Research Article

Detection of Abrupt Changes in Runoff in the Weihe River Basin

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Climate change and human activities are two major driving factors for variations in hydrological patterns globally, and it is of significant importance to distinguish their effects on the change of hydrological regime in order to formulate robust water management strategies. Hilbert-Huang transform-based time-frequency analysis is employed in this study to detect abrupt changes and periods of the runoff at five hydrological stations in the Weihe River Basin, China, from 1951 to 2010. The key part of the method is the empirical decomposition mode with which any complicated data set can be decomposed into small number of intrinsic mode functions that admit well adaptive Hilbert transforms. Moreover, an attempt has been made to find out the specific reason for the abrupt point at the five hydrological stations in the Weihe River Basin. The results are presented as follows: (1) annual runoff significantly declined in the basin in intervals of 8~15 years; (2) abrupt changes occurred in 1971, 1982, and 1994 at Huaxian, 1972 and 1982 at Xianyang, 1992 at Zhangjiashan, 1990 at Zhuangtong, and 1984 at Beidao; (3) changes were more frequent and complex in the mainstream and downstream reaches than in tributaries and upstream reaches, respectively.

1. Introduction

Global climate changes and human activities are strongly affecting the spatial and temporal patterns of river runoff and other key hydrological variables [1–3]. Clearly, it is important to characterize these changes and identify the causal factors in order to formulate appropriate water management strategies [4, 5]. Thus, numerous authors have examined these changes in diverse regions using various methods. Notably, Richter et al. [6] studied changes in runoff of the Colorado River employing a method called the Range of Variability Approach (RVA), intended for application in cases where the conservation of native aquatic biodiversity and protection of natural ecosystem functions are primary river management objectives. In a subsequent contribution, Richter et al. [7] demonstrated the utility of the approach for assessing hydrological changes at sites throughout a river basin. Perreault et al. [8] used a Bayesian approach to detect changes in annual energy inflows of eight hydropower systems in Québec and pointed out the (often neglected) need to consider hydrological variations for robust forecasting. Burn and Hag Elnur [9]

investigated 18 hydrological variables reflecting various components of hydrological cycles in a network of 248 Canadian catchments selected to reflect natural conditions, using the Mann-Kendall nonparametric test to detect abrupt changes and trends in runoff. They observed more significant trends than expected to occur by chance, with variations in geographic location implying that impacts of the causal factors are not spatially uniform. Similarly, Bao et al. [10] used the Mann-Kendall test to detect abrupt changes in runoff in the Haihe and Kaidu River Basins of China, respectively. They then quantitatively distinguished effects of climate variability and human activities on runoff, which (as mentioned) is essential for formulating appropriate regional water resources assessment and management regimes.

In addition to Mann-Kendall and Bayesian approaches, the Pettitt test [11] and two-stage linear regression [12, 13] have also been used to detect changes in runoff series. However, all of these methods have severe limitations for handling highly complex nonlinear systems; thus, various nonlinear analysis methods have been introduced recently. These methods include rescaled range analysis [14] and approximate

entropy [15] techniques, which can solve the problems of nonstationarity and nonlinearity, but the window size affects the results. Wavelet transform analysis can also effectively detect points of change [16–18], but false points may be detected if an inappropriate wavelet function is selected, so other diagnostic tools must also be applied.

In the late 1990s, NASA (the US National Aeronautics and Space Administration) proposed an alternative method of time series analysis [19], the Hilbert-Huang transform (HHT), which combines empirical mode decomposition (EMD) and the Hilbert transform [20]. EMD decomposes complex signals of local characteristics into a series of finitely intrinsic mode functions (IMFs), which are subjected to the Hilbert transform to detect changes in their amplitude and frequency over time, yielding three-dimensional (time-amplitude-frequency) spectra. Since changes over time in the amplitude and frequency of the focal signals are captured, no physically significant harmonic is eliminated which reflects nonlinear and nonstationary processes [21]. HHT incorporates the advantages of wavelet analysis but also provides higher resolution [22]. The EMD method is adaptive to changes in local signals; thus it is highly suitable for processing complex nonlinear and nonstationary signals [23]. Hence, the HHT approach is widely used to process diverse signals in biomedical, chemical engineering, meteorological, seismic, and speech recognition applications [24–26]. This paper serves as an introduction to the HHT runoff time series analysis. Thus, the method is applied to detect abrupt changes in time series of runoff data collected at five hydrological stations (Beidao, Xianyang, Huaxian, Zhangjiashan, and Zhuangtuo) in the Weihe River Basin from 1951 to 2010.

