Modal analysis of annual runoff volume and sediment load in the Yangtze river-lake system for the period 1956–2013
Huai Chen, Lijun Zhu, Jianzhong Wang, Hongxia Fan and Zhihuan Wang

ABSTRACT
This study focuses on detecting trends in annual runoff volume and sediment load in the Yangtze river-lake system. Times series of annual runoff volume and sediment load at 19 hydrological gauging stations for the period 1956–2013 were collected. Based on the Mann-Kendall test at the 1% significance level, annual sediment loads in the Yangtze River, the Dongting Lake and the Poyang Lake were detected with significantly descending trends. The power spectrum estimation indicated predominant oscillations with periods of 8 and 20 years are embedded in the runoff volume series, probably related to the El Niño Southern Oscillation (2–7 years) and Pacific Decadal Oscillation (20–30 years). Based on dominant components (capturing more than roughly 90% total energy) extracted by the proper orthogonal decomposition method, total change ratios of runoff volume and sediment load during the last 58 years were evaluated. For sediment load, the mean CRT value in the Yangtze River is about −65%, and those in the Dongting Lake and the Poyang Lake are −92.2% and −87.9% respectively. Particularly, the CRT value of the sediment load in the channel inflow of the Dongting Lake is even −99.7%. The Three Gorges Dam has intercepted a large amount of sediment load and decreased the sediment load downstream.

Key words | coefficient of variation, Dongting Lake, Mann-Kendall test, power spectrum estimation, Poyang Lake, proper orthogonal decomposition (POD), Three Gorges Dam

INTRODUCTION
Runoff volume and sediment load maintain a major interest in engineering, as they play an important role in modifying river morphology and patterns through time and space (Chen et al. 2001). Trend detection of hydrological variables presents meaningful statistics of the time series. Runoff variation may strongly affect water demand, flood control and aquatic species, and the trend information is necessary for long-term water resources planning and management (Jung & Chang 2011). As sediment load is closely associated with nutrient transportation, fluvial process and reservoir deposition, the variation of riverine sediment load has become an important index for the effects of climate change and human activities (Wang et al. 2007).

The Yangtze River basin has a drainage area of 1.8 million km², about one-fifth of the land area of the People’s Republic of China. As the cradle of Chinese civilization, the Yangtze River is very important in Chinese history, culture and economy. Two largest freshwater lakes (namely, the Dongting Lake and the Poyang Lake) in China naturally connect to the middle reach of the Yangtze River, and they have strong hydrodynamic interactions with the Yangtze River. These two lakes play very important roles in maintaining the sustainability of water resources and the health of the aquatic ecosystem in the Yangtze River basin, and they are also crucial for local economic development, such as aquaculture and tourism.

Since the 1950s, the Chinese have built more than half of the large dams (generally defined as higher than 15 meters) in the world, and more than 45,700 dams with a total capacity of 220.0 billion m³ have been constructed in the Yangtze River basin (Li et al. 2011; Sun et al. 2012). Among these dams, the Three Gorges Dam (TGD) Project is the most noticeable one. This project began in 1994, dammed the Yangtze River in 1997, and impounded its first water on 1st June 2003. Despite their valuable services, dams intercept a large amount of water and sediment load, and remarkably impact the hydrological, geomorphological and hydrodynamic conditions of downstream rivers and
their river-connected shallow lakes (Sun et al. 2012). In previous studies, the main cause of sediment load reduction has been attributed to reservoirs built in the Yangtze River, while other factors (such as decreased precipitation, sand mining and soil conservation measures) can also decrease the sediment load transported to the river (Dai et al. 2008).

Variations of runoff volume and sediment load in the Yangtze river-lake system have drawn considerable concerns from scientific community (Zhang et al. 2006), such as variations of runoff volume and sediment load at three stations (namely, Yichang, Hankou and Datong) in the Yangtze River (Chen et al. 2001; Chen et al. 2005; Yang et al. 2006; Dai et al. 2008; Hu et al. 2009; Xu & Milliman 2009; Hassan et al. 2011; Li et al. 2011; Dai & Lu 2014, to cite a few) and variations in the Dongting Lake and the Poyang Lake (Dai et al. 2005; Gao et al. 2014; Zhang et al. 2014, to cite a few). However, these results mainly depend on subjective description, therefore many studies turn to the Mann-Kendall test for detecting trends. Based on the Mann-Kendall test and linear regression analysis, Zhang et al. (2006) and Zhao et al. (2012) reported that no significant trend is detected for annual runoff volume while the sediment load changes differently at Yichang, Hankou and Datong stations. Zhang et al. (2014) used the Mann-Kendall test to analyze the runoff inflow and outflow of the Poyang Lake, and found a decreasing trend in inflows before 1993, while an increasing trend occurs thereafter. Dai et al. (2015) used the Mann-Kendall test for the detection of abrupt changes in annual runoff volume series at Yichang, Hankou and Datong stations, and found abrupt runoff changes took place simultaneously around 2000, while more abrupt runoff changes occurred in the period between 1970 and 1990 at Yichang station. Besides, in some studies, the power spectrum estimation is used to detect periodical oscillations inside the runoff volume time series. For example, Wang et al. (2008) analyzed the intra-annual variability of the daily Yangtze runoff volume at Cuntan and Yichang stations, and found these intra-annual power spectra follow within timescales from 1 week to 1 year.

