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Fluctuations in the tidal limit of the Yangtze River estuary in the last decade

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Abstract The tidal limit is the key interface indicating whether water levels will be affected by tidal waves, which is of great significance to navigation safety and regional flood control. Due to limitations in research methods, recent changes in the Yangtze River tidal limit, caused by sea level rise and large-scale engineering projects, urgently need to be studied. In this study, spectrum analysis was undertaken on measured water level data from downstream Yangtze River hydrological stations from 2007 to 2016. The bounds of the tidal limit were identified through comparisons between the spectra and red noise curves, and the fluctuation range and characteristics were summarized. The results showed that: (1) During the extremely dry period, when the flow rate at Jiujiang station was about 8440 $m^3 s^{-1}$, the tidal limit was near Jiujiang; whereas during the flood season, when the flow rate at Jiujiang station was about 66700 $m^3 s^{-1}$, the tidal limit was between Zongyang Sluice and Chikou station. (2) From the upper to lower reach, the effect of the Jiujiang flow rate on the tidal limit weakens, while the effect of the Nanjing tidal range increases. The tidal limit fluctuates under similar flow rates and tidal ranges, and the fluctuation range increases with increasing flow rate and decreasing tidal range. (3) With the continued influence of rising sea levels and construction in river basin estuaries, the tidal limit may move further upstream.

Keywords Yangtze River estuary, Tidal limit, Extreme flow, Fluctuation characteristics, Spectrum analysis

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1. Introduction

As the tidal wave propagates upstream from the estuary, its influence on water levels weakens and completely disappears at the tidal limit (Samoilov, 1958). As the upper bound of the tidal reach, the tidal limit is the key interface that indicates whether the water level is affected by tide dynamics. At high tide, runoff in the downstream reaches of tidal rivers is blocked, and the water level is high. Complex tidal flow characteristics are important to the evolution of the river regime and stability of the bank slope. Therefore, fluctuations in the tidal limit under different hydrological conditions are of great significance to the safety of ports and navigation, and to regional flood control.

Tides are an important driving force on the hydrodynamics of the Yangtze Estuary. Previous studies generally agree that the tidal limit of the Yangtze River estuary in the dry season moved from its historical position above Jiujiang in the Jiangxi Province more than a thousand years ago, to near Anhui Datong around 30 years ago (Chen et al., 1979; Huang, 1986). Some studies have stated that the tidal limit in the early 21st century was between Tongling and Wuhu in

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the Anhui Province (Yun, 2004; Li et al., 2005; Xu et al., 2012). However, Datong in the Anhui Province is the most widely accepted location of the tidal limit. In recent years, a series of major water conservancy projects have drastically changed the spatial and temporal distribution of runoff in the Yangtze River basin. In particular, regulation and adjustment by the Three Gorges Project have smoothed the flow processes in the middle and lower reaches of the Yangtze River (Cai et al., 2012; Guo et al., 2015). The conversion of mechanical energy into electrical energy has reduced the total energy of the streamflow. In addition, the rising sea level affects tidal wave tracing (Wang et al., 2011; Cheng et al., 2018). These factors will inevitably cause changes to the location of the tidal limit, which has become a major issue of concern. Coincident with the catastrophic flood caused by the strong El Niño in 2016, elevations in water levels caused by the tidal range were very important for flood control.

The location of the tidal limit is usually studied by analyzing historical water levels (Xu et al., 2012), the correlation between water level and the tidal level at the estuary (Li, 1985), and the consistency between multi-segment observations (Liu and Ren, 2002). The response of the tidal limit to a water conservancy project is mainly determined through empirical curve fitting (Yang et al., 2012) and numerical simulation (Friedrichs and Aubrey, 1994; Unnikrishnan et al., 1997; Godin, 1999; Li, 2004; Shen H T et al., 2008; Shen H Y et al., 2008; Lu, 2009; Li, 2007; Hou, 2013). The tidal reach of the Yangtze River is hundreds of kilometers long, with numerous branches and complex geomorphology. Water levels along the reach vary, and it is costly to carry out simultaneous surveys of cross-sections along the river. Numerical simulations of water levels mostly lack in-depth verification with recent observations. In this study, measured water level data since 2007 was selected from hydrological stations along the middle and lower reaches of the main Yangtze River stream for spectrum analysis. Considering that runoff is the major factor controlling the location of the tidal limit, extreme flow processes were studied to identify the most recent location of the tidal limit and its response to different hydrological situations. Possible influencing factors were discussed, to provide guidance for future scientific research and development planning of the estuary in the context of global climate change and intensive construction of water conservancy projects.

2. Materials and methods

2.1 Hydrological data collection and processing

The study area stretches from Jiujiang, Jiangxi, to Wuhu, Anhui, with a total length of approximately 340 km (Figure 1).Water level data from 2007 to 2016 was measured at 12 hydrological stations, which from upstream to downstream are Jiujiang, Hukou, Pengze, Yangwan Sluice, Huayang Sluice, Anqing, Zongyang Sluice, Chikou, Datong, Tongling, Fenghuangjing Sluice, and Wuhu stations. Flow data at Jiujiang, Hukou, and Datong, and tide level data at Nanjing City were also collected during the study period. All the above data were sorted into one-hour intervals and outliers were excluded. In order to reduce the impact of non-tidal fluctuations, such as ship transportation, sluice dispatch, and the effect of seasonal climate change on water level changes, 80 short-term data sets of 5–10 days, showing relatively smooth water level changes, were selected from the data for spectrum analysis.

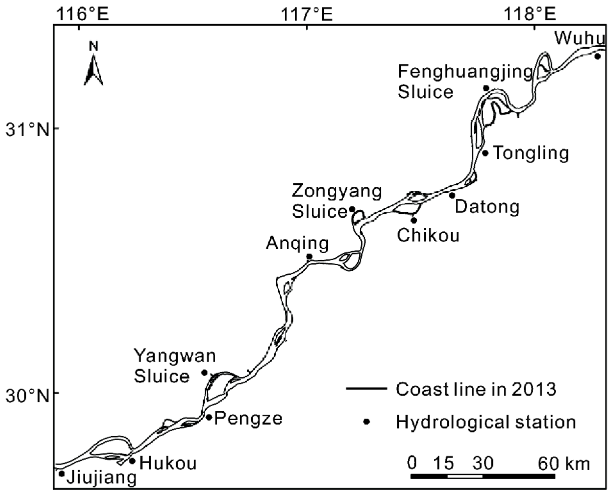

Figure 1 Distribution of the main hydrological sites along the Jiujiang to Wuhu Reach.

