Multifractal analysis of streamflow records of the East River basin (Pearl River), China

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\textbf{A B S T R A C T}

Scaling behaviors of the long daily streamflow series of four hydrological stations (Longchuan (1952–2002), Heyuan (1951–2002), Lingxia (1953–2002) and Boluo (1953–2002)) in the mainstream East River, one of the tributaries of the Pearl River (Zhujiang River) basin, were analyzed using multifractal detrended fluctuation analysis (MF-DFA). The research results indicated that streamflow series of the East River basin are characterized by anti-persistence. MF-DFA technique showed similar scaling properties in the streamflow series of the East River basin on shorter time scales, indicating universal scaling properties over the East River basin. Different intercept values of the fitted lines of log–log curve of $F_q(s)$ versus $s$ implied hydrological regulation of water reservoirs. Based on the numerical results, we suggested that regulation activities by water reservoirs could not impact the scaling properties of the streamflow series. The regulation activities by water reservoir only influenced the fluctuation magnitude. Therefore, we concluded that the streamflow variations were mainly the results of climate changes, and precipitation variations in particular. Strong dependence of generalized Hurst exponent $h(q)$ on $q$ demonstrated multifractal behavior of streamflow series of the East River basin, showing 'universal' multifractal behavior of river runoffs. The results of this study may provide valuable information for prediction and assessment of water resources under impacts of climatic changes and human activities in the East River basin.

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1. Introduction

Water resource is one of the key factors influencing the sustainable development of the human society. It is well accepted that water stress is a central challenge facing the human society. It seems inevitable that during the first half of the 21st century, water shortage will be among the world’s most pressing problems [1]. Hydrological system is a complex and dynamical system characterized by nonstationary input (precipitation) and output (evaporation, human withdrawal and infiltration), which display self-similar and exhibit self-affine fractal behaviors over a certain range of time scales [2–7]. Hydrologists have developed many hydrological models or applied statistical methods to explore the hydrological

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characteristics of a region and the impacts of climatic changes on water resources in watersheds [5,8–12]. More and more studies have shown that the hydrological characteristics and hydrological responses to the changing climate depend on the season, the climate and the geographic regions [13]. Since streamflow fluctuations depend on the size of watersheds, and also on the topography, land-use patterns, hydrogeology and drainage network morphology, the usefulness of hydrological models depend, therefore, heavily on how well they can be extrapolated across spatial and temporal scales [14]. Just as the National Research Council [15] pointed out, the hydrological science committee will pay considerable effort on the research of the invariance property across scales in the hydrologic phenomena, which will be greatly helpful for the development of specific models and new measurement methods. Several recent studies have shown that a remarkable wide variety of natural systems display fluctuations that may be characterized by long-range power-law correlations [16,17]. Such correlations hint toward fractal geometry of the underlying dynamical system. Existence and determination of power-law correlations would be helpful in quantifying the underlying process dynamics [18]. Peng et al. [19] introduced the detrended fluctuation analysis (DFA) which has become a widely used technique to detect the long-range correlations in stationary and nonstationary time series [20,21], which has been applied successfully in diverse fields such as DNA and protein sequences, heart rate dynamics, neuron spiking, weather records, economical time series [22–24]. The multifractal detrended fluctuation analysis (MF-DFA) proposed by Kantelhardt et al. [22] is a modified version of DFA with aim to detect multifractal properties of time series. It allows a reliable multifractal characterization of nonstationary time series, and geophysical phenomena in particular [22,25,26].

The East River, one of the main tributaries of the Pearl River (Fig. 1), is 562 km long and has a drainage area of 27 040 km², accounting for about 5.96% of the Pearl River basin. Water resources in the East River basin have been highly developed and heavily committed for a variety of uses such as water supply, hydropower, navigation, irrigation, and suppression of seawater invasion. The East River provides water supply of about 80% of Hong Kong’s annual water demands. Therefore the availability and variability of water resources in the East River basin is of great importance for sustainable social and economic development in the Pearl River Delta, one of the economically developed regions in China. Hydrologists have tried to detect the fundamental statistical features of the hydrological series such as frequency distribution [27] and have also tried to explore possible impacts of human activities and climatic changes on hydrological regimes in the East River basin using statistical methods and hydrological models [28,29]. So far, no report is available addressing scale invariance and nonstationarity features of the hydrological series in the East River basin although researches about the spatial fractals of the river basins and those of possible scaling, nonlinearity, multifractal behaviors of the streamflow series of the world are widely available in the published literatures [17,30,31]. Therefore, this study aims to explore some scaling properties of streamflow series in the East River basin. The objectives of this study are:

1. (1) to detect variability characteristics...
Table 1
Detailed information of the hydrological gauging stations.

