Investigation of the drought–flood abrupt alternation of streamflow in Poyang Lake catchment during the last 50 years

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ABSTRACT

Drought–flood abrupt alternation (DFAA) is one of the remarkable manifestations of the summer monsoon anomaly at the subseasonal scale and can result in severe damage. This study identified and analyzed DFAA in terms of streamflow in the Poyang Lake catchment over the last 50 years based on a DFAA index (DFAAI). The study also investigated the intra-annual distribution characteristics and long-term tendencies associated with DFAA, as well as the relationship with precipitation patterns. A statistical analysis showed that drought-to-flood events in the Poyang Lake catchment generally occur in March and April, while flood-to-drought events occur in July and August. A Mann–Kendall test indicated a long-term decreasing trend in DFAAI in March and April and a slight increasing trend in July and August; however, the trends were not statistically significant. Flood-to-drought events occurred more frequently than did drought-to-flood events at the decadal scale, especially in the 1960s and 1970s. The particular distribution of precipitation in the Poyang Lake catchment mainly determined the occurrence patterns of DFAA events, but intensive human activities are also significant factors that have decreased and mitigated DFAA disasters since the 1980s in the Poyang Lake catchment.

Key words | DFAAI, drought–flood abrupt alternation, Poyang Lake catchment, precipitation, streamflow

INTRODUCTION

It is evident that the frequency and number of water-related hazards, e.g., floods and droughts, are on the rise compared with geophysically induced disasters (Ramos & Reis 2002; Krausmann & Mushtaq 2008; Adikari & Yoshitani 2009). The impacts of climate change on hydrological processes and water resources have become an important area of research in hydrology (Scanlon et al. 2007). Climate change or increased climatic variability are expected to alter the timing and magnitude of runoff, thereby threatening global water resources, with strong implications for ecosystem health and human security (Brouwer & Falkenmark 1989; Milly et al. 2005; Wagener & Franks 2005; Wada et al. 2010; Vörösmarty et al. 2010; Omer et al. 2016).

Changes observed in many extreme weather and climate events since 1950 suggest an increased risk of hydro-meteorological disasters, including more extreme precipitation, higher peak river flows, and increased intensity of extreme tropical cyclones (World Bank 2013; Zeng et al. 2016). The Intergovernmental Panel on Climate Change also released a special report in 2012 to evaluate the influences of climate change on extreme disaster events, such as floods and droughts (Field 2012; Li et al. 2016b).

In China, floods and droughts are also the most frequently occurring natural disasters (Liu & Liu 2002; Yu et al. 2009). Most Chinese territories and over half of the total population are affected by flood and/or drought
events almost every year (Nakayama & Watanabe 2008; Wang et al. 2012), especially in the Yangtze River basin (Zhao 2000; Cai et al. 2003). Poyang Lake, the largest freshwater lake in China, is located in the middle and lower reaches of the Yangtze River and directly exchanges water with the Yangtze River (Hu et al. 2007). The frequent severe floods and droughts in the Poyang Lake region during the last several decades have caused considerable damage to the environment and the agricultural economy (Shankman et al. 2006; Li et al. 2006a) and threatened the lives of approximately ten million people in the region. Moreover, the frequency and severity of floods and droughts in the Poyang Lake area have increased since 1990 (Guo et al. 2008). Statistics indicate that the Poyang Lake region experienced as many as four severe floods (e.g., in the summers of 1995, 1996, 1998, and 1999) with the lake stages higher than 21.0 m during the 1990s (Li et al. 2015). Among them, the lake stage in summer 1995 was higher than that during the 1954 flood, which was the highest ever recorded until the mid-1990s (Wang & Gong 2000; Jiang & Shi 2003). However, a more severe flood occurred in 1998, with a lake stage as high as 22.53 m, which exceeded the highest recorded water level by 0.74 m (Shankman et al. 2006). Catastrophic levee failures resulted in extensive agricultural losses, serious damage to several cities and many villages, and massive population relocation (Shankman & Liang 2003; Shankman et al. 2006). On the other hand, serious drought events are also common and have frequently occurred in the Poyang Lake region, e.g., in 1992 and 1996, with severe drought disasters also occurring. In the last ten years, droughts in the Poyang Lake area have worsened, and the lake stage in the dry season has declined continually (Zhang et al. 2012a, 2014; Liu et al. 2015; Ye et al. 2016; Yao et al. 2016). Especially in December 2007, the lake level at Duchang hydrological station was lower than the lowest historical level for more than 20 consecutive days, and Poyang Lake almost dried up. The drought issues in the Poyang Lake region have attracted great international attention (Lu et al. 2011; Zhang et al. 2012a; Liu et al. 2015).

