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Research Article
Detecting the Temporal and Spatial Changes of Suspended Sediment Concentration in Hanjiang River Estuary During the Past 30 Years Using Landsat Imageries

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Abstract

Background and Objective: Monitoring the spatiotemporal variation of suspended sediment (SSC) concentrations in estuaries and coasts can be helpful to improving the understanding of material cycle and environmental change. This study analyzed the temporal and spatial changes of suspended sediment concentrations in Hanjinag River Estuary. **Materials and Methods:** Based on the suspended sediment concentrations retrieved from 50 scenes of Landsat imageries during 1988-2015, the temporal and spatial changes of suspended sediment concentration in high flow season and low flow seasons in the regions within different distance from the coastline of Hanjiang River Estuary were analyzed and compared. **Results:** It was found that the result of suspended sediment concentration retrieved from Landsat imageries has a high accuracy compared to the record of Chao'an hydrological station in lower reaches of Hanjiang River. The suspended sediment concentrations in Hanjiang River Estuary showed a significant spatial distribution, with a spatial decreased trend from the outlets of Hanjiang River to the South China Sea, at a change rate of about 7.56 mg L^{-1} km^{-1}. From 1988-2015, there are decreased trend change of suspended sediment concentrations in both high and low flow seasons in Hanjiang River Estuary but no period change. The annual average suspended sediment concentration decreased by about 7 and 6.8 mg L^{-1} in high and low flow season in Hanjiang River Estuary from 1988-2015, respectively. Besides, it was also found that suspended sediment concentrations in low flow season in Hanjiang River Estuary were 56 mg L^{-1} higher than that of high flow season, which deserves the further study. **Conclusion:** Evidently, retrieving suspended sediment concentrations from a long time series of remote sensing data is very helpful to understand the temporal and spatial change of suspended sediment concentrations in estuaries, coasts and P to increase awareness of environmental changes, material cycle and human activity effects.

Key words: Suspended sediment, temporal and spatial changes, high and low flow seasons, landsat imageries, Hanjiang River Estuary

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

The temporal and spatial changes of suspended sediment (SS) concentrations in estuaries and coasts are not only the focus of sustainable development of the human society, but also the important part of the global material cycle[1-4]. Thus, there are many associated research works have been conducted to assess the spatial and temporal variation of suspended sediment in different regions, such as Tiete and Piracicaba Rivers[5], Guyana, Scheldt, Gironde and Rio de la Plata estuaries[6, 7], Danube River plume[8], Mekong River[9], Amazon River[10], Mississippi River[11], Yangtze River[1,12,13], Yellow River[13, 14], Pearl River[15-17].

It should be noted that the studies analyzed the change law and trends of total sediment load/transport in the basin based on long time of hydrological and meteorological data, have limitation of showing the spatial distribution of suspended sediment concentrations[12,15,16,18]. Although remote sensing have the advantage of being able to reflect the real state of the scene, the current studies that based on remote sensing mainly focus on the establishment of retrieval model[2,11,13,19], or analysis of the spatial and temporal variations of suspended sediment concentrations from short series (less than 15 years) of remote sensing data[1,10,14,20].

Hanjiang River is the second largest river in Guangdong Province with the runoff second only to the Pearl River. Considering the fact that little of research about the variations of suspended sediment concentrations in the region based on long time of remote sensing data, this research uses the Landsat imageries of 50 scenes during the past 30 years (1988-2015) to analyze the temporal and spatial changes of suspended sediment concentrations in Hanjinag River Estuary.

MATERIALS AND METHODS

Study area: Hanjiang River Estuary (Fig. 1), is located at East of Guangdong Province and Southwest of Fujian Province (longitudes 116.62°-117.05°E and latitudes 23.03°-23.5°N). It has a length of 470 km and has the second largest drainage area (3.01.104 km^2) in Guangdong Province. The annual mean surface runoff of Hanjiang River is $2.45\times10^{10}m^3$ with sediment load is 6.93×10^6 t/year on average. The lower reaches of Hanjiang River include Beixi water way (Northeast), Dongxi water way (middle) and Xixi water way (West). Xixi water way also crosses with the three water ways of Waishahe River, Xinjinhe River and Meixi River and flows into the South China Sea. In addition, a dam (the flow guiding line) connected to Longhu District, Shantou City, was built in 1996 (Fig. 1. Solid black line).

Remote sensing data and preprocessing: Due to frequent cloud coverage in estuaries and coasts, this study had obtained 50 scenes of Landsat TM and OLI imageries (1988~2015) covering Hanjiang River Estuary with good quality only (Fig. 2). The dates of 29 scenes of Landsat imageries were corresponding to high flow season (HFS, April-October) and other 21 scenes of Landsat imageries were corresponding to low flow season (LFS, November-next March) (Fig. 2). The 6S code was applied for atmospheric correction of the remote sensing imageries. The method developed by Jiang *et al.*[21], was used to extract water bodies. Partial areas covered with clouds were masked based on difference of spectral profile across water and cloud[22].

Suspended sediment retrieval model: Although many Landsat-based suspended sediment concentration retrieval models including empirical, semi-empirical, semi-analytical and analytical algorithms have been published, the general inversion method that is applicable to different water conditions is still under research. With the advantages of simplicity and sufficient accuracies, the empirical model, especially the semi-empirical methods are still used to estimate suspended sediment concentration widely[23]. This study used a semi-empirical method (Eq. 1) to retrieve suspended sediment concentration of Hanjiang River Estuary during 1988-2015[24,25]. The semi-empirical method has a higher accuracy compared to the previous models[5,26,27].

$$\mathrm{Log}(R_1)/\mathrm{Log}(R_2) = a*\left(\mathrm{Log}(SS)\right)2 + b*\mathrm{Log}(SS) + c \quad (1)$$

where, R1 and R2 represent near infrared band and red band of OLI and TM sensors. Parameters a, b and c are -0.3575, 1.1135, 0.7162 (Landsat OLI sensor) and -0.2821, 0.8506, 0.8295 (Landsat TM sensor), respectively. The unit of suspended sediment concentration is in mg L^{-1}.

