



Dramatic variations in water discharge and sediment load from Nanliu River (China) to the Beibu Gulf during 1960s–2013



Shushi Li ^{a, b}, Zhijun Dai ^{a, *}, Xuefei Mei ^a, Hu Huang ^{b, *}, Wen Wei ^a, Jinjuan Gao ^a

^a State Key Lab of Estuarine & Coastal Research, East China Normal University, Shanghai 200062, China

^b School of Resources and Environment of Qinzhou University, Qinzhou 535099, China

ARTICLE INFO

Article history:

Available online 1 April 2016

Keywords:

Water discharge
Sediment load
Anthropogenic activities
Nanliu River

ABSTRACT

River discharge and sediment variation is vital to material transport between river and sea, which is the focus of research on river–sea interaction. This study takes Nanliu River, a typical independent river into the sea in Beibu Gulf as an example, analyzing river regimen and river bed morphology variations during 1960s–2013 in response to climate change and human activities based on wavelet analysis and Man–Kendall test methods. The results indicate that river discharge and sediment in Nanliu River have significant seasonal characters with over 70% and 90% river discharge and sediment occur in summer half year. Compared with 1960s–1980s, the time of peaked monthly river water discharge and Suspended Sediment Concentration (SSC) during 1990s–2000s had shifted from June/August to July and from April to July, respectively. Meanwhile, both river flow and SSC present 4–6 years and 11 years fluctuations. In the recent 50 years, annual river discharge and SSC present downward trends with discharge decreased by 13.9% and 22.28% respectively in upstream and downstream while SSC decreased by 33.72% and 49.05% in upstream and downstream, respectively. Rating-curve between flow and SSC turns from clockwise rotation with enveloped area during 1965–1989 to a relatively narrow appearance during 1990–2012 in upstream, but indicates relatively mild variation in downstream. Evolution of river bed morphology is characterized by “erosion in flood season and deposition in dry season”. Moreover, the river flow entering the sea is dominated by precipitation while the sediment entering to the sea is controlled by middle and lower reaches supply. Human activities, including soil erosion, forest conservation and hydraulic engineering along the river, are responsible for the decrease of river water and sediment discharge entering the sea.

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1. Introduction

Transport of water discharge and sediment load from river to sea plays a key role in earth surface processes, which could induce dramatic geomorphological evolution in the river, estuarine delta and continental environment (Syvitski et al., 2005; Zhang et al., 2008; Milliman and Farnsworth, 2011; Dai and Liu, 2013). Variations in river water discharge and sediment load have profound impacts on catchment and estuarine delta developments, population and economic growth since the industrial revolution in the 18th century (Syvitski et al., 2005, 2009). However, most large river

basins and estuarine deltas around the world are under growing risks of water resources shortage, riverbed undercutting, coastal retreat and infrastructure loss due to impacts of intensive human activities on river water discharge and sediment load (Petit et al., 1996; Meybeck et al., 2003; Milliman and Farnsworth, 2011). Thereafter, there is increasing concerns on inter-annual variability and long-term changes in water discharge and sediment load from river to ocean worldwide (Walling and Fang, 2003; Oki and Kanae, 2006; Dai et al., 2008).

In the past decades, some studies indicated that water discharge and sediment load in most large rivers around the world had been seriously regulated by anthropogenic activities, such as irrigation, diversions and dam operations (Nilsson et al., 2005; Syvitski et al., 2005). In the Colorado River, the declining river discharge and sediment load induced delta recession with flow transformation from an estuarine setting to a hypersaline

* Corresponding authors.

E-mail addresses: zjdai@sklec.ecnu.edu.cn (Z. Dai), mrhuanghu@126.com (H. Huang).

and inverse-estuarine environment (Kowalewski et al., 2000; Carriquiry et al., 2001; Mujumdar, 2013). Because of human interference, diversion of water and sediment load in the Mississippi River has caused substantial wetland loss in the delta (Rosen and Xu, 2013). It is reported that the Colorado River lost almost 100% of its sediment load since 1941, while the Danube lost 35% of its sediment load compared to the last century (Milliman and Farnsworth, 2011). The Yellow River (Huanghe) in China had world's largest sediment load in the nineteenth century, which had sharply decreased to less than 100×10^6 t/yr with water discharge regulation due to dam construction (Yang et al., 2004). Meanwhile, due to operation of the world's largest dam, Three Gorges Dam, sediment decreased by about 70% in the Changjiang with water discharge represented as 'no flood in the flood season, no drought in the drought season' (Dai et al., 2008, 2014; Yang et al., 2014; Mei et al., 2015a,b). Similar results due to dam regulation can be also found in the Red River (Dang et al., 2010; Gao et al., 2015), Ebro River (Batalla, 2003; Batalla et al., 2004), Mekong River (Lu and Siew, 2006), and Nile River (Aleem, 1972). Further, researchers tried to detect all the possible impact factors on water discharge and sediment load variations. Yang et al. (2015) highlighted that 60%–70% of water discharge decline in Changjiang River over 1950–2012 can be attributed to decreased precipitation while TGD explained approximately 65% of sediment decline over the same period.

Wang et al. (2015) found that landscape engineering, terracing and check dams construction were the primary factors resulted in sediment load reduction over Yellow River from 1970s to 1990s while large scale vegetation restoration projects reduced soil erosion to some extent since 1990s. Mei et al. (2015a,b) quantified the average contributions of precipitation variation, human activities in the Poyang Lake catchment and TGD regulation to the Poyang Lake recession as 39.1%, 4.6% and 56.3%, respectively. It is worth noting that impacts of human activities on river regime can be overruled by episodic extreme climates. Dai et al. (2012) quantified that the contribution of the extreme climate (drought) on discharge and SSD reduction over Yangtze River in 2006 were as high as 95% and 82% of the total, respectively. While there are extensive studies on changes in water discharge and sediment load in large rivers over American, Europe, and Asian, little concern has been given to the inter-annual and long-term river hydrological variations of small rivers, such as Beibu Gulf in China.

The Nanliu River, located in the northern part of Beibu Gulf, is the largest river in the southwest China (Fig. 1). The total area of the river basin is 9700 km² with a length of 287 km. The Nanliu River is controlled by the distinct monsoon climate with rainy season from May to October and dry season from November to April. The mean annual rainfall in the Nanliu River catchment is between 1400 and 1760 mm with average temperatures ranging from 21.5 °C to