Nevertheless, within the background of global warming, the dual influences of regional climate change and intensive human activities have increased not only the frequency and intensity of floods and droughts but also the risk of drought–flood abrupt alternation (DFAA) (Wu et al. 2006; Cheng et al. 2012). DFAA, including both drought-to-flood and flood-to-drought processes, is one of the remarkable manifestations of the East Asian summer monsoon at the subseasonal scale, and these processes can result in more severe damage than separate flood or drought disasters (Wu et al. 2006; Feng et al. 2012). In practice, DFAA events are ubiquitous in many regions across the world due to the influences of the atmospheric intraseasonal oscillation (ISO), which is generally a low-frequency oscillation with a period of 30–60 days (Madden & Julian 1972). The ISO is a global phenomenon; therefore, it affects not only local precipitation but also monsoons, tropical cyclones, and global weather and climate patterns (Zhang 2005; Sun & Ding 2008; Qi et al. 2009). China is strongly influenced by the East Asian monsoon (Liu & Liu 2002; Yu et al. 2009), and the increased variability in East Asian summer monsoon precipitation caused by the ISO (Li & Luo 2011) has increased the frequency and intensity of DFAA events, especially in the Yangtze River basin, Huai River basin, and Southwest China (Wu et al. 2006; Feng et al. 2012). For instance, several DFAA events occurred in Guangxi Province in 2005, 2009, and 2013, and others occurred in the Huai River basin in 2005 and 2006 (Tang et al. 2007). The middle and lower reaches of the Yangtze River experienced a severe DFAA disaster in spring–summer 2011 (Shen et al. 2012). Serious disaster situations, rapid alternations from drought-to-flood, and widely affected areas are rare in recent years, but cause huge economic losses and serious damage to agriculture and the environment. Therefore, the severe consequences of DFAA have become the focus of governments and researchers.

Numerous studies have been carried out to explain the changing characteristics, trends, influencing factors, and impacts of DFAA. For example, Wu et al. (2006) quantified the characteristics of DFAA in summer in the middle and lower reaches of the Yangtze River based on a defined long-period (approximately two months) DFAA index (DFAAI), which compared precipitation in July and August with that in May and June. Tang et al. (2007) also quantitatively described DFAA in the northern Huai River basin from temporal and spatial perspectives. Wang et al. (2009) discussed the climatic characteristics of these alternations during the principal flood season and described a new criterion based on the percentage of rainfall anomaly. Then, they analyzed...
its spatiotemporal distribution characteristics. In addition, Cheng et al. (2012) defined an intensity index for DFAA events based on the standardized precipitation index and explored the spatiotemporal distribution and intensity difference in the Huai River basin. Zhang et al. (2012b) and Luo et al. (2013) studied the trends of DFAA occurrence from the perspective of runoff when they dealt with abnormal changes in streamflow. Recently, Bela et al. (2015) investigated ozone production and transport during the dry-to-wet and wet-to-dry transition seasons in the Amazon basin.

The mechanisms of DFAA have also been investigated by many researchers and from different perspectives, such as atmospheric circulation anomalies, water vapor transfer, sea surface temperature (SST), and so on. Long-term persistence of the subtropical high in the Northwest Pacific Ocean and abnormal westward shifting of the summer East Asian trough has generally resulted in the encounter of warm and cold air. Shen et al. (2012) believed that the encounter of the warm and wet airflow from the Indian Ocean and the cold air from the north are the direct causes of DFAA in the middle and lower reaches of the Yangtze River. It has also been found that before or after DFAA occurrence, the situations of the convective activity and water–vapor transfer may reverse and the vorticity features of low-frequency oscillations change noticeably (Feng et al. 2012). In addition, the SSTs in the central East Pacific Ocean and Indian Ocean during the previous winter were also key factors associated with DFAA events. Feng et al. (2012) concluded that both the persistence of La Niña events and the relatively low SST in the Indian Ocean area were precursor signals of the DFAA event in the middle and lower reaches of the Yangtze River in 2011. Furthermore, Wang et al. (2014) suggested that DFAA is usually a result of the combined effects of several processes, such as the influences of the ocean on atmospheric circulation and the influences of changes in the seasonal heating power effect over land on ascending motion in the rainstorm zone.

Recognizing the changing characteristics of DFAA, as well as the factors that affect DFAA, is a basic issue and has raised extensive concern (Wang et al. 2012). More importantly, notably understanding these characteristics is indispensable to flood and/or drought disaster prediction systems (Adhikari et al. 2010), and this has become an important prerequisite of disaster prevention and mitigation (Nie et al. 2012). However, the Poyang Lake catchment, as an important national rice-producing base in China, has received far less attention with respect to DFAA disasters, which is unfavorable to the development of society, the economy and agricultural production. Most previous DFAA-related studies were performed from the perspective of precipitation rather than runoff (Li & Ye 2015; Shao et al. 2016). Floods and/or droughts in streamflow are the propagation of extreme meteorological events, and moreover, the floods and/or droughts in streamflow have more significant environmental, agricultural, economic, and social consequences, such as water restrictions for irrigation, agricultural crop failures, power generation reductions, and recreation activity limitations (Mishra & Singh 2010; Tabari et al. 2013). It is necessary to expand upon available studies of DFAA and the factors that affect DFAA from the perspective of runoff, and recognizing these factors will benefit sustainable economic development in the local catchment.