RESULTS AND DISCUSSION

The spatial distribution of suspended sediment in Hanjiang River Estuary during the past 30 years: The suspended sediment concentration in Hanjiang River Estuary had a wide variables, ranging from 5.7-392.2 mg L^{-1}, with a mean value of 81.4 mg L^{-1} (Fig. 3). The record of Chao'an hydrological station in lower reaches of Hanjiang River showed that the mean value of suspended sediment during 1955~2008 was 261 mg L^{-1} (http://www.hjj.gd.cn/). Compared to the record, the results of suspended sediment concentrations retrieved

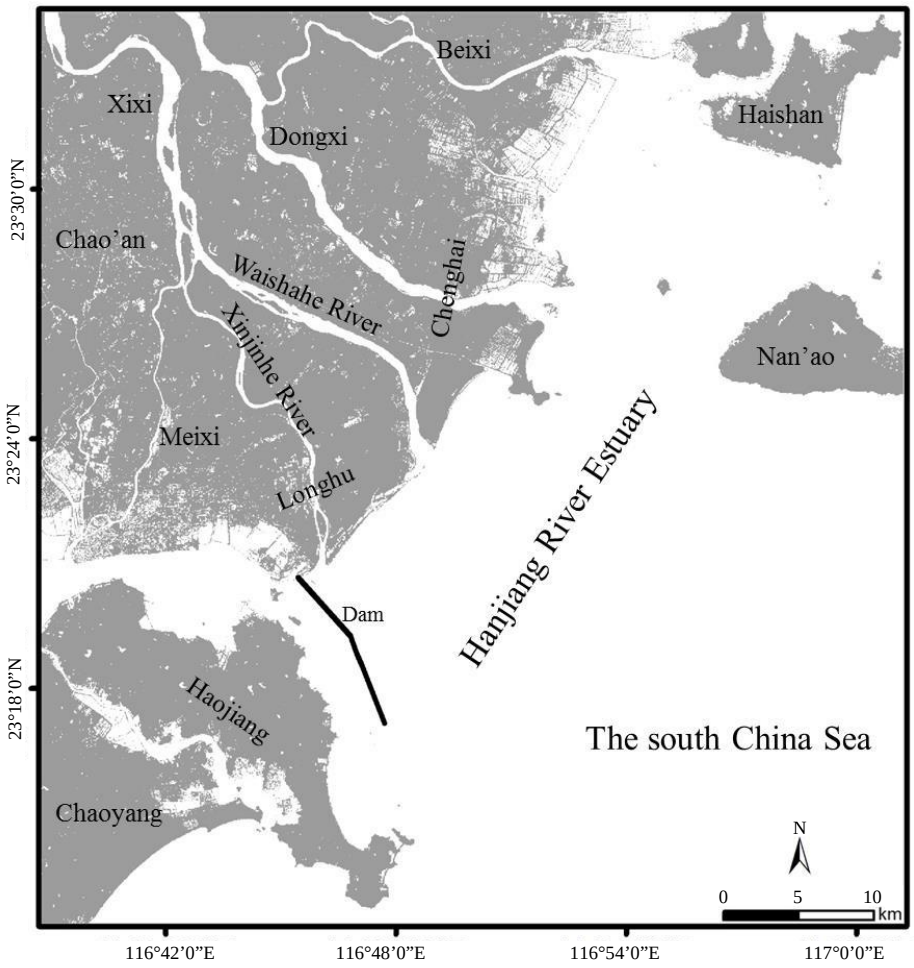

Fig. 1: Sketch map of the Hanjiang River Estuary

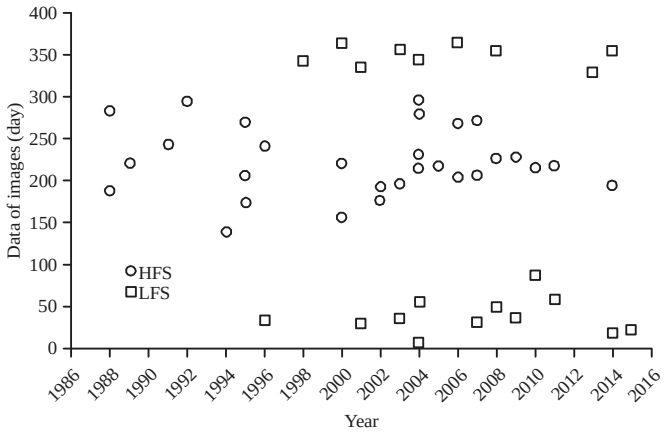

Fig. 2: Landsat imageries of 50 scenes used corresponding to high flow season (HFS) and low flow season (LFS) in Hanjiang River Estuary

from Landsat imageries have a high accuracy. The water bodies with high suspended sediment concentrations in Hanjiang River Estuary were mainly in the outlet of each water way (Beixi, Dongxi, Waishahe River water way and Xinjinhe River water way of Xixi). Thus, the sharp fronts of suspended sediment were found clearly in the regions. The distribution of extremely turbid waters (suspended sediment concentration higher than 120 mg L^{-1}) is the largest (about 39 km^2) in outlets