<table>
<thead>
<tr>
<th>Station</th>
<th>Location</th>
<th>Drainage area (km²)</th>
<th>Series length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longchuan station</td>
<td>115°15 E 24°07' N</td>
<td>7699</td>
<td>1952.1.1–2002.12.31</td>
</tr>
<tr>
<td>Heyuan station</td>
<td>114°42 E 23°44' N</td>
<td>15750</td>
<td>1951.1.1–2002.12.31</td>
</tr>
<tr>
<td>Lingxia station</td>
<td>114°34 E 23°15' N</td>
<td>20557</td>
<td>1953.1.1–2002.12.31</td>
</tr>
<tr>
<td>Boluo station</td>
<td>114°18 E 23°10' N</td>
<td>25325</td>
<td>1953.1.1–2002.12.31</td>
</tr>
</tbody>
</table>

Fig. 2. Daily streamflow data of four stations in the Dongjiang River basin.

of hydrological stochastic processes; and (2) to explore possible persistence and anti-persistence or monofractal and multifractal behaviors in the hydrological series.

2. Data and methods

2.1. Data

In this study, the long daily streamflow series from four hydrological stations along the mainstream East River were analyzed. The detailed information of the dataset can be referred to Table 1 and the locations of the hydrological stations can be referred to Fig. 1. Fig. 2 displays raw streamflow series of four hydrological gauging stations of the East River basin. The data series are of good quality with only two days having missing data in total. The missing data were interpolated using the neighboring days.

2.2. Multifractal detrended fluctuation analysis (MF-DFA)

Simple multifractal analyses have been proposed to characterize multifractal properties of normalized, stationary time series, and are not suitable for nonstationary time series which are affected by trends or cannot be normalized [22].
Multifractal detrended fluctuation analysis is a generalization of the standard DFA, being based on the identification of the scaling of the qth-order moments of the time series which may be nonstationary [22]. As described in Movahed et al. [32], the modified multifractal DFA (MF-DFA) procedure consists of five steps. The first three steps are the same as those in the conventional DFA procedure. Suppose that $x_i$ is a series of length $N$.

Step 1. Determine the ‘profile’ $Y_i = \sum_{t=1}^{T_i} (x_t - \langle x \rangle)$, $i = 1, \ldots, N$, where $\langle x \rangle = \frac{1}{N} \sum_{i=1}^{N} x_i$.

Step 2. Divide the profile $Y(i)$ into $N_s = \text{int}(N/s)$, non-overlapping segments of equal lengths $s$. Since the length $N$ of the series is often not a multiple of the timescale $s$, a short part at the end of the profile may remain. In order not to disregard this part of the series to be analyzed, the same procedure is performed repeatedly starting from the opposite end. Thereby, 2Ns segments are obtained altogether.

Step 3. Calculate the local trend for each of the 2Ns segments by a least squares fit of the series. Then determine the variance, $F^2(s, \nu) = \frac{1}{s} \sum_{i=1}^{s} |\nu| \sum_{t=1}^{T_i} (y(i) - y(i+1))^2$, for each segment $\nu$, $\nu = 1, \ldots, N_s$, and $F^2(s, \nu) = \frac{1}{s} \sum_{i=1}^{s} |\nu| (N - (\nu - N_s)s + i) - y(i))^2$, for $\nu = N_s + 1, \ldots, 2Ns$. Herein, $y(i)$ is the fitting polynomial in segment $\nu$. Linear, quadratic, cubic or higher-order polynomials can be used in the fitting procedure (DFA1, DFA2, DFA3, ... , DFAm).

Step 4. Average over all segments to obtain the qth-order fluctuation function, $F_q(s) = \left[ \frac{1}{2N_s} \sum_{\nu=1}^{2Ns} (F^2(s, \nu))^{q/2} \right]^{1/q}$, where $q \neq 0$, $s \geq m + 2$ where, in general, the index variable $q$ can take any real value except zero [22].