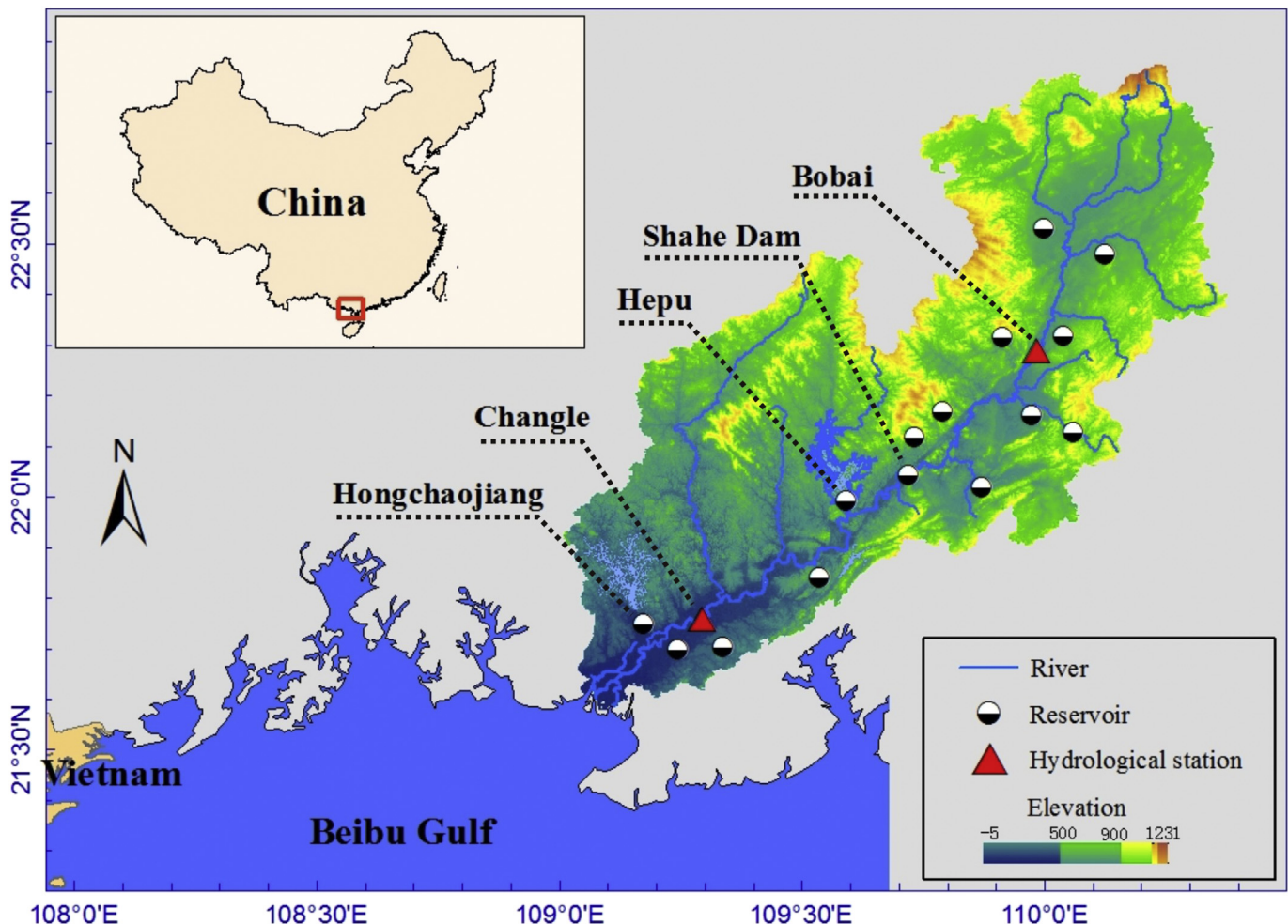


Fig. 1. Location of Nanliu River with hydrological stations and reservoirs.

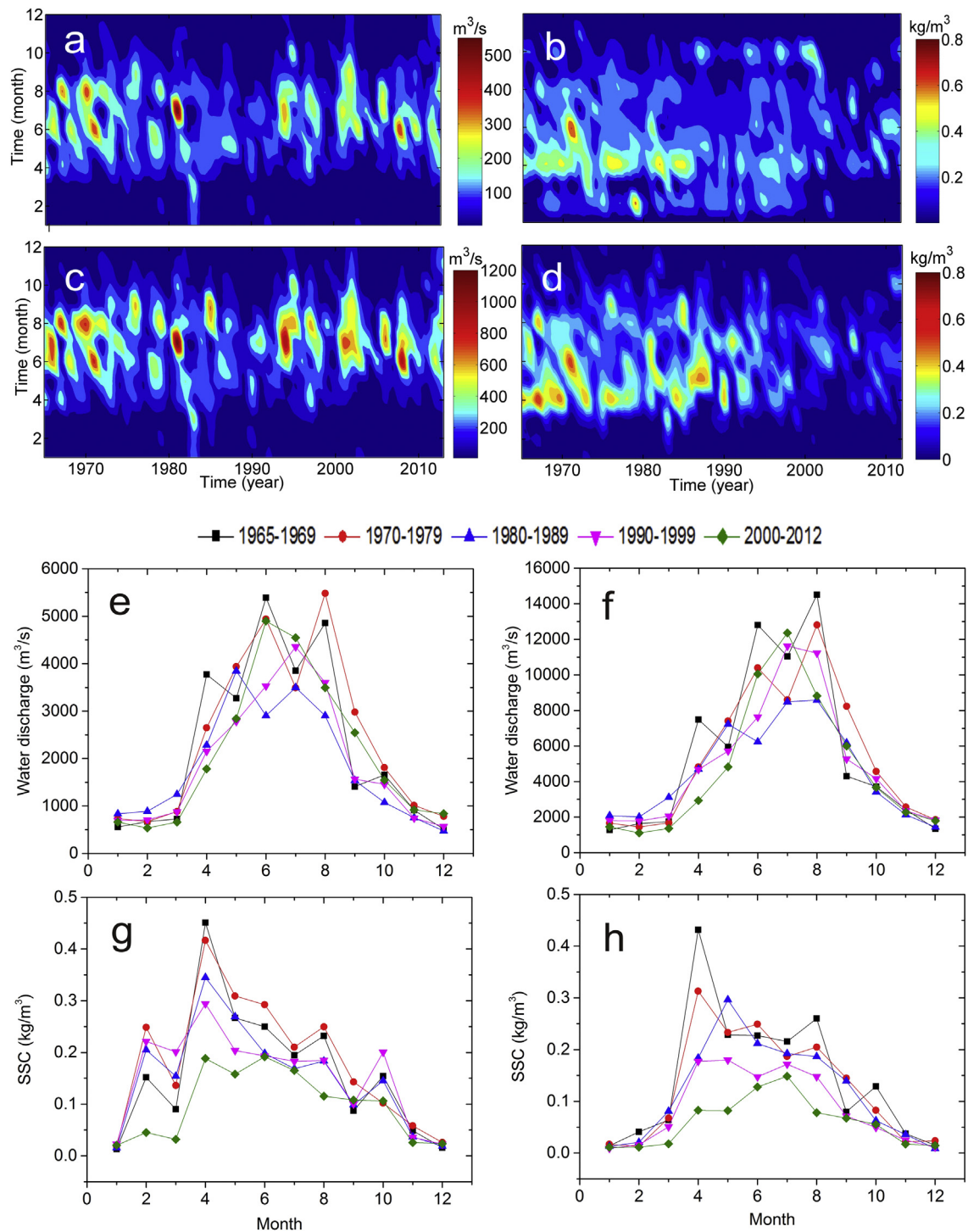


Fig. 2. Monthly and decadal water discharge and sediment load at Bobai and Changle (a. monthly water discharge at Bobai; b. monthly suspended sediment concentration at Bobai; c. monthly water discharge at Changle; d. monthly suspended sediment concentration at Changle; e. decadal water discharge of Bobai; f. decadal water discharge of Changle; g. decadal suspended sediment concentration of Bobai; h. decadal suspended sediment concentration of Changle.).