Although many of the studies above discussed the trends in the runoff volume and sediment load in the Yangtze River basin, the employed detection methods are qualitative description, linear regression and the Mann-Kendall test, and results based on them are just qualitative, short of quantitation, and cannot extract patterns embedded inside. Furthermore, hydrological data in the published papers above are just from a small number (mostly three) hydrological stations in the Yangtze River, or parts of the Yangtze River basin with different timescales, so joint investigation of the sediment load and runoff volume over the whole basin is necessary.

In this study, annual runoff volume and sediment load series during 1956–2013 from 19 hydrological gaging stations (five in the Yangtze River, eight in the Dongting Lake and six in the Poyang Lake) in the Yangtze River basin were collected. In order to capture principal components and evaluate trends quantitatively, the proper orthogonal decomposition (POD) was applied to analyze times series of runoff volume and sediment load. Based on POD modes, change ratios of these hydrological data during the last 58 years were calculated. With comparison between the results of the Yangtze River and its two connected lakes, the river-lake interaction was evaluated. Moreover, detected trends were interpreted by relevant environmental changes and human activities.

DATA AND METHODOLOGY

Study area and data

The Yangtze River, also popularly known as Chang Jiang, is the longest river (around 6,300 kilometers) in China. Originating from glaciers in the Tibet Plateau, it flows across southwest, central and east China, and finally ends in the East China Sea (Figure 1):

• The upper reaches of the Yangtze River, from Tanggula Mountain on the Tibet Plateau to Yichang City, are as long as 4,500 kilometers. Three gaging stations, namely the Zhutuo, Beibei and Wulong stations, distribute in this area (Figure 1), and the summation of their measured data is a good representation of the hydrologic conditions in the upper reaches. After the construction of the Three Gorges Reservoir (TGR), the inflow condition of TGR is mostly based on these three gaging stations.

• The middle reaches of the Yangtze River, from Yichang City to Hukou, are about 1,000 kilometers long. As the distance between Yichang gaging station and TGR is relatively short, about 30 kilometers, the hydrologic condition at Yichang station is always regarded as the TGR outflow condition (Figure 1).

• The lower reaches of the Yangtze River, from Hukou to the estuary, are about 800 kilometers long. The most downstream gaging station is Datong station (Figure 1). Runoff and sediment load conditions in Datong significantly affect the estuary evolution.

The Dongting Lake, connected to the Yangtze River in the middle reach, is the second largest freshwater lake in
China (Figure 1). It gets inflow from the Yangtze River through three inflow channels (Songzi Channel, Taiping Channel and Ouchi Channel), whose inlets are on the south bank of the middle Yangtze River. And there are four other inflow rivers (Lishui River, Yuanjiang River, Zishui River and Xiangjiang River) to the Dongting Lake. The outflow of the Dongting Lake flows into the Yangtze River at Chenglingji. The Dongting Lake plays an important role in adjusting the flow of the Yangtze River.

The Poyang Lake, the largest freshwater lake in China, is located to the east of Dongting Lake and connected to the Yangtze River at Hukou (Figure 1). Five rivers (Xuushui River, Gangjiang River, Fuhe River, Xingjiang River and Raohe River) flow into the Poyang Lake, and its outlet is at Hukou. This lake is famous for its bird habitat conservation area, which supports half a million migratory birds in winter, and its wetland has been included in the list of international important wetlands in the Ramsar Convention.

Data of annual runoff volume and suspended sediment load over the Yangtze River basin from 1956 to 2013, were published online by the Yangtze River Water Resources Commission (YRWRC) of China (YRWRC 2014). Time series from 19 gaging stations (Figure 1, five in the Yangtze River, eight in the Dongting Lake and six in the Poyang Lake) were collected for analysis in this paper.