Therefore, the objectives of the study are as follows: (1) identify and analyze the DFAA in terms of streamflow in five sub-tributaries in the Poyang Lake catchment, including both drought-to-flood and flood-to-drought scenarios, during the period of 1960–2010; and (2) investigate the intra-annual distribution characteristics and long-term tendencies of DFAA events and explore their relationships with precipitation patterns in the catchment. The study is expected to provide a useful reference and valuable information for flood and/or drought mitigation and regulation in the Poyang Lake catchment, as well as in other regions.

**STUDY AREA AND DATA**

**Study area**

Poyang Lake is the largest freshwater lake in China and is located in the middle and lower reaches of the Yangtze River (28°22′–29°45′ N and 115°47′–116°45′ E). The lake receives water primarily from five sub-tributaries in its catchment (i.e., Xiushui River, Ganjiang River, Fuhe River, Xinjiang River, and Raohe River) and connects and interacts with the Yangtze River through a channel in its northern part (Figure 1). Among the five major rivers, the Ganjiang is the largest river in the region, extending 750 km and
contributing almost 55% of the total discharge into Poyang Lake (Shankman et al. 2006). The catchment of Poyang Lake has an area of 16.22 × 10⁴ km², accounting for 9% of the drainage area of the Yangtze River basin, and varies in elevation from 2,200 m (above sea level) in highly mountainous and hilly regions to about 30 m in the lake floodplain area. The Poyang Lake catchment has a subtropical wet climate influenced by the East Asia monsoon. The mean annual precipitation was 1,630 mm for the period of 1960–2010 (Li et al. 2018), and the annual mean temperature was 17.6 °C, with an average of 27.3 °C in summer (June–August) and 7.1 °C in winter (December–February) (Zhang et al. 2014). Annual precipitation shows a wet season and a dry season and a short transition period in between (Ye et al. 2013). Generally, the rainy season in the Poyang Lake catchment begins in April, and the water flows in the local catchment increase quickly from April to June (Zhang et al. 2011). The streamflow in the rainy season accounts for more than 50% of the total annual streamflow, and it is particularly important when heavy rainfall produces large surface flows from the sub-catchments into the lake (Shankman et al. 2006). Rainfall decreases sharply from July to September. Then, the dry season begins and lasts through December; surface flow in the catchment is very low during this period, e.g., the streamflow between October and the following January accounts for only 15.7% of the annual total (Ye et al. 2013). As a result, Poyang Lake expands and forms a large lake, with an inundation area reaching >3,000 km² and volume of 320 × 10⁸ m³ in the flood season (Shankman et al. 2006); however, it shrinks to <1,000 km² and forms a narrow meandering channel during the dry season, exposing extensive floodplains and
wetland areas. The largest streamflow occurs in June (approximately $246 \times 10^8$ m$^3$), accounting for 20.4% of the total annual streamflow, and the lowest occurs in December ($32.2 \times 10^8$ m$^3$), accounting for only 2.8% (Zhang et al. 2011). Moreover, statistics indicate that the annual runoff in the Poyang Lake catchment showed a moderate long-term increasing trend during the last 60 years, and these increasing trends were also observed in low-water discharges series (Zhang et al. 2014). However, the flood flow rates of the five rivers are very different, e.g., a decreasing trend was observed at Waizhou and increasing trends were observed at the other hydrological stations (Guo et al. 2008).

Data

Observed daily streamflows from the five sub-tributaries in the Poyang Lake catchment were collected from the Hydrology Bureau of Jiangxi Province, China. In the sub-catchments of the Ganjiang, Fuhe, and Xinjiang Rivers, only one gauging station on each main stream was selected to represent river discharge, including the Waizhou, Lijiadu, and Meigang stations. In the sub-catchments of the Xiushui and Raohe Rivers, two gauging stations on each stream (the Wanjiabu and Qiujin stations on the Xiushui River and the Shizhenjie and Dufengkeng stations on the Raohe River) were included to account for the runoff contributions to the main stream. Streamflow values measured at Qiujin station are shown in Figure 1, and additional information is summarized in Table 1. Additionally, daily rain gauge data from 24 meteorological stations in the Poyang Lake catchment from 1960 to 2010 were collected from the National Meteorological Information Center of China to measure and examine the distribution characteristics of precipitation in the catchment. Note that these rain and hydrological data have been widely used in different studies previously (Hu et al. 2007; Guo et al. 2008, 2012; Ye et al. 2011, 2013; Zhang et al. 2014; Li et al. 2015; Li & Zhang 2015), and the quality of the data is quite reliable.