2. Study Area and Data

The Weihe River originates in Weiyuan County, Gansu Province, northwest China, and is the largest tributary of the Yellow River. It passes through several major cities, including Tianshui, Xianyang, and Weinan, situated in the southern margins of the Loess Plateau, before discharging into the Yellow River at Tongguan. The Weihe Basin covers an area of 134,800 km², extending between longitudes 104°00'E and 110°20'E and latitudes 33°50'N and 37°18'N, the stream length is 818 km, and the Qinling Mountains mark its southern borders (Figure 1). The basin is in the continental monsoon climate zone, with cold and dry winters as well as hot and wet summers governed by the Mongolian and West Pacific subtropical high pressure systems, respectively.

This study focuses on detecting changes of annual runoff at the five hydrological stations which are Beidao, Huaxian, Zhuangtuo, Zhangjiashan, and Xianyang in Weihe River of Northeastern China. The data analyzed here are annual average runoff data collected at five hydrological stations from 1951 to 2010 archived by the Weihe River Hydrological Bureau. Three of these stations (Beidao, Xianyang, and Huaxian) are located in the mainstream reaches, while the other two (Zhangjiashan and Zhuangtuo) are in the largest and second largest tributaries of the Weihe River; the River Jing is 455 km long with basin areas of 454,000 km², accounting for 33.7% of the River Weihe Basin, whereas River Beiluo is

FIGURE 1: Map of the Weihe River Basin showing the five hydrological stations and corresponding catchments.

680 km long with basin areas of 26,900 km² accounting for 20% of the River Weihe Basin (Figure 1).

3. Methods

3.1. Empirical Mode Decomposition (EMD). EMD [19] sequentially decomposes time series of data into a series of IMFs, with smoothing to eliminate riding waves. Each IMF must have the same number of extreme values and zero crossings, with its envelopes being symmetric with respect to zero. The first condition is similar to the traditional narrow-band requirements for a stationary Gaussian process, whereas the second condition guarantees meaningful instantaneous frequencies by turning global into local limits. EMD can decompose any complex signal into finite numbers of IMFs, as follows.

Suppose $x(t)$ is original time series; $u(t)$ is upper envelope of $x(t)$; $v(t)$ is lower envelope of $x(t)$; $m(t)$ is the mean of upper envelope and lower envelope.

First, local maximum and minimum values of the original time series are calculated to acquire upper and lower envelope sets: $m(t) = [u(t) + v(t)]/2$. If $h_1(t) = x(t) - m(t)$, $h_1(t)$ meets the two conditions of an IMF. If not, local maximum and minimum values are recalculated until $h_k(t)$ meets the two IMF conditions, $h_k(t)$ is the first component $c_1(t)$ of the IMF, and the residual part of the sequence is $r_1(t) = x(t) - c_1(t)$.

Finally, these steps are applied to the residual component $r_1(t)$ until it forms a monotonic sequence. The standard deviation (SD) of the IMF is

$$SD = \sum_{t=0}^T \frac{[h_{k-1}(t) - h_k(t)]^2}{h_{k-1}^2(t)}. \quad (1)$$

$h_k(t)$ in formula (1) is the component of the IMF. When the SD is ≤ 0.3 , the IMF is deemed to have sufficient stability for robust physical interpretation.

3.2. Hilbert Transformation. $c_i(t)$ is the sequence of IMF. The Hilbert transform of $c_i(t)$ is defined as

$$y_i(t) = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{c_i(t')}{t - t'} dt'. \quad (2)$$

Here, P is the Cauchy principal value and $y_i(t)$ is the Hilbert transform of $c_i(t)$. According to (2), when $c_i(t)$ and $y_i(t)$ are complex conjugates, the following analytic signal is obtained:

$$C_i(t) = c_i(t) + iy_i(t) = a_i(t) e^{i\theta_i(t)}. \quad (3)$$

Here, $a_i(t)$ is the instantaneous amplitude and $\theta_i(t)$ is the phase, where

$$a_i(t) = |c_i(t) + iy_i(t)| = \sqrt{c_i^2(t) + y_i^2(t)}, \quad (4)$$

$$\theta_i(t) = \arctan \left[\frac{y_i(t)}{c_i(t)} \right].$$

And the corresponding instantaneous frequency $\omega_i(t)$ is [26]

$$\omega_i(t) = \frac{d\theta_i(t)}{dt}. \quad (5)$$

The instantaneous frequency is a single-valued function of time, and the time series of the Hilbert transform must be a single component to make the instantaneous frequency physically meaningful. When we need to predict runoff, $r(t)$ component is ignored and the runoff sequence $x(t)$ can be reconstructed as follows:

$$x(t) = \text{Re} \left\{ \sum_{i=1}^n a_i(t) \exp \left(j \int \omega_i(t) dt \right) \right\}. \quad (6)$$

Here, t is the time and j is imaginary unit. Re is the real part of the complex.