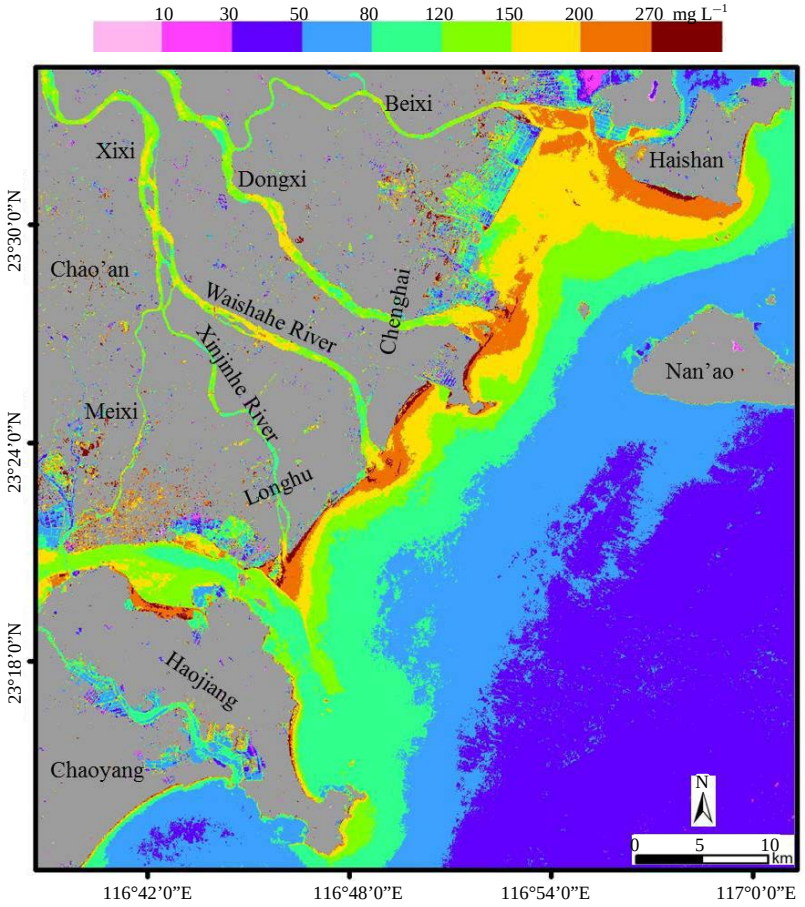

Fig. 3: Mean values of suspended sediment concentration in Hanjiang River Estuary during 1988-2015

of Beixi because of the obstruction from Haishan Island. The second largest distribution of extremely turbid waters were in the outlets of Dongxi, with an area of about 22 km^2. Besides, the extremely turbid waters have relatively smaller distribution in outlets of Waishahe River and Xinjinhe River water ways. In Hanjiang River Estuary, within a distance of about 5 km from the coastline, the value of suspended sediment concentrations were higher than 80 mg L^{-1} usually. The value of suspended sediment concentrations down to a low level (lower than 50 mg L^{-1}) until far away 11 km from the outlets of water ways. The farther distance from the coastline was, there was the lower suspended sediment concentration. Thus, it was found that there was a significant spatial distribution and decreasing trend in suspended sediment concentration from the outlets of waterways (Beixi, Dongxi and Xixi) to Southeast of Hanjiang River Estuary, at a change rate of about 7.56 mg L^{-1} km^{-1}. The spatial characteristic and decreasing trend of suspended sediment concentrations in Hanjiang River Estuary similar to many other estuaries of China (Yangtze River Estuary, Yellow River Estuary and Pearl River Estuary), which mainly due to the interaction between runoff and tide. In addition, a dam (the flow guiding line, solid black line in Fig. 1) connected to Longhu District, Shantou City was built in 1996, which causes the significant difference of suspended sediment concentrations between its two sides.

The trend change of suspended sediment concentrations in high and low flow seasons in Hanjiang River Estuary: Beside the analysis of the spatial change of suspended sediment concentration in Hanjiang River Estuary (Section 3.1), the annual mean value of suspended sediment concentrations in high and low flow season in Hanjiang River Estuary from 1988 to 2015 were also calculated, for further analyzing the trend and period change of suspended sediment in Hanjiang River Estuary. As a result, it was found that there were decreased trend change of suspended sediment concentrations in both high and low flow seasons in Hanjiang River Estuary, but no period change. In the following figure (Fig. 4), the results of suspended sediment

