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Interference of natural and anthropogenic forcings on variations in continental freshwater discharge from the Red River (Vietnam) to sea

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ABSTRACT

Continental freshwater discharge is vital to global human development. Intensive studies have been conducted on changes of river discharge around the world (Dai et al., 2009; Milliman and Farnsworth, 2011). However, little work has been carried out on the daily continental freshwater discharge of the Red River in response to influence of the natural and anthropogenic forcings. This paper presents results of change analysis of daily continental freshwater discharge over the period 1956–2009 in the Red River. The wavelet analysis results showed observable periodicities in the continental freshwater discharge series with 4–6 months, 8–12 months, 1.5–2 years, and 4–7 years (48–80 months), respectively. The results from Mann–Kendall test indicated insignificant trends in annual continental freshwater discharge during the study period, but there is clearly decrease in annual suspended particulate matter of the Red River. It is shown that the continental freshwater discharge from the Red River was dominated by precipitation over the catchments. Moreover, changes in the continental freshwater discharge are closely related to SASM (the South Asia Summer Monsoon) and ENSO (EI Niño Southern Oscillation). Variations in daily discharge are lagged behind SASM 13–29 days. It revealed that El Niño and La Niña events are likely to induce extreme low and extreme high continental freshwater discharge from the Red River into the Tokin Gulf, respectively. Meanwhile, continental freshwater discharge from the Red River into the Tonkin Gulf experienced abrupt changes with present characteristics as 'no flood in the flood season, no drought in the drought season' due to water regulation induced by dam.

1. Introduction

Continental freshwater discharge, occurs mainly at the mouths of the world's major rivers, is of vital importance to estuary ecosystem and adjacent areas. The continental freshwater discharge provides primary link in land and sea, hydrological cycle and thermodynamic stability of the oceans, and biogeochemical processes (Dai et al., 2009; Milliman and Farnsworth, 2011; Restrepo et al., 2014). In addition, continental runoff represents a major portion of freshwater resources available to terrestrial inhabitants (Dai et al., 2009). However, the continental freshwater discharge has been subjected to significant changes in recent decades due to climate change and anthropogenic activities (Nilsson et al., 2005; Dai et al., 2011; Milliman and Farnsworth, 2011). Therefore, Understanding of changes in continental freshwater discharge is central to assessing the impact of climate and interferences of anthropogenic activities on water resources (Vörösmarty et al., 2000).

It is indicated that there was 4% increase in global runoff per 1 °C global surface warming, although continental runoff had large decadal to multidecadal variations (Labat et al., 2004). Different areas present different variation tendency in water discharge. For instance, the water discharge present upward trend in the United States over latter half of the twentieth century because of precipitation increase, and decreases in 64 Canadian rivers from 1964 to 2003 in response to rainfall decrease (Groisman et al., 2001; Déry and Wood, 2005).

Moreover, river discharge around the world has been regulated by extensively anthropogenic activities, such as impoundments and diversions (Nilsson et al., 2005). Annual discharge of Changjiang (Yangtze River) showed a decreasing trend over the Industrial Period as a result of human impacts, in particular, reservoir construction and water consumption (Dai et al., 2008a; Yang et al., 2010). Dam regulation in upper Mekong River produced declining trend in downstream flows during dry season (Lu and Siew, 2006).

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It is clearly that river discharges around the world exhibit various characteristics correspond to a series of complicate factors. Milliman et al. (2008) indicated that the continental freshwater discharge had decreased more than that implied by changes in precipitation only over rivers with low water, such as the Indus, Yellow, and Tigris–Euphrates. Dai et al. (2009) suggested that effects of human activities on yearly continental freshwater discharge of the many of the world's large rivers are likely small compared with those of climate variations during 1948–2004.

By far, most studies on water discharge were based on annual or monthly mean data, which fails to provide accurate analysis on hydrological processes. It is important to obtain daily information to understand how the river hydrology and extreme events changes in response to climate change and human activities, especially to those large river basins with dense populations.

The Red River (Song Hong), located in South-East Asia, is the second largest river in Vietnam. The total area of the basin is approximately 160 000 km^2, of which 50.3% in Vietnam, 48.8% in China and 0.9% in Laos (Le et al., 2007; Van Maren, 2007) (Fig. 1). Situated in the tropical monsoon climate region, the Red River is characterized by a distinct monsoon climate with rainy season from May to October and dry season from November to April. The mean annual rainfall is 1300–1800 mm, about 85–95% of which contributed by the summer rainy season (Li et al., 2006; Le et al., 2007; Dang et al., 2010). The Red River basin has a warm and humid summer with average temperatures ranging from 27 °C to 29 °C, a cool and dry winter with average monthly temperatures varying from 16.3 °C to 20.9 °C (Li et al., 2006). Different from the Changjiang River, which originates from glaciers in the Tibet Plateau and get a large amount of water from ice melting, discharge of Red River is mostly generated from basin precipitation (Isupova and Mikhailov, 2011). Moreover, the continental freshwater discharge of the Red River is strongly influenced by the South Asia Summer Monsoon (SASM) (Isupova and Mikhailov, 2011) with seasonal characteristics (Simonovic and Carson, 2003). EI Niño Southern Oscillation (ENSO) can also trigger occurrence of some extreme hydroclimatological events in rivers, such as floods, droughts and precipitation anomalies (Zhang et al., 2013a; Nguyen et al., 2014).