The joint Hilbert-Huang spectrum is defined as

$$H(\omega, t) = \sum_{i=1}^n a_i(t) \left| \exp \left(j \int \omega_i(t) dt \right) \right|. \quad (7)$$

The joint spectrum is a full time-frequency distribution that can accurately reflect the amplitude of the variation across the band with the frequency and time.

In order to analyze the runoff series in greater detail and verify the findings, the instantaneous frequencies and Hilbert-Huang spectra were examined.

3.3. Detecting Variant Points. Points of abrupt changes in a focal time series ("mutation points") are detected as follows. First, for the decomposition of the IMF components, correlation coefficients between extreme values of each IMF component and the original sequence are calculated, and then the differences in amplitude and intervals of adjacent maxima and minima are calculated. Abrupt changes are located at positions of maximum absolute difference between the extrema and the minimum intervals between them. In other words, maxima of the first-order differentials for each IMF component indicate points of significant change (usually changes in the frequency and/or amplitude of runoff in this context). In order to eliminate influence of different station and different IMF, the absolute first-order differentials were standardized. Frequency variations are reflected in changes

TABLE 1: Correlation coefficients of IMF components and original sequence.

	IMF1	IMF2	IMF3	IMF4
Beidao	0.768	0.502	0.215	0.127
Xianyang	0.703	0.533	0.258	0.131
Huaxian	0.722	0.534	0.232	0.118
Zhangjiashan	0.759	0.572	0.197	0.106
Zhuangtuo	0.697	0.511	0.225	0.191

in the characteristic scales, while amplitude variations are reflected in changes in peak values of the HHT spectra. Thus, changes in peaks of the instantaneous frequency and the HHT spectra can pinpoint locations of mutation points, as outlined in the Results.

4. Results

4.1. Detection of Abrupt Changes. Positions of abrupt changes (mutation points) in the runoff time series are detected by the following:

Decomposing the original signal by EMD, seeking IMF components (Figure 2) in accordance with formula (1).

Detecting the extrema in the sequence of IMF components.

Calculating differences in the amplitudes and intervals of adjacent maxima and minima and standardizing absolute of differences.

Identifying mutation points as positions where differences in extrema are maximal and differences in intervals are minimal. That is the maximum value of standardized coefficients (Figure 3).

The correlation coefficients (Table 1) for IMF1 and IMF2 are greater than 0.49, which exceeds the 95% significance level. The years when differentials of the amplitude of IMF1 were maximal at five stations are shown in Figure 3.

As shown in Figure 3(b), there were abrupt changes in runoff at Huaxian in 1971, 1982, and 1994. Abrupt changes were also detected in 1984 at Beidao (Figure 3(a)), 1991 at Zhuangtuo (Figure 3(c)), 1994 at Zhangjiashan (Figure 3(d)), and 1972 and 1982 at Xianyang (Figure 3(e)).

Hilbert transforms of each IMF component of the runoff at Huaxian, and the average frequencies and amplitudes obtained (from the arithmetic means of the frequencies and amplitudes during the averaging periods, resp.), are shown in Table 2.

It can be seen from Figure 2 and Table 2 that the amplitude and frequency of IMF1 to IMF4 at Huaxian successively declined, while the wavelength successively increased. Cycles in the runoff at this station with 8.21, 15.38, 25.64, and 32.25 periods, significant quasi 8~15 yearly oscillations, and a declining trend were detected. Significant changes in the Hilbert-Huang spectral peaks occurred in 1971, 1982, and 1994, verifying the previous findings. Results of the analyses

FIGURE 2: EMD coefficients of runoff at each hydrological station.

FIGURE 3: Standardization absolute of IMF1 at each hydrological station.

FIGURE 4: The average annual runoff and the abrupt change points.

TABLE 2: Statistical parameters of the IMFs.

Mode	Mean frequency	Mean period (year)	Mean amplitude ($\text{m}^3 \cdot \text{s}^{-1}$)
IMF1	0.122	8.21	28.55
IMF2	0.065	15.38	19.13
IMF3	0.039	25.64	15.89
IMF4	0.031	32.25	0.006

of runoff changes at Beidao, Xianyang, Zhangjiashan, and Zhuangtuo were verified using the same methodology.