In the Yangtze River, the summation of measured data (either runoff volume or sediment load) at Zhutuo, Beibei and Wulong stations is always used as the inflow condition of the TGR, so this summation is a good representation of the hydrologic condition in the upper reach. Yichang and Datong stations are representative hydrological stations in the middle and lower reaches respectively.

In the Dongting Lake, inflow consists of two parts, inflow from four rivers (Lishui River, Yuanjiang River, Zishui River and Xiangjiang River) and inflow from three channels (Songzi Channel, Taiping Channel and Ouchi channel). Its outflow is measured at Chenglingji station.

In the Poyang Lake, inflow is only from five rivers (Xuushui River, Gangjiang River, Fuhe River, Xingjiang River and Raohe River) and outflow is measured at Hukou station.

Let $x(n)$ ($n = 1, \ldots, N$) be the time series (either runoff or sediment load) hereafter. To extract meaningful statistics from the time series data, four special methods were used for analysis.

**Mann-Kendall trend test**

The Mann-Kendall test is a non-parametric and very robust method, and it is widely used to detect trends and their significance level in time series. Bonfils (2012) used the Mann-Kendall test to analyze the trend of annual temperature in Rwanda during the last 52 years.

The Mann-Kendall $S$ statistic is defined as follows:

$$S = \sum_{n=2}^{N} \sum_{j=1}^{n-1} \text{sign}(x_n - x_j)$$  \hspace{1cm} (1)$$

where $\text{sign}(\cdot)$ denotes the sign function. The value of $S$ is the net result of all such increments and decrements. So $S$ reflects the general trend of the time series.
For large samples (about $N > 8$), the statistic $S$ is approximately normally distributed with

$$
\mu_S = 0, \quad \sigma_S^2 = \frac{N(N - 1)(2N + 15)}{18}
$$

The significance of trend is evaluated by the standard test statistic $Z$, which is given by

$$
Z = \begin{cases} 
\frac{(S - 1)/\sigma_S}{\sqrt{N}} & \text{if } S > 0 \\
0 & \text{if } S = 0 \\
\frac{(S + 1)/\sigma_S}{\sqrt{N}} & \text{if } S < 0 
\end{cases}
$$

A positive $Z$ indicates an increasing trend in the time series, while a negative $Z$ indicates a decreasing trend embedded inside. To test for the trend at a significant level of $p$, the null hypothesis $H_0$ (assuming that the data have no trend) is rejected if $|Z| > Z_{(1-p/2)}$, where $Z_{(1-p/2)}$ denotes the standard normal deviates and can be obtained from the standard normal cumulative distribution tables. When $p = 0.05$, $Z_{0.975} = 1.96$; and when $p = 0.01$, $Z_{0.995} = 2.58$.

**Coefficient of variation**

The coefficient of variation, also known as relative standard deviation, is a dimensionless parameter and can compare variation degrees between data sets with widely different means, which is just the case for the Yangtze River and its two connected lakes. It is defined as the ration of the standard deviation $\sigma$ to the mean $\mu$ (Everitt & Skrondal 2010):

$$
C_v(n) = \frac{\sigma(n)}{\mu(n)}
$$

where

$$
\mu(n) = \frac{\sum_{k=1}^{n} x(k)}{n}, \quad \sigma(n) = \sqrt{\frac{\sum_{k=1}^{n} [x(k) - \mu(n)]^2}{n}} \quad (k = 1, \ldots, n).
$$

The $C_v$ series is a set of dimensionless numbers, so it can be used to compare the variation degree between data sets with different units or even widely different means.

**Welch’s method for power spectrum estimation**

Welch’s method is one of the most popular spectrum estimation methods. This method consists of dividing the time series data into successive segments (possibly overlapping), computing individual periodograms of each windowed segment, and then averaging estimates over all segments (Welch 1967). It is given by

$$
P(f) = \frac{1}{F_s M W} \sum_{l=1}^{M} \left| \sum_{j=1}^{M} x_l(j) w(j) e^{-ij} \right|^2
$$

where $f$ is the frequency, $F_s$ is the sample frequency, $M$ is the length of each segment, $i$ is the imaginary unit, the frequency resolution is $F_s/M$; $L = (N-ol \times M)/(M-ol \times M)$ is the number of total segments, $ol$ is the length ratio of the overlapped block to the segment; $x_l(j)$ is the $j$-th element in the $l$-th segment, $w(j)$ is the window function and $W = \sum_{j=1}^{M} w(j)^2/M$.

The power spectral density is often expressed in dB:

$$
\text{PSD}(f) = 10 \cdot \log_{10} \left( \frac{P(f)}{\max(P(f))} \right)
$$

where $\max(.)$ returns the largest value in the array. The power spectrum estimation can detect periodic signals embedded inside the time series, which may be related with specific climate events.