METHODS

The DFAAI

The DFAAI event is described quantitatively in the study using a DFAAI, which was defined by Wu et al. (2006) and Zhang et al. (2012) as follows:

$$\text{DFAAI} = \frac{(NQ_i - NQ_{i-1}) \cdot (|NQ_i| + |NQ_{i-1}|)}{(\sqrt{\sum (NQ_i)^2})} \cdot \alpha^{\frac{|NQ_i + NQ_{i-1}|}{\sigma^2}}$$

$$i = 2, 3, 4, \ldots, n$$

where $NQ_i$ and $NQ_{i-1}$ are the normalized monthly discharges in the month $i$ and $i-1$, respectively; $Q_i$ is the monthly average discharge; $\bar{Q}$ and $\sigma$ are the mean and standard error of $Q_i$, respectively; $\alpha$ is a weight coefficient, for which a value of 3.2 is suitable at the monthly scale according to Zhang et al. (2012); $i$ is the month number; and $n$ is the total months during the study period.

<table>
<thead>
<tr>
<th>Station</th>
<th>Sub-tributary</th>
<th>Coordinates</th>
<th>Sub-catchment area (km$^2$)</th>
<th>Runoff ($10^8$ m$^3$/y)</th>
<th>Average runoff depth (mm/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waizhou</td>
<td>Ganjiang River</td>
<td>115.83°, 28.63°</td>
<td>80,948</td>
<td>683</td>
<td>844</td>
</tr>
<tr>
<td>Meigang</td>
<td>Xinjiang River</td>
<td>116.82°, 28.43°</td>
<td>15,535</td>
<td>179</td>
<td>1,152</td>
</tr>
<tr>
<td>Lijiadu</td>
<td>Fuhe River</td>
<td>116.17°, 28.22°</td>
<td>15,811</td>
<td>123</td>
<td>780</td>
</tr>
<tr>
<td>Shizhenjie</td>
<td>Raohe River (south)</td>
<td>116.97°, 28.85°</td>
<td>8,367</td>
<td>92</td>
<td>1,099</td>
</tr>
<tr>
<td>Dufengkeng</td>
<td>Raohe River (north)</td>
<td>117.12°, 29.16°</td>
<td>5,013</td>
<td>45</td>
<td>898</td>
</tr>
<tr>
<td>Wanjiabu</td>
<td>Xiushui River (south)</td>
<td>115.65°, 28.85°</td>
<td>3,548</td>
<td>35</td>
<td>978</td>
</tr>
<tr>
<td>Qiujin</td>
<td>Xiushui River (north)</td>
<td>115.41°, 29.10°</td>
<td>9,914</td>
<td>92</td>
<td>951</td>
</tr>
</tbody>
</table>
According to Wu et al. (2006), the item \((NQ_1 - NQ_{-1})\) represents the intensity term of the DFAA event, the item \((|NQ_1| + |NQ_{-1}|)\) denotes the magnitude of the droughts and floods, and \(\alpha^{-|NQ_0 + NQ_{-1}|}\) is the weight coefficient which may decrease the weight of droughts or floods in two consecutive months and increase the weight of the DFAA events. Meanwhile, the absolute magnitude of those discharge anomalies within 0.5 standard deviations is regarded as normal, while the anomalies over 0.5 standard deviations and under −0.5 standard deviations are defined as floods and droughts, respectively. A positive DFAAI value indicates a drought-to-flood event has occurred in that period, while a negative DFAAI value shows the occurrence of a flood-to-drought event and the larger the absolute value means the stronger intensity of drought-to-flood or flood-to-drought events (Wu et al. 2006). Therefore, the frequency analysis of DFAA events is based on the occurrence times of the drought-to-flood events with the DFAAI > 0.5 and the flood-to-drought events with the DFAAI < −0.5 in the five rivers.

**The Mann–Kendall test**

The Mann–Kendall (M-K) test (Mann 1945; Kendall 1975) was applied to analyze trends associated with the DFAA events. The M-K test is a rank-based non-parametric method, which is robust against the influence of extreme data and good for use with biased variables. It has been widely applied for trend detection in hydro-climatic time series (e.g., refer toNovotny & Stefan 2007; Zhao et al. 2010; Ye et al. 2013; Zhang et al. 2014).

