Periodicity of sediment load and runoff in the Yangtze River basin and possible impacts of climatic changes and human activities

QIANG ZHANG1,2,3 GUIYA CHEN4, BUDA SU2, MARCUS DISSE5, TONG JIANG1,2 & CHONG-YU XU6

1 Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China
2 Key Laboratory of Climate Change Research, China Meteorological Administration, Beijing 100081, China
3 Department of Geography and Resource Management and Institute of Space and Earth Information Science, The Chinese University of Hong Kong, Shatin, NT, Hong Kong, China
4 Changjiang Water Resources Commission (CWRC), Ministry of Water Resources, Wuhan 430000, China
5 Universität der Bundeswehr München, Institut für Wasserwesen, Lehrstuhl für Wasserrirtschaft und Ressourcenschutz, Werner-Heisenberg-Weg 39, D-85577 Neubiberg, Germany
6 Department of Geosciences, University of Oslo, PO Box 1047 Blindern, N-0316 Oslo, Norway

Abstract Periodicity of the runoff and the sediment load, and possible impacts from human activities and climatic changes, in the Yangtze River basin during 1963–2004 are discussed based on the monthly sediment and runoff data, and using the wavelet approach. Research results indicated that: (a) Sediment load changes are severely impacted by the different types of human activity (e.g. construction of water reservoirs, deforestation/afforestation); and the runoff variability is the direct result of climatic changes, e.g. the precipitation changes. (b) The impacts of human activity and climatic changes on the sediment load and runoff changes are greater in smaller river basins (e.g. the Jialingjiang River basin) than in larger river basins. The response of sediment load and runoff changes to the impacts of human activities and climatic changes are prompt and prominent in the Jialingjiang River basin relative to those in the mainstem of the Yangtze River basin. (c) Construction of the Three Gorges Dam has already had obvious impacts on the sediment transport process in the middle and lower Yangtze River basin, but shows no obvious influence on the runoff changes. Construction of the Three Gorges Dam will result in further re-adjustment of the scouring/filling process within the river channel in the middle and lower Yangtze River basin, and have corresponding effects on the altered sediment load because of the Dam’s operation for the river channel, ecology, sustainable social economy and even the development of the Yangtze Delta. This will be of concern to local governments and policy makers.

Key words sediment load; runoff changes; wavelet approach; Yangtze River basin

Périodicité de la charge sédimentaire et de l’écoulement dans le bassin du Fleuve Yangtze et impacts possibles des changements climatiques et des activités humaines

Résumé La périodicité de l’écoulement et de la charge sédimentaire, ainsi que les impacts possibles des activités humaines et des changements climatiques, dans le bassin du Fleuve Yangtze durant la période 1963–2004, sont discutés sur la base de données mensuelles d’écoulement et de sédiments, et à l’aide d’une approche par ondelettes. Les résultats de la recherche indiquent que: (a) Les changements de charge sédimentaire sont sévèrement influencés par les différents types d’activité humaine (e.g. la construction de barrages, la déforestation/afforestation); et la variabilité de l’écoulement est le résultat direct de changements climatiques, e.g. les changements dans les précipitations. (b) Les impacts de l’activité humaine et des changements climatiques sur la charge sédimentaire et sur les changements d’écoulement sont plus importants dans les plus petits bassins versants (e.g. le bassin de la Riviére Jialingjiang) que dans les plus grands. La réponse de la charge sédimentaire et des changements d’écoulement aux impacts des activités humaines et des changements climatiques sont rapides et dominants dans le bassin de la Riviére Jialingjiang, par comparaison avec ce qu’on observe dans le cours principal du Fleuve Yangtze. (c) La construction du Barrage des Trois Gorges a déjà eu des impacts évidents sur le processus de transport sédimentaire dans la partie centrale et inférieure du bassin du Fleuve Yangtze, mais ne montre pas d’influence nette sur les changements d’écoulement. La construction du Barrage des Trois Gorges va conduire à un réajustement supplémentaire du processus d’érosion/sédimentation dans le lit du cours d’eau, dans la partie centrale et inférieure du Fleuve Yangtze; et avoir, en raison de la gestion du barrage des effets sur la charge en sédiments altérés et sur le cours d’eau, l’écologie, l’économie sociale durable et même le développement du Delta du Yangtze. Cela va concerner les gouvernements et les décideurs locaux.