22.4 °C. Different from those alluvial rivers such as Changjiang River and Mississippi River, Nanliu River originates from local mountain of Darong with large river slope (0.37‰). Due to relatively short river course and large river slope, Nanliu River has unique inlet connecting with the Beibu Gulf. These characteristics of Nanliu River are very similar to mountainous rivers in Taiwan (Kao et al., 2005; Liu et al., 2008). However, no study related to

Nanliu River has been carried out, even though mountainous rivers have been detailed researched (Milliman and Meade, 1983; Kao et al., 2005; Liu et al., 2008). Thereafter, the aims of this study include: (1) to examine changes of water discharge and sediment load over the period 1960s–2013; (2) to discern relationship between water discharge and sediment load; (3) to detect possible impacted factors on water discharge and sediment load variations.

2. Material and methods

2.1. Data collection

Daily water discharges and sediment loads at Bobai, Changle stations along the Nanlijiang River are available from 1965 to 2013 (Fig. 1). Bobai station and Changle station, respectively representing the upper reach and lower reach, are the controlled stations of water and sediment load from river to Beibu Gulf (Table 1). Occasional missed data at Bobai station, including monthly sediment load of Jan.–Nov. in 1967 and monthly water discharge and suspended sediment load of Jan.–Oct. in 2003, are reconstructed based on linear regression. Meanwhile, discontinuously data of river sections at Bobai and Changle were recorded from 1965 to 2012. All above mentioned data are collected from the Pearl River Water Resources Commission (Table 1). The monthly precipitation records in the Nanliu River catchment from 1970 to 2007 are obtained from the China Meteorological Administration. Moreover, water consumption information over the Nanliu River catchment during 2003–2014 are collected from the Guangxi Province water resources bulletin. The South Asian Summer Monsoon (SASM) index is defined as an area-averaged, seasonal (June, July, and August), dynamical normalized seasonality at 850 hPa within the East Asian monsoon domain (10°–40°, 110°–140°E) (Li and Zeng, 2002, 2003, 2005). The El Niño–Southern Oscillation (ENSO) index is defined as sea surface temperature anomalies in the Nino3 region in the eastern tropical Pacific (5°S–5°N, 90°–150°W), which is obtained from the National Center for Atmospheric Research, U.S.A.

Table 1
Main characteristic of Bobai and Changle stations.

Station	Location	Watershed area (km ²)	Data series	
Bobai	109°57'E 22°17'N	2805	Water discharge	1965–2013
			SSC	1965–2012
			Riverbed profile	1977, 1982, 2001, 2012
Changle	109°25'E 21°50'N	6645	Water discharge	1965–2013
			SSC	1965–2012
			Riverbed profile	1977, 1982, 2001, 2007, 2012

2.2. Methods

Wavelet analysis is a powerful tool for detecting signals in hydrological time series compared to those of Fourier transform analysis (Briciu, 2014). Given a set of hydrological data, it can be decomposed into frequency space through wavelet analysis. The obtained frequency information then should be associated to singularities or anomalies of the original data. This allows for determining both the dominant modes of variability and how those modes vary in space (Doglioni and Simeone, 2014). Up to now,

detailed calculation of wavelet analysis follows the guide of Torrence and Compo (1998).

Meanwhile, Mann-Kendall method (Mann, 1945; Kendall, 1975; Memarian et al., 2012; Dai et al., 2015) was applied to the trend analysis in water discharge and sediment load at Bobai and Changle stations. Assuming a normal distribution at the significance level of $p = 0.05$, a positive Mann-Kendall statistic $Z > 1.96$ indicates a statistically significant increasing trend; while a negative $Z < -1.96$ represents a statistically significant decreasing trend. Furtherly, in order to determine the abrupt changes in river hydrology records, the Mann-Kendall abrupt change test was applied (Gerstengarbe and Wener, 1999). Moreover, to quantify the influence of possible impacted factors on river regime variations, linear regression analysis approach is adopted. Hydrological parameters such as coefficient of variation (Cv), monthly and yearly average values were also calculated (Greenwood et al., 1979).

3. Results

3.1. Changes in monthly water discharge and sediment load

Monthly runoff and sediment load at Bobai and Changle stations along Nanliu River were calculated by averaging the daily flow and sediment load of each month during 1965–2013. It is indicated that there are clear seasonal changes in water discharge and sediment load (Fig. 2, Table 2). The mean monthly water discharge and sediment load between different decades are compared at Bobai and Changle as well. The flow series at the two stations were

peaked in June or August while had minimums in February between 1960s and 1980s. However, the peaked flow for the two stations had been shifted to July with 14.81% reduction between 1990s and 2000s (Fig. 2). The peaked sediment load at Bobai and Changle were found in April and corresponding minimum occurred in January between 1960s and 1980s (Fig. 2). Meanwhile, the peaked sediment load at Changle had been shifted from previous April between 1960s and 1980s to July between 1990s and 2000s. In addition, there is similar pattern in changes in monthly sediment load at Bobai (Fig. 2).

Table 2
Variation of discharge and sediment load at Bobai and Changle stations.

Time	Changle station				Bobai station			
	Discharge (m ³ /s)	Percentage (%)	Sediment (10 ⁴ t)	Percentage (%)	Discharge (m ³ /s)	Percentage (%)	Sediment (10 ⁴ t)	Percentage (%)
Summer half-year	258.80	78	3370.46	95	110.08	79	1744.83	90
Winter half-year	73.56	22	179.94	5	29.68	21	192.25	10
The whole year	332.36	100	3550.40	100	139.76	100	1937.08	100

wavelet analysis method has been widely used in geophysics and hydrogeology (Briciu, 2014; Doglioni and Simeone, 2014; Gao et al., 2015). Here, the periodic changes in water discharge and sediment load of the Nanliu River are analyzed by wavelet method. The

Meanwhile, the wavelet analysis results of monthly water discharge and sediment load at these two stations show clear periodic changes with 4–6 years and 11 years (Fig. 3). These periodic oscillations are also reflected by recycle peaked values in flow and