The Red River comprises two major tributary systems: Da River on the right and the Lo River on the left (Dang et al., 2010; Isupova and Mikhailov, 2011) (Fig. 1). Both tributaries originate from China. The Da River is the largest tributary of the Red River. There are two large reservoirs in the Red River watershed: Hoa Binh Reservoir along the Da River and Thac Ba reservoir in the Lo River. Hoa Binh Reservoir, the largest reservoir in Vietnam with a storage capacity of 9.5 billion m^3 was complicated in 1994, plays a vital role in flood mitigation and hydropower generation (Tinh, 2001; Luu et al., 2010). Thac Ba reservoir, with a storage volume of 2.49 billion m^3, was in operation in 1971. It is mainly used for hydropower generation (Ranzi et al., 2012).

Impacts of dams on runoff and suspended sediment discharge of most large rivers had received worldwide attentions (Lu and Siew, 2006; Milliman et al., 2008; Dai et al., 2009), as well as those of the Red River in North Vietnam. Some studies showed that dam constructions in the Red River Basin cause significant change in water and sediment budgets (Dang et al., 2010; Luu et al., 2010; Vu et al., 2014). In addition, some previous researches indicated that the hydrology character of Red River could be affected by climatic and environmental conditions (Simonovic and Carson, 2003; Pruszak et al., 2005; Le et al., 2007). However, few studies addressed how human and climate changes affect water discharge variations of the Red River, especially for extreme flood/drought events. In recent several decades, floods and droughts were mainly occurred in tropical zone and present an increased trend due to global warming (IPCC, 2007). It is necessary to study continental freshwater discharge changes in the tropical zone, such as the Red River. Thereafter, based on the long-term daily continental freshwater

Fig. 1. Map of study area including the Red River and its tributaries with Hoa Binh Reservoir on the Da River – right tributary of Red River and Thac Ba reservoir on the Lo River – left tributary of Red River. Daily water discharge was observed at Son Tay gauging station.

discharge over 1956–2009 at Son Tay station, this paper aims to (1) detect the trends in discharge series of the Red River; (2) identify the factors that affect the discharge variations and (3) evaluate the occurrences of extreme events in recent decades.

2. Materials and methods

2.1. Materials

In this study, daily freshwater discharge data during 1956–2009 and yearly suspended particulate matters (SPM) during 1959–2006 at Son Tay gauging station (Fig. 1) were collected from the Vietnam Institute of Meteorology, Hydrology and Environment (IMHE) (http://www.imh.ac.vn/). In order to reconstruct the occasionally missing data in 1959 and 2006, linear regression function was proposed. Precipitation data during 1975–2006 at 42 meteorological stations were obtained from China Meteorological Administration National Meteorological Information Center (http://cdc.cma.gov.cn/) and Vietnam's HydroMeteorological Data Center (http://www.hymetdata.gov.vn/). And then the mean annual precipitation of Red River Basin was calculated by the Thiessen polygon method (Unwin and Unwin, 1998).

Meanwhile, the SASM index and ENSO index were also considered for statistical analysis. SASM is defined as an area-averaged seasonally (June to September) dynamical normalized seasonality (DNS) at 850 hPa within the South Asia domain (5°–22.5°N, 35°–97.5°E) (Li and Zeng, 2002, 2003, 2005; available at: http://ljp.lasg.ac.cn/dct/page). ENSO index is described by sea surface temperature (SST) over the tropical Pacific (4°S–4°N, 150°W–90°W). If the SST values are at or above 0.5 °C for 6 consecutive months (including October–December (OND)), the ENSO year of October through the following September is categorized as El Niño (warm events). When the index values are equal or below −0.5 °C for 6 consecutive months, the ENSO year is categorized as La Niña (cold events). Consequently, the El Niño and La Niña events during 1959–2006 were obtained. The index is a 5-month running mean SST anomaly for the region, and is available from ftp://www.coaps.fsu.edu/pub/JMA_SST_Index/.

Here, the extreme drought and flood events in the Red River were assessed using percentile-based indices, as described by Bonsal et al. (2001). According to the IPCC Fourth Assessment Report, the extreme climate is usually defined as the occurrence of a value of a weather or climate variable above (or below) a fixed threshold (IPCC, 2007). Here, we selected the 10th and 90th percentile of the daily freshwater discharge as the threshold. 10th percentile presents extreme low discharge, while 90th percentile indicates extreme high discharge. Five statistical indicators, including coefficient of variation (Cv), maximum/minimum monthly mean discharge, and mean wet/dry season discharge of each year were calculated by the Moment method (Greenwood et al., 1979). Lag correlation analysis was carried out to examine when the southwest monsoon suggests most significant impact on the daily water discharge (Zhang et al., 2013b). Moreover, simple frequency analysis was applied to detect difference between pre and post-dam water discharge before and after dam construction.

2.2. Methodology

Three techniques have been used in this study: Wavelet analysis, Mann–Kendall test, Sequential Mann–Kendall test. Details of these techniques are list in following sections.

2.2.1. Wavelet analysis

Wavelet analysis (also known as wavelet theory) is a common tool for providing accurate localized temporal and frequency information, which decompose a complicated time series into a finite number of components (Torrence and Compo, 1998). Compared with other signal analysis methods, wavelet analysis method can explore a signal, or a field, in terms of time and scale, and possibly directions (Farge, 1992). It has been widely applied in hydrological research (Sang et al., 2013). Here, Morlet wavelet analysis and associated global wavelet spectrum of Red Noise test (at a significant level of 0.1) is performed on the long-term dataset to obtain the periodic variation.

The long-term continental freshwater discharge dataset in the Red River suggests fluctuation in various time scales. Therefore, the Morlet wavelet analysis is firstly applied to the normalized monthly freshwater discharge to extract the short-term fluctuation, such as dominant seasonal characteristics. And then, the Morlet wavelet analysis is applied to the reconstructed normalized monthly freshwater discharge to obtain long-term variations.