2.2 Time series analysis

Statistical analysis was undertaken using PAST 3.13 statistical analysis software. The REDFIT module (Schulz and Mudelsee, 2002) was used to analyze the frequency of water level variables. The Yangtze River is characterized by the semidiurnal tide (12-h period) in the coastal regions outside the estuary. The peak corresponding to the frequency of the half-day tide in the Yangtze River estuary was extracted and compared with the red noise curve under the first-order autoregressive model (Gilman et al., 1963; Hasselmann, 1976).

Taking Jiujiang station as a reference, the upper and lower bounds of the tidal limit were determined by analyzing extreme flows over the past ten years. The amplitude of the tidal cycle in water level observations at various stations, corresponding to different flow rates at Jiujiang, were analyzed to determine the relationship between the tidal limit and flow. The spectrum analysis results at different stations under different flow rates were analyzed to study the range and characteristics of recent changes in the tidal limit of the Yangtze River.

3. Results

3.1 Range of tidal limit fluctuations

3.1.1 Extreme flow conditions

Hydrograph data from the Jiujiang and Datong hydrological stations were used to identify the extreme flow conditions in the lower reaches of the Yangtze River over the past ten years. The minimum flow rate at Jiujiang station was approximately 8440 $m^3 s^{-1}$ on January 4, 2008, and on January 17, the second smallest value in the last decade was recorded at Datong station, approximately 9570 $m^3 s^{-1}$. The maximum flow rate at Jiujiang Station was about 66700 $m^3 s^{-1}$ on July 8, 2016. On July 13, 2016, the flow rate at Datong Station also reached the maximum in nearly ten years, at approximately 70700 $m^3 s^{-1}$. Therefore, these two periods represent the upper and lower bounds of the tidal limit at these locations (Figure 2).

3.1.2 Upper bound of the tidal limit

The lowest recorded water level at Jiujiang station in 10 years, approximately 8.01 m, was reached on December 23, 2007, during an extremely dry period. From December 20 to 26, the water levels showed a period of fluctuation of approximately half a day (Figure 3a). The peak in the power spectrum at the frequency corresponding to the 12-h tidal period, is higher than the red noise curve (Figure 3b), indicating that there is a significant half-day period to the water level variation. Jiujiang station is obviously affected by the half-day tide in the Yangtze River estuary. However, the tidal wave is very weak, with a tidal range less than 1 cm. Therefore, the upper bound of the tidal limit is near Jiujiang.

3.1.3 Lower bound of the tidal limit

The water level at Datong station peaked at approximately 15.66 m on July 8, 2016, during a period of extreme flooding. From July 7 to 13, the water level curve fluctuated significantly with a half-day period, but with a small amplitude. Figure 4a shows that the waveform is not complete. In the power spectrum curve (Figure 4b), the peak corresponding to the half-day period is higher than the red noise curve, indicating that there is a significant half-day period to the water level variation. During this period, the water level at Datong station was affected by the half-day tide in the Yangtze River estuary. The maximum tidal range was about 3 cm, with relatively limited tidal influence. The lower bound of the Yangtze River tidal region is likely near Datong.

The water level variation in the upper reaches of the Chikou station was similar to that of the Datong station, in which the half-day periodic fluctuation was relatively weak, and the amplitude and period were not obvious (Figure 4c). The peak corresponding to the 12-h period in the power spectrum is relatively flat, only slightly higher than the red noise curve (Figure 4d). Figure 4d shows that the water level was still affected by the half-day tide in the Yangtze River estuary, but the effect was weak, and the maximum tidal range was only about 2 cm.

While the overall trend in water level variations in the

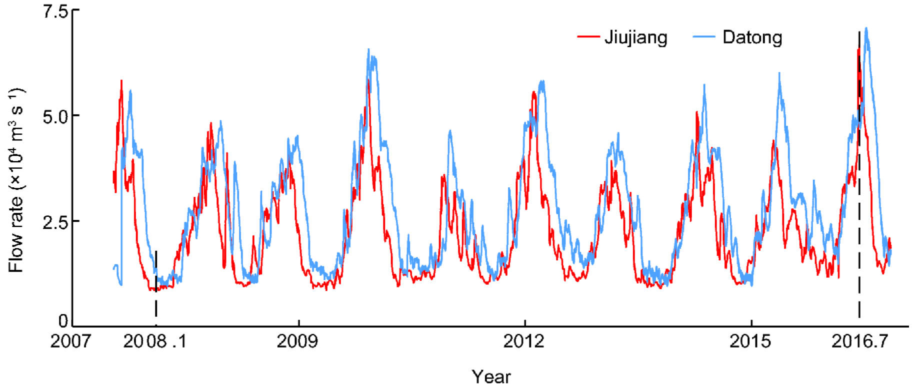

Figure 2 Hydrographs at Jiujiang and Datong stations, 2007–2016.

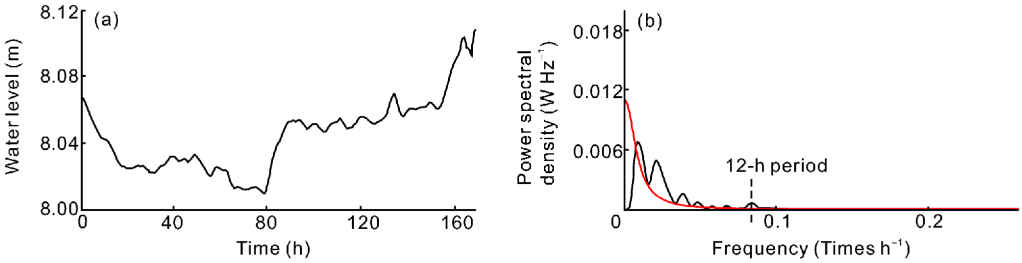

Figure 3 Water level spectrum analysis during the extreme dry period, 20–26 December 2007. (a) Water level curve; (b) power spectral density curve.