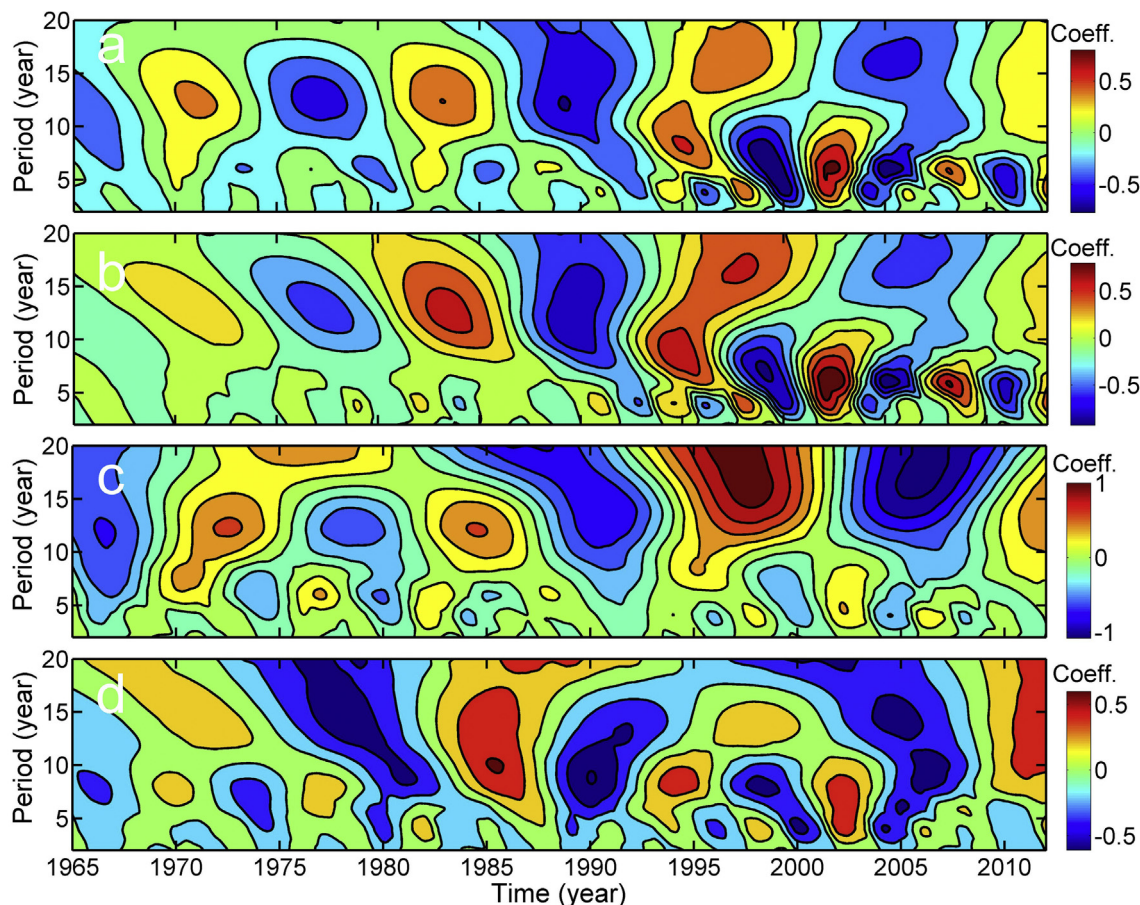


Fig. 3. Wavelet analysis on monthly water discharge and Suspended Sediment Concentration (SSC) (a. monthly water discharge at Bobai; b. monthly SSC at Bobai; c. monthly water discharge at Changle; d. monthly SSC at Changle).

sediment load (Fig. 2). Moreover, it can be seen in Fig. 4 that monthly water discharge and sediment load during 1965–2013 at these two stations had clear decrease in April, May, and August (Fig. 4).

3.2. Changes in yearly water discharge and sediment load

It can be seen in Fig. 5 that there was no statistically significant trend in water discharge of the Nanliu catchment from decadal scales, which stabled around 26,100 m³/s at Bobai and 61,000 m³/s at Changle, respectively. Differences in water discharge at these two stations indicate that about 60% flows from Nanliu River to the sea is contributed by the downward reaches, which could be caused by catchment precipitation (Table 3, Fig. 5). Meanwhile, the decennial Suspended Sediment Concentration (SSC) had decreased from 0.26 kg/m³ in 1960s to 0.15 kg/m³ in 2000s at Bobai, and from 0.25 kg/m³ in 1960s to 0.11 kg/m³ in 2000s at Changle, respectively (Table 3, Fig. 5). Moreover, linear regression analysis of both water discharge and SSC between 1965 and 2013 show obvious downward trends, which had hydrological peak extremes in 1971, 1981, 1994, 2002, and 2006 and minimums in 1980, 1989, 2000, and 2005 (Fig. 6).

3.3. Rating-curve variation

Although there is positive closely relationship between monthly water discharge and SSC at significant level of 0.05, rating-curve

Table 3

Decadal water discharge and sediment load variation at Bobai and Changle.

Time	Changle		Bobai	
	Discharge (m ³ /s)	Sediment (kg/m ³)	Discharge (m ³ /s)	Sediment (kg/m ³)
1965–1969	68255.48	0.25	31828.14	0.26
1970–1979	66075.93	0.20	27019.70	0.26
1980–1989	55616.79	0.19	19832.09	0.21
1990–1999	60170.85	0.15	26732.38	0.20
2000–2012	58561.78	0.11	25343.72	0.15

between flow and SSC present distinct temporal and spatial variations (Figs. 7 and 8). In upper reaches at Bobai during 1965–1989, SSC is in a rising stage from January to April with peak value at April, following with rapid fluctuation from April to August. However, from August and December, SSC gradually moves to the minimum (Fig. 8a). The whole rating-curve variation is clockwise with enveloped area presenting unregularly diamond pattern. In the period of 1990–2012, the peak value of the rating-curve variation in April obviously decreases with minor peak value found in July (Fig. 8). The whole rating-curve becomes a relatively narrow appearance with obviously decreased enveloped area in compared to those during 1965–1989.

When in comparison with those at upper reaches, rating-curve variation in the lower reach at Changle is relatively mild (Fig. 8b). However, there is almost similar pattern for the rating-curve