2.2.2. Mann–Kendall test

Two types of trend tests, including linear regression method and nonparametric Mann–Kendall test are presented in this study respectively, to determine whether the time series changes over time. The Mann–Kendall test states a monotonic trend when Z values exceed the critical values ±1.96 ($\alpha = 0.05$). A positive Z value indicates an increasing trend, while a negative Z value suggests a decreasing trend (Mann, 1945; Kendall, 1975).

2.2.3. Sequential Mann–Kendall test

The Sequential version of Mann–Kendall test is suggested to detect the abrupt change in the discharge series, following the procedures described by Gerstengarbe and Werner (1999) and Miao et al. (2010). The test is composed of two series: a progressive statistic variable UF_k and a backward one UB_k. If the UF_k and UB_k curves cross each other and the intersection of the two series locates beyond the specific threshold value ±1.96 (significant level of 0.05), an abrupt change at that point can be inferred (Miao et al., 2010).

In attention, lag-correlation analysis was used to examine the relation between SASM index and continental freshwater discharge of the Red River. To evaluate the influence of ENSO events on water discharge of Red River, correlation analysis was conducted between ENSO index and monthly mean discharge anomalies during the La Niña phase and El Niño phase, respectively.

3. Results

3.1. Periodicities of continental freshwater discharge

The results of Morlet wavelet analysis of monthly continental water discharge were shown in Fig. 2. Common spectral oscillated characteristics were detected at Son Tay station. It can be found that oscillations with about 4–6 months and 8–12 months in water discharge are at significant level of 0.1 (Fig. 2b-1, c-1). It means that continental water discharge in the Red River has seasonal flood and drought cycles. Meanwhile, the high values correspond to the historical floods in 1966, 1968, 1971, 1973, 1986, 1990, 1996 and 2008, and droughts in 1963, 1987, 1988, 1992, 2003, 2004 and 2006, respectively (Fig. 2b-1). The results derived here are consistent with previous study (Dang et al., 2010). Floods occurred frequently in the Red River before 1975, following by a low frequency since the late 1980s. Compared with flood events, the degree of droughts are insignificant, although there are some large negative values corresponded to drought even. The reconstructed normalized water discharge with filtered periods at 4–6 and 8–12 months was decomposed again by Morlet wavelet, it can be seen from Fig. 2 (b-2 and c-2) that there are relatively long-term periodic oscillations at

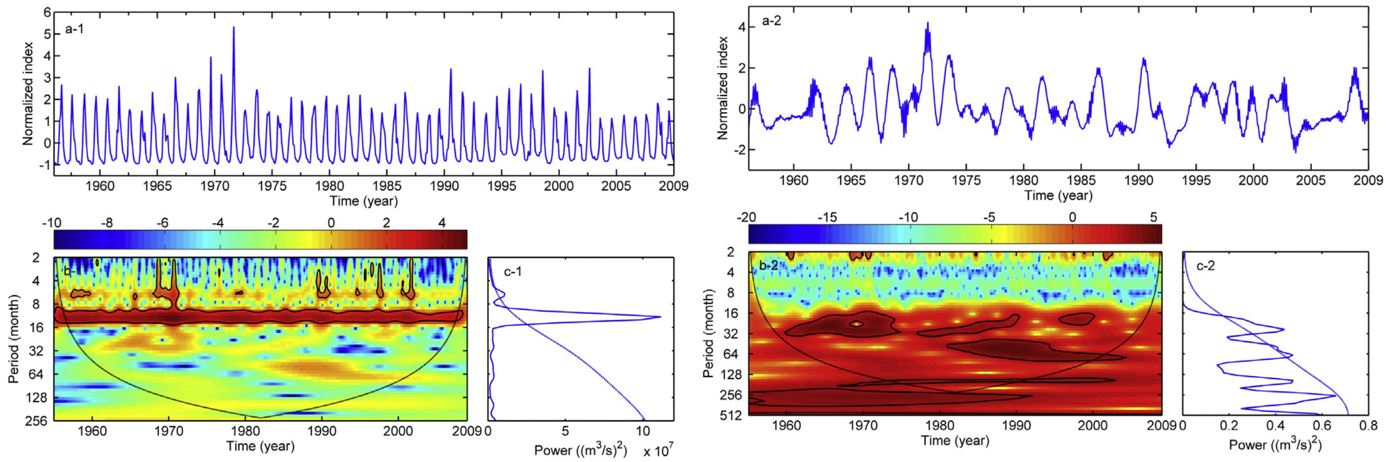

Fig. 2. Plots of wavelet power spectrum of water discharge time series at Son Tay station by Morlet wavelet: (a-1) The normalized time series of monthly discharge used for the wavelet analysis. (b-1) The wavelet local power spectrum of (a-1). (c-1) the global wavelet power spectrum of (a-1). (a-2) The normalized time series of monthly discharge filtrated short-term oscillations of4–20 months. (b-2) The wavelet local power spectrum of (a-2). (c-2) The global wavelet power spectrum of (a-1). In Fig. b-1 and b-2, The black contour encloses regions of greater than 90% confidence for a red-noise process as shown in b-1 and b-2. The end of the large curve indicates the "cone of influence". In Fig. c-1 and c-2, the dashed line indicate the red noise power spectrum.

the significant level of 0.1, with 18–32 months (1.5–2 years) and approximately 48–80 months (4–7 years) periodicities.

3.2. Trends of continental freshwater discharge

Linear regression analysis and Mann–Kendall test were applied to detect trends in the discharge series. The results of the two techniques were approximately similar.

Outputs of linear regression analysis for mean annual discharge, mean seasonal discharge, and maximum and minimum monthly discharge were shown in Fig. 3. It was observed that mean annual water discharge was dominated by decreasing trend, but failed to pass the significant level of 0.05 (Fig. 3a). Over the period of 1956–2009, the mean water discharge in wet season and maximum mean discharge present significant decreasing trend (Fig. 3b, d). On the other hand, significant increasing trends for mean discharge in dry season and minimum monthly discharge were detected (Fig. 3c, e).