Mots clés charge sédimentaire; changements d’écoulement; approche par ondelettes; bassin du Fleuve Yangtze
INTRODUCTION

Human activities (e.g. land-use changes, dam construction) and climatic changes in a fluvial system can result in alterations to the sediment load and runoff variability, which are complicated dynamic processes (Schumm, 1977; Leopold et al., 1964; Crooks & Davies, 2001; Xu, 2002). Runoff and sediment loads exert significant influences on the fluvial morphology through time and space, supporting the fluvial ecosystems along the adjoining fluvial surfaces (Gupta et al., 1999; Chen et al., 2001). Modification of the river channel appears to be initiated by the increase or decrease in either the water or the sediment load. Kondolf et al. (2002) contrasted changes in the land use, bed load and channel response of the Pine Creek basin (200 km²) of Idaho, USA and the Drôme basin (1640 km²), France, showing that in the former, hard-rock mining near the end of the 19th century, road construction, etc., resulted in an increased bed load, which in turn led to the channel instability.

Construction of the Three Gorges Dam and its possible impacts on the runoff and sediment loads in the middle and lower Yangtze River basin have attracted concern (e.g. CAS, 1988; Williams, 1993). The Yangtze River (Changjiang) originates on the Qinghai-Tibet Plateau and flows about 6300 km eastwards to the East China Sea; it is the longest river in China and the third longest river in the world. As it is a large river, the runoff and sediment load changes of the Yangtze River basin have attracted considerable attention (e.g. Xu, 1996; Lu et al., 2003; Zhang et al., 2006). Zhang & Wen (2004), after analysing the sediment flux and annual runoff of the upper Yangtze River, indicated that the sediment load of the upper Yangtze River has no visible changing trend; this may be due to sediment load changes in the two biggest tributaries: Jinsha and Jialingjiang rivers. Yang et al. (2002) analysed suspended sediment concentration (SSC) at two hydrological stations (Datong and Yichang stations) for the period 1951–2000 to determine sediment supply to the delta and discussed the possible human influences on the sediment variations.

Evidently, there has been much research on sediment loads and runoff changes in the Yangtze River basin, which is very useful for developing further understanding of the temporal and spatial changes in sediment loads and runoff in the region. However, it should be noted that: (a) the length of the hydrological series has not been updated (e.g. Chen et al., 2001) and so it is difficult to elucidate the recent changes in sediment loads and runoff, and possible human impacts (e.g. construction of the Three Gorges Dam); and (b) conventional statistical methods (e.g. correlation analysis), or simply the original series, are demonstrated to show changing patterns of runoff and sediment loads, but do a relatively poor job in evaluating changes within the cyclic phenomena, which are limited by the time frame selection and characterize cyclic phenomena by mean and variance of each time interval (White et al., 2005). In this paper, we apply the wavelet approach to detect possible impacts of climatic changes and human activities on changes in runoff and sediment loads.

Here, the monthly suspended sediment load and runoff data of Pingshan, Yichang, Hankou and Datong stations located on the mainstem of the Yangtze River, and Beipei station on the Jialingjiang River, were analysed. The Jialingjiang is the main tributary of the Yangtze, and acts as one of the main sources of sediment load (Fig. 1). The objectives are: (a) to detect the changes in the periodicity of the runoff and sediment load of the Yangtze River basin over time; and (b) to explore and discuss the possible influences of human activities and climatic changes on the runoff and sediment load in the Yangtze River basin.

DATA AND METHODOLOGY

The monthly runoff and suspended sediment load data of the four mainstem stations (Pingshan, Yichang, Hankou and Datong) and of Beipei station on the Jialingjiang River for 1963–2004 were analysed; these data were provided by the Changjiang Water Resources Commission, China (CWRC). The sediment load in this study refers to suspended sediment only. The location,
Fig. 1 Location of the study region and hydrological gauging stations.