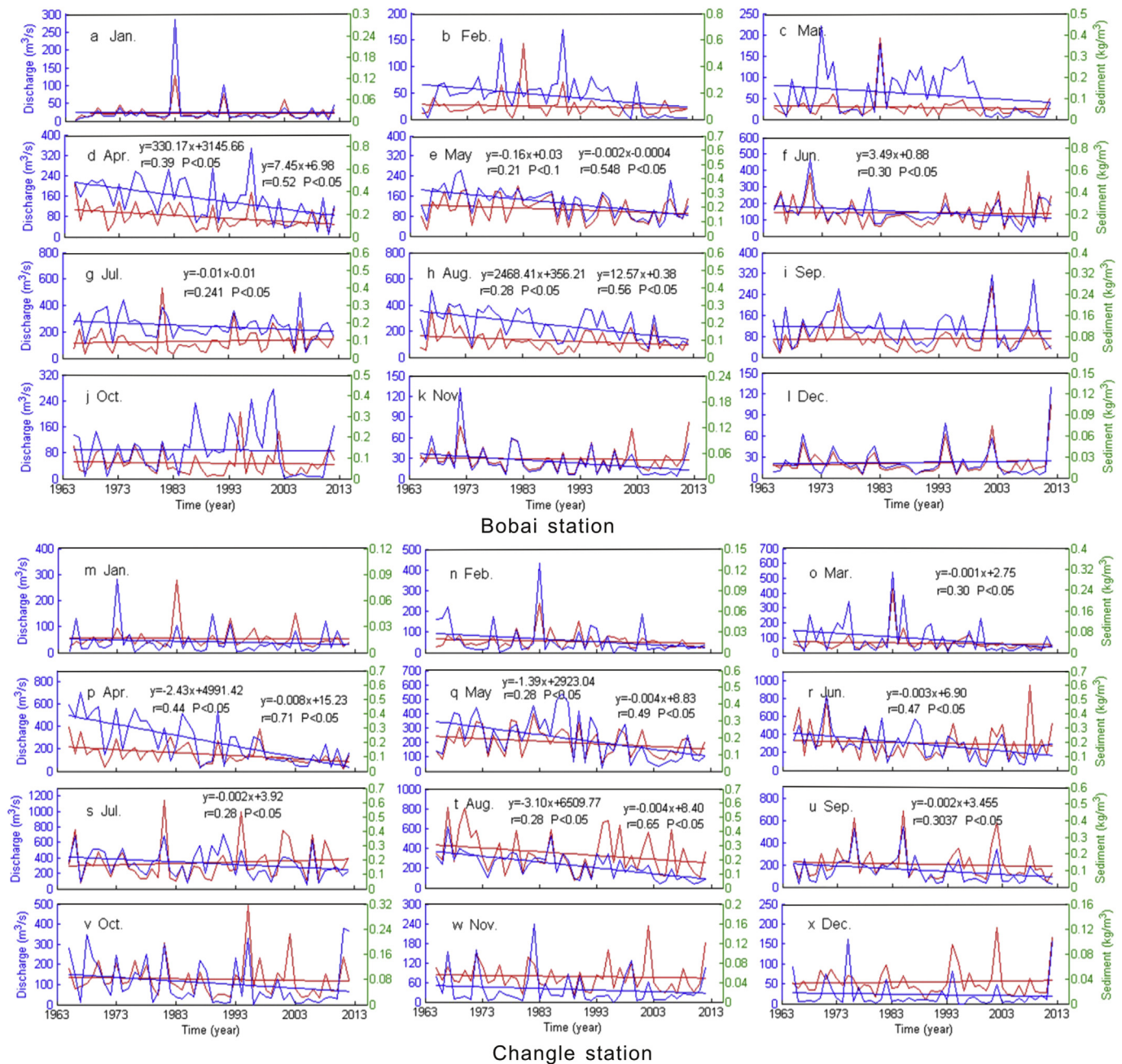


Fig. 4. Trends in water discharge of each month at Bobai and Changle stations during 1965–2012.

variation at the lower reaches. The peak value of the rating-curve in April drops rapidly from 1960s to 2000s. For mountainous river like Nanliu, bedload is the main part for sediment load, especially in the upper stream. As the water discharge to downstream, SSC becomes more important and makes a larger contribution to the lower reaches. This can be the possible reason for the rating-curve differences between Bobai and Changle.

4. Discussions

4.1. Climate change

Climate change dominants river discharge and SSC variation, which can be directly reflected by precipitation change over time

under natural situation. It is shown that annual mean precipitation in Nanliu River presents downward trend, with high precipitation (over 1800 mm) been observed in 1981, 1994, 2001 and 2002 while the lowest historical precipitation occurs in 1989, which coincides with the variation of river discharge and SSC (Fig. 9a). According to contour map of monthly precipitation, Nanliu River experiences a rainy season from April to September and a dry season from October to March, which coincides with the former results (Fig. 9b). Moreover, dramatic periods of 4–6 years and 11 years are detected in annual precipitation, which agrees well with the periodicities of river discharge and sediment load (Figs. 3 and 10). The high relationship between monthly precipitation and monthly SSC at Changle indicates that precipitation controls flow and SSC variation in Nanliu River (Fig. 10).

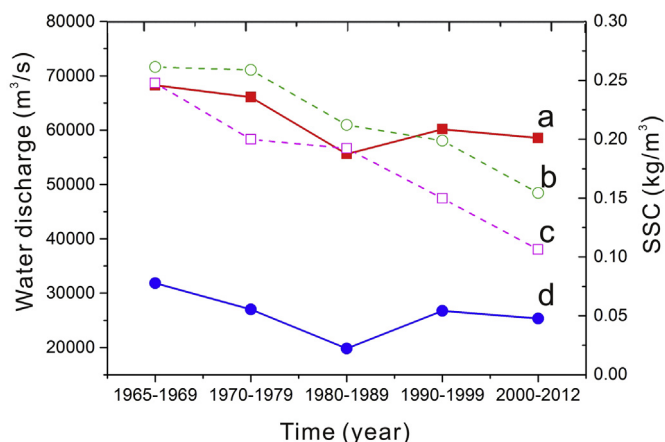


Fig. 5. Decadal water discharge and Suspended Sediment Concentration (SSC) variation at Bobai and Changle stations (a. water discharge of Changle; b. SSC of Bobai; c. SSC of Changle; d. water discharge of Bobai).

ENSO and monsoon determine the river basin precipitation around the world, which further affect the streamflow characteristics (Kane, 1999; Kiem and Franks, 2001; Xue et al., 2011; Misir et al., 2013; Wei et al., 2014). It is shown that river discharge and sediment load of Nanliu River are slightly affected by El Niño event and La Niña event but closely related to SASM (Figs. 6 and 11). The relationship between SASM and river

discharge at Bobai and Changle stations indicate statistical significant positive relationships with $p < 0.05$, which indicate that Nanliu river discharge is sensitive to SASM.

Therefore, the rainfall variation over the Nanliu River agrees with the river discharge and sediment load variation and been significantly affected by SASM, which can be a main driving factor for hydrology regime change in Nanliu River. Despite of the downward tendencies in both river discharge and sediment load, they are out of sync with more notable trend in sediment load. Therefore, more dominators may exist to explain the river discharge and sediment load variations in the Nanliu River.

4.2. Anthropogenic activities

Anthropogenic activities can dramatically affect the hydrological characters in the river (Dai et al., 2011, 2014). Located at the east of Beibu Gulf economic zone, Nanliu River is dominated by increasingly intensive human activities.

4.2.1. Soil erosion and forest conservation

Nanliu River catchment suffers from series soil erosion problem. Taking Linshan County, a county in Nanliu River upstream as an example, its soil erosion area is 3120 ha in 1974, which increased to 5500 ha in 1980 and furtherly increased to 214,100 ha in 1987. Accordingly, water discharge and sediment load in up-reach of Nanliu River increased from 1974 to 1987, with annual increase rates of 1.4% and 0.8%, respectively (Fig. 6).

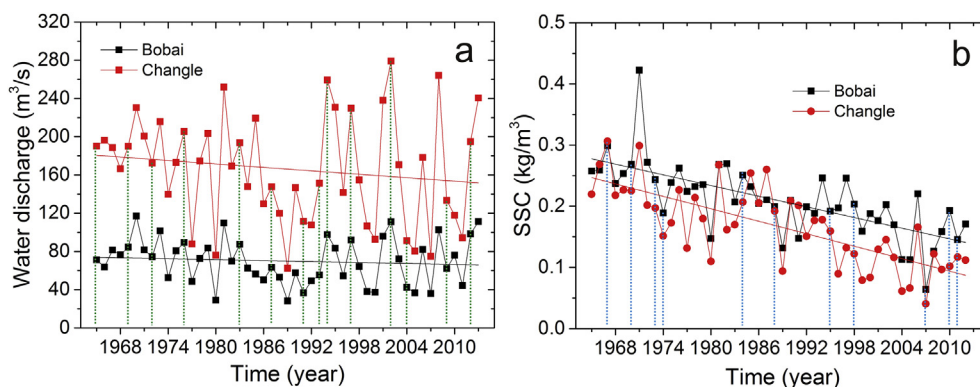


Fig. 6. Annual water discharge and Suspended Sediment Concentration (SSC) variation at Bobai and Changle stations (a. water discharge with green lines indicating El Niño events; b. SSC with blue lines denoting La Niña events). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