Step 5. Determine the scaling behavior of the fluctuation functions by analyzing log–log plots of $F_q(s)$ versus $s$ for each value of $q$, $F_q(s) \propto s^{h(q)}$.

In terms of stationary time series such as fGn (fractional Gaussian noise), $Y(i)$ in step 1 will be a fBm (fractional Brownian motion) signal, thus, $0 < h(q = 2) < 1$, being identical to the well-known Hurst exponent $H$. As for nonstationary signal such as fBm noise, $Y(i)$ in step 1 will be a sum of fBm signal. In this case, the scaling exponent of $F_q(s)$ is identified by $h(q = 2) > 1.0$. The relation between $h(2)$ and $H$ will be changed to $H = h(q = 2) - 1$ known as generalized Hurst exponent [33]. For uncorrelated series, the scaling exponent $H$ is equal to 1/2. The range $1/2 < H < 1.0$ indicates the long memory; while the range $0 < H < 1/2$ indicates short memory. Generally, $h(q)$ may be dependent on $q$. This behavior represents the presence of multifractality [34]. In terms of monofractal signal, $h(q)$ is independent of $q$. For positive values of $q$, $h(q)$ describes the scaling behavior of the segments with large fluctuations. With respect to negative values of $q$, the segments $v$ with small variance $F^2(s, v)$ will dominate the average $F_q(s)$. Therefore, for negative values of $q$, $h(q)$ describes the scaling behavior of the segments with small fluctuations [33].

3. Results and discussion

Fig. 3 illustrates the log–log plots of fluctuation function with $q = 2$ for the raw streamflow data of these four hydrological gauging stations.

The estimated values of $h(2)$ (the slope for small scales) demonstrated in Fig. 3 indicated that $h(2)$ of these four stations were larger than 1.0 and smaller than 1.5. The curves of the log–log plot of $F_q(s)$ versus $s$ for the four stations (i.e. Longchuan, Heyuan, Lingxia and Boluo) were divided into two segments visually and by numerical techniques. The existence of these regions may be partly due to the competition between noise and sinusoidal trend [20,32]. Moreover, the slopes of the curves of the log–log plot of $F_q(s)$ versus $s$ on small scales for the four stations were similar. What is different is that the slope value of log–log curve on large scales of Heyuan station is larger than 0.6. However, the slope values on the large scales of other three stations (i.e. Longchuan, Lingxia and Boluo) were close to 0.5. The slope values of the log–log curves of the four stations under considered in this study indicate similar scaling properties on shorter time scales. This result indicated universal scaling properties of streamflow series, at least within the study river basin, i.e. the East River basin. The numerical results indicated similar slopes of the log–log curves on the shorter time scales, but displayed different intercept values. The numerical results showed the intercept values of $1.3451 \pm 0.066$ on the shorter time scale for the Heyuan station, $1.1688 \pm 0.0124$ for the Longchuan station, $1.485 \pm 0.0106$ for the Lingxia station, and $1.6011 \pm 0.0163$ for the Boluo station. It is well known that the streamflow variations are the result of climatic changes, and the precipitation changes in particular. Similar slope values at shorter time scales may indicate similar periodicity properties, but the difference of intercept values of fitted lines may implied altered magnitude of the streamflow variations, which will be discussed with more details in the following sections. Therefore, in addition to impacts of climatic changes on streamflow, other factors such as topographical properties and human activities were also exerting impacts on hydrological processes of different river channels. For scale larger than 1 year, the Hurst exponents of $F_q(s)$ versus $s$ in log–log plot for Longchuan, Lingxia and Boluo ranged from 0.44 to 0.55, which indicated that these three streamflow series had approximately random behavior for large scale of $> 1$ year. $F_q(s)$ versus $s$ in log–log plots of Heyuan station at larger scale of $> 1$ year, the slope of $F_q(s)$ versus $s$ in log–log plot was larger than 0.6. Kosielný-Bunde et al. [35] indicated that there is no universal scaling behavior in the hydrological series since the exponents vary strongly from river to river due to different drainage areas, topography, land-use pattern and drainage network morphology [14]. In this study, similar scaling behaviors can be identified in different parts of the East River basin on shorter time scales. Therefore, we can tentatively conclude that, within the same river basin, universal scaling behavior can be expected on the shorter time scales. However, just as mentioned above, different intercept values of fitted lines may imply other factors except climatic changes influencing the streamflow variations of these four stations. It can be seen from Fig. 1 that there is a large water reservoir, Xinfeijiang water reservoir, in one of tributaries upstream.
Fig. 3. Crossover behavior of log–log plots of \( F_q(s) \) versus \( s \) of daily streamflow data of four gauging stations: Longchuan, Heyuan, Lingxia and Boluo. The slope and associated errors have been computed. Location of these four stations can be referred to Fig. 1. Length of the daily streamflow data can be referred to Table 1.

