring and forecasting. The selection of the drought threshold has an important influence on the identification results of the fixed drought threshold method, and this may lead to overestimation of the drought severity in the dry season. The average hydrological drought duration and severity extracted using the fixed drought threshold were smaller than when using a variable drought threshold. The fixed and variable drought threshold methods have different background concepts, and there are significant differences in the identified propagation processes of hydrological drought. Research on hydrological droughts needs to be based on the research objectives that select appropriate methods and corresponding thresholds, for conducting a targeted drought analysis and reducing drought disaster losses under a changing environment.

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