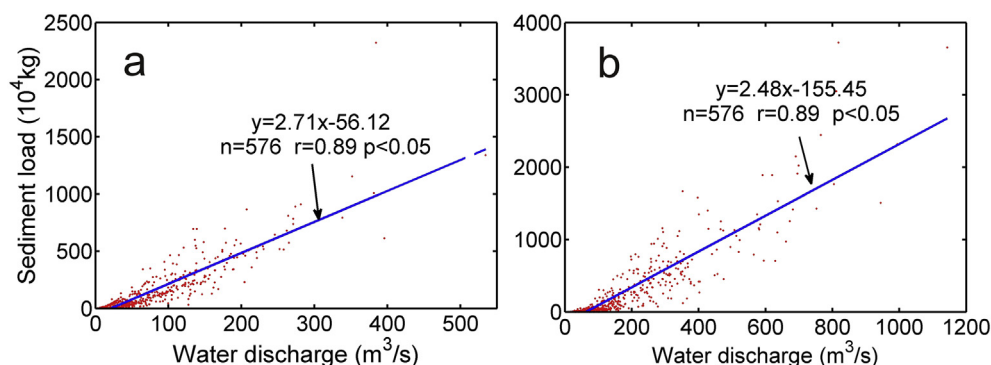


Fig. 7. Relationship between monthly river discharge and sediment load (a. Bobai; b. Changle).

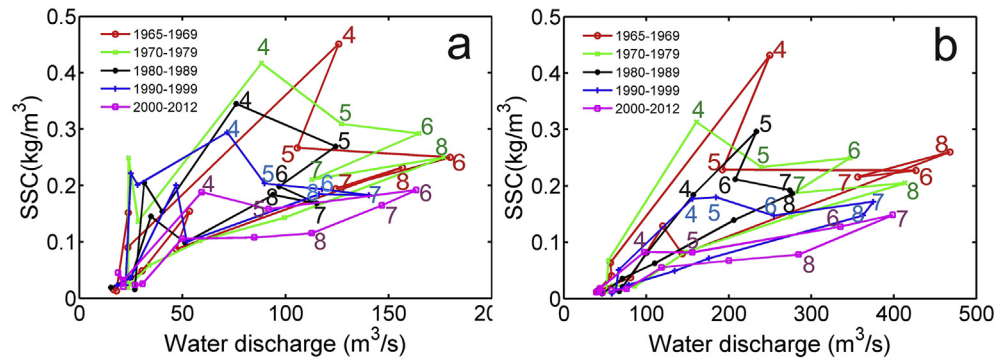


Fig. 8. Decadal rating curves between monthly river discharge and Suspended Sediment Concentration (SSC) (a. Bobai; b. Changle).

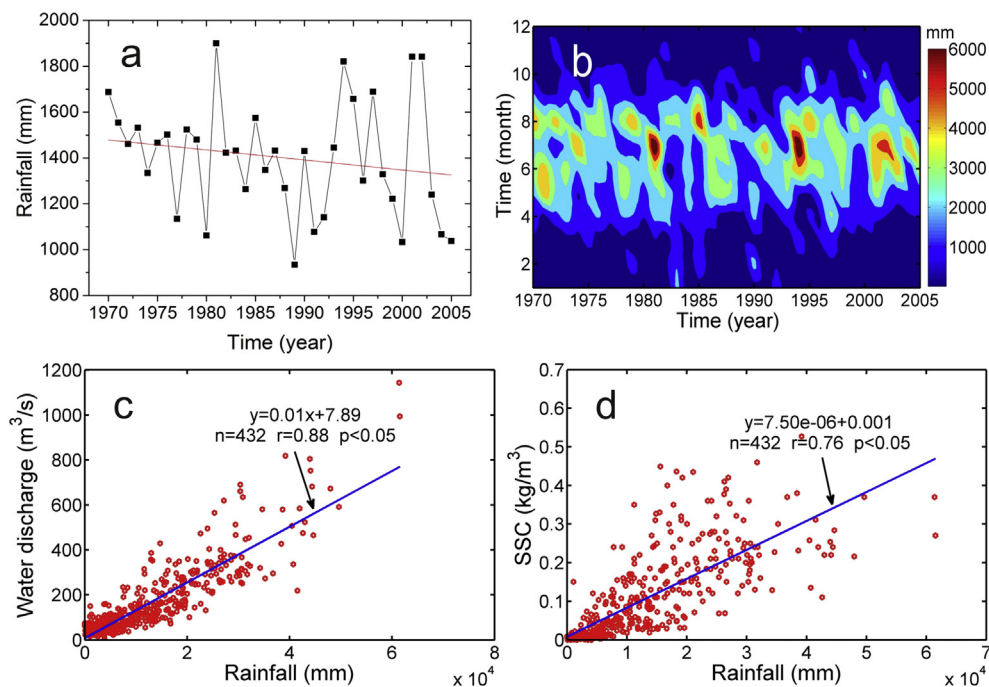


Fig. 9. Yearly and monthly precipitation in Nanliu River during 1970–2005 and correlation with monthly river discharge and Suspended Sediment Concentration (SSC) at Changle station (a. yearly precipitation; b. monthly precipitation; c. relationship between rainfall and water discharge; d. relationship between rainfall and SSC).

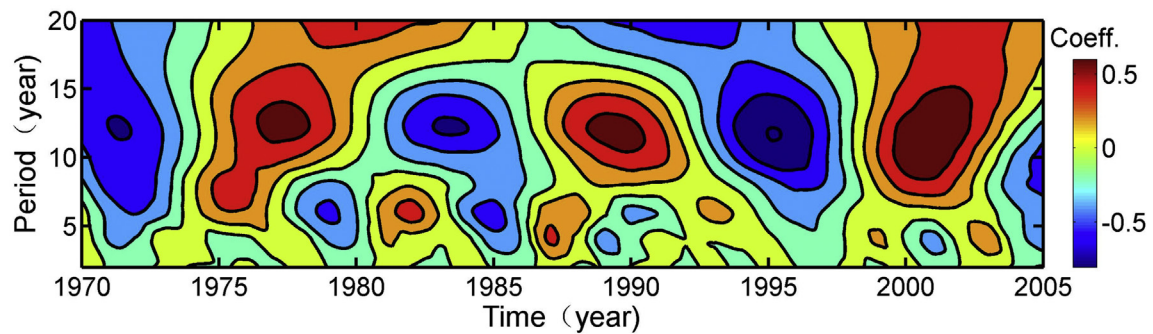


Fig. 10. Wavelet analysis on yearly precipitation.