The results of Mann–Kendall test for discharge and precipitation series are illustrated in Table 1. Significant increasing trend in dry season and decreasing trend in wet season were detected during the period 1956–2009. The ratios of maximum to minimum month discharge present remarkable reductions during the study periods of 1956–2009 and 1975–2006. However, no significant trends were detected in the precipitation during 1975–2006. Mann–Kendall test was applied to analysis the abrupt change in the annual discharge series (Fig. 4). The test identified curve junction in 1986, 1989, 1991 and 1993.

3.3. Extreme values of continental freshwater discharge

It is important to understand the changes in extreme events, because they are closely related to flood and drought events, and may cause serious damage to agriculture and energy sectors (Cruz et al., 2013). In this section, we address trend analysis of extreme water discharge, refers to 10th (a) and 90th (b) percentiles of annual daily discharge, and the number of annual extreme events (discharge below 10th and over 90th percentiles), variation coefficient of daily discharge and the ratio between annual maximum discharge and minimum discharge (Fig. 5).

It is indicated that the annual 10th and 90th percentiles present different trend over the period of 1956–2009: the annual 10th percentile showed increasing trends while the annual 90th percentile revealed opposite tendencies (Fig. 5 (a–b)). By investigating the number of annual extreme events, this study suggested that both extreme low and extreme high discharges present negative trends (Fig. 5 (c–d)). The analysis of variation coefficient and maximum discharge/minimum discharge ratio indicated significant decreasing trend at the significance level of 0.001 and 0.05, respectively (Fig. 6). Taken altogether, it can be concluded from those results that the deviation between extreme low and extreme high discharge was diminishing. This phenomenon can be described as 'no flood in the flood season, no drought in the drought season', which is similar to those occurred in the Changjiang River (Dai et al., 2008b).

3.4. Changes of SPM

Unlike the river discharge, annual SPM diacharge of Red River showed dramatic variations with a wide range of 24–201 (10^6 t/yr) and a mean value of 88.57 (10^6 t/yr) from 1960 to 2008 (Fig. 7). Linear fitting analysis showed that SPM discharge showed a remarkable reduction during the whole observed period of 1960–2008 (Fig. 7). Furtherly, it can be found that SPM had increased significantly during the period of 1960–1973 and rapidly decreased during 1990–2008 (Fig. 7).

4. Impacts on the continental freshwater discharge

4.1. Impacts of climate factors

The influence of climatic factors, including the precipitation, SASM and ENSO events on the Red River discharge will be discussed in this part.

The Relationship between basin precipitation and water discharge of the Red River was detected by linear regression analysis. Results showed that there is a strong positive correlation between the precipitation and discharge (Fig. 8), indicating that precipitation is the main replenishment of the river discharge. The high dependence of discharge on precipitation was similar with that of Mekong River (Xue et al., 2011). While no significant change

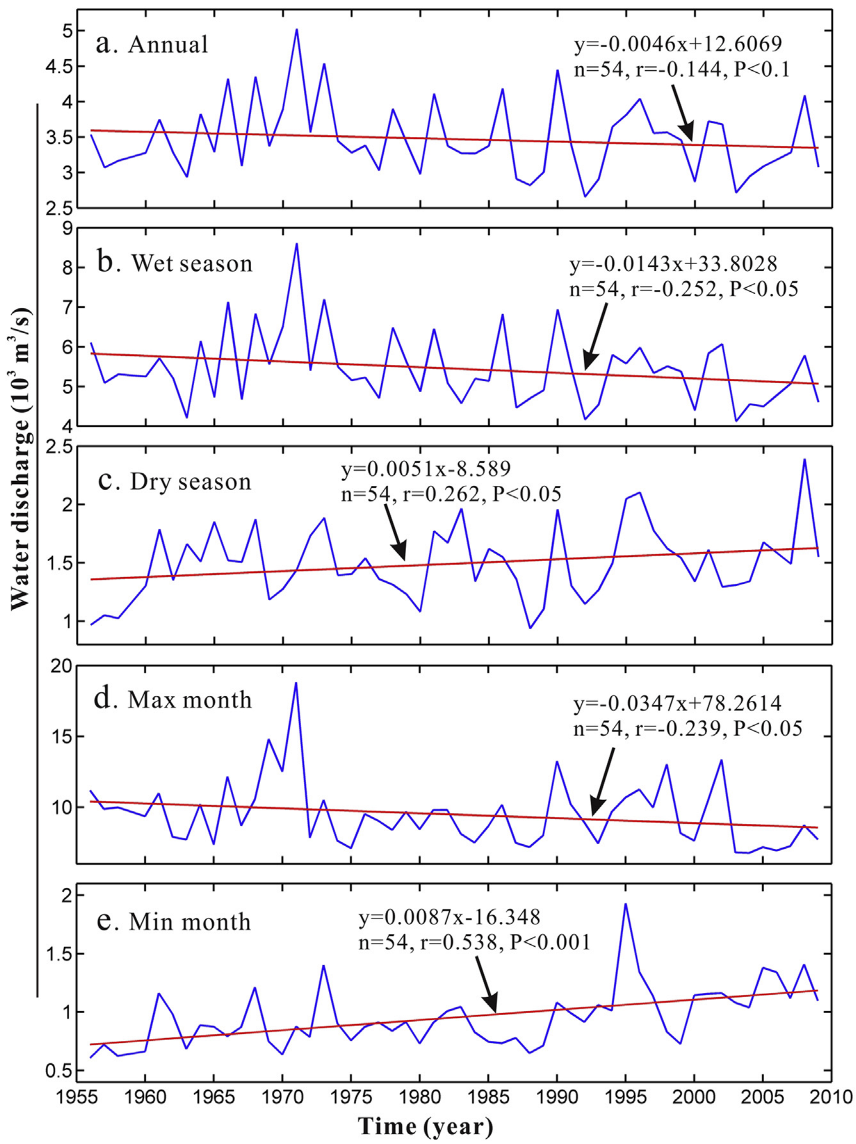

Fig. 3. Trends of water discharge at Son Tay station in Vietnam. (a) Trends of the annual mean discharge, (b) Trends of the mean discharge in wet season, (c) Trends of the mean discharge in dry season, (d) Trends of the maximum monthly average discharge and (e) Trends of the minimum monthly average discharge.