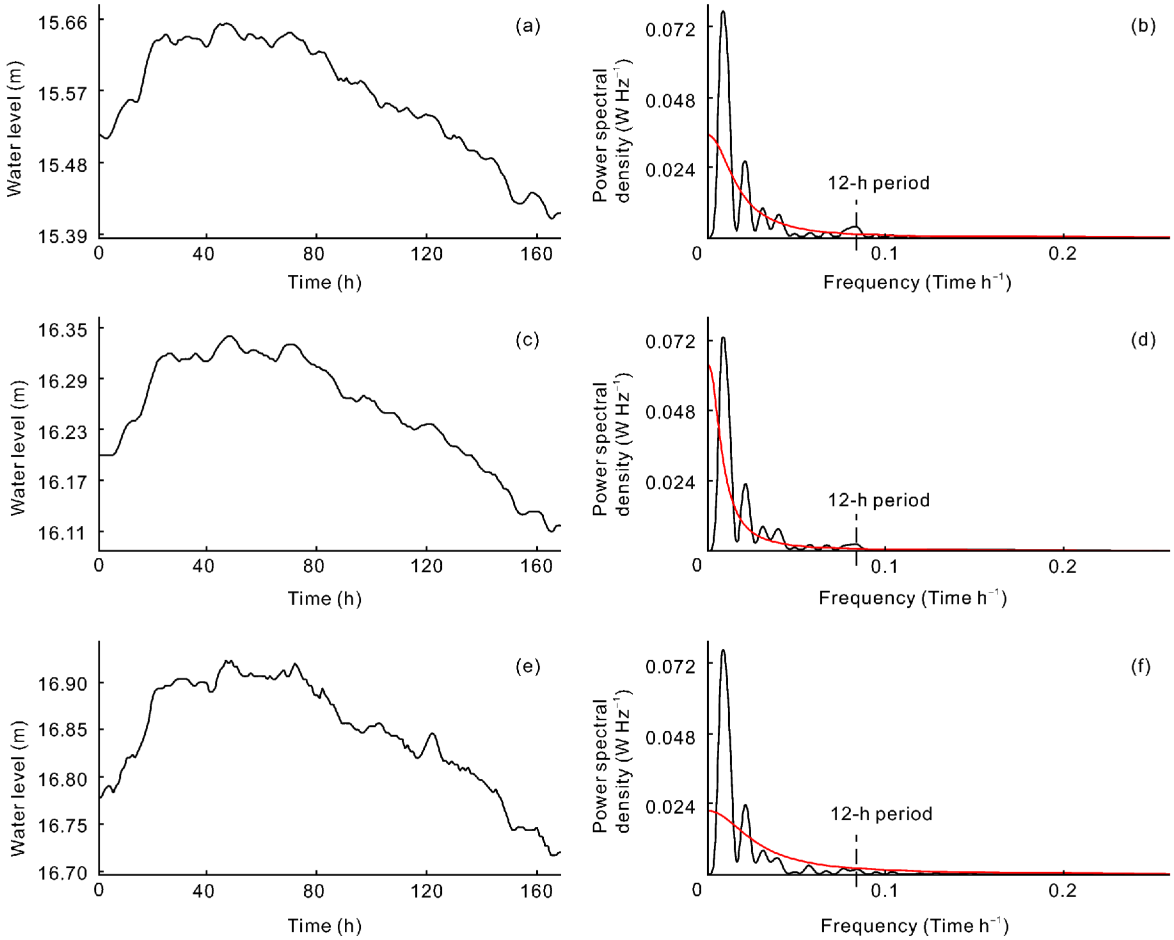

Figure 4 Water level spectrum analysis during the extreme flood period at Datong station ((a), (b)), Chikou station ((c), (d)), Zongyang Sluice station ((e) and (f)).

upper reach of Zongyang Sluice was the same as at the downstream Chikou and Datong stations, but the water level changes were less smooth, and the periodic fluctuations disappeared (Figure 4e). The peak corresponding to the 12-h period in the power spectrum is low and beneath the red noise curve (Figure 4f), indicating that the water level changes during the half-day cycle were not significant. During the extreme flood period, the water level was hardly affected by the half-day tide in the Yangtze River estuary. Therefore, the lower bound of the tidal limit lies between the Zongyang Sluice and Chikou stations.

3.2 Characteristics of tidal limit fluctuations

3.2.1 Jiujiang station

The results of spectrum analysis show that when the flow rate at Jiujiang station is less than 10000 $m^3 s^{-1}$ (Figure 5a), the 12-h periodic peak in the power spectrum is generally higher than the red noise curve, and the water level is affected by the tidal range. When the flow rate is greater than 10000 $m^3 s^{-1}$, the 12-h periodic peak gradually approaches the red noise curve (Figure 5b and 5c), and the influence of the tidal range gradually weakens or disappears. When the flow rate exceeds 12000 $m^3 s^{-1}$, the 12-h periodic peak in the power spectrum is negligible (Figure 5d), and the water level is not affected by the tidal range.

3.2.2 Hukou station

When the flow rate at Jiujiang station exceeds 12000 $m^3 s^{-1}$, the tidal range no-longer affects the water level at the station. However, during these periods, there is a significant 12-h periodic peak in the power spectrum of the water level at Hukou station, which is higher than the red noise curve (Figure 6a and 6b). When the flow rate at Jiujiang exceeds 19000 $m^3 s^{-1}$, the 12-h periodic peak gradually approaches the red noise curve (Figure 6c), indicating the tidal range effect is weak; and when the flow exceeds 21000 $m^3 s^{-1}$, the 12-h periodic peak is generally lower than the red noise curve (Figure 6d), and the water level is not affected by the tidal range.

3.2.3 Pengze station

When the flow rate at Jiujiang station exceeds 21000 $m^3 s^{-1}$, the water level at Hukou station is not affected by the tidal

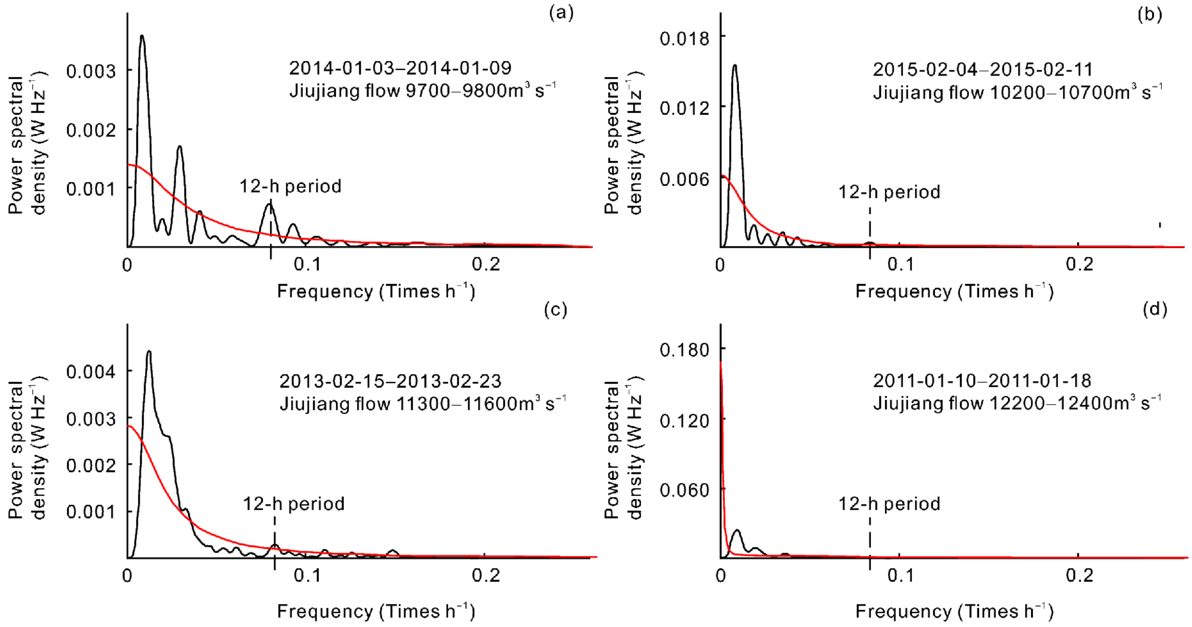

Figure 5 Water level spectrum analysis at Jiujiang station for different flow rates.