Fig. 3. Crossover behavior of log–log plots of \( F_q(s) \) versus \( s \) of daily streamflow data of four gauging stations: Longchuan, Heyuan, Lingxia and Boluo. The slope and associated errors have been computed. Location of these four stations can be referred to Fig. 1. Length of the daily streamflow data can be referred to Table 1.

to the Heyuan station. Xinfengjiang water reservoir was constructed during 1958–1962 with the storage capacity of 1.398 billion m\(^3\). There is another water reservoir located upstream to Longchuan station, i.e. Fengshuba water reservoir. This water reservoir was built during 1970–1974 with storage capacity of 0.194 billion m\(^3\). The hydrological regulation of these water reservoirs may be expected to impact the variations of the streamflow series of the Heyuan station and Longchuan station. Visual comparison of the upper first panel of Fig. 2 indicates that, after 1970–1974 (corresponding to 6500–8400 data points in the \( x \)-axis); the streamflow fluctuations of the Longchuan station came to be moderate when compared to those before 1970–1974. After 1958–1962 (corresponding to 2550–4380 data points in the \( x \)-axis), the streamflow variations of the Heyuan station came to be moderate. However, the streamflow changes of the Heyuan station were not so obvious, and this may be due to the influences of the hydrological processes upstream to the Heyuan station.

To further understand influences of Xinfengjiang and Fengshuba water reservoirs on scaling properties of streamflow series of the East River basin, we analyzed scaling properties of daily streamflow series of Heyuan station and Longchuan station before and after the construction of Xinfengjiang and Fengshuba water reservoirs. Fig. 4 demonstrates the scaling properties of log–log plots of \( F_q(s) \) versus \( s \) of daily streamflow data of Longchuan and Heyuan stations before and after construction of Xinfengjiang and Fengshuba water reservoirs. It can be seen from Fig. 4 that no distinct difference can be observed for scaling properties of daily streamflow series before and after the construction of water reservoirs, particularly on the shorter time scales. Comparatively, difference in scaling properties of streamflow series of Heyuan station on the longer time scales before and after construction of Xinfengjiang water reservoir was more distinct than that of Longchuan station (Fig. 4). This is mainly represented by difference of slopes of log–log plots of \( F_q(s) \) versus \( s \) before and after the second crossover. Similarities of scaling properties of streamflow series for these two stations, i.e. Heyuan station and Longchuan station, before and after the construction of water reservoirs, particularly on the shorter time scale, has much in common. Numerical results showed different intercept values of log–log plots of \( F_q(s) \) versus \( s \) before and after construction of water reservoirs. The intercept values of Longchuan station before and after the construction of the Fengshuba water reservoir were \( 1.359 \pm 0.0105 \) and \( 0.8539 \pm 0.0151 \) respectively. The intercept values of the fitted line of the Longchuan station after the construction of the Fengshuba reservoir were distinctly different from that before the construction of the Fengshuba water reservoir. The same results can also be achieved for the Heyuan station: the intercept values of the fitted lines before and after the construction of the Xinfengjiang water reservoir are \( 1.5054 \pm 0.0127 \) and \( 1.2535 \pm 0.0141 \) respectively. The smaller intercept values of the fitted lines after the construction of the water reservoir may be due to the hydrological
Fig. 4. Scaling properties of log–log plots of $F_q(s)$ versus $s$ of daily streamflow data of Longchuan and Heyuan stations before and after construction of Xinfengjiang and Fengshuba water reservoirs. The construction of the Xinfengjiang reservoir is during 1958–1962; and that of the Fengshuba reservoir is during 1970–1974.