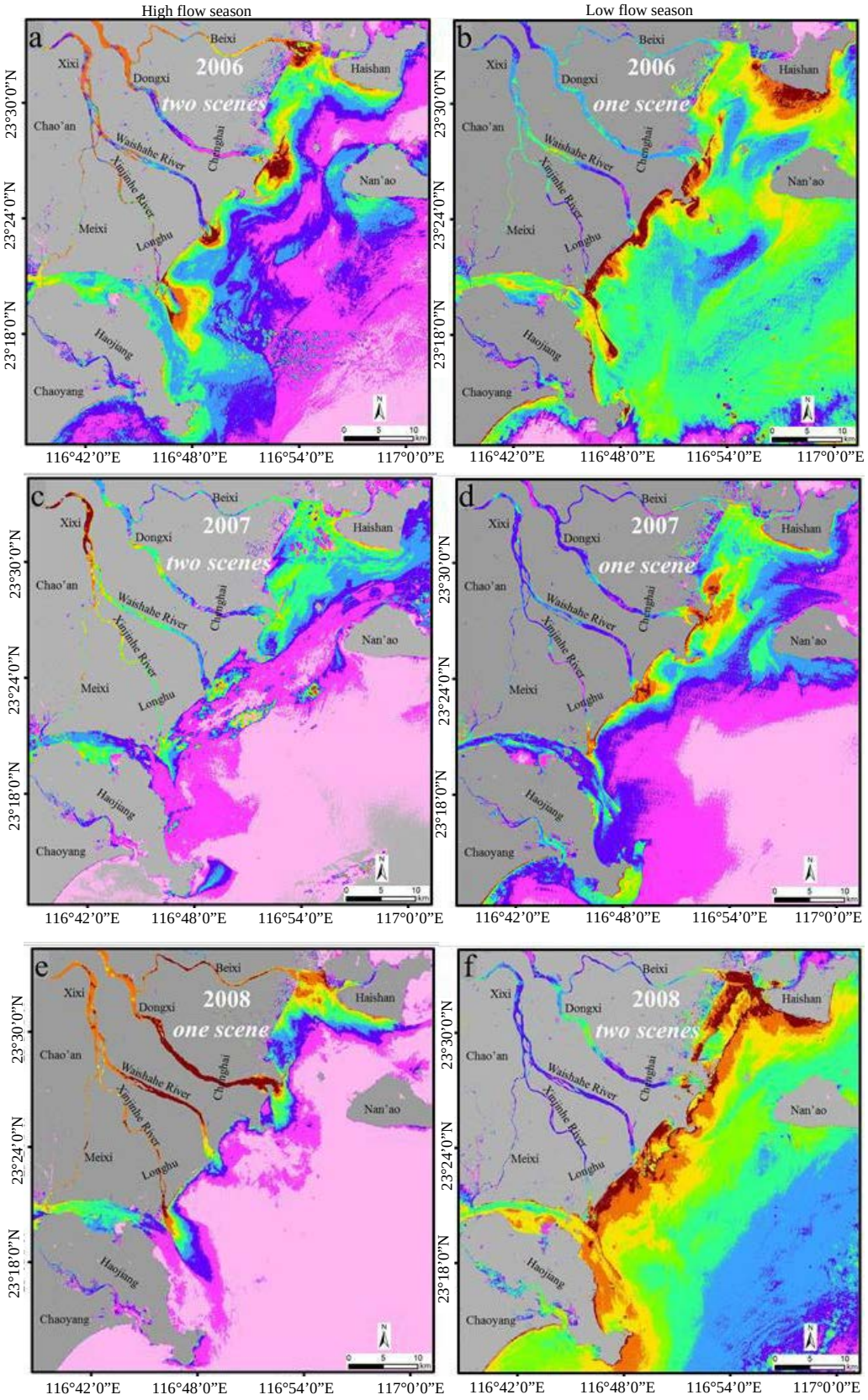

Fig. 4(a-j): Continue

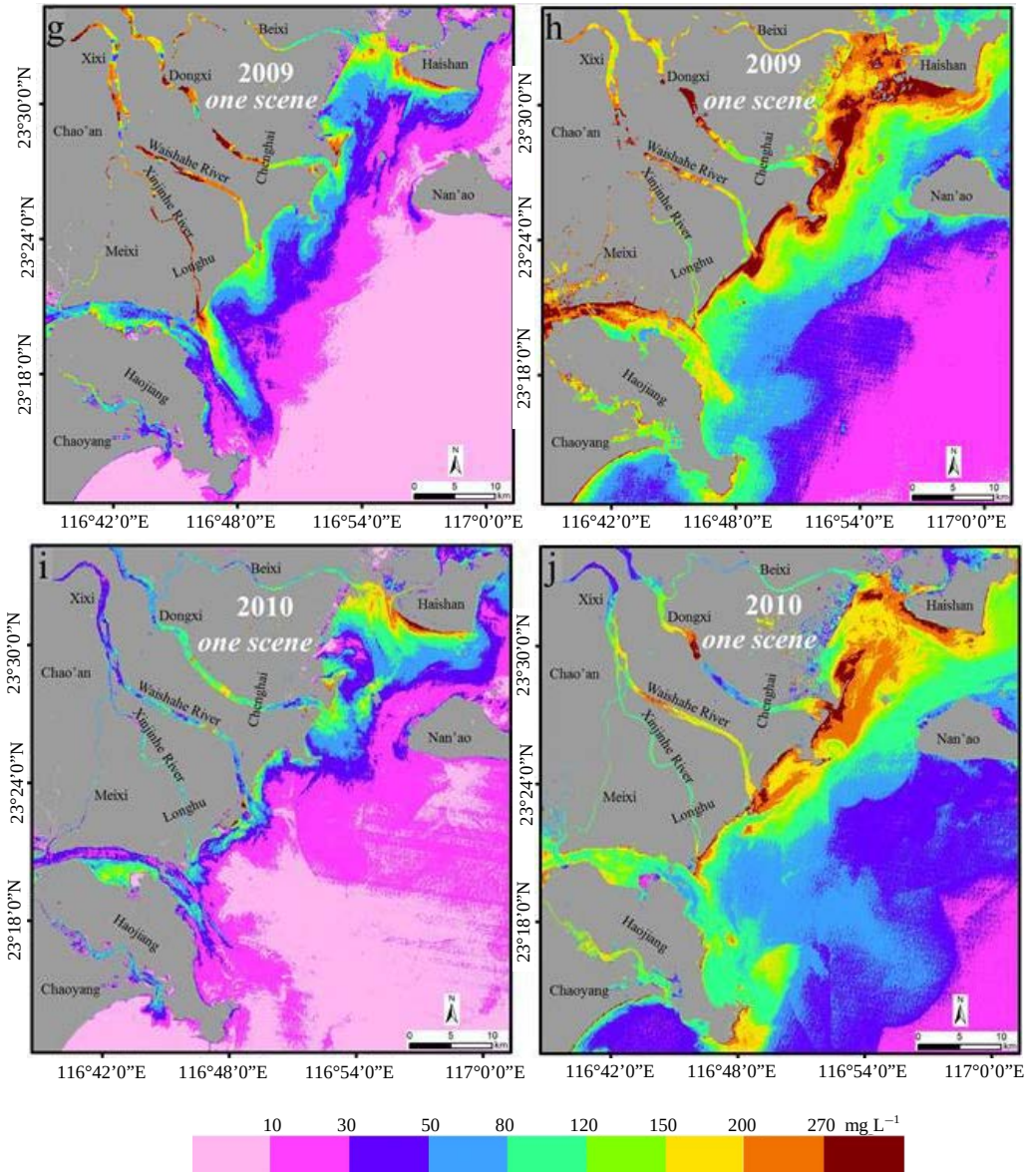

Fig. 4(a-j): Mean value of suspended sediment concentrations in high flow season and low flow season in Hanjiang River Estuary from 2006 to 2010

concentrations from 2006 to 2010 was taken as an example to illustrate the decreased trend of suspended sediment concentrations in Hanjiang River Estuary.