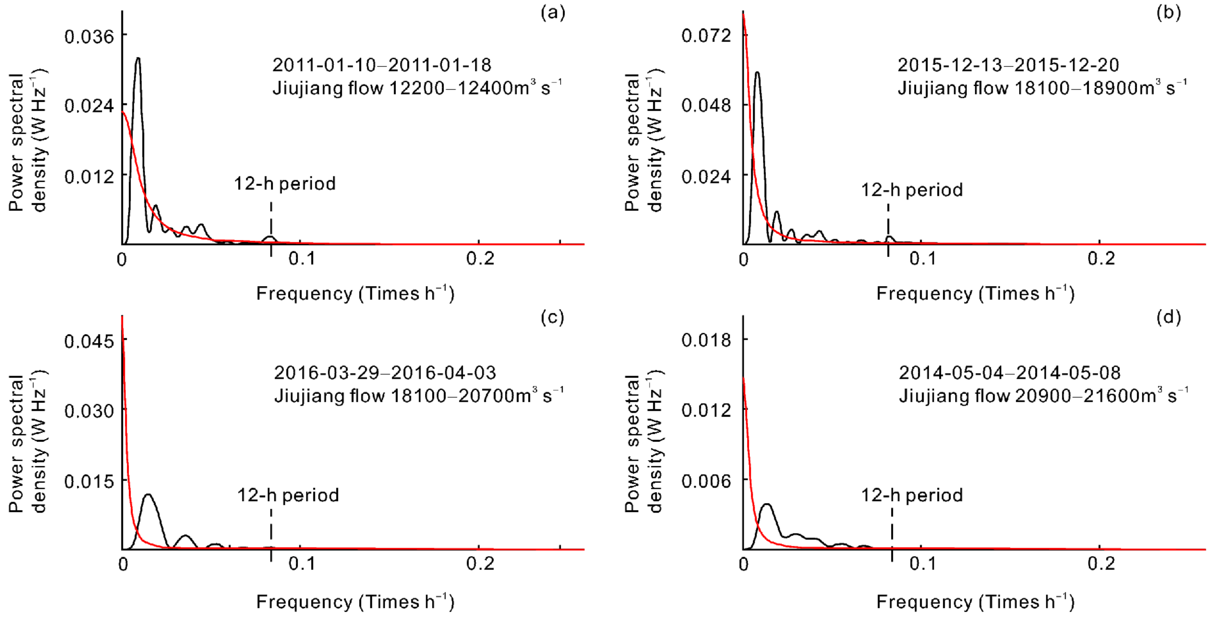

Figure 6 Water level spectrum analysis at Hukou station, corresponding to during different flow rates at Jiujiang station.

range. During these periods, there is still a significant 12-h periodic peak in water levels at Pengze station (Figure 7a). The influence of the tidal range partially disappears when the flow rate is higher than 34000 m^3 s^{-1} (Figure 7b and 7c), and the water level is not affected by tidal range when the flow rate exceeds 38000 m^3 s^{-1} (Figure 7d).

3.2.4 Anqing station

While the effects of the tidal range cannot be seen at Pengze station at flow rates exceeding 38000 m^3 s^{-1} at Jiujiang station, there is still a significant 12-h periodic peak visible in the power spectrum of water level at Anqing station (Figure 8a). Above 44000 m^3 s^{-1}, the influence of tidal range gradually decreases (Figure 8b and 8c), and when the flow exceeds 58000 m^3 s^{-1}, the 12-h periodic peak is generally lower than the red noise curve (Figure 8d).

3.3 Relationship between flow rate, tidal range, and tidal limit

The response of the water level to the tidal range at each hydrological station in the 80 selected study periods was

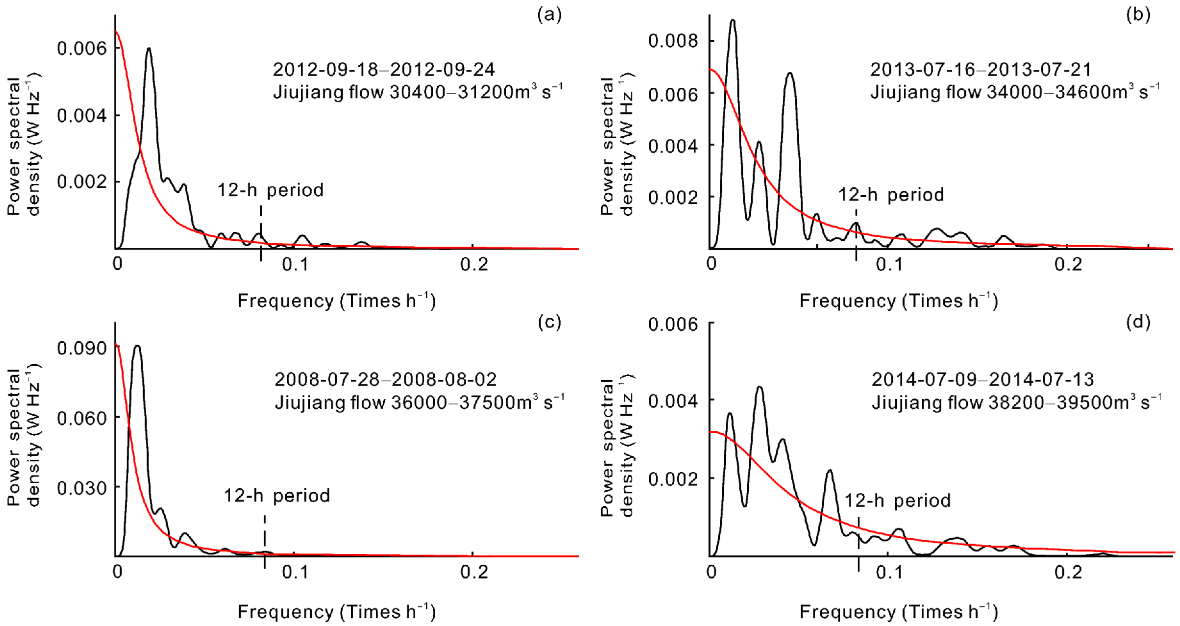

Figure 7 Water level spectrum analysis at Pengze station, corresponding to during different flow rates at Jiujiang station.