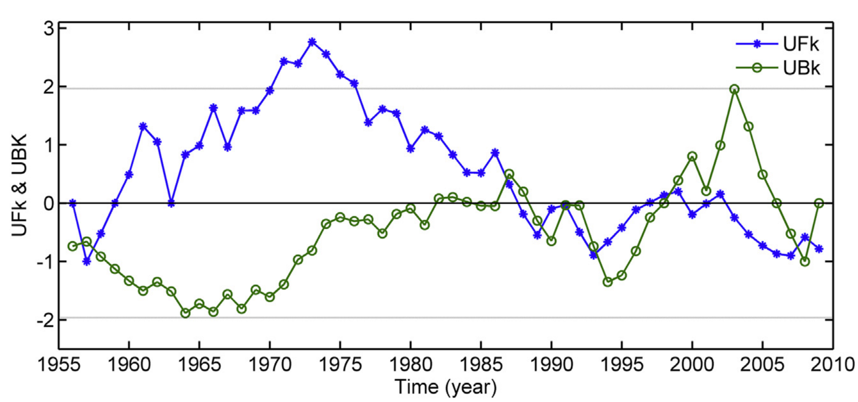

Fig. 4. The result of Mann–Kendall abrupt change analysis. UF_k is statistic calculated with progressive series and UB_k is calculated with retrograde series. The dotted lines are significance level threshold. The intersection point of the two series between two dotted lines indicates the time that abrupt change takes place.

Table 1
Results of Mann–Kendall trend tests of discharge and precipitation.

Statistics	Discharge		Precipitation
	1956–2009	1975–2006	1975–2006
Annual average	−1.54	−0.97	−0.71
Dry season	3.27	1.23	0.19
Wet season	−3.6	−1.62	−0.91
Extreme[a]	−8.22	−4.87	−1.04

[a] Extreme represents trend test results based on the ratios of maximum to minimum month value for the hydro-meteorological elements during the observed period.

was occurred in the precipitation during the period of 1975–2006, significant decrease was observed in the ratio of maximum and minimum month discharge (Table 1), indicating that changes of extreme water discharge may be not controlled by the variations of precipitation.

Meanwhile, lag-correlation analysis was used to examine the relation between SASM index and water discharge of the Red River. The lagged-correlation coefficient between SASM and daily discharge is 0.408 (lag time = 0), at the 0.001 significant level against the null hypothesis the true correlation is 1. Therefore, obvious coupling behavior is indicated between SASM index and daily water discharge (Fig. 9). This means SASM has a strong impact on the water discharge. Moreover, the lagged-correlation coefficients between SASM and daily water discharge increased gradually from −0.30 to the peak of 0.599 when the lagged day numbers is 23 (Table 2). And then the lagged correlation coefficients decreased gradually to 0.36 with lag time of 60 days (Fig. 9). It can be found that the lagged correlation coefficients rang of 0.586–0.580 is relatively stable with corresponding lagged time span of 13–29 (Fig. 9), indicating that variations of daily water discharge could have intensive responses to the SASM impacts with lagged time of 13–29 days. Similar study was conducted by Xue et al. (2011), who found that runoff lagged 20–35 days behind