For any sample of \(n\) variables, \(x_1, x_2, x_3, \ldots, x_n\), the cumulative number \(n_i\) of samples that \(x_i > x_j\) (\(1 \leq j \leq i\)) should first be calculated (Ye et al. 2013). The statistical parameter \(d_k\) can be calculated as follows:

\[
d_k = \sum_{i=1}^{k} n_i \quad (2 \leq k \leq n)
\]  

(3)

Under the null hypothesis of no trend, \(d_k\) is asymptotically normally distributed, with an expected mean value \(E(d_k)\) and variance \(Var(d_k)\) as follows:

\[
E(d_k) = \frac{k(k-1)}{4}
\]

(4)

\[
Var(d_k) = \frac{k(k-1)(2k+5)}{72}
\]

(5)

Under the above assumption, the normalized variable statistic \(Uf(d_k)\) is calculated as follows:

\[
Uf(d_k) = \frac{d_k - E(d_k)}{\sqrt{Var(d_k)}} \quad (k = 1, 2, 3, \ldots, n)
\]

(6)

where \(Uf(d_k)\) is the forward sequence and the backward sequence \(Ub(d_k)\) is calculated using the same equation but with a reversed series of data.

The null hypothesis of no trend is rejected when any of the points in the forward sequence are outside the confidence interval of ±1.96 at the 0.05 significance level (Zhang et al. 2014). A positive value \((Uf(d_k) > 0)\) denotes an increasing trend, and a negative value \((Uf(d_k) < 0)\) corresponds to a decreasing trend (Ye et al. 2013). It is also necessary to do autocorrelation (serial correlation) analysis before the trend test because of the presence of serial correlation, which can influence the identification of trends (Yue et al. 2003; Khaliq et al. 2009).

**The precipitation concentration degree**

The precipitation concentration degree (PCD) was proposed by Zhang & Qian (2003) to evaluate the annual distribution of each monthly precipitation in annual total precipitation. It was developed based on the assumption that monthly precipitation is a vector containing both magnitude and change of direction represented by an arctangent function as a 360° circle (Zhang & Qian 2003; Wang et al. 2013). For a given place, the yearly PCD can be defined as follows:

\[
PCD = \sqrt{\frac{R_x^2 + R_y^2}{R}}
\]

(7)

\[
R_x = \sum_{i=1}^{12} r_i \cdot \sin \theta_i
\]

(8)

\[
R_y = \sum_{i=1}^{12} r_i \cdot \cos \theta_i
\]

(9)
where $R$ is the annual total precipitation; $r_i$ is the monthly precipitation in the $i$th month; $\theta_i$ is the azimuth of the $i$th month, i.e., $\theta_1 = 15^\circ$, $\theta_2 = 45^\circ$, $\theta_3 = 75^\circ$, and so on; and $i$ denotes the month of the year.

From the above equations, it is easy to see that the yearly PCD can reflect the precipitation concentration level in a year and it ranges between 0 and 1. If the annual precipitation occurs only in one month of a year, the ratio of the synthetic component with respect to the annual precipitation would be 1, the PCD having reached its maximum value. In contrast, if total precipitation of each month within a year is evenly distributed, the PCD will reach the minimum 0 (Zhang & Qian 2003; Wang et al. 2013).

**RESULTS**

**Characteristics of DFAA from the perspective of total runoff**

The sum of streamflows from the five rivers at seven hydrological gauging stations represents the total runoff in the Poyang Lake catchment. The monthly DFAAI of total runoff is calculated according to Equations (1) and (2). Figure 2 shows the variation in DFAAI from 1960 to 2010. The DFAAI fluctuates around zero during the study period, with a maximum of 1.71 and minimum of −2.67, although most values are distributed between −1.0 and 1.0. Both the times and absolute values of the negative DFAAI values smaller than −1.0 are distinctly higher than those of the positive DFAAI values larger than 1.0, indicating that flood-to-drought events were more frequent and intense than drought-to-flood events in the Poyang Lake catchment. Additionally, the extent of the fluctuation is more remarkable before 1980 than after 1980, suggesting that the DFAA events were more frequent and strong in the Poyang Lake catchment before 1980.

To verify the characteristics of the relationship between DFAAI values and the catchment streamflows, the normalized total runoff values in current and previous months for each DFAAI value higher than 0.5 and lower than −0.5 are plotted in Figure 3. It is seen that, for the positive DFAAI values, high flows usually occur in current months, but low flows are generally observed in the previous month. Moreover, with the increase of DFAAI, the streamflow is inclined to become larger in the current month and drier in the previous month (Figure 3(a)). Conversely, negative DFAAI months have low streamflows in the current month and high streamflows in the previous month, and smaller DFAAI values (larger absolute value) correspond to severe drought in the current month and higher flows in the previous month (Figure 3(b)). Figure 3 indicates that the DFAAI can be considered a vigorous index that describes DFAA events in the Poyang Lake catchment, as explained in the Methods section.
Intra-annual distribution of DFAA in the Poyang Lake catchment

The intra-annual distributions of DFAAI values in the five rivers at seven hydrological gauging stations and the total runoff during the study period are summarized using box plots of the mean, upper, and lower quartiles, and max and min of monthly DFAAI values, as shown in Figure 4. It is seen that the DFAAI values at most stations exhibit consistent temporal distributions and intra-annual variations. Specifically, positive DFAAI values are mainly observed in the first half of the year, and negative DFAAI values are principally observed in the second half of the year. Although the Qiujin station is an exception compared to other stations (Figure 4(g)), which may be due to its short streamflow record, its small discharge does not affect the intra-annual distribution of DFAAI for the total runoff. Accordingly, the distributions of DFAA are similar between the five subtributaries in the Poyang Lake catchment.