**Proper orthogonal decomposition**

The POD is a powerful and elegant method for a modal decomposition from an ensemble of signals, offering the most efficient way of capturing principal components and analyzing trends quantitatively. Recently, the widespread applications of POD have enabled it to be a popular tool in many engineering fields, such as signal analysis, data compression, and feature extraction. For example, the POD method has been successfully applied in fluid dynamics to extract coherent structures in turbulence (Chen et al. 2014).

POD uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called modes (or principal components). It can be done by eigenvalue decomposition of a data covariance matrix, detailed procedures can be found in Chatterjee (2000).

The time series $x(n)$ is divided into overlapped segments and reshaped as a matrix:

$$
V(\bar{x}, t_l) = \begin{bmatrix} x(1) & x(2) & \ldots & x(N_l) \\
x(2) & x(3) & \ldots & x(N_l + 1) \\
\vdots & \vdots & \ddots & \vdots \\
x(M) & x(M+1) & \ldots & x(N) \end{bmatrix}
$$

where $\bar{x}$ is the segment with a length of $M$, and $l_t$ is the time series with $l = 1, \ldots, N_s$ ($N_s$ is the number of total segments,
$N_s = N - M + 1). The field $V(\bar{x}, t_t)$ at time $t_t$ can be reconstructed based on the POD modes such that

$$
\begin{align*}
V(\bar{x}, t_t) &= \sum_{k=1}^{M} a_k(t_t) \Psi_k(\bar{x}) \\
\psi_k(\bar{x}) &= V(\bar{x}, t_t), \Psi_k(\bar{x})
\end{align*}
$$

(8)

where $(,)$ indicates operation of inner product, $\Psi_k(\bar{x})$ are orthonormal basis functions, and $a_k(t_t)$ are orthonormal amplitude coefficients.

$\Psi_k(\bar{x})$ can be evaluated as follows:

$$
\begin{align*}
C &= V V^T \\
[\Phi, \Lambda] &= \text{eign}(C) \\
\Psi &= V \Phi \Lambda^{1/2}
\end{align*}
$$

(9)

where $C$ is the temporal correlation matrix. ‘eign’ means evaluating eigenvalues $(\Lambda)$ and eigenvectors $(\Phi)$ of matrix $C$, so that $C \Phi = \Phi \Lambda$. $\Lambda$ is a diagonal matrix with $C$’s eigenvalues $(\lambda_k, k = 1, \ldots, M)$ on the main diagonal. All the eigenvalues are positive reals and are sorted in decreasing order such that $\lambda_k > \lambda_{k+1}$. The total energy is defined as the sum of all eigenvalues, i.e., $E = \sum_{k=1}^{M} \lambda_k$, and the energy fraction of the $k$-th mode is $E_k = \lambda_k / E$.

After the modal decomposition of time series, those extracted POD modes can be used to quantitatively calculate their change ratios. Take the first POD mode as an example, its change ratio is given by

$$
\psi = k \left( \frac{\lambda_1}{N_t} \right)^{0.5}
$$

(10)

where $k$ is the slope (evaluated with the least square method) of the first POD mode.

RESULTS AND DISCUSSION

Time series of annual data

Time series of annual runoff volume and sediment load in the Yangtze River, the Dongting Lake and the Poyang Lake are shown in Figures 2–4.

![Figure 2](https://iwaponline.com/wst/article-pdf/76/1/1/451702/wst076010001.pdf)

**Figure 2** | Time series of annual (a) runoff volume and (b) sediment load in the Yangtze River, where ‘Bt’ means one billion tons and ‘Mt’ means one million tons hereafter.
Figure 2 presents annual runoff volume and sediment load in the Yangtze River as a function of time. In these three reaches, runoff volume tends to fluctuate with time, but is around the mean without notable trend, as in Xu & Milliman (2013) and Dai & Liu (2015). With no abrupt change in the runoff volume series, the completion of TGD (in 2003) seems to have no influence on the annual runoff volume in the Yangtze River.