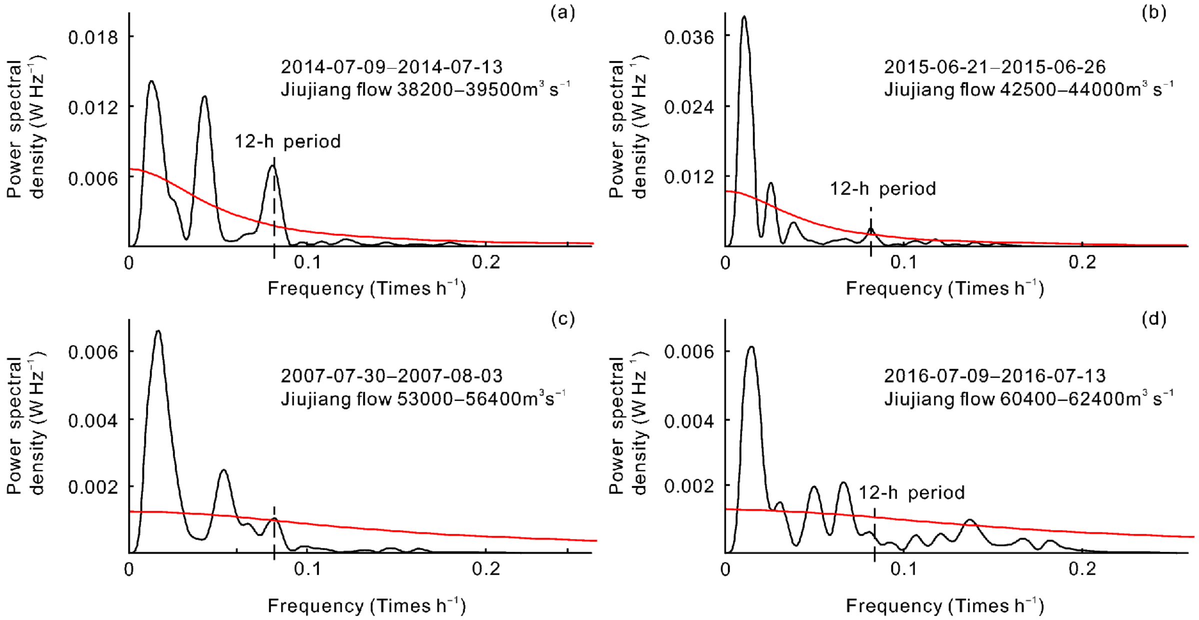

Figure 8 Water level spectrum analysis at Anqing station, corresponding to during different flow rates at Jiujiang station.

obtained through spectrum analysis. Among the statistical results, 53 time periods showed significant tidal limit characteristics, that is, the water level was affected by the tidal range, but the amplitude was very small. Their locations were considered to represent the tidal limit at the corresponding point in time. The average flow rate at Jiujiang station and the average tidal range at Nanjing station during the same period were calculated to analyze the relationship between the flow rate, tidal range, and the tidal limit. The distances between major hydrological stations, and the stations and the shoreline, are shown in Table 1.

3.3.1 Relationship between the Jiujiang flow rate and the tidal limit

The analysis results show that there is a significant positive correlation between the distance from Jiujiang to the tidal limit and the average flow rate at Jiujiang. When the average flow at Jiujiang is 8000–10000 m^3 s^{-1}, the tidal limit is lo-

Table 1 Distances between major hydrological stations along the main stream of the Yangtze River[a)]

Hydrological station	Jiujiang	Hukou	Pengze	Yangwan Sluice	Anqing	Zongyang Sluice	Chikou	Datong	Nanjing
Yangtze River channel mileage (km)	790	768	733	715	637	605	580	565	355
Jiujiang mileage (km)	0	22	57	75	153	185	210	225	435
50# buoys mileage (km) (Yangtze River estuary)	948				778			699	462

a) The channel mileage data is derived from the Wuhan-Shanghai navigation reference map, 2013. The starting point is Shanghai Wusongkou, and the distance is the mileage of the navigation channel. The 50# buoy mileage is from Yang et al. (2012), the distance is the shoreline mileage

cated near Jiujiang; when the average flow at Jiujiang is 12000–21000 $m^3 s^{-1}$, the tidal limit is located near Hukou; when the average flow at Jiujiang is 21000–27000 $m^3 s^{-1}$, the tidal limit is located near Pengze; when the average flow at Jiujiang is 29000–38000 $m^3 s^{-1}$, the tidal limit is between Pengze and Anqing; and when the average flow at Jiujiang is above 38000 $m^3 s^{-1}$, the tidal limit is between Anqing and Chikou. Fluctuations in the tidal limit were observed at similar flow rates. When the average flow rate at Jiujiang is about 10000 $m^3 s^{-1}$, the fluctuation range of the tidal limit is small, less than 20 km. The fluctuation range increases with increased flow rate; above 30000 $m^3 s^{-1}$, the tidal limit fluctuates widely, sometimes exceeding 100 km (Figure 9).

The flow rate-tidal limit relationship was divided into three periods, 2007–2010, 2011–2013, and 2014–2016 for comparative analysis. The results show that the three periods have similar overall trends, but the curves become steeper with time. This indicates that the range of the tidal limit has gradually decreased: the tidal limit during flood periods has shifted upstream, the tidal limit during the dry season has shifted slightly downstream, and the range of fluctuation in the tidal limit has gradually decreased at similar flow rates (Figure 9).

3.3.2 Relationship between the Nanjing tidal range and the tidal limit

The analysis results show that there is a significant negative correlation between the distance from Jiujiang to the tidal limit and the average tidal range at Nanjing. When the Nanjing average tidal range is above 1 m, the tidal limit is located near Jiujiang; when the Nanjing average tidal range is 0.5–1 m, the tidal limit is mainly located between Jiujiang and Pengze; when the Nanjing average tidal range is 0.35–0.5 m, the tidal limit is mainly located between Hukou and Anqing; when the Nanjing average tidal range is 0.28–0.35 m, the tidal limit is mainly located between Pengze and Zongyang Sluice; and when the Nanjing average tidal range is less than 0.28 m, the tidal limit is mainly located between Anqing and Chikou (Figure 10). Fluctuations in the tidal limit were observed at similar tidal ranges, with the fluctuation range increasing as the tidal range decreases.