It is also seen from Figure 4 that the positive DFAAI values in March and April are larger than those in other months according to the statistical analysis, while the negative DFAAI values with lower means, quartiles, and minimum values are mainly observed in July and August. These distribution patterns indicate that drought-to-flood events in the Poyang Lake catchment generally occur in March and April, while flood-to-drought events occur in July and August.

Inter-annual variations in DFAA in the Poyang Lake catchment

The above analysis suggests that DFAA, including both drought-to-flood and flood-to-drought events, in the Poyang Lake catchment principally occurred in March, April, July, and August; therefore, the DFAAI values in these months during the study period were selected for a long-term trend analysis using the M-K test. Figure 5 shows the inter-annual variation in DFAAI for total runoff and the corresponding M-K test trends in March, April, July, and August. It is seen that the monthly DFAAI values in March and April display long-term decreasing trends, with M-K statistics of $-0.31$ and $-0.89$, respectively, but they are not significant at the 5% significance level. Slight increasing trends can be observed in July and August, with M-K statistics of $0.63$ and $0.64$, respectively. This trend is also not significant. Although
the long-term trends in DFAAI in selected months are not significant, large fluctuations are obvious in different decades, especially before 1980, when its fluctuating extent is more remarkable, as depicted in Figure 5.

In addition, the trends in DFAA events in each sub-tributary of the Poyang Lake catchment were also examined based on the M-K test. Table 2 shows the results of the M-K tests of DFAAI at each hydrological gauging station in March, April, July, and August, respectively. It is seen that although the increasing trends can be observed at most stations with positive M-K statistics in March, including a significant trend at the 5% significance level at Qiujin, the Gangjiang and Fuhe Rivers show slight decreasing trends. Moreover, the downward trends are also presented in April with negative M-K statistics in every river; however, none exceeds the 5% significance level. By contrast, the DFAAI values in July and August display slight upward trends at all stations, with positive Z-statistics, except at Qiujin station in July and Dufengkeng station in August; however, most are not significant. Table 2 indicates that the intensity of DFAA, both the drought-to-flood and the flood-to-drought, in the Poyang Lake catchment has an alleviative tendency during the last few decades.

Decadal frequency of DFAA events in five rivers

The variation characteristics of DFAA in the Poyang Lake catchment are also analyzed at the decadal scale to provide insight into the decadal frequency of DFAA events in each
sub-tributary. Figure 6 shows the decadal occurrence times of drought-to-flood events with $DFAAI > 0.5$ and flood-to-drought events with $DFAAI < -0.5$ in five rivers. It is seen that the total number of DFAA events in the five rivers, including both drought-to-flood and flood-to-drought events, was 8–16 events per ten years. However, an uneven distribution in different decades is also displayed in each river. The occurrence frequency per ten years in the Ganjiang River decreased from 15 times in the 1960s to nearly 8–9 times in the 1990s and 2000s. The Xinjiang River shows an increasing trend since the 1960s, peaking in the 1990s. Then, the occurrence times of DFAA events decreased in the 2000s. Similarly, the Raohe River presents an upward to downward trend, peaking in the 1980s (as many as 19 events), regardless of the south or north one. The Fuhe and Xiushui Rivers show similar distributions, with lower frequencies in the 1990s, excluding the incomplete data from the northern Xiushui River.

Moreover, Figure 6 shows that the number of flood-to-drought events is higher than the number of drought-to-flood events in every sub-tributary, especially in the 1960s and 1970s, indicating that the five sub-tributaries of the Poyang Lake catchment are more likely to experience an anomalous dry period following the flood season.
and/or droughts. Figure 7 compares the annual variation of precipitation in the Meigang Xinjiang River, and Lijiadu Fuhe River. Anomalies are responsible for the occurrences of droughts, which peaked in late June. After July, the flow decreased sharply. The inflow peak occurred in April–June, corresponding to the main wet season in the Poyang Lake catchment. This is particularly evident in the rose diagram of monthly precipitation (Figure 7(b)). Therefore, the occurrence patterns of DFAA events in the five sub-tributaries, i.e., drought-to-flood events, mainly occurred in March and April, and flood-to-drought events usually occurred in July and August, as largely determined by the annual distribution of precipitation in the Poyang Lake catchment.