Fig. 5. The $h(q)$ curves of daily streamflow of Longchuan, Heyuan, Lingxia and Boluo stations in the Dongjiang River basin, the Pearl River basin.

regulations of the water reservoirs. Research performed on periodicity changes of sediment load and streamflow series as results of hydrological regulations of water reservoirs [36] indicated that water reservoirs cannot influence the periodicity of streamflow variations, which further support the results and viewpoints of this study.

The MF-DFA1 results for daily streamflow series of the four gauging station were shown in Fig. 5, where $h(q)$ values for positive and negative $q$ values were demonstrated. Fig. 5 clearly shows that the streamflow series of the four stations studied in this study were multifractal processes as indicated by strong $q$-dependence of generalized Hurst exponents, $h(q)$. This result well supported the idea of a ‘universal’ multifractal behavior of river runoffs [34].
4. Summary and conclusions

In this study, we analyzed the scaling behavior of the daily hydrological series from four hydrological stations (Longchuan station, Heyuan station, Lingxia station and Boluo station) in the East River, one of the tributaries of the Pearl River (Zhujiang River) basin using multifractal detrended fluctuation analysis (MF-DFA) method, and different multifractal behaviors have been identified. MF-DFA technique helps to characterize multifractal properties in the nonstationary and stationary time series. The concept of MF-DFA of streamflow changes of rivers can be used to obtain deeper insight into the processes occurring in climate and hydrological systems [25]. We also analyzed the values of the generalized Hurst exponent \( h(q = 2.0) \) using MF-DFA1. Based on the relation between the exponents \( h(2) \) and \( H \) (the well-known Hurst exponent \( H \)), i.e. \( H = h(q = 2) - 1 \), we obtained the \( H \) values of streamflow series of these four hydrological stations studied in this study. The \( H \) values are all larger than 0 and are less than 0.5, implying that the streamflow series are of anti-persistence.

Different scaling behaviors have been identified in the hydrological series from river to river of the world due to some external forces such as precipitation changes, different topography and drainage network morphology [35]. Within the same river basin, however, universal scaling properties have been identified. There are two large water reservoirs, i.e. Fengshuba and Xinfengjiang water reservoirs, which may exert influences on hydrological processes. Our results indicated that streamflow series of Heyuan station and the Longchuan station were heavily influenced by hydrological regulation of the water reservoirs. Smaller intercept values after the construction of the water reservoirs when compared to those before the construction of the water reservoir may imply that the influences of water reservoirs on the hydrological processes are reflected mainly by smaller magnitude of streamflow fluctuation after the construction of the water reservoirs. The scaling properties of the streamflow series of these four hydrological stations in this study showed similar characteristics on the shorter time scales. This result may imply universal scaling properties of hydrological processes within the same river basin though no universal scaling properties can be identified from river to river over the world [14]. Furthermore, similar scaling properties can also be observed even after the construction of the water reservoirs. This result indicated that the scaling properties of the hydrological processes cannot be influenced by the hydrological regulations by the water reservoirs. Hydrological regulations of the water reservoirs may impact the magnitude of the streamflow fluctuations. This conclusion was well supported by former research results that hydrological regulation of water reservoir can not alter periodicity properties of streamflow series [36]. Furthermore, strong \( q \)-dependence of generalized Hurst exponents, \( h(q) \), demonstrated that the streamflow series of the East River basin had multifractal behavior, which well supports the viewpoint of ‘universal’ multifractal behavior of river runoffs [34]. The results of this study may provide valuable information for prediction and assessment of water resources under the impacts of climatic changes and human activities. It should be noted here that the precipitation in the East River basin is decreasing, particularly in autumn [37]. Annual precipitation of the East River is decreasing but is not significant. Therefore, decreasing precipitation may also contribute to decreasing magnitude of streamflow fluctuations. Altered hydrological properties are in no way the results of one factor such as regulation activities of water reservoir or precipitation changes. Therefore, further work will be carried out on scaling behaviors of the hydrological series under specific impacts of the different land-use patterns, regulation activities of water reservoirs, spatial and temporal variations of precipitation and other influencing factors in the East River basin. We believe that the results of this study will be helpful for better understanding of hydrological scaling behaviors under the influences of human activities.

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