In high flow season, it was found that the mean value of suspended sediment concentration in Hanjiang River Estuary in 2006 (Fig. 4a) was the highest than that of 2007-2010. Within a distance of about 2 km from coastline towards Southeast, the mean value of suspended sediment concentration was higher than 120 mg L^{-1} (extremely turbid water bodies). The suspended sediment concentrations in the region of about 35% of Hanjiang River Estuary were higher than 30 mg L^{-1} (Fig. 4a). In 2007, the mean value of suspended sediment concentrations in outlets of Xinjihe River and Waishahe River water ways of Xi and Southern Chaoyang coastal water bodies were much lower than that of 2006 (Fig. 4c). Besides, the distribution of extremely turbid water bodies in 2007 (Fig. 4c) became smaller, and were found in outlets between Dongxi and Beixi only. Compared to 2006 and 2007 (Fig. 4a and Fig. 4c), the mean value of suspended sediment concentration of Hanjiang River Estuary in 2008

Table 1: Variation and trends of suspended sediment concentrations in high flow season (HFS) and low flow season (LFS) in the regions within different distance from the coastline of Hanjiang River Estuary from 1988 to 2015

	The regions within different distance from the coastline of Hanjiang River Estuary		
	2 km	2-5 km	5-10 km
Mean value			
HFS	129.1 (mg L^{-1})	101.1 (mg L^{-1})	80.4 (mg L^{-1})
LFS	184.1 (mg L^{-1})	159.6 (mg L^{-1})	134.3 (mg L^{-1})
Trend change			
HFS	-7 (mg L^{-1})/year (whole region)		
LFS	-6.8 (mg L^{-1})/year (whole region)		
Trend change	7.56 (mg L^{-1} km^{-1})		
from coastline to sea			
Period change	Not found		

(Fig. 4e) showed a significant decreased trend. The suspended sediment concentration of almost whole Hanjiang River Estuary were lower than 10 mg L^{-1} except for the river courses of Hanjiang River. From Fig. 4g, it was found that the mean value of suspended sediment concentration in Hanjiang River Estuary in 2009 was a little higher than that of 2007 and 2008 (Fig.4c and Fig. 4e). It is clear that the distribution that the suspended sediment concentrations were higher than 50 mg L^{-1} had increased. The mean values of suspended sediment concentration in Hanjiang River Estuary in 2010 (Fig. 4i) was the lowest among 2006-2010. The suspended sediment concentrations in most regions of Hanjiang River Estuary in 2010 were lower than 30 mg L^{-1} except for the outlets of Beixi. Based on the above analysis, this study comes to the conclusion that suspended sediment concentrations in high flow season (Fig.4a,c,e,g,i) showed a decreased trend in Hanjiang River Estuary from 2006 to 2010.

In low flow season, within a distance of about 10 km from coastline towards Southeast, the trend change of suspended sediment concentrations in Hanjiang River Estuary was similar to that of high flow season from 2006 to 2010. That is a decreased trend of suspended sediment concentrations also found in low flow season in Hanjiang River Estuary from 2006-2010 (Fig. 4b,d,f,h,j). It should be noted that suspended sediment concentrations in low flow season in Hanjiang River Estuary in 2007 were relatively lower. However, it has little impact on the long time trend change of suspended sediment concentrations in Hanjiang River Estuary. In addition, it was found that suspended sediment concentrations in low flow season in Hanjiang River Estuary were higher than that of high flow season (Fig. 4) based on the results retrieved from Landsat imageries.

Detecting of temporal and spatial changes of suspended sediment concentrations in Hanjiang River Estuary from 1988 to 2015: Based on the representative results of Landsat imageries mapping in Section 3.1 and 3.2, the following analysis shows the results of statistical analysis of trend change of suspended sediment concentrations in the regions within different distance from the coastline of Hanjiang River Estuary during 1988-2015.

In high flow season, Fig. 5a showed that the mean value of suspended sediment concentration in the region within a distance of 2 km from the coastline of Hanjiang River Estuary was 129.1 mg L^{-1} (Fig. 5a, red line of dashes. Table 1), which was 28 mg L^{-1} higher that of the region within a distance of 2-5 km from the coastline (Fig. 5b, red line of dashes. Table 1). From Fig. 5c, it was found that the mean value of suspended sediment concentration in the region within a distance of 5-10 km from the coastline of Hanjiang River Estuary was the lowest among the three regions, with a value of 80.4 mg L^{-1} (Fig. 5c, red line of dashes. Table 1). It was about 20.7 mg L^{-1} and 48.7 mg L^{-1} lower than that of the regions within a distance of 2-5 km and 2 km from the coastline, respectively (Table 1). It was also found that there was a significant decreasing trend of suspended sediment concentration from the coastline to southeast of Hanjiang River Estuary, at a change rate of about 7.51 mg L^{-1} km^{-1} (Table 1). The nearer the distance from the coastline was, there was the higher change rate in the region. Because suspended sediment concentrations in the region far away from the coastline (more than 10 km) were always at very low level, the trend change of suspended sediment concentrations in the region was small usually.