The PCD emphasizes the distribution of each monthly precipitation in the annual total precipitation by reflecting the distribution of annual total precipitation over the 12 months of a year (Zhang & Qian 2005; Li et al. 2010). The variation in precipitation in the five sub-catchments (Figure 8) suggests that the PCD changed in different years, although most ranged between 0 and 0.4, with some larger than 0.4 and even over 0.5. Notably, the average PCD values in the 1960s and 1970s were larger than those in other periods, indicating that higher precipitation concentrations, i.e., heavy or intense precipitation, occurred in the 1960s and 1970s. This may help explain why the DFAA events occurred more frequently and intensely before 1980 in the Poyang Lake catchment.

In addition, intensive human activities, such as construction of dams, river regulation, extensive reforestation, and so on, have significantly affected the occurrence and magnitude of DFAA events in the Poyang Lake catchment. Statistics indicate that from 1950 to 2006, thousands of water reservoirs were constructed in the Poyang Lake catchment, with a total storage capacity of more than 28 billion m³, in which, the total storage capacity of 25 large reservoirs (storage capacity > 100 million m³) is as large as 17 billion m³ (Statistic Bureau of Jiangxi Province 2006). The construction and management of these reservoirs have a considerable impact on watershed hydrology (Verbunt et al. 2005). For example, the Wan’an reservoir (built in 1990, with a total storage capacity of 2.2 billion m³) decreased the peak flood flow that occurred in 1994 by 21% and the peak flood flow that occurred in 1995 by 23.1% (Zhang et al. 2011). Thus, reservoirs, especially large reservoirs, have markedly reduced the risk of streamflow DFAA since the 1980s due to water storage and releases. In addition, forestation began in the 1980s in the Poyang Lake catchment, and the forest coverage increased from 30% to over 60% in 2010 (Ye et al. 2013). To a certain degree, this increase in forestation can reduce the peak flood flow. For instance, a modeling study in the Xinjiang River sub-catchment indicated that when agricultural land was converted into forest, accounting for up to 23.3% of

<table>
<thead>
<tr>
<th>Station</th>
<th>Sub-tributary</th>
<th>March</th>
<th>April</th>
<th>July</th>
<th>August</th>
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</thead>
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<tr>
<td>Waizhou</td>
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<td>−0.35</td>
<td>−0.35</td>
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<td>Meigang</td>
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<td>−0.25</td>
<td>0.64</td>
<td>0.56</td>
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<td>Lijiadu</td>
<td>Fuhe River</td>
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<td>−1.13</td>
<td>0.58</td>
<td>0.50</td>
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<td>Shizhenjie</td>
<td>Raohe River (south)</td>
<td>1.08</td>
<td>−1.63</td>
<td>0.61</td>
<td>0.71</td>
</tr>
<tr>
<td>Dufengkeng</td>
<td>Raohe River (north)</td>
<td>0.02</td>
<td>−1.39</td>
<td>2.04*</td>
<td>−1.16</td>
</tr>
<tr>
<td>Wanjiabu</td>
<td>Xiushui River (south)</td>
<td>0.48</td>
<td>−0.95</td>
<td>0.85</td>
<td>0.76</td>
</tr>
<tr>
<td>Qiujin</td>
<td>Xiushui River (north)</td>
<td>2.17*</td>
<td>−1.94</td>
<td>−1.19</td>
<td>0.71</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>−0.31</td>
<td>−0.89</td>
<td>0.63</td>
<td>0.64</td>
</tr>
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</table>

*Delineates significance at 0.05 significance level.

**DISCUSSION**

The previous sections presented the spatiotemporal distribution characteristics of DFAA in terms of streamflow in the Poyang Lake catchment over the last 50 years, which shows that DFAA events are common and ubiquitous in sub-tributaries of the Poyang Lake catchment, and the frequency and intensity of events change in different periods. Possible factors that influence these spatiotemporal distributions in intra-annual and long-term trends include climatic characteristics and human activities in the Poyang Lake catchment. However, precipitation, as the primary source of streamflow, its intensity, amount, duration, timing, and rate directly affect the natural cycles of water resources, and the variable precipitation patterns and anomalies are responsible for the occurrences of floods and/or droughts. Figure 7 compares the annual variation in the discharges of the five rivers and provides a rose diagram of monthly precipitation in the Poyang Lake catchment from 1960 to 2010. Rapidly increasing streamflow in the Poyang Lake catchment began in March and peaked in late June. After July, the flow decreased sharply. The inflow peak occurred in April–June, corresponding to the main wet season in the Poyang Lake catchment. This is particularly evident in the rose diagram of monthly precipitation (Figure 7(b)). Therefore, the occurrence patterns of DFAA events in the five sub-tributaries, i.e., drought-to-flood events, mainly occurred in March and April, and flood-to-drought events usually occurred in July and August, as largely determined by the annual distribution of precipitation in the Poyang Lake catchment.