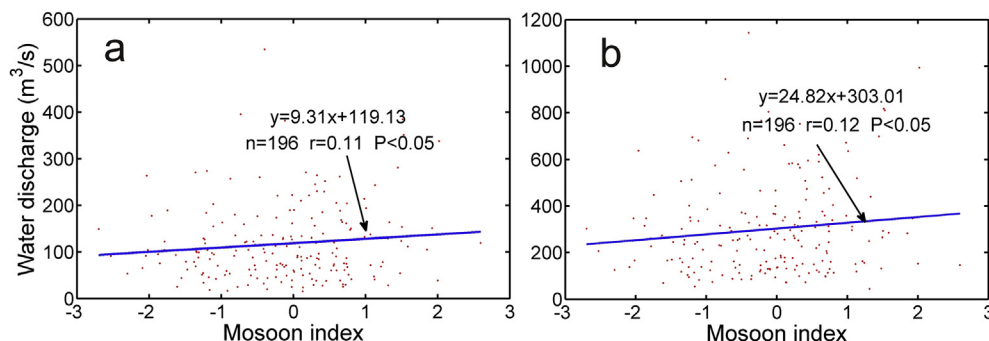


Fig. 11. Relationship between SASM index and water discharge.

In order to settle the series soil erosion problem in Nanliu River catchment, the project of forest conservation is carried out by the local government. Soil erosion and forest conservation along Nanliu River basin directly affect the river discharge and sediment load variations. The early soil erosion provides sediment to the river and results in riverbed deposition while the following forest conservation slows down the soil erosion rate and reduces the sediment flux amount.

4.2.2. Hydraulic engineering

Dam regulation is the primary factor that leads to sediment discharge reduction into the sea. Studies of large rivers, such as Amazon, Nile, Henghe, Changjiang and Yellow rivers indicate that SSC into the river estuary are significantly affected by the upstream dams (Yang et al., 2004; Nilsson et al., 2005; Syvitski et al., 2005; Dai et al., 2014). There are two large hydraulic engineering along the Nanliu River, namely, Hepu Reservoir in the middle reach and Hongchaojiang Reservoir in the lower reach, both of which were constructed in the 1960s (Table 4). According to an investigation in 1999, following the construction of Shahe Dam, a small dam been constructed in 1969 in the mainstream of Nanliu River, river bed in the upstream area raised by 1.5–2 m while the reservoir area elevation raised by 1.5 m with an accumulated deposition amount of 1.11 million m^3 (Xiao, 2000). It can be expected that dam regulation is one of the main causes for sediment reduction in the recent decades in Nanliu River. Besides, other hydraulic structures, such as flood control and drainage facilities, street affiliate facilities and sewage interception engineering, can affect the river discharge and sediment load behavior in the Nanliu River to different degrees as well.

Table 4
Main hydraulic engineering along the Nanliu River.

Reservoir		Capacity (10^8 m^3)	Area precipitation (km^2)	Storage (10^8 m^3)	Outflow (m^3/s)	Finish year
Hongchaojiang	—	7.03	400	392	11	1964
Hepu	Shengwangjiang	1.5	—	98.87	—	1960
	Xiaojiang	6.63	919.8	494	—	1960
	Qingshuijiang	0.705	52	—	—	1959

4.2.3. Water consumption

Nanliu River provides water to three cities, namely, Qinzhou, Beihai and Yulin. By analyzing the water consumption in the three cities over 2003–2014, it is found that water consumption presents insignificant upward trend in terms of total water use. Specifically, industry and living water consumption indicate slight increases while that for agriculture demonstrates slight decrease (Fig. 12).

Therefore, water consumption over the Nanliu River basin has limited contribution on water and sediment load variations.

4.3. River bed evolution response to water and sediment discharge variation

River bed evolution and periodicity characters directly reflect the river discharge and sediment load variations over time. By analyzing the cross section morphology in flood and dry season between 1965 and 2012, it is found that the section configuration evolution in Bobai and Changle are characterized by “deposition in dry season and erosion in flood season”, especially for 2001 and 2012 (Fig. 13).

Generally, low river discharge in dry season has small sediment transport capacity. Therefore, most sediments are stay in river bed. River discharge starts to increase in April, the sediment transport capacity increases accordingly. The river bed sediment goes up with the flow and the SSC reaches the annual maximum in April, which decreases gradually in the following months as discharge decrease. It is worth noting that Nanliu River's annual peak SSC occurs in April while the maximum discharge occurs in June or August. As flood season starts in April, the sudden increased discharge immediately takes most of the sediment and leads to the yearly maximum SSC. Although river discharge arrives the maximum value in June and August, the rest sediment is not enough to increase with the river flow. This coincides with the former conclusion that summer river discharge and SSC dominate the river regime.

In the recent decades, river discharge in the Nanliu River presents smaller fluctuation with decreasing Cv values in Bobai and

Changle station (Fig. 14). This can be explained by gradually decreased river discharge and sediment load.

5. Conclusions

The variation in water discharge and sediment load in the river is of vital importance to land–sea interaction, which plays a

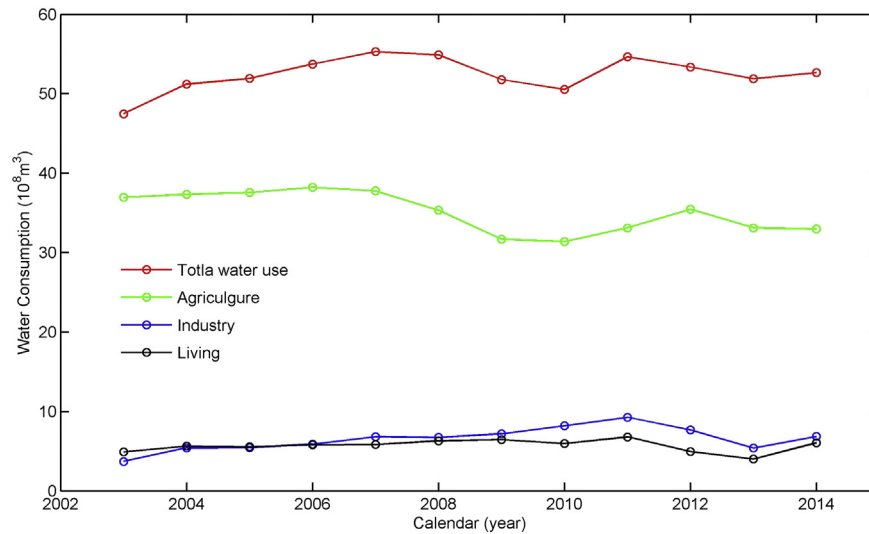


Fig. 12. Water consumption in Nanliu River catchment over 2003–2014.