Table 1 Detailed hydrological record of stations along the tributary and mainstream of the Yangtze River.

<table>
<thead>
<tr>
<th>Station name</th>
<th>Drainage area (km²)</th>
<th>Time interval: Runoff</th>
<th>Sediment load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stations along the mainstem of the Yangtze River:</td>
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<tr>
<td>Stations along the tributary of the Yangtze River:</td>
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</tbody>
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drainage areas and lengths of the series are displayed in Fig. 1 and Table 1. The homogeneity and reliability of the data were firmly controlled by the CWRC before the data were released. The series used in this study show good consistency with no missing data. The lengths of the series are various and, for consistency in the series length, a time interval of 1963–2004 is accepted.

The continuous wavelet transform (CWT) technique (Farge, 1992; Torrence & Compo, 1998; Grinsted et al., 2004), as a tool for analysing localized variations of power within a time series, is applied in the current study. The wavelet transform has also been applied successfully to analyse the hydrological effects of the construction and operation of the Grand Canyon Dam on the Colorado River in (White et al., 2005). More recently, the authors have applied this method in the
study of annual maximum streamflow series of the Yangtze River basin (Zhang et al., 2007). In the current study, before the technique was applied, we tested the normality of the hydrological series by using the Kolmogorov-Smirnov test (Xu, 2001). Through CWT analysis, we decomposed the hydrological series into time–frequency space to determine both the dominant modes of variability and how those modes vary in time (Torrence & Compo, 1998). The concept and procedure of the wavelet method are thoroughly explained and discussed by Torrence & Compo (1998), who have provided wavelet software at: http://paos.colorado.edu/research/wavelets/.

RESULTS

Sediment load and runoff changes in the mainstream of the Yangtze River

The Yangtze River basin is climatically characterized by the subtropical monsoon; precipitation events mainly occur in summer and there is less precipitation in winter (Zhang et al., 2005). The wavelet power spectra of the monthly runoff changes of the stations on the mainstream of the Yangtze (upper panels of Fig. 2(a)–(d)) demonstrate the pronounced annual and sub-annual cycles of the runoff changes. The upper panels of Fig. 2 clearly show that the prominent 1-year band dominates the whole monthly runoff series along the mainstream of the Yangtze River. The inter-annual variance changes in the runoff series are significant at >95% confidence level. Furthermore, significant 0.5- and 0.25-year bands are sparsely distributed along the whole runoff series. What is interesting is that the shorter periods can be identified in the runoff series when serious flood events occurred. The 1998 flood extended over the whole Yangtze basin but the 1983 flood can be identified using the wavelet transform method featured by appearance of the shorter periods.

As for the wavelet power spectrum of the monthly sediment load (lower panels of Fig. 2(a)–(d)), different changing patterns can be identified compared to the corresponding upper panels. The local wavelet power is relatively broadly and uniformly distributed in the 0.25- to 1-year band, but the 1-year band was prevalent, which illustrates the obvious influences of streamflow on transportation of the sediment load. Walling & Moorehead (1987) and Walling & Webb (1992) found that, at local scales, the relationship between suspended sediment load and water discharge is complicated and can be generalized as different patterns. Furthermore, more areas featured by the significant wavelet power are identified in the 0.25- to 0.5-year bands, showing possible impacts from flash climatic events (e.g. rainstorm events) on the sediment load (Kirkby, 1978; Yu et al., 1997). The lower panels of Fig. 2 show that larger areas dominated by the significant wavelet power spectrum are identified in the 0.25- to 1-year band in the time intervals near to 1980, 1981 and 1998, when serious flood events occurred in the Yangtze basin, indicating the significant influence of flood events on the sediment transportation. After about 2002, the annual cycle of the sediment load series was removed. However, the removal of the annual cycle of the sediment load series at Pingshan station was relatively slow. The time when the removal of the annual cycle of sediment load series of Yichang (Fig. 2(b)), Hankou (Fig. 2(c)) and Datong (Fig. 2(d)) stations occurred is in good agreement with the functioning of the Three Gorges Dam, where water storage commenced at the end of 2002, and reflects the impacts on sediment transportation. It should be noted that the Gezhouba Dam (construction of which started in 1970 and operation in the 1980s, with a total storage of $1.58 \times 10^9$ m$^3$) had little influence on the runoff changes (Chen & Huang, 1991), but it had a major effect on sediment load transport (Chen & Huang, 1991). However, the lower panel of Fig. 2(b) shows that the influence of the Gezhouba Dam on suspended sediment transport was not enough to completely remove the annual cycle of the sediment load series. The removal of the annual cycle of the sediment series at Pingshan station may partly be the result of the decreasing precipitation in the upper Yangtze River basin. Furthermore, up to the end of the 1980s, 1880 water reservoirs were constructed in the Jinshajiang River basin with a total storage of $2.813 \times 10^9$ m$^3$ (Xu, 2005), which may in part be responsible for the removal of the annual cycle of the sediment load series at Pingshan.
Fig. 2 Continuous wavelet power spectrum for the normalized time series of monthly runoff (upper panel) and monthly sediment loads (lower panel) of (a) Pingshan station; (b) Yichang station; (c) Hankou station; and (d) Datong station. The thick black contour designates the 95% confidence level against red noise, and the cone of influence (COI), where edge effects might distort the picture, is shown as a U-shaped line.
Sediment load and runoff changes in the tributary of the Yangtze River