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the sub-catchment area, the surface runoff decreased substantially in April–June, causing flows to decrease during the wet period. Decreases in discharge also occurred in the periods prior to and after wet periods (Guo et al. 2012). Moreover, the variations in streamflow were further increased by extensive water utilization due to the expansion of irrigated agricultural areas. The Poyang Lake catchment is the major agricultural production region in China. There are ten irrigated agricultural regions, and seven are larger than 6,672 hm² (Zhang et al. 2014). The large area of irrigated farmland and the irrigation systems notably increased water utilization and directly decreased streamflow, especially in dry years (Ye et al. 2015). Therefore, the joint influences of these intensive human activities are also significant factors responsible for the decrease in and mitigation of DFAA disasters after the 1980s in the Poyang Lake catchment.

Finally, although the method used in the study has inherent advantages in reflecting the changing characteristics of DFAA events in the Poyang Lake catchment quantitatively, several uncertainties still exist regarding the application of the DFAAI. For example, $\alpha$ is an important weight coefficient in the equation used by the DFAAI, and its value is related to the time scale of the study and the climate and catchment characteristics (Wu et al. 2006). A value
of 3.2 is adopted in this study according to the research of Zhang et al. (2012b), which was conducted in a different catchment. This may introduce weighting uncertainties into the calculations of droughts or floods in two consecutive months, as well as the weights of DFAA events. In addition, due to its slow onset and non-structural impacts (Wilhite 1992), it is difficult to detect and measure the emergence and distribution of drought based only on streamflow, which may also be associated with uncertainties when identifying DFAA events. Further studies would be enhanced by investigating the relationship between parameter $\alpha$ and climate and catchment characteristics, including precipitation, temperature, discharge, elevation, drainage area, land use, etc., thereby diminishing the uncertainty in the parameter value. Moreover, it is necessary to include more variables, such as precipitation, soil moisture, and groundwater level, in the drought analysis.

CONCLUSIONS

This study identified and analyzed DFAA in terms of streamflow in the Poyang Lake catchment over the last 50 years and investigated the intra-annual distribution characteristics and long-term tendencies associated with the events, as well as the relationships with precipitation patterns and human activities in the Poyang Lake catchment. In this study, DFAA events were described quantitatively using the DFAAI, and the results revealed that DFAA events were more intense and frequent in the Poyang Lake catchment.

Figure 7 | Distribution of average discharges in the five rivers (a) and precipitation (b) in the Poyang Lake catchment from 1960 to 2010.

Figure 8 | Variation of PCD in the five sub-catchments from 1960 to 2010 (the thick solid lines represent the average per ten years).
before the 1980s. Additionally, flood-to-drought events were more frequent and intense than the drought-to-flood events. A statistical analysis showed that drought-to-flood events in the Poyang Lake catchment generally occur in March and April, while flood-to-drought events occur in July and August. M-K tests indicated long-term decreasing trends in DFAAI in March and April, with M-K statistics of −0.31 and −0.89, respectively, and slight increasing trends in July and August, with M-K statistics of 0.63 and 0.64, respectively; however, none were statistically significant. At the decadal scale, 8–16 DFAA events occurred in the five rivers per ten years. Additionally, the number of flood-to-drought events is higher than the number of drought-to-flood events in every sub-tributary, especially in the 1960s and 1970s. Although the occurrence patterns of DFAA events are mainly determined by the distribution of precipitation in the Poyang Lake catchment, intensive human activities are also significant factors responsible for decreasing and mitigating DFAA disasters after the 1980s in the Poyang Lake catchment.

The outcomes of this study suggest that DFAA events are common and ubiquitous in monsoon regions. Although extreme climate events are expected to be more frequent in the future according to climate models, which will increase the number of DFAA-related hazards, intensive human activities such as the construction of dams, river regulation, extensive reforestation, and integrated watershed management, can alleviate the frequency and severity of DFAAs to a large extent. In addition, this study is only a preliminary attempt at analyzing DFAA events quantitatively. The DFAAI has inherent advantages in depicting DFAA events and provides a useful reference and valuable information. However, the method used in the study cannot explore the physical mechanisms associated with DFAA events, which is the main problem that must be addressed in the future.

ACKNOWLEDGEMENTS

This work is jointly funded by the National Basic Research Program of China (973 Program) (2012CB417003), the National Natural Science Foundation of China (41571023 and 41401032), the Natural Science Foundation of Jiangxi Province (20161BAB203103) and the Collaborative Innovation Center for Major Ecological Security Issues of Jiangxi Province and Monitoring Implementation (JXS-EW-00). The authors are grateful to the anonymous reviewers and the editor who helped in improving the quality of the original manuscript.

REFERENCES


First received 21 December 2015; accepted in revised form 17 August 2016. Available online 26 September 2016.