In low flow season, the mean value of suspended sediment concentration in the region within a distance of 2 km from the coastline of Hanjiang River Estuary was 184.1 mg L^{-1} (Fig. 5a, blue line of dashes. Table 1), which was 55 mg L^{-1} higher that of high flow season usually (Fig. 5a, red line of dashes. Table 1). The mean value of suspended sediment concentration in the region within a distance of

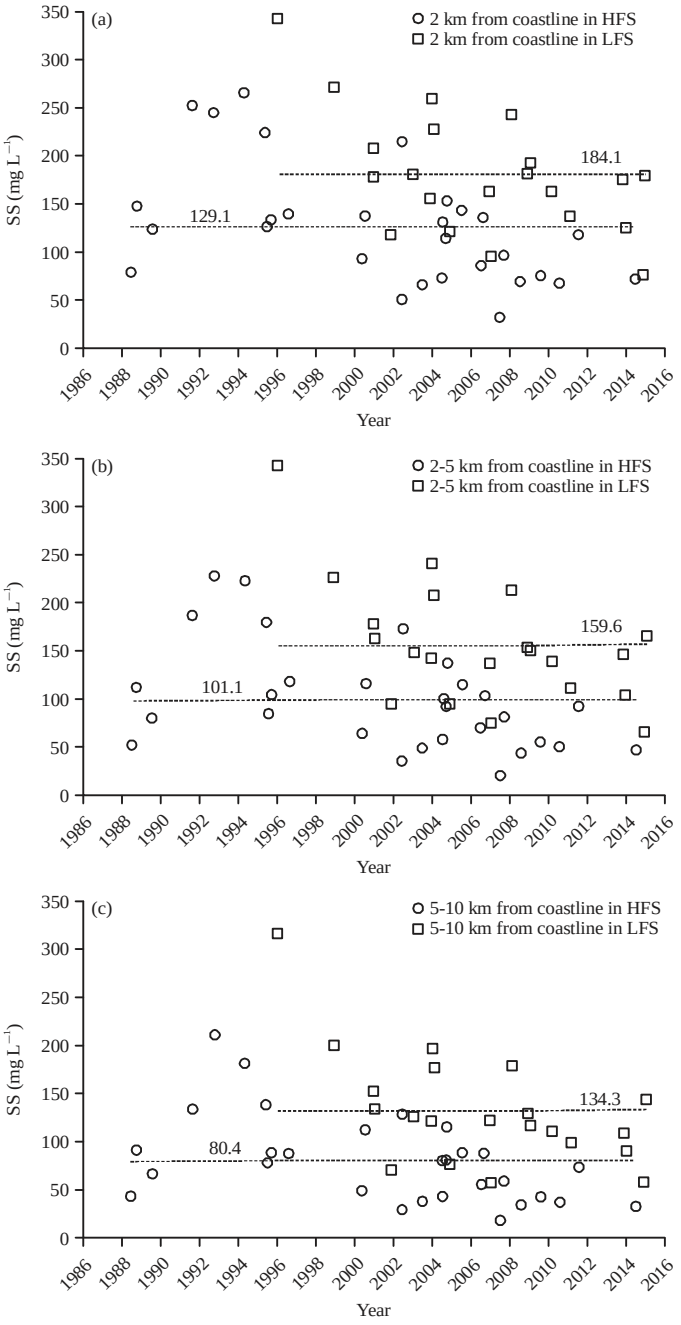

Fig. 5(a-c): Suspended sediment concentrations retrieved from Landsat imageries of 50 scenes in high flow season (HFS) and low flow season (LFS) in three regions within different distance (2 km, 2-5 km and 5-10 km) from the coastline of Hanjiang River Estuary during 1988-2015

2-5 km from the coastline was 159.6 mg L^{-1} (Fig. 5b, blue line of dashes Table 1), which was 24.5 mg L^{-1} lower that of the region within a distance of 2 km from the coastline (Fig. 5a, blue line of dashes Table 1), but 58.5 mg L^{-1} higher than that of high flow season (Fig.5a, red line of dashes Table 1). Similar to high flow season, the mean value of suspended sediment concentration in low flow season in the region within a distance of 5-10 km from the coastline was the lowest, with a value of 134.3 mg L^{-1} (Fig.5c, blue line of dashes Table 1). It was still about 54 mg L^{-1} higher than that of high flow season (Fig. 5c, red line of dashes Table 1). Besides, the decreased trend of suspended sediment concentration in low

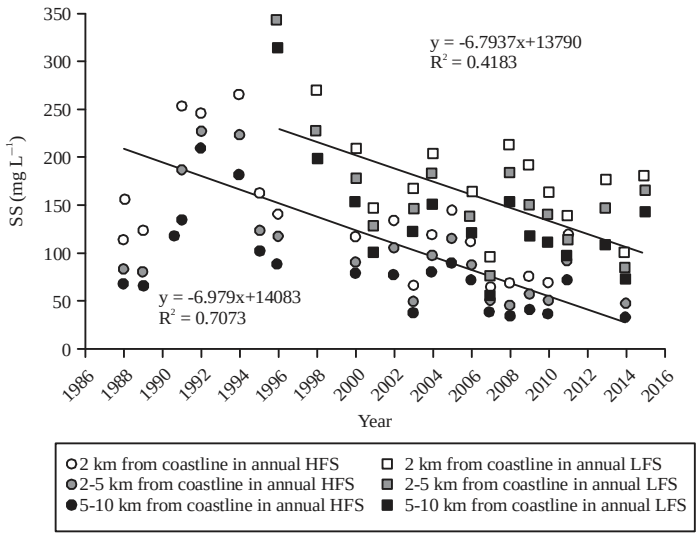

Fig. 6: Mean value of suspended sediment concentrations and their changes in annual high flow season (HFS) and low flow season (LFS) in the three regions within different distance (2, 2-5 and 5-10 km) from the coastline of Hanjiang River Estuary from 1988 to 2015

flow season from the coastline to Southeast of Hanjiang River Estuary was a little higher than of high flow season, at a change rate of about 7.69 mg L^{-1} km^{-1} (Table 1).