Annual sediment load in Figure 2(b) fluctuates during 1955–1980, beyond which there exists a significantly descending trend even before the TGD completion. This phenomenon, related with three main factors (the construction of a large number of reservoirs/dams, the implementation of soil and water conservation measures and the decreased precipitation in the upper Yangtze River basin), is also reported in Li et al. (2011) and Dai & Liu (2013). During 1980–2000, the amount of sediment load in the middle reach is the largest, while that in the lower reach is the smallest, which implies that a large amount of sediment is imported into the Dongting Lake through its three inflow channels (Songzi C., Taiping C. and Ouchi C.). This phenomenon changed after the completion of TGD, the amount of sediment load at Yichang station is the smallest, meaning a huge amount of sediment load is intercepted by the Three Gorges Reservoir (TGR). Xu & Milliman (2009) reported that during the 4 years (2003–2006) after TGD impoundment, about 60% of sediment load entering the TGR was trapped.

Figure 3 shows the annual runoff volume and sediment load in the Dongting Lake. As illustrated in Figure 3(a), during the last 58 years, the magnitude of runoff inflow to the lake has an obviously descending trend, the same as the outflow. However, the inflow volume is always slightly smaller than the outflow volume, which means the size of the Dongting Lake has been progressively shrinking for 60 years (Hu et al. 2015). The magnitudes of the river inflow and channel inflow are nearly the same in the 1960s, while after 1990 the river inflow is about twice as large as the channel inflow. This infers that the river inflow is
gradually playing a more important role than the channel inflow, agreeing with Ou et al. (2014). Consistent with that in Figure 2(a), the TGD has little influence on runoff volume in the Dongting Lake.

According to Figure 3(b), the sediment inflow and outflow of the Dongting Lake generally decreased with time. Before 2005, the inflow was always greater than the outflow, and the Dongting Lake had persistent sediment deposition. During the last 58 years, the descending rate of sediment load in the channel inflow is very large, while that in the river inflow is relatively gentle. Sediment load in the channel inflow is much larger than that in the river inflow before 2005, beyond which they tend to be at the same level. This implies that the contribution of sediment load from the channels to the total sediment inflow is decreasing, while that from rivers is increasing.

Figure 4 displays the variation of annual runoff volume and sediment load in the Poyang Lake. There is no notable trend in the time series in Figure 4(a). As is the case for runoff volume in the Dongting Lake, the inflow volume is always smaller than the outflow volume in the Poyang Lake. This condition leads to the shrinkage of the Poyang Lake.

As shown in Figure 4(b), the sediment inflow to the Poyang Lake has a notably descending trend during 1970–2010. Meanwhile, the sediment outflow fluctuates around the mean. Before the year 2000, the volume of sediment inflow is greater than that of sediment outflow, further exacerbating the lake shrinkage; while after 2000 the opposite situation occurs, which helps to restore the lake, agreeing with results in Gao et al. (2014) and Li et al. (2015). The TGD seems to have no influence on the annual runoff volume and sediment load in the Poyang Lake.

Statistical test

Mann-Kendall trend test

Results of the Mann-Kendall test are given in Figure 5. In the Yangtze River, Z-values of runoff volume in three reaches
fall inside the 95% confidence interval, which means there is no significant trend embedded inside runoff series. Compared with that in the lower reach, runoff in the upper and middle reaches have a slightly descending trend. Contrasted with the runoff, the sediment load shows a significant decrease with Z values outside the 99% confidence interval. Reforestation in the upper drainage basin of the Yangtze River and the completion of the TGD have led to a rapid and significant decrease in the downstream sediment load (Gleick 2009).

In the Dongting Lake, only the runoff volume of the river inflow remains in a relatively steady state without notable change. However, the runoff volume of the channel inflow has a significantly descending trend (Ou et al. 2014), as is the case for runoff outflow, and the Z values of these are both outside the 99% confidence level. In accordance with the sediment load in the Yangtze River, sediment inflow and outflow of the Dongting Lake display a remarkable decrease, and the sediment descending trend in the channel inflow is more significant than that in the river inflow.

In the Poyang Lake, runoff inflow and sediment outflow have no significant trend, with their Z values inside the 95% confidence interval, which is same as the sediment outflow. However, the sediment inflow has a significantly descending trend with a Z value outside the 99% confidence interval.

**Coefficient of variation**

Figure 6 shows the coefficient of variation ($C_v$) as a function of time. Only results with sample size $n > 15$ (after 1970) are plotted, in order to make sure values of $C_v$ are relatively convergent.

As detailed in Figure 6(a), $C_v$ values of runoff in the Yangtze River are the smallest and almost stable, among which the lower reach is slightly larger. This implies that the variation of the degree of runoff volume in the Yangtze River is small, with slightly larger variation in the lower reach. Xu & Milliman (2009) reported that runoff volume has changed little in the Yangtze River. Dai & Liu (2013) reported that runoff volumes at Yichang, Hankou and Datong stations do not show apparent changes between 1955 and 2010. Compared with the Yangtze River, $C_v$ values of runoff volume in the Dongting Lake and the Poyang Lake are much larger, which means large variations happen in these two lakes. Reflected by the nearly constant value of $C_v$, inflow and outflow of the Poyang Lake varied slightly, as did the river inflow and outflow of the Dongting Lake. Nevertheless, an almost monotonic increase is found in the channel inflow, which reflects that the channel inflow to the Dongting Lake has been decreasing in Figure 3(a).