The tidal range-tidal limit relationship was divided into three periods, 2007–2010, 2011–2013, and 2014–2016 for comparative analysis. The results show that the three groups have similar overall trends; however, the trend line fitted to the 2014–2016 data is skewed more to the left than the other two periods. Figure 10 shows that in the past three years, the location of the tidal limit has shifted slightly upstream while the tidal range remained largely constant (Figure 10).

3.3.3 Influence of flow rate and tidal range on the tidal limit

The relationship between the average flow rate at Jiujiang and the tidal range at Nanjing was established for different tidal limit locations, to analyze the combined effect of streamflow and tides on the tidal limit fluctuation (Figure 11). The results show that moving from upstream to downstream, the influence of the flow rate at Jiujiang on the tidal limit fluctuation decreases, while the impact of the Nanjing tidal range increases. When the tidal limit is located near Jiujiang, similar low flow rates are recorded for large variations in the tidal range. When the tidal limit moves downstream to Hukou and Pengze, the tidal limit is affected significantly by the flow rate, and both the flow rate and tidal range fluctuate. When the tidal limit is located near Anqing and Zongyang, the influence of tidal range is significant; with large changes in the Jiujiang flow rate, small tidal range variations are recorded, demonstrating that the tidal limit is significantly affected by the tidal range (Figure 11).

4. Discussion

4.1 Validation of the analysis results

The results of this study show that the tidal limit of the Yangtze River in the dry season reaches close to Jiujiang, which is about 225 km upstream from Anhui Datong, widely considered to be the tidal limit in previous studies (Chen et al., 1979; Huang, 1986; Chen and Chen, 2000; Yun, 2004). To ensure the results were not impacted by non-tidal fluctuations in water level, the process of propagation of tidal waves along the Jiujiang-Datong reach during the dry period was further verified. Because there is a large difference in the water level at each site, it is difficult to compare water level

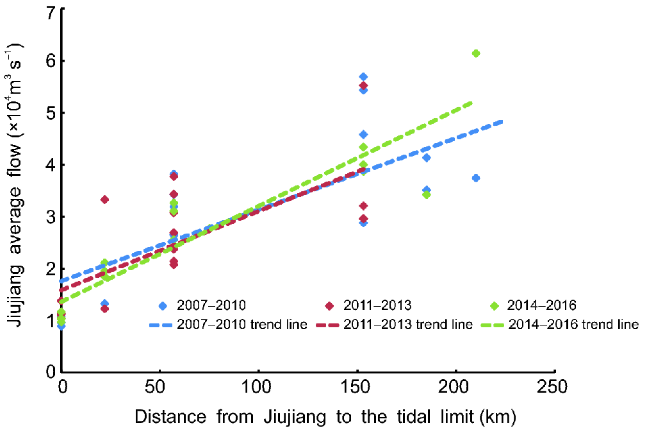

Figure 9 Relationship between the average flow rate at Jiujiang and the tidal limit.

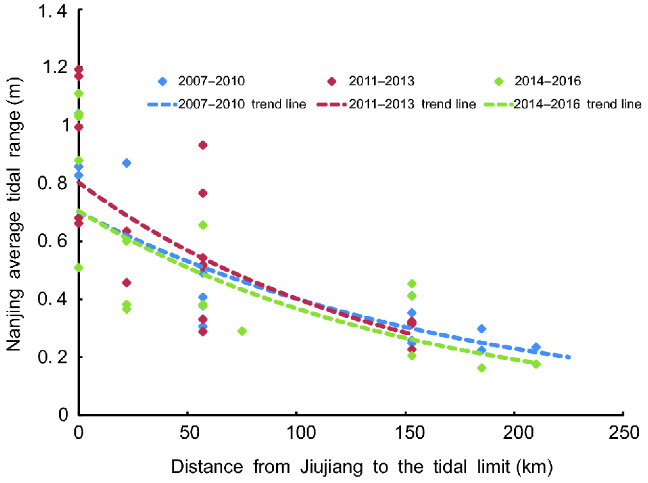

Figure 10 Relationship between Nanjing average tidal range and the tidal limit.

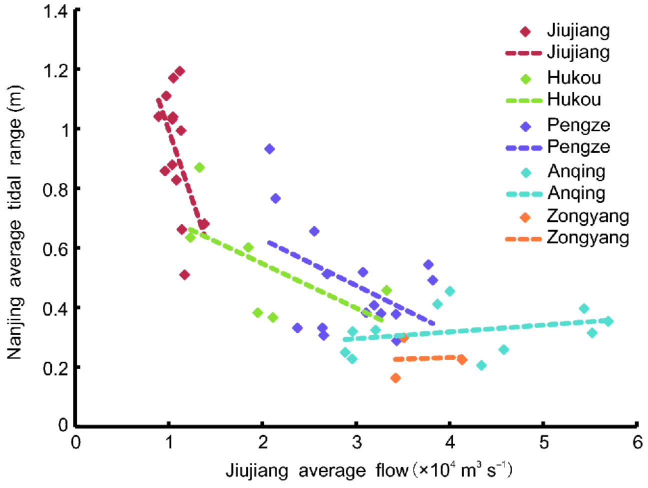

Figure 11 Relationship between Jiujiang flow rate, Nanjing tidal range, and the tidal limit.

changes between stations directly. To simplify the analysis, firstly the measured water level data were transformed to standardized water levels (Guo and Yi, 2008):

$$u = \frac{x-\mu}{\sigma}, \qquad (1)$$

where u is the standardized water level, x is the observed water level, μ is the sample mean, and σ is the sample standard deviation.

From December 18 to 27, 2007, the standardized water level time series showed that, at Datong station, the period of fluctuation in the water levels was stable, the process line waveforms were regular and complete, and the tidal range was significant. The maximum tidal range in the measured water levels was about 19 cm, the minimum tidal range was about 1 cm, and the average tidal range was about 8 cm. Over the same timeframe, the waveform and period of fluctuations in the water levels at Anqing station were in good agreement with Datong Station. The tidal range was still significant but had decreased, and the crest and trough of the tidal wave appeared at Anqing station around 1–4 h later than at Datong (Figure 12a). At Pengze station, the variation in water levels was similar to Anqing station, with most waveforms clearly observable. However, the tidal range was further reduced, and the crest and trough of the tidal wave appeared 2–5 h later than at Anqing (Figure 12b). When the water level changes drastically, like at Juijiang station, the water level fluctuations become less cyclic and relatively scattered. The water level variation at Jiujiang station was weakly consistent with Pengze station, but a small tidal range, corresponding to the significant waveforms downstream, could be observed. The crest and trough of the tidal wave occurred around 1–2 h later than at Pengze station (Figure 12c).