4.2. The Amplitude Variation of Average Runoff. In order to further explain the occurrence of the abrupt change points, the amplitude variation of average runoff is calculated, as shown in Figure 4 and Table 3.

The data in Figure 4 and Table 3 show that average runoff has a significant decrease in Beidao, Zhangjiashan, and Zhuangtuo, 53.4%, 69.5%, and 41.4%, respectively. Meanwhile, there are periodic changes in Huaxian and Xianyang in the study period. The average runoff of Huaxian was 9.161 billion m^3 before 1971 but decreased to 5.895 billion m^3 during the period of 1972 to 1982, increased to 7.262 billion m^3 from 1983 to 1994, and dropped to 4.015 billion m^3 in the past several years. The average runoff of Xianyang is 5.509 billion m^3 before the first abrupt change point but decreased to 3.032 billion m^3 from 1972 to 1982 and has increased to 3.357 billion m^3 since 1983. Its corresponding variation amplitude is 53.4%, 69.5%, and 41.4%, respectively.

4.3. Significance Test of the Mutation Points. Since annual mean runoff series spanning periods with significant mutation points should significantly differ from a white noise series (Gaussian distribution with mean 0 and variance

TABLE 3: The variation amplitudes of average runoff.

Stations	Periods	Average runoff (10^8 m^3)	Variation in runoff (%)
Beidao	1951–1984	15.28	—
	1984–2010	7.12	53.4
Huaxian	1951–1971	91.61	—
	1971–1982	58.95	35.7
	1983–1994	72.62	23.2
	1995–2010	40.15	44.7
Zhuangtuo	1951–1991	21.36	—
	1992–2010	6.51	69.5
Zhangjiashan	1951–1992	19.21	—
	1993–2010	11.26	41.4
Xianyang	1951–1972	55.09	—
	1972–1982	30.32	45.0
	1983–2010	33.57	10.7

FIGURE 5: Results of significance test of detected abrupt change points in runoff at Huaxian.

0.01), we compared the series examined here to computer-generated white noise to test the significance of the mutation points. As shown in Figure 5, the results show that confidence levels were $\geq 99\%$ for one point (in 1982) and $\geq 95\%$ for the other two points (in 1971 and 1994). The abrupt changes in runoff detected at the other hydrological stations (Beidao, Xianyang, Zhangjiashan, and Zhuangtuo) also met 95% confidence criteria.

5. Discussion

Hydrological cycles and water resources are strongly influenced by climatic factors, such as El Niño events and global climate changes, and human activities, such as large-scale water conservation constructions and ecological restoration measures [10, 27, 28]. The Weihe River Basin is in the continental monsoon climate zone of China and thus is affected

by the West Pacific subtropical high pressure system. In 1972, weakness of this system in combination with development of an El Niño event caused substantial atmospheric circulation and climate anomalies in China [29], leading to a sharp fall in precipitation in the Weihe River Basin, thus contributing to the mutation point detected in that year. In 1982, another El Niño event occurred (the strongest warming event in the 20th century), which had a substantial climatic impact on China during the summer, including another major turning point in precipitation in the basin. In 1994, a third ENSO event occurred, while the West Pacific subtropical high pressure system was strong, resulting in a further significant drop (14.9%) in precipitation in the basin [30], which substantially contributed to a 42.4% reduction in average annual runoff.

However, human activities have also markedly influenced runoff patterns. Notably, the construction of terraces, reservoirs, and irrigation canals (e.g., the Dongfanghong pumping and Wei irrigation installations constructed in 1970 and the Baojixia canal completed in 1971), and other water conservancy measures, reduced the efficiency and runoff of watershed source area. Completion of the Fengjiashan reservoir contributed to anomalous conditions in 1982, and continuous increases in industrial and agricultural water consumption, combined with climate change, contributed to both the abrupt change of runoff in 1994 and its tendency to decline. Similarly, increases in the area irrigated by the Jinghui and Huiluo canals, fed by the Jinghe and Beiluohe Rivers, respectively, contributed to both abrupt changes in runoff and the significantly declining trend detected at Zhangjiashan and Zhuangtuo [27, 28]. In addition, other reference information [29, 30] of Wei River has shown that there is a certain relationship of precipitation, evaporation, and runoff. Since the 1960s, Wei River annual precipitation has been decreasing in Wei River Basin and an abrupt change of precipitation in 1982 and a sharp variation of evaporation occurred in 1993.