Compared with the runoff volume, $C_v$ values of sediment load are much larger in Figure 6(b). In the Yangtze River, before 1993, $C_v$ values in these three reaches nearly remain constant, and during 1993–2003 a slight increase occurs; however, a rapid increase happens after 2003, especially for the middle reach. This strongly reflects that the TGD plays a very important role in the decrease of sediment load in the middle reach (Xu & Milliman 2009). Meanwhile, the reforestation and reservoirs upstream of the TGR also make some contribution to the decrease. $C_v$ values in the Dongting
Lake are increasing with time, consistent with their decreasing trends in Figure 5. Different to the river inflow and outflow, the $C_v$ value of the channel inflow increases at a rapid rate after 2003, which implies it is strongly influenced by the completion of TGD. Illustrated by the variation of $C_v$ in the Poyang Lake, there is an ascending trend in the outflow and a descending trend in the inflow.

Modal decomposition

Power spectrum

The power spectrum of annual runoff volume and sediment load is shown in Figure 7, with segment length $M = 40$, overlapped ratio $\alpha = 97.5\%$, sample frequency $F_s = 1 \text{ Hz}$, frequency resolution $F_s / M = 0.025 \text{ Hz}$ and a hamming window function. Based on the results in Figure 5, only those whose $Z$ values are inside the 95% confidence interval are calculated with power spectrum. In order to obviously show periods embedded inside the time series, the variable in the abscissa of Figure 7 is selected as period ($1$/frequency).

The Fourier period of the runoff volume in the Yangtze River is plotted in Figure 7(a). There exists a very obvious oscillation with a period of 8 years embedded inside the runoff series in the three reaches.

Insistent with that in the Yangtze River, the river inflow of the Dongting Lake also has an oscillation with an 8 year period, and it is the same with the inflow and outflow of the Poyang Lake (Figure 7(b)). Besides, an oscillation with a period of 20 years is evident in the runoff volume series of the two lakes. However, the sediment outflow of Poyang Lake has a predominant oscillation with a 40 year period, and the period of the second predominant oscillation is about 4.5 years.

As reported by Mote et al. (2003), runoff variability is closely associated with multi-year or multi-decadal scale climate variability such as the El Niño Southern Oscillation (ENSO, whose irregular oscillation has a period of 2 to 7 years) and the Pacific Decadal Oscillation (PDO, whose
irregular period is several decades, about 20 to 30 years). These predominant oscillations may be closely related to global climate change (ENSO and PDO).

POD modes

Based on the results in Figure 7, the largest period of predominant oscillations is 20 years, so the segment length for POD analysis is set as 20 with $N_s = 39$. Results of the POD mode spectrum, used to describe the energy fraction each mode captures of the total ensemble, are listed in Figure 8. For clarity, only energy fractions of the first 15 modes are plotted, and specific values of the first and second modes are listed in Table 1.

For each statistic (either runoff or sediment load), its energy fraction decreases with the mode number, and most energy concentrates in the first mode. As detailed in Table 1, energy fractions of the first mode of runoff volume in the Yangtze River and the two lakes are all above 93%, with about 1% energy in the second mode, while those of the sediment load are above 84% with around 2% energy in the second mode. This implies that the runoff volume series is relatively more ordered than the sediment load series.

As the first mode captures the most energy of the total ensemble, its eigenvector (the principal component) can make a good representation of the original data. Normalized eigenvectors of the first mode are displayed in Figure 9. The trend of the eigenvector reveals the predominant trend embedded in the original series. As shown in Figure 9(a), runoff volumes in the upper and middle reaches of the Yangtze River and the channel inflow and outflow in the

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**Figure 7** | Power spectra of annual runoff volume and sediment load time series: (a) in the Yangtze River and (b) in the Dongting Lake and the Poyang Lake.
Figure 8 | Energy fractions of POD modes extracted from time series of (a) annual runoff volume and (b) annual sediment load.