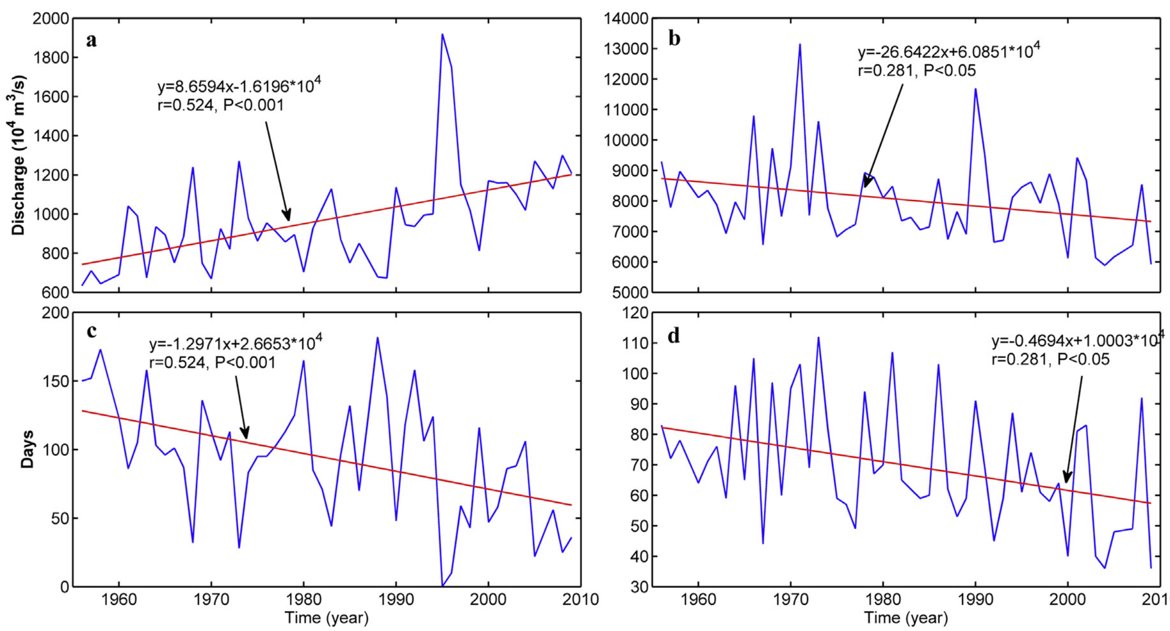

Fig. 5. Trends of extreme discharge from 1956 to 2009 for (a) The 10th percentile of daily discharge; (b) The 90th percentile of daily discharge; (c) Number of days with discharge less than the 10th percentile; (d) Number of days with discharge more than the 90th percentile.

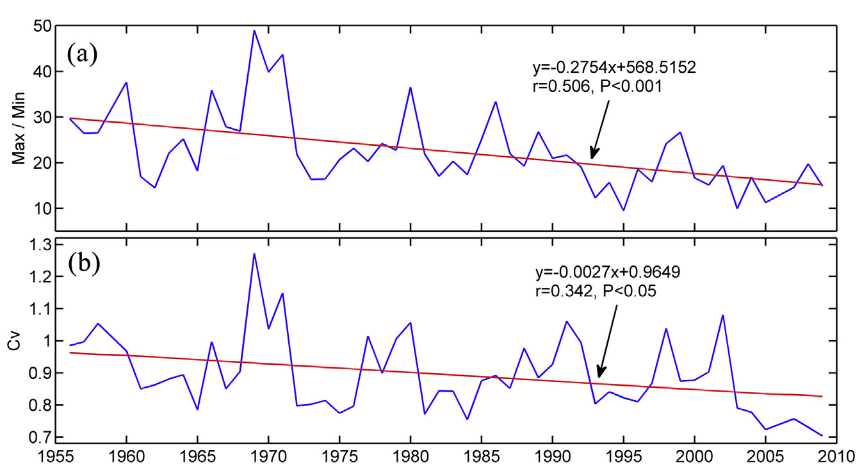

Fig. 6. Temporal change of ratio of maximum to minimum discharge (a) and Cv (b) of daily discharge during 1956–2009.

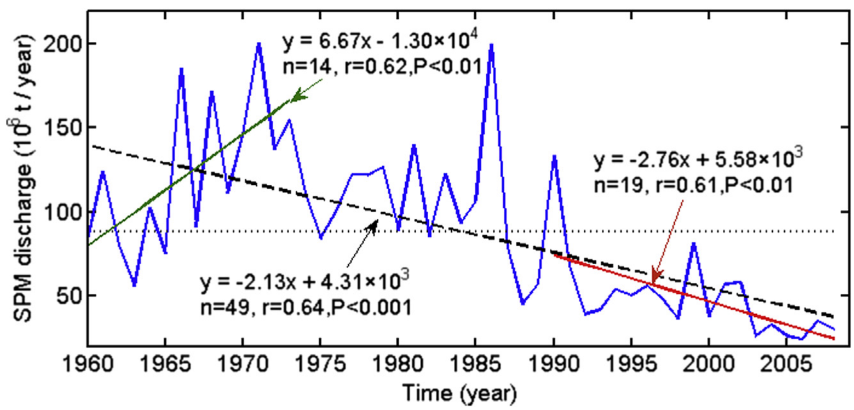

Fig. 7. Changes of SPM flux during 1960–2008.

precipitation in Mekong River Basin. In contrast to those of the Mekong River, continental freshwater discharge of Red River could be more sensitive to climatic impacts.

The ENSO related patterns affect extreme climate, as well as precipitation and discharge around the world (Kane, 1999; Kiem and Franks, 2001; Xue et al., 2011; Misir et al., 2013). As shown in Fig. 10, there are 13 warm events (El Niño) occurred in 1957, 1963, 1965, 1969, 1972, 1976, 1982, 1986, 1987, 1991, 1997, 2002 and 2009, respectively. In addition, there are 11 cold events (La Niña) in 1956, 1964, 1967, 1970, 1971, 1974, 1975, 1984, 1988, 1998 and 2007. Furtherly, monthly anomalies of El Niño and La Niña years were calculated with basis on the occurrence of all El Niño and La Niña events, respectively (Fig. 11). And then the correspondingly month water discharge anomalies during these El Niño and La Niña years were calculated (Fig. 11). There were significant positive relations between the La Niña index and discharge anomalies, while negative relationships were observed between the El Niño index and discharge anomalies (Fig. 11). As a consequent, El Niño events over the Red River basin may induce lower water discharge with possible droughts, and this phenomenon is in agreement with that of Yellow River and Changjiang River (Wang et al., 2006; Wei et al., 2014). La Niña events will cause higher water discharge with possible flood events, and this can be supported by studies on other Asia rivers, such as Changjiang River (Wei et al., 2014).

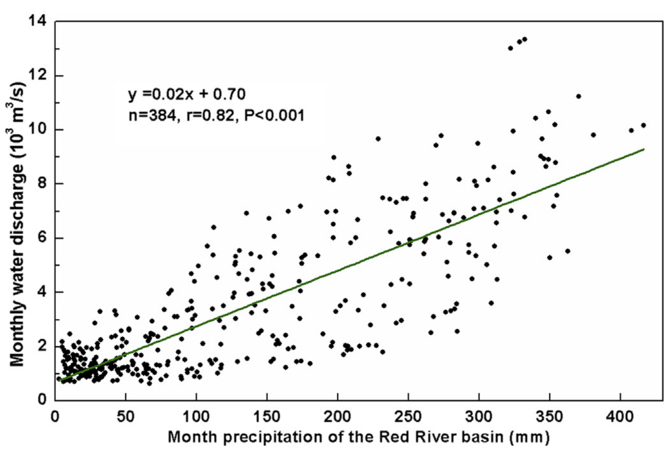

Fig. 8. Correlations of monthly precipitation with monthly continental water discharge of Red River Basin.