6. Conclusions

This study applied HHT method to analyze the periodicity, trends, and abrupt change point of the annual runoff in the Weihe region. The results can be summarized as follows:

- (1) The instantaneous frequencies and IMFs, calculated as described above, show multitime-scale features with significant 8~15-year periods. Significant ($\alpha = 0.05$) decreasing trends in annual runoff throughout the study period were detected at four hydrological stations at Beidao, Huaxian, Zhangjiashan, and Xianyang but at Zhuangtuo it increased before 1968 and then decreased. Thus, annual runoff significantly declined throughout the Weihe River Basin.
- (2) During the period of records, the Weihe River Basin has been becoming drier. Meantime, the local human activities have become more and more extensive. Because of climate changes and a series of water conservancy measures, there are 3 changes of Weihe River runoff in Huaxian station (1971, 1982, and 1994), two in Xianyang station (1972 and 1982), and one in Zhangjiashan station (1992), Zhuangtuo station (1991), and Beidao station (1984). That is, one mutation point is detected in the tributary, two mutation points are detected in the upstream reaches, and three mutation points are detected in the central mainstream and downstream station. These findings indicate that changes were more frequent and complex in the mainstream and downstream reaches than in tributaries and upstream reaches, respectively, presumably because the mainstream reaches are affected by changes in all of their tributaries and all points upstream.
- (3) The reductions of average annual runoff in Beidao (in the upstream reaches), Zhangjiashan, and Zhuangtuo (in the tributary) are 53.4%, 69.5%, 41.4%, respectively. The study period can be divided into four stages by three abrupt change points in Huaxian (in the mainstream reaches and downstream reaches), and the amplitude variation of average runoff is 35.7%, 23.2%, and 44.7%, respectively. The period 1951–2010 can be divided into three stages, and the amplitude variation of average runoff is 45.0% and 10.7% in Xianyang (in the midstream reaches).
- (4) ENSO events, variations in West Pacific subtropical high pressure systems, and various identified human activities appear to have contributed to the changes in runoff. However, sunspot activity patterns, other climatic factors, and other human activities may also have contributed. Thus, further research is required to elucidate the causal factors comprehensively.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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References

- [1] M.-V. Birsan, P. Molnar, P. Burlando, and M. Pfaundler, "Stream-flow trends in Switzerland," *Journal of Hydrology*, vol. 314, no. 1–4, pp. 312–329, 2005.
- [2] C. B. Field, V. Barros, T. F. Stocker, and Q. Dahe, *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK, 2012.
- [3] T. P. Barnett, D. W. Pierce, H. G. Hidalgo et al., "Human-induced changes in the hydrology of the western United States," *Science*, vol. 319, no. 5866, pp. 1080–1083, 2008.
- [4] J. T. Overpeck and J. E. Cole, "Abrupt change in earth's climate system," *Annual Review of Environment and Resources*, vol. 31, pp. 1–31, 2006.