For the long term trend of suspended sediment concentration in Hanjiang River Estuary, it was found that there are a significant decreased trend change in high and low flow season but no period change (Fig. 6. Table 1). The annual average suspended sediment concentration decreased by 7 mg L^{-1} in high flow season in Hanjiang River Estuary from 1988 to 2015 (Fig. 6, red fitting line of solid Table 1). The decreased trend of suspended sediment concentration in low flow season was a little lower than of high flow season, with an average annual suspended sediment concentration decrease of 6.8 mg L^{-1} in low flow season from 1988 to 2015 (Fig. 6, blue fitting line of solid. Table 1). At present, many studies considered that suspended sediment concentrations in high flow season in were higher than that of low flow season usually. However, from Fig. 5, 6, this study comes to the result that suspended sediment concentrations in high flow season in Hanjiang River Estuary were lower than that of low flow season, with a mean value of about 56 mg L^{-1} (Table 1). For explaining the "unusual" situation in Hanjiang River Estuary, the true color images and the corresponding results of suspended sediment concentrations in high flow season and low flow season in 2004 were shown in Fig. 7. It was found that the water bodies were more turbid in low flow seasons in Hanjiang River Estuary than that of high flow season intuitively.

From the above analysis, it was found that suspended sediment concentrations in Hanjiang River Estuary showed a significant spatial and temporal variation (Table 1). There was a significant spatial decreased trend of suspended sediment concentration from the outlets of Hanjiang River to the South China Sea, at a change rate of about 7.56 mg L^{-1} km^{-1} (Table 1). It was also found that the annual average suspended sediment concentration decreased by 7 and 6.8 mg L^{-1} in high and low flow season in Hanjiang River Estuary from 1988 to 2015, respectively (Table 1). Besides, this study found that suspended sediment concentrations in low flow season in Hanjiang River Estuary were 56 mg L^{-1} higher than that of high flow season (Table 1). It is "unusual" situation in Hanjiang River Estuary and deserves the further research.

There were some studies [15,16] having analyzed the spatial and temporal variation of sediment load based on long time series of hydrological and meteorological data. However, those works were more difficult to reflect the spatial difference of suspended sediment distribution and its regional change or trend. At present, the studies that based on remote sensing concentrated mostly on the development of suspended sediment retrieval model [2,11,13,19].

Evidently, researches of the spatial and temporal variations of suspended sediment concentrations based on remote sensing big data was insufficient. The results of this study about the suspended sediment concentration in high and low flow season in Hanjiang River Estuary are a