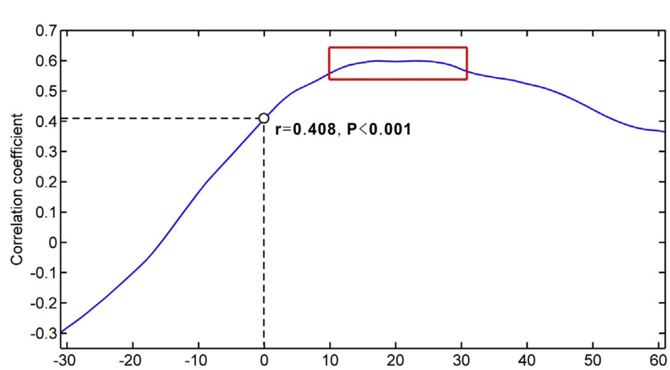

Fig. 9. The lagged correlation between discharge and southwest Asia summer monsoon index. Positive time value means discharge lag behind monsoon, whereas negative means discharge lead monsoon.

4.2. Impacts of anthropogenic activities

Besides climatic factors, anthropogenic activities such as dam construction and reservoir regulation may affect the natural behavior of rivers. Studies of Mekong River showed that dam construction on upper streams can produce a series of induced effects downstream, particularly in terms of water, sediment, channel and ecological changes (Lu and Siew, 2006). There are two large reservoirs in the Red River Basin, which may cause significant change to river SPM and continental freshwater discharge by cutting off the flood flow, especially the Hoa Binh dam (Vu et al., 2014). As shown in Fig. 7, SPM flux increased significant during the period of 1960–1973, which can be set as a reference period before the operation of Hoa Binh Reservoir. SPM flux had a remarkable reduction during 1990–2008 (the operation period of the Hoa Binh

Table 2
Correlation coefficients of lag analysis with different lag times.

Lag time (day)	Correlation coefficient	Lag time (day)	Correlation coefficient
10	0.558	21	0.597
11	0.569	22	0.599
12	0.578	23	0.599
13	0.586	24	0.599
14	0.590	25	0.597
15	0.594	26	0.596
16	0.597	27	0.592
17	0.599	27	0.588
18	0.599	29	0.580
19	0.597	30	0.571
20	0.597	31	0.564

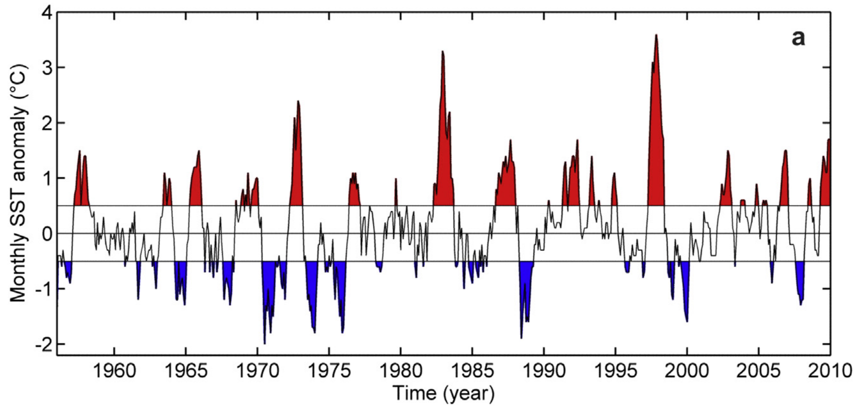

Fig. 10. Plot of ENSO events during 1956–2009.

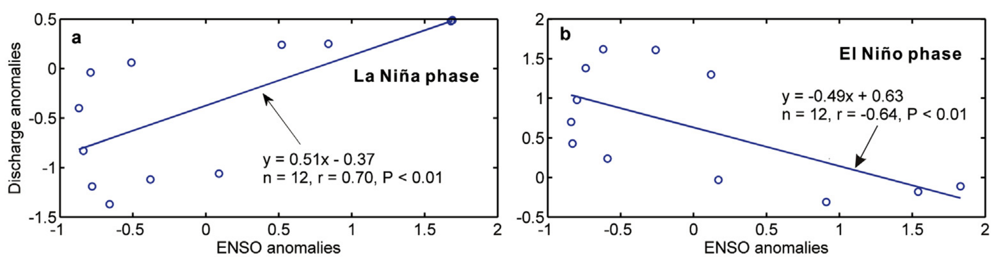

Fig. 11. Plot of monthly ENSO index and corresponding monthly discharge anomalies during El Niño and La Niño phases.

Reservoir). The trends of SPM flux demonstrate that Hoa Binh Reservoir plays an important role in SPM trapping, which is consistent with the previous studies (Dang et al., 2010; Vu et al., 2014). The changes of continental freshwater discharge and SPM of the Red River is similar with that of Pearl River in South China, which is due to the more dominant influence of anthropogentic activities (Zhang et al., 2008).

Meanwhile, abrupt changes of water discharge series were detected in 1986, 1989, 1991 and 1993 (Fig. 4). The occurrence of frequent abrupt change could be likely explained by the construction of Hoa Binh dam from 1979 to 1994. This is comparable with those of the Changjiang River (Dai et al., 2012; Dai and Liu, 2013).