- [5] G. T. Narisma, J. A. Foley, R. Licker, and N. Ramankutty, "Abrupt changes in rainfall during the twentieth century," *Geophysical Research Letters*, vol. 34, no. 6, Article ID L06710, 2007.
- [6] B. D. Richter, J. V. Baumgartner, R. Wigington, and D. P. Braun, "How much water does a river need?" *Freshwater Biology*, vol. 37, no. 1, pp. 231–249, 1997.
- [7] B. D. Richter, J. V. Baumgartner, D. P. Braun, and J. Powell, "A spatial assessment of hydrologic alteration within a river network," *Regulated Rivers: Research & Management*, vol. 14, no. 4, pp. 329–340, 1998.
- [8] L. Perreault, J. Bernier, B. Bobée, and E. Parent, "Bayesian change-point analysis in hydrometeorological time series. Part 1. The normal model revisited," *Journal of Hydrology*, vol. 235, no. 3–4, pp. 221–241, 2000.
- [9] D. H. Burn and M. A. Hag Elnur, "Detection of hydrologic trends and variability," *Journal of Hydrology*, vol. 255, no. 1–4, pp. 107–122, 2002.
- [10] Z. Bao, J. Zhang, G. Wang et al., "Attribution for decreasing streamflow of the Haihe River basin, northern China: climate variability or human activities," *Journal of Hydrology*, vol. 407, pp. 117–129, 2012.
- [11] D. Zuo, Z. Xu, H. Yang, and X. Liu, "Spatiotemporal variations and abrupt changes of potential evapotranspiration and its sensitivity to key meteorological variables in the Wei River basin, China," *Hydrological Processes*, vol. 26, no. 8, pp. 1149–1160, 2012.
- [12] S. L. Zhang, Y. H. Wang, and P. T. Yu, "Impact of human activities on the spatial and temporal variation of runoff of Jinghe Basin, Northwest China," *Journal of Arid Land Resources and Environment*, vol. 25, pp. 66–72, 2011.
- [13] Y. Zhang, Q. Shao, J. Xia, S. Bunn, and Q. Zuo, "Changes of flow regimes and precipitation in Huai River Basin in the last half century," *Hydrological Processes*, vol. 25, no. 2, pp. 246–257, 2011.
- [14] A. L. Yan, Q. Huang, and Z. Liu, "Complicated property of runoff time series studied with R/S method," *Journal of Applied Sciences*, vol. 25, pp. 214–217, 2007.
- [15] D. Y. Sun, *The Mutation Diagnosis and Analysis of River Runoff Series in the Changing Environment*, Xi'an University of Technology, 2012.
- [16] Y. L. Li and Q. X. Chang, "Detection of the abrupt changes in runoff based on the Morlet wavelet," *Journal of Xi'an University of Technology*, vol. 28, pp. 322–325, 2012.
- [17] R. V. Andreoli and M. T. Kayano, "Multi-scale variability of the sea surface temperature in the Tropical Atlantic," *Journal of Geophysical Research C: Oceans*, vol. 109, no. 5, Article ID C05009, 2004.
- [18] K.-M. Lau and H. Weng, "Interannual, decadal-interdecadal, and global warming signals in sea surface temperature during 1955–97," *Journal of Climate*, vol. 12, no. 5, pp. 1257–1267, 1999.
- [19] N. E. Huang, Z. Shen, S. R. Long et al., "The empirical mode decomposition and the Hubert spectrum for nonlinear and non-stationary time series analysis," *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 454, no. 1971, pp. 903–995, 1998.
- [20] N. E. Huang, Z. Shen, and S. R. Long, "A new view of nonlinear water waves: the Hilbert spectrum," *Annual Review of Fluid Mechanics*, vol. 31, pp. 417–457, 1999.
- [21] F. Y. Wei, "Progresses on climatological statistical diagnosis and prediction methods," *Journal of Applied Meteorological Science*, vol. 17, pp. 736–740, 2006.
- [22] P. Zhang and G. M. Hu, "Detection of network traffic anomaly on instantaneous frequency analysis," *Journal of University of Electronic Science and Technology of China*, vol. 36, pp. 1007–1011, 2007.
- [23] Z. H. Zhu, Y. L. Sun, and H. Li, "Power fault detection using empirical mode decomposition," *Engineering Journal of Wuhan University*, vol. 40, no. 5, pp. 119–122, 2007.
- [24] Z. K. Peng, P. W. Tse, and F. L. Chu, "An improved Hilbert-Huang transform and its application in vibration signal analysis," *Journal of Sound and Vibration*, vol. 286, no. 1–2, pp. 187–205, 2005.
- [25] R. Yan and R. X. Gao, "Hilbert-huang transform-based vibration signal analysis for machine health monitoring," *IEEE Transactions on Instrumentation and Measurement*, vol. 55, no. 6, pp. 2320–2329, 2006.
- [26] N. E. Huang and Z. Wu, "A review on Hilbert-Huang transform: method and its applications to geophysical studies," *Reviews of Geophysics*, vol. 46, no. 2, Article ID RG2006, 2008.
- [27] C. J. Vörösmarty, P. Green, J. Salisbury, and R. B. Lammers, "Global water resources: vulnerability from climate change and population growth," *Science*, vol. 289, no. 5477, pp. 284–288, 2000.
- [28] K. Kezer and H. Matsuyama, "Decrease of river runoff in the Lake Balkhash basin in central Asia," *Hydrological Processes*, vol. 20, no. 6, pp. 1407–1423, 2006.
- [29] H. Bai, X. Mu, F. Wang, and P. Gao, "Analysis on evolution law of meteorological and hydrological drought and wetting," *Agricultural Research in the Arid Areas*, vol. 30, pp. 237–241, 2012.
- [30] H. L. Zhang, Y. Chen, and G. X. Ren, "The characteristics of precipitation variation of Weihe River Basin in Shaanxi Province during recent 50 years," *Agricultural Research in the Arid Areas*, vol. 26, no. 4, pp. 236–240, 2008.