The wavelet spectrum is broadly and uniformly distributed in the 0.25- to 1-year band for the runoff series (upper panel, Fig. 3) and sediment load series (lower panel, Fig. 3) of Beipei station. The upper Jialingjiang River basin is dominated by the decreasing precipitation trend (Zhang et al., 2005), which is demonstrated by gradual removal of the annual cycle and other cyclic components (e.g. 0.5-year cycle) of the runoff series. The decreasing precipitation in the upper Jialingjiang River was enough to remove the annual cycle of the runoff series at Beipei station after about 1995. Up to the end of the 1980s, 11,931 water reservoirs were constructed in the Yangtze River basin, with a total storage of $2.05 \times 10^{10}$ m$^3$, of which 4,542 reservoirs were on the Jialingjiang River with a total storage of $3.61 \times 10^9$ m$^3$ (Xu, 2005). To a large extent, the reservoirs retained much sediment, resulting in abrupt removal of the annual cycle of the sediment load series of Beipei station (lower panel, Fig 3). Figure 3 indicates four periods with different periodicity characteristics of the sediment load: 1965–1970, 1970–1977, 1977–1985, and 1985–2004. According to research by Xu (2000), large-scale and intensive deforestation during 1958–1968 led to serious soil erosion and high sediment loads in the river channel. Between 1969 and 1979, many reservoirs were built and started to function; they retained much of the sediment load, so greatly decreasing the sediment load of the river downstream of the reservoirs. The sediment load in the river channel began increasing after 1978 because of deforestation-induced soil erosion. This is the direct result of the flexible (not fixed) ownership of the forest which enabled large-scale deforestation (Xu, 2000). After 1985, however, extensive forestation and construction of water reservoirs in the Jialingjiang River basin, together with a significant decrease in precipitation (Zhang et al., 2005), resulted in a considerably reduced sediment load in the river, and these are the key factors responsible for the removal of the annual cycle of the sediment load series at Beipei station after about 1985. It should be noted that the areas that feature a significant annual cycle for the runoff series were not yet persistent, especially after about 1995. This is mainly because of significantly decreased precipitation in the upper Jialingjiang River basin (Zhang et al., 2005). Impacts of the 1998 flood events on the runoff and sediment load are also identified by the significant wavelet power in the 0.25- to 0.5-year band in 1998 (Fig. 3). Figure 3 also indicates that the reservoirs may have exerted more influence on sediment loads than on runoff variations.