On December 18 and 19, the tidal range was significant and the waveforms were relatively complete at all four stations analyzed above. The analysis of tidal wave propagation showed that the propagation time between Datong and Anqing was about 2.5 h. Considering the hydrological station locations (Table 1), the average wave speed was about 28.8 km h^{-1} from Datong to Anqing. The propagation time was about 4.7 h from Anqing to Pengze, with an average wave speed of about 20.4 km h^{-1}, and 1.7 h from Pengze to Jiujiang, with an average speed of about 33.5 km h^{-1} (Figure 13). The water levels at these stations show the complete propagation of the tidal wave from Datong to Jiujiang during the dry period. The tidal range decreases from downstream to upstream and there is a clear delay in wave arrival. The average propagation speed is similar to that of the tidal wave in the estuary. These characteristics confirm the result of the spectrum analysis, that the upper bound of the tidal limit is near Jiujiang.

Compared with recent studies (Xu et al., 2012; Li, 2007; Hou, 2013; Yang et al., 2012) the tidal limit has shifted upstream, which may in part be due to different research methods. Previously, the tidal limit was often determined

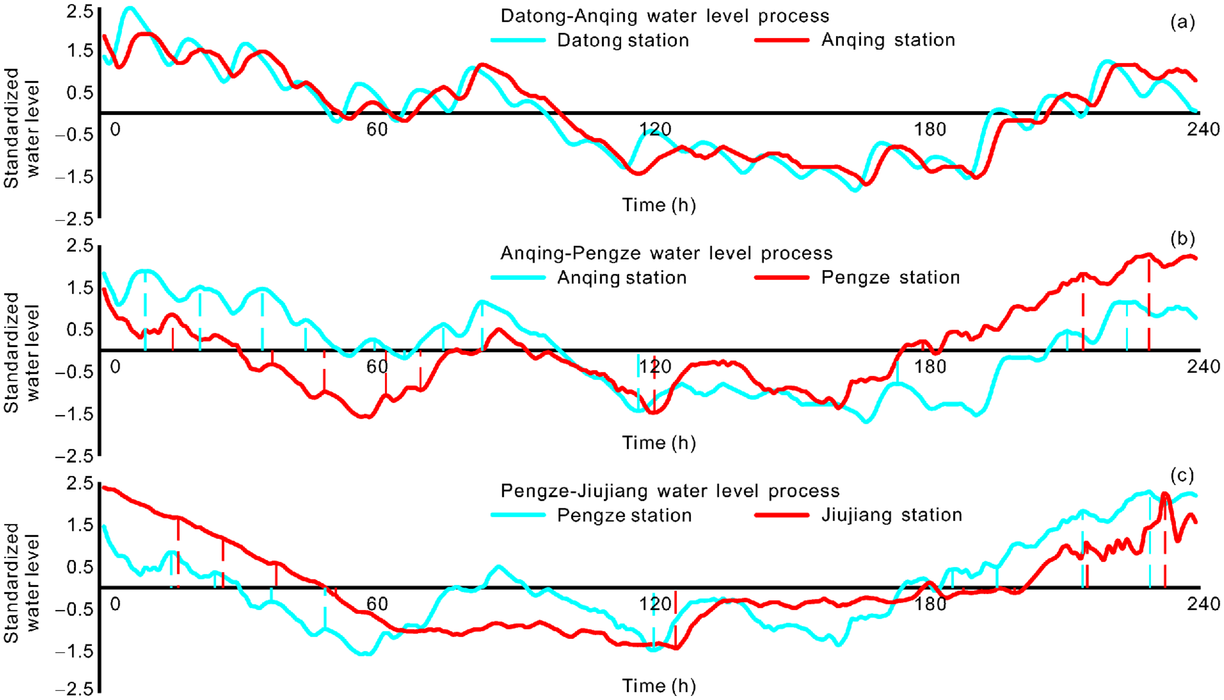

Figure 12 Standardized water levels along the Jiujiang-Datong reach, 18–27 December 2007.

through directly analyzing the observed water level changes, taking the location where a significant tidal range occurred as the tidal limit. Sometimes, the tidal range was around 10 cm at the selected location. While this method can reflect changes in the tidal limit, the result is subjective because of the limitations of the research methods and reliance on judgment. The theoretical tidal limit should be upstream of the previously identified location. The tidal limit is defined as the critical location where the tidal wave disappears completely, and the water level is mainly affected by streamflow. It is difficult to intuitively judge the influence of the tidal range from the timeseries of water levels. In this study, spectrum analysis and red noise curves were used to determine whether the water level was affected by the tidal range, and the results were validated using a standardized water level process curve. Validation proved that spectrum analysis is a reasonable and effective method for tidal limit research. In determining the upper and lower bounds of the tidal limit, the average tidal range observed in the water levels was less than 2 cm. Therefore, this method also improves the accuracy of research on the tidal limit.

4.2 Parameters to characterize streamflow and tide

Considering the transmission time for tidal waves, the suitability of the average tidal range at Nanjing station to characterize the estuarine tidal dynamics was examined. Previous studies found that the average velocity of tidal wave propagation in the tidal reach of the Yangtze River is 35.6 km h^{-1} (Li, 2004). The distance from Jiujiang to Nanjing is about 435 km. The time for the tidal wave to reach Jiujiang is about half a day, only 5% to 10% of the analysis period, and the tidal range at Nanjing can affect the water levels at Jiujiang within the same time. Therefore, it is reasonable to choose the average tidal range at Nanjing station to reflect the estuary tidal intensity.

The tidal limit, which is the location where the tidal range just disappears, should be predominantly affected by streamflow. However, with increasing average flow at Jiujiang, the impact on the tidal limit was reduced. When the difference of Jiujiang flow was around 30000 $m^3 s^{-1}$, the tidal limit has fluctuated around Anqing (Figure 9), which probably means that flow processes at Jiujiang are not a good predictor of the flow rate at Anqing. Previously, the prediction of the tidal limit often used the measured flow rate at a single station to characterize streamflow intensity. However, the recent tidal limit fluctuation range was about 210 km, along a river reach with numerous lakes and tributaries and many water conservancy projects. The flow rate at a single station cannot represent the streamflow intensity over the entire tidal reach. Therefore, further analysis of runoff parameters is required for tidal limit prediction.