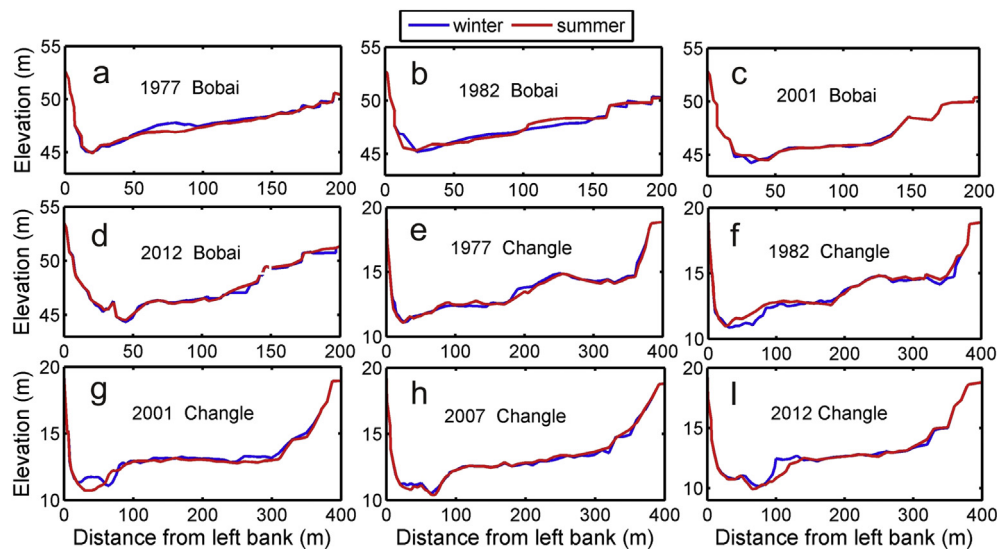


Fig. 13. Comparison of cross sections between summer and winter at Bobai and Changle stations.

significant role in material migration and estuary evolution. Nanliu River, located in the subtropical zone, is the largest independent river into the sea in Beibu Gulf. The significance of water discharge and sediment load variation study in the Nanliu River is self-evident with main results as follows:

- (1) River discharge and sediment load present downwards trends during 1960s–2013, especially for sediment load.
- (2) River hydrology in the Nanliu River has significant seasonal characters, with water discharge and sediment load in summer half year accounts for over 70% and 90%, respectively. Meanwhile, the priorities of 4–6 years and 11 years are detected in water discharge and sediment load.
- (3) Rating-curve between flow and SSC in upstream shows clockwise rotation with enveloped area presenting unregularly diamond pattern during 1965–1989, which becomes a relatively narrow appearance with obviously decreased enveloped area during 1990–2012. On the other hand, flow

and SSC rating-curve variation in the lower reach is relatively mild.

- (4) River bed geomorphology along Nanliu River is significantly response to river discharge and sediment load variations, which is characterized by “erosion in flood season and deposition in dry season”.
- (5) River discharge in the Nanliu River is controlled by precipitation while sediment load mainly comes from lower reaches supply. The decreases of river discharge and sediment load are driving by human activities, including soil erosion, forest conservation and hydraulic engineering.

Even if the data presented here show that river discharge and SSD in Nanliu River present downward trends due to the impacts of soil erosion, forest conservation and hydraulic engineering, further work remains to be done on a full sustainability quantification of the impacts of various factors on the river change.

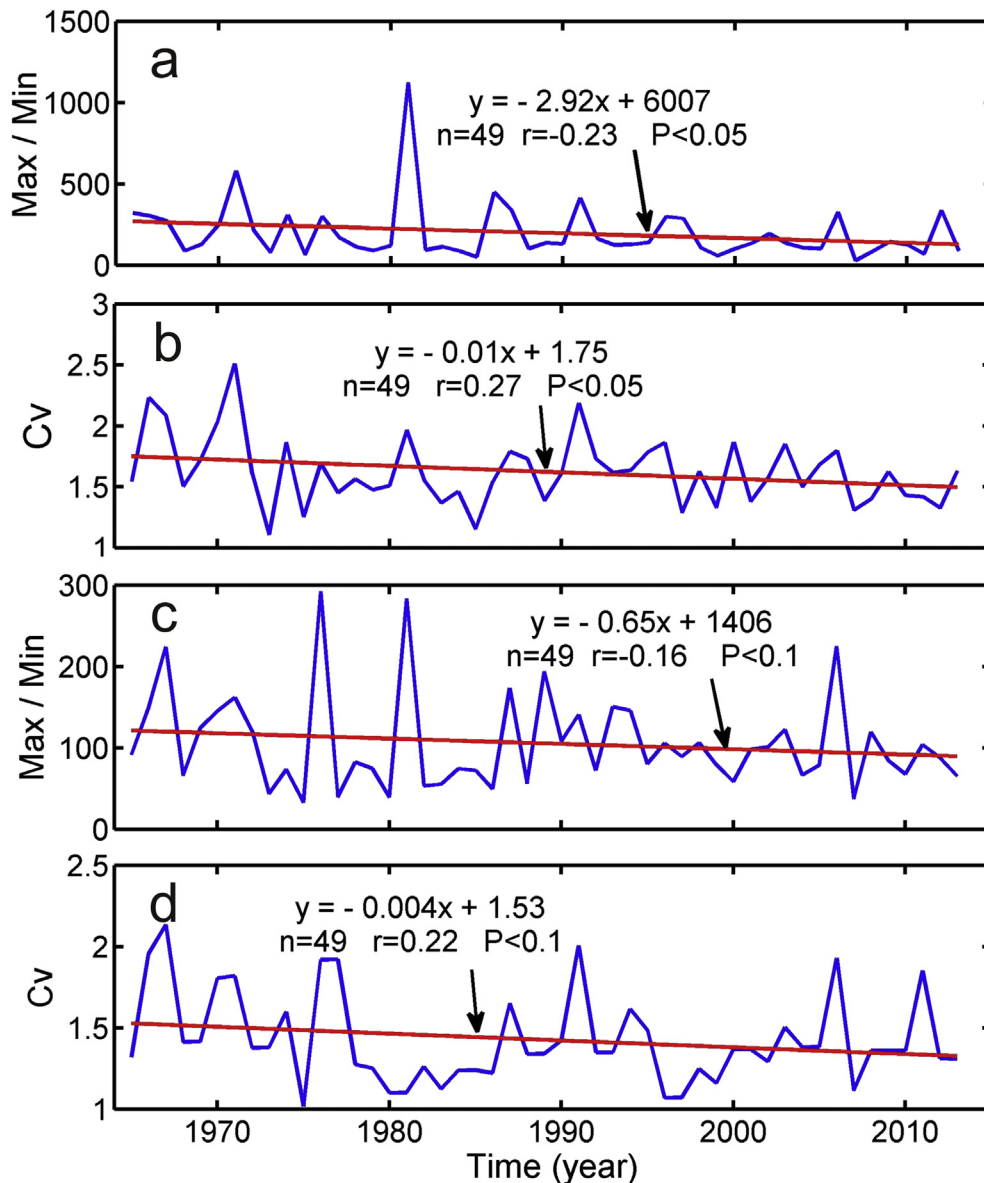


Fig. 14. The ratio between Max/Min and coefficient of variance for water discharge at Bobai and Changle stations (a. max/min of Bobai; b. Cv of Bobai; c. max/min of Bobai; d. Cv of Changle).

Acknowledgments

This study was supported by the Natural Science Foundation in China (41376097), Autonomous Program of Guangxi Key Laboratory of Beibu Gulf Marine Biodiversity Conservation (2015ZA01), Guangxi Natural Science Foundation (2015GXNSFBA139207) and Opening Fund of Key Laboratory of Environment Change and Resources Use in Beibu Gulf, Ministry of Education (NO. 2014BGERLKF04). We are also very grateful for two anonymous reviewers for their constructive suggestions to improve previous manuscript.

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