Table 1 | Energy fractions of the first and second modes extracted from time series of annual runoff volume and sediment load

<table>
<thead>
<tr>
<th>Energy fraction (%)</th>
<th>Yangtze River</th>
<th>Dongting Lake</th>
<th>Poyang Lake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runoff volume</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st mode</td>
<td>Upper reach</td>
<td>99.08</td>
<td>97.28</td>
</tr>
<tr>
<td></td>
<td>Middle reach</td>
<td>99.08</td>
<td>95.45</td>
</tr>
<tr>
<td></td>
<td>Lower reach</td>
<td>98.44</td>
<td>97.43</td>
</tr>
<tr>
<td>2nd mode</td>
<td></td>
<td>0.14</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.11</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.17</td>
<td>0.31</td>
</tr>
<tr>
<td>Sediment load</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st mode</td>
<td>Upper reach</td>
<td>94.16</td>
<td>90.71</td>
</tr>
<tr>
<td></td>
<td>Middle reach</td>
<td>92.95</td>
<td>90.90</td>
</tr>
<tr>
<td></td>
<td>Lower reach</td>
<td>97.15</td>
<td>98.47</td>
</tr>
<tr>
<td>2nd mode</td>
<td></td>
<td>0.83</td>
<td>1.76</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.16</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.69</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Figure 9 | Eigenvectors of the first POD mode extracted from time series of (a) annual runoff volume and (b) annual sediment load.
Dongting Lake have descending trends, the same as those in Figure 5. However, runoff volume in the lower Yangtze reach, river inflow in the Dongting Lake and both inflow and outflow in the Poyang Lake have ascending trends, in accordance with those in Figure 5. Variation trends of sediment load in the Yangtze River and its two connected lakes in Figure 9(b) are also the same as those in Figure 5. So in terms of detecting qualitative trends, the POD method is equivalent to the Mann-Kendall test.

Slopes of the curves in Figure 9 are fitted with the least square method, and change rates of annual runoff volume and sediment load are listed in Tables 2 and 3. It should be noted that regression line slopes in Tables 2 and 3 return the real change rates only when multiplied by the eigenvalues. As indicated in Figure 9(a) and Table 2, a significantly descending trend (−1.97 Bt/year) is found in the channel inflow of the Dongting Lake, as is the case for the outflow of the Dongting Lake, about −1.58 Bt/year. Besides, runoff volumes in the upper and middle reaches decrease slightly with time, at a rate of −0.45 Bt/year and −0.69 Bt/year respectively. However, runoff volume in the lower reach has a slightly ascending trend (0.48 Bt/year), as has the outflow of the Poyang Lake (0.53 Bt/year). Increase rates of river inflows are much smaller (0.07 Bt/year in the Dongting Lake and 0.21 Bt/year in the Poyang Lake).

Total change ratio (TCR), the ratio of the total change with the initial value in 1956, is listed in Table 2. TCR values in Table 2 show variation degrees of annual runoff volume during the last 58 years. In the Yangtze River, the absolute TCR value is smaller than 10%, which means the variation degree of runoff volume in the upper, middle and lower reaches is not large. In the Dongting Lake, the TCR value of the channel inflow is −84.1%, meaning the annual runoff volume in the channel significantly decreased during the last 58 years. And TCR values of river inflow and outflow are 2.7% and −29.2% respectively. In the Poyang Lake, the TCR values of inflow and outflow are 13.4% and 25.8% respectively.

Figure 9(b) and Table 3 present eigenvectors and change rates extracted from sediment load time series. Except for the case of sediment outflow in the Poyang Lake, sediment load for all other seven cases notably decreases with time. As listed in Table 3, the annual change rate of sediment load in the Yangtze River is around −6 Mt/year, which is

### Table 2 | Change rates of annual runoff volume based on the first POD mode

<table>
<thead>
<tr>
<th>Yangtze River</th>
<th>Dongting Lake</th>
<th>Poyang Lake</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Upper reach</strong></td>
<td><strong>Middle reach</strong></td>
<td><strong>Lower reach</strong></td>
</tr>
<tr>
<td>Slope k of fit line (×10^−3/year)</td>
<td>0.69</td>
<td>0.48</td>
</tr>
<tr>
<td>Eigenvalue λ₁ (×10^9 Bt)</td>
<td>11.10</td>
<td>14.32</td>
</tr>
<tr>
<td>Annual change rate ψ (Bt/year)</td>
<td>−4.05</td>
<td>−0.69</td>
</tr>
<tr>
<td>Total change δ = 58ψ (Bt)</td>
<td>−26.1</td>
<td>−39.9</td>
</tr>
<tr>
<td>Initial value in 1956 μ (Bt)</td>
<td>377.5</td>
<td>414.5</td>
</tr>
<tr>
<td>TCR ϕ = δ/μ (%)</td>
<td>−6.9</td>
<td>−9.6</td>
</tr>
</tbody>
</table>