![Continuous wavelet power spectrum for the normalized time series of monthly runoff (upper panel) and monthly sediment loads (lower panel) of Beipei station. The thick black contour designates the 95% confidence level against red noise, and the cone of influence (COI), where edge effects might distort the picture, is shown as a U-shaped line.](image-url)
CONCLUSIONS AND DISCUSSION

The sediment load and runoff are the key components of the fluvial system. The changes in the sediment load and runoff from the upper Yangtze River basin are the main causes of flood hazards in the middle and lower Yangtze River basin (Li et al., 2002; Zhang et al., 2006). Changes in the sediment load and runoff have considerable influences on the fluvial ecological system. The negative influences of the decreasing sediment load on the development of the Yangtze Delta have already caused concern (Yang et al., 2003). The variability of the sediment load and the runoff of the Yangtze River basin are analysed using the continuous wavelet approach. Interesting results were obtained as follows:

1. The factors influencing the sediment load and runoff changes, e.g. precipitation, land-use changes and construction of reservoirs, are various and are different in different parts of the Yangtze River basin. The reservoirs had more influence on the sediment transport process than on the runoff changes (Xu, 2000). This is clearly shown by the wavelet analysis of the sediment load and the runoff series along the mainstem of the Yangtze River. The Gezhouba Dam has not influenced the runoff processes, but has had considerable effect on the sediment transport process. However, this is not great enough to impact the annual cycle of the sediment load series at Yichang station. The annual cycle of the sediment series in the Jialingjiang River was removed after the construction and operation of reservoirs, but the annual cycle of the runoff series was not affected, demonstrating the greater influence of water reservoirs on sediment transport than on the runoff processes.

2. Sediment generation is directly influenced by different types of human activity. In the Jialingjiang River basin, the land exploitation was extensive due to socio-economic development, and led to a serious degradation of vegetation coverage. The succeeding 10-year cultural revolution maintained this vegetation deterioration (Xu, 2000). The significant wavelet power spectrum during 1963–1970 illustrates these influences. Water reservoirs exerted their tremendous influences on sediment transport after 1968, as elucidated by the removal of the annual cycle after 1968 (Fig. 3). Large-scale deforestation started after 1978, and the annual cycle appears again. Large-scale water and soil conservation commenced after the 1980s and the vegetation of about 230,000 km² recovered, which greatly decreased the sediment generation (Zhang & Wen, 2004). The removal of the annual cycle after the 1980s in the lower panel of Fig. 3 illustrates this phenomenon. Decreased precipitation after about 1980 influenced the persistence of the annual cycle of the runoff series of Beipei station and finally removed the annual cycle after about 1995.

3. The basin area can alter the influence of human activities (construction of reservoirs, land-use changes) and climatic changes (particularly precipitation changes) on the sediment load and runoff. These influences are less prominent in the larger basins than in the smaller ones. The 0.25- to 0.5-year band is more pronounced in the sediment and runoff series of Beipei station than in those of the other stations along the mainstem of the Yangtze River. The construction of reservoirs in the tributaries has had a significant influence on sediment transport in the Jialingjiang River. The effects of the Gezhouba Dam on sediment transport are not great enough to remove the annual cycle. Furthermore, the thousands of reservoirs in the tributaries of the Yangtze River do not show obvious impacts on sediment transport and runoff processes within the mainstem of the river. The impact of river basin size is closely related to the degree of human activities and climatic changes.

4. We can tentatively conclude that the runoff in the Yangtze River is mainly influenced by climatic changes (especially precipitation changes). The removal of the annual cycle in the runoff series at Beipei station post-1995 may be the direct result of the significant decrease in precipitation in the Jialingjiang River basin in recent years. The annual cycle of the sediment and runoff series is seriously impacted by human activities and climatic changes in the Jialingjiang River basin. The annual cycle in the sediment series was removed after the construction of the dam; however, the annual cycle of the runoff series was not impacted by
the dam construction. Wavelet analysis results clearly demonstrate the tremendous influence of the Three Gorges Dam on sediment transport in the middle and lower Yangtze River basin. Dai et al. (2005) indicate that the Three Gorges Dam retains considerable amounts of sediments; the sediment retained during June–December 2003 amounted to $1.24 \times 10^8$ t. The Three Gorges Dam does not show obvious influences on the runoff process so far, the annual cycle being apparent throughout the study period. However, the Three Gorges Dam has already exerted tremendous influence on sediment transport processes, which will alter the spatial and temporal distribution of the scouring and filling processes within the river channel. This should concern local governments and policy makers.

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