Previous researchers have used the ratio of the tidal range to the flow rate to characterize the process of dynamic change between the two variables, which can reflect the characteristics of tidal limit fluctuations to some extent (Yang et al., 2012). However, it can be seen from the relationship between the Nanjing tidal range, the Jiujiang flow

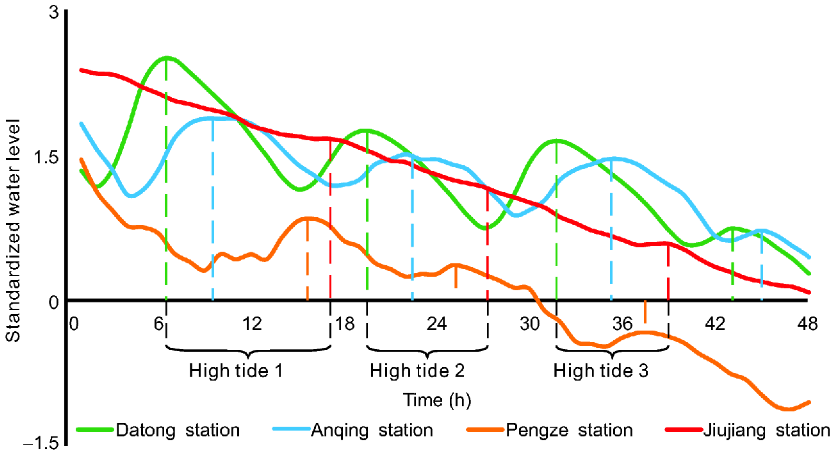

Figure 13 Tidal wave propagation along the Jiujiang-Datong reach, 18–19 December 2007.

rate, and the tidal limit (Figure 11) that the effect of streamflow and tidal range on the tidal limit is not a simple linear relationship. The ratio varies even with small changes in the location of the tidal limit, and the fluctuation range changes significantly throughout the year. Therefore, this parameter has to be improved for accurate prediction of the tidal limit.

4.3 Factors influencing the tidal limit

In general, the tidal limit of the Yangtze River is the result of interaction between the flow rate and the tidal range, which are the direct influencing factors of tidal limit fluctuations. The relationship between the average flow rate at Jiujiang and the average tidal range at Nanjing indicates that the contribution of each factor differs along the reach. Similar phenomena have been identified in previous studies through numerical simulations of tidal wave propagation in an ideal estuary (Li, 2004). From the dynamic point of view, since the tidal range exponentially decays (Wang, 1991), the differences may gradually decrease when tidal waves of different amplitude propagate upstream. The tidal wave propagates far upstream under low-flow conditions during the dry season, and the tidal range has reached a similar level when arriving at Jiujiang. Therefore, the tidal limit in the dry season has no obvious response to the tidal range at Nanjing and is mainly controlled by the flow rate. During the flood season, the volume and convergence of runoff in the lower Jiujiang river basin, as well as storage and flow regulation by the Poyang Lake, tributaries, and sluices, are all enhanced, which may result in the smaller impact of the Jiujiang flow rate on the downstream water level. The tidal limit in the flood season is not only controlled by the flow rate at Jiujiang, but also by factors affecting local runoff such as lakes, tributaries, and water conservancy projects, and estuarine tidal factors. Overall, the flow rate is still the dominant factor affecting the location of the tidal limit.

The continuous development and utilization of hydropower resources along the Yangtze River has reduced the total energy of streamflow and caused the tidal limit to move upstream. Among the hydropower projects, the Three Gorges Project, which began production in 2003, is the most representative. Its annual design power generation capacity is 88.2×10^9 kWh. It has been operating stably and efficiently for 14 years, and the total power generated has exceeded 10^{12} kWh. In 2014, the total power generated was 98.8×10^9 kWh, a world record for annual power generation by a single hydropower station. Kinetic energy in the Yangtze River is converted into electrical energy on a large scale. Since the closure of the Three Gorges Dam, the runoff energy has been reduced by at least 3.18×10^{17} J per year, making it possible for tidal energy to be transported further upstream. Thus, the tidal limit has moved significantly upstream under relatively stable flow conditions.

In recent years, rising sea levels have also caused the reference plane of tidal waves to rise. The reduction in water surface slopes indirectly enhances the tidal power and allows tidal waves to propagate farther, which may lead to the tidal limit moving upstream under similar tidal ranges. The evolution of the river regime after the construction of many large-scale projects in the Yangtze River basin also indirectly impacts the tidal limit. On the one hand, water conservancy projects in the main stream of the Yangtze River intercept sediment while regulating flow, which may lead to erosion of the lower reaches, decreasing the longitudinal slope of the riverbed. On the other hand, reclamation and waterway regulation in the Yangtze River estuary have narrowed the river channel and stabilized the depth, which allows tidal waves to propagate upstream more easily. In addition, as the Yangtze River waterway is an important resource for economic development, the cross-strait shoreline has generally been strengthened, and the lateral diffusion of tidal waves has been constrained, which may also result in significant upstream movement of the tidal limit under similar flows during the flood season. The evolution of the river bed along the reach affected by tidal limit fluctuations may have a significant impact on the regularity of the tidal limit.

5. Conclusion

On the basis of previous research, spectrum analysis was performed on measured water level data at hydrological stations in the lower reaches of the Yangtze River and combined with red noise curves to determine the observable tidal range and the upper and lower bounds of the tidal limit. Statistical analysis was used to determine the characteristics of temporal changes in the tidal limit. The main findings are as follows:

From 2007 to 2016, the flow rate at Jiujiang station was between 8440 and 66700 $m^3 s^{-1}$. Spectrum analysis showed that during the extreme dry season, the tidal range was slightly visible in the Jiujiang water level data, indicating that the upper bound of the tidal limit is near Jiujiang. During the extreme flood period, the tidal range was observed at Chikou station and disappeared at Zongyang Sluice. Therefore, the lower bound of the tidal limit is located between Zongyang Sluice and Chikou station.

The overall fluctuation range of the recent tidal limit in the Yangtze River estuary is from Jiujiang, Jiangxi Province to Chikou, Anhui Province. The distance from Jiujiang to the tidal limit is significantly positively correlated with the average flow rate at Jiujiang station, and significantly negatively correlated with the average tidal range at Nanjing station. The tidal limit fluctuates under similar flow rates and tidal ranges. The range increases with increasing flow rate and decreasing tidal range.

From upstream to downstream, the influence of the Jiujiang flow rate on the tidal limit weakens, and the influence of the Nanjing tidal range increases. The spectrum analysis method can effectively improve accuracy in determining the tidal limit. However, the parameters that characterize the flow rate and the tidal range still need to be improved.

The tidal limit has moved upstream in recent years. Rising sea levels and riverbed evolution caused by large-scale engineering construction may lead to further upstream shifts in it.

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