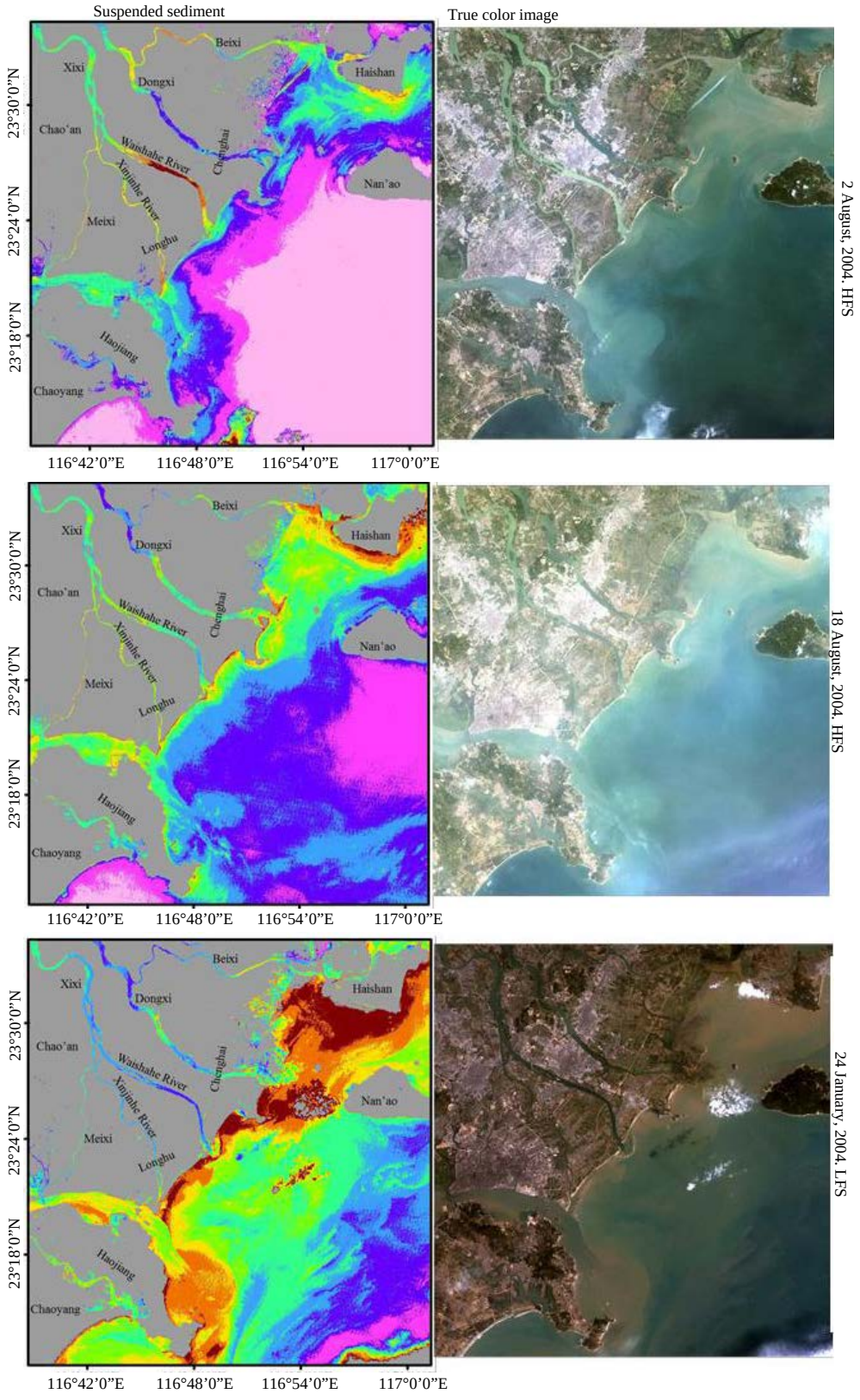

Fig. 7(a-h): Continue

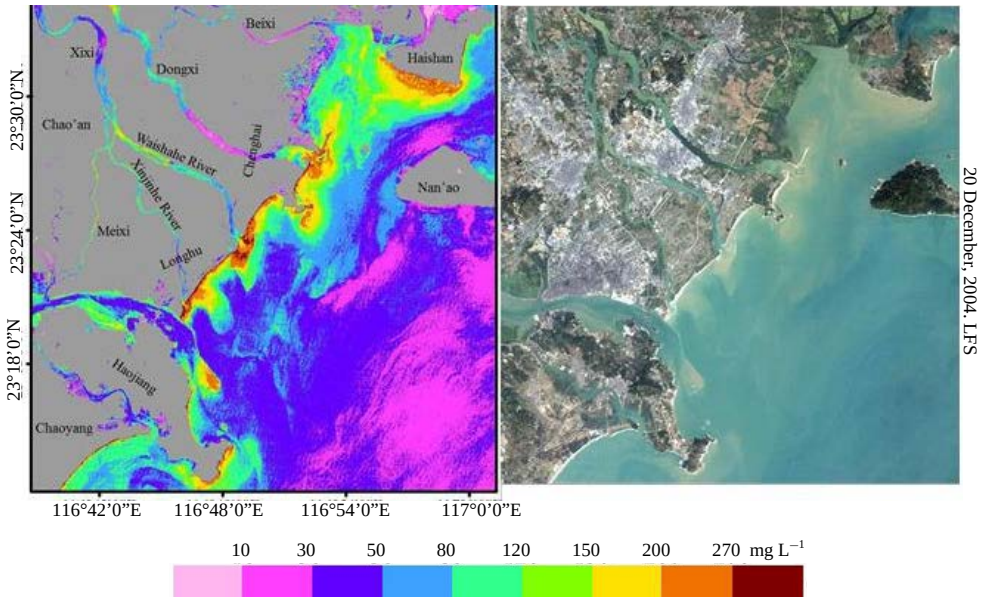

Fig. 7(a-h): Suspended sediment concentration in high flow season and low flow season in Hanjiang River Estuary in 2004 and the corresponding Landsat imageries (true color)

good complement of existing researches, which is helpful to improve the understanding of the spatial and temporal variation of sediment of estuaries and coasts.

CONCLUSION

This paper analyzed the spatial and temporal variations of suspended sediment concentration in high and low flow seasons in Hanjiang River Estuary during 1988-2015 based on the results retrieved from 50 scenes of Landsat imageries. Some notable results had been obtained. Compared to the record of Chao'an hydrological station in lower reaches of Hanjiang River, the result of suspended sediment concentration retrieved from Landsat imageries has a high accuracy. There were significant spatial variation of suspended sediment concentrations in Pearl River Estuary, ranging from 5.7-392.2 mg L^{-1}. The mean value of suspended sediment in Hanjiang River Estuary was 81.4 mg L^{-1}. The water bodies with high suspended sediment concentrations were mainly in the outlets of Hanjiang River. Within a distance of about 5 km from the coastline, the value of suspended sediment concentrations were higher than 80 mg L^{-1} usually. There was a significant spatial decreased trend of suspended sediment concentration from the coastline of Hanjiang River Estuary to the South China Sea, at a change rate of about 7.56 mg L^{-1} km^{-1}. The nearer the distance from the coastline was, there was the higher change rate in the region. The spatial characteristic and decreasing trend of suspended sediment concentrations in Hanjiang River Estuary were mainly due to the interaction between runoff and tide. In high and low flow season, it was found that there are significant decreased trend change of suspended sediment concentrations in Hanjiang River Estuary from 1988 to 2015 but no period change. The annual average suspended sediment concentration decreased by about 7 and 6.8 mg L^{-1} in high and low flow season, respectively. In addition, it was also found that suspended sediment concentrations in low flow season in Hanjiang River Estuary were 56 mg L^{-1} higher than that of high flow season. Based on the results of suspended sediment concentrations retrieved from Landsat imageries, this study analyzed the temporal and spatial changes of suspended sediment concentrations in Hanjiang River Estuary from 1988 to 2015. The results of suspended sediment concentration based on long time series of remote sensing big data are very helpful to conducive to the spatial and temporal evolution of suspended sediment concentrations of estuaries and coasts, but also the research of human activity effects, material cycle and environmental change.

SIGNIFICANCE STATEMENTS

This study discovers the trend and period change of suspended sediment concentration in Hanjiang River Estuary that can be beneficial for increasing awareness of environmental change and material cycle. This study help the researchers to uncover the critical areas of temporal and

spatial characteristic of suspended sediment concentration that many researchers were not able to explore. Thus, a new theory on the spatial and temporal evolution of suspended sediment concentrations in estuaries and coasts based on long series of Landsat imageries, may be arrived at.

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