Furtherly, the daily water discharge during the pre- and post-dam period were grouped respectively to evaluate the influence of the Hoa Binh Reservoir (Fig. 12). Compared to the pre-dam period (1956–1978), water discharge in the post-dam period (1990–2009) has been regulated, with discharge increasing in Jan–May (mainly in the dry season) and decreasing in Jun–Dec (mainly in the wet season) (Fig. 12a), which is comparable with the results of MIKE11 numerical model (Vu et al., 2014). The dam regulation mainly increased the occurrence probability of discharge interval of 1–4 (10^3 m^3/s) (Fig. 12b). On the other hand, regulation decreased the occurrence probability of extreme low and extreme high discharge, the influence of dam on the discharge interval of 4–6 (10^3 m^3/s) is unremarkable (Fig. 12b). These changes are coincided with that of maximum/minimum and the 10th/90th as mentioned in former section. Thereafter, it can be concluded that the abnormal hydrological behavior of the Red River were caused by dam adjustments.

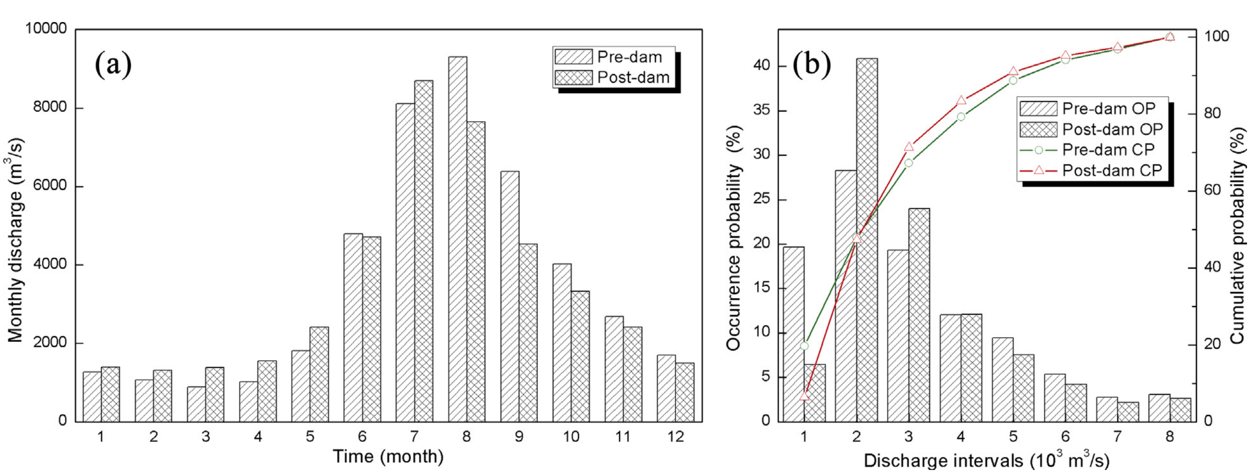

Fig. 12. Influence of Hoa Binh Reservoir construction on the Red River continental water discharge. (a) Comparison of grouped discharge between pre-dam and post-dam period; (b) Occurrence probability changes of different discharge intervals during the pre-dam and post-dam period.

When compared to those rivers with extreme frequently flood and drought in the tropical zone (IPCC, 2007), the Red River continental freshwater discharge exhibited trends of decreasing yearly maximum discharge, increasing yearly minimum discharge, and decreasing deviation degree of Cv (Fig. 6). Due to dam operations, most of the larger rivers around the world had been regulated (Nilsson et al., 2005). It is firstly found in this paper that the daily continental freshwater discharge had been regulated as 'no flood in the flood season, no drought in the drought season', while the previous studies only indicated continental freshwater discharge decrease following dam operations (Milliman and Farnsworth, 2011).

With the rapid development of Vietnam, the requirement of energy and water may lead to the construction of more large dams in large rivers (Ranzi et al., 2012). For instance, the new Tuyen Quang Reservoir in the Lo River started to operation in 2005 (Ranzi et al., 2012). As a consequent, the continental freshwater discharge will suffer intensive change in future. It can be expected that the continental freshwater discharge in the Red River to the sea might be regulated with more water in the drought period and less water in the flood period.

5. Conclusions

The continental freshwater discharge from the Red River to the sea had experienced serious challenges from climate change and intensive anthropogenic activities. This paper studied the periodicities, secular trends, and extreme hydrological events of the runoff from Red River into the Tonkin Gulf based on the daily continental freshwater discharge. Conclusions can be summarized as follows:

(1) The continental freshwater discharge series of the Red River suggested four major periodicities: 4–6 months for seasonal change, 8–12 months for approximately annual cycle, 1.5–2 years (18–32 months) and 4–7 years (48–80 months) for inter-annual fluctuation cycles.
(2) Although there is clearly decrease in the mean annual SPM during 1960–2008, the mean annual discharge shows insignificant trends over the period of 1956–2009. However, discharge in wet season and the maximum monthly discharge suggested observable downward trend, while the minimum monthly discharge and discharge in dry season are increasing. Moreover, the extreme events demonstrate different tendency characters: extreme high daily discharge show decreasing trend, whereas the extreme low discharge indicate increasing trend. This phenomenon can be described as 'no flood in the flood season, no drought in the drought season'.
(3) Continental freshwater discharge from the Red River was mainly affected by the precipitation, SASM and ENSO. Variations in daily continental freshwater discharge had a delayed response to SASM, with 13–29 days. Moreover, La Niña events are likely to cause floods while the El Niño events are likely to lead to drought events.
(4) Dam constructions with water regulation along the Red River since 1970s had significant influence to the continental freshwater discharge, as well as the SPM flux.

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