### Table 3 | Change rates of annual sediment load based on the first POD mode

<table>
<thead>
<tr>
<th>Yangtze River</th>
<th>Dongting Lake</th>
<th>Poyang Lake</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Upper reach</strong></td>
<td><strong>Middle reach</strong></td>
<td><strong>Lower reach</strong></td>
</tr>
<tr>
<td>Slope k of fit line (×10^−3/year)</td>
<td>−3.11</td>
<td>−3.34</td>
</tr>
<tr>
<td>Eigenvalue λ₁ (×10^6 Mt)</td>
<td>142.51</td>
<td>167.02</td>
</tr>
<tr>
<td>Annual change rate ψ (Mt/year)</td>
<td>−5.94</td>
<td>−6.91</td>
</tr>
<tr>
<td>Total change δ = 58ψ (Mt)</td>
<td>−344.7</td>
<td>−400.8</td>
</tr>
<tr>
<td>Initial value in 1956 μ (Mt)</td>
<td>532.7</td>
<td>622.9</td>
</tr>
<tr>
<td>TCR ϕ = δ/μ (%)</td>
<td>−64.7</td>
<td>−64.3</td>
</tr>
</tbody>
</table>

Note: ‘/’ means no remarkable monotonous trend is found.
larger than those in the two lakes. The sediment load descending rate in the channel inflow of the Dongting Lake is \(-3.75\) Mt/year, while others (Dongting Lake’s river inflow and outflow and Poyang Lake’s inflow) are smaller than \(-1.0\) Mt/year.

TCR values in Table 3 show variation degrees of annual sediment load during the last 58 years. In the Yangtze River, the mean TCR value of the sediment load is around \(-65\%\). The variation degree of the sediment load is about 10 times as large as that of the runoff volume. In the Dongting Lake and the Poyang Lake, the mean TCR values are \(-92.2\%\) and \(-87.9\%\) respectively, which means variation degrees of the sediment load in the two lakes are much larger than those in the Yangtze River. And the CRT value of the sediment load in the channel inflow of the Dongting Lake is even \(-99.7\%\).

CONCLUSIONS

Trends of annual runoff volume and sediment load in the Yangtze River, the Dongting Lake and the Poyang Lake were analyzed. Time series of annual runoff volume and sediment load for the period ranging from 1956 to 2013 were collected from the Yangtze River Water Resources Commission (YRWRC) of China. The Mann-Kendall test, the coefficient of variation and the power spectrum estimation were used to detect variation trends, variation degrees and periods in those time series. Furthermore, the POD method was employed for the extraction of dominant components embedded inside, and quantitative evaluation of the variation. The detected trends were interpreted by relevant environment changes and human activities.

Major findings are summarized as follows:

1. For the runoff volume time series in the Yangtze River, there exists no significant trend in three reaches, and TCR (absolute value) during the last 58 years are smaller than \(10\%\). Besides, a predominant oscillation with a period of 8 years was observed. However, for the sediment load time series, remarkably descending trends, outside the 99% confidence interval, occur in all three reaches, and their TCR are around \(-65\%\).

2. In the Dongting Lake, the runoff volume of channel inflow and outflow decreases significantly with time, while that of the river inflow is an exception, with a notable oscillation with a period of 20 years. TCR of the river inflow and outflow are \(2.7\%\) and \(-29.2\%\) respectively, while it is \(-84.1\%\) for the channel inflow case. Sediment inflow and outflow have significantly descending trends, outside the 99% confidence interval. During the last 58 years, the mean TCR of the sediment load is \(-92.2\%\), and the sediment load in the channel inflow in particular varies about \(-99.7\%\).

3. In the Poyang Lake, runoff volume and sediment load have no remarkable trend, except for the case of sediment inflow, with a significantly descending trend. For the annual runoff volume time series, the period of predominant oscillation in the inflow is 20 years, while that in the outflow is 8 years. During the last 58 years, TCR of the runoff inflow and outflow are about 13.4% and 25.8% respectively. However, the sediment inflow varied about \(-87.9\%\), meanwhile the sediment outflow has no obvious trend.

4. The Three Gorges Reservoir has no remarkable influence on the annual runoff volume in the Yangtze River and the Poyang Lake. Influence of other factors (infiltration to ground, evaporation and use in irrigation) on annual runoff volume in this river-lake system needs investigation in the future. However, the Three Gorges Reservoir accelerates the sediment load descending rate in the Yangtze River, particularly for the middle and lower reaches, which is the same for the sediment inflow from the channels to the Dongting Lake.

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