

Response Relationship between Channel Morphological Adjustment and Bank Collapse in Typical Reaches of the Middle Yangtze River

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Abstract. Based on daily discharge and water level data from Shashi and Luoshan stations, Landsat remote sensing images, fixed cross-section topography, and bank collapse records in typical reach of the middle Yangtze River, this study integrates Mann–Kendall trend analysis, water body index extraction, cross-sectional analysis, and other methods to investigate the evolution characteristics and driving relationships of discharge–water level variation, shoal-bar erosion and deposition, cross-sectional adjustment, and bank collapse. The results indicate that: (1) Runoff exhibits a pattern of “increased low-flow period, and stable flood-season flow,” while water levels show a significant annual decline, reflecting the dominant control of channel incision on water level changes. (2) Between 1987 and 2017, pre- and post- Three Gorge reservoir operation, the shoals shifted from substantial rightward migration to localized erosion, with dramatic cross-sectional adjustments (e.g., the thalweg of cross-section Jing-178 dropped by 10.9 m, and the right bank of Jing-182 retreated by 1200 m). (3) From 2003 to 2024, the cross-sectional areas of the low-water channel and bankfull channel increased by 2,600 m² and 4,050 m², respectively, indicating pronounced erosion expansion. (4) Bank collapses were concentrated at the right bank of Jing181 (16 events) and the left bank of Li8 (10 events), displaying stage-specific activity. (5) Bank collapse length is highly positively correlated with cumulative erosion and deposition volume of the low-water channel ($R^2 = 0.84$), indicating that lateral erosion of the low-flow channel is a key factor in bank slope instability. These findings provide a scientific basis for channel evolution understanding and bank collapse prevention.

Keywords: Middle Yangtze River; channel morphology; bank collapse; Three Gorges Reservoir.

1. Introduction

Shoal-bars (including sidebars and mid-channel bars) in alluvial rivers are critical landforms of riverbeds, and their evolution directly affects flood control, navigability, and ecosystem services [1–2]. Large-scale reservoir construction alters downstream hydro-sediment regimes, profoundly influencing shoal-bar morphology and channel stability [3–4]. Since the impoundment of the Three Gorges Reservoir, the incoming water and sediment conditions downstream in the middle Yangtze River have changed significantly, leading to persistent channel erosion, shoal-bar shrinkage, and bank instability [5–9]. In particular, the reach from Xiongjiazhou to Chenglingji, characterized by strong bend flow dynamics and complex boundary conditions, experiences frequent bank erosion events, posing serious threats to levee safety and channel stability. Zhu et al. [6] observed continuous erosion in low and mid-elevation shoals and pronounced retreat of high shoal edges; Huang [9] identified four scouring-silting patterns in the Jingjiang reach based on the centroid position of shoal-bars, defining a characteristic flow range of 10,000–20,000 m³/s as the most influential on shoal-bars. Yang et al. [10], using 1960–2020 hydrological, sediment, and topographic data, revealed that riverbed scouring significantly reduced the area of mid-channel bars and side bars, with hydro-sediment variations and channel regulation projects being the main factors affecting channel depth and shoal-bar stability. However, existing studies mostly focus on

macro-scale erosion and deposition along the whole river reach, and knowledge of shoal evolution, cross-sectional morphological adjustment, and spatial-temporal differentiation of bank collapse in typical reverse-curved bends remains insufficient. Moreover, the driving relationships between runoff–water level variations and channel adjustments require further investigation.

Therefore, this study, based on long-term hydrological data from Shashi and Luoshan stations, focuses on dry-season shoal morphology under consistent water level conditions, combined with multi-temporal Landsat imagery, and cross-sectional topographic data. Methods including Mann–Kendall trend analysis, water body index extraction, cross-sectional morphological analysis, and regression modeling were applied to: (1) investigate intra-annual variation characteristics of discharge and water levels; (2) examine shoal erosion-deposition evolution and cross-sectional adjustments in typical reverse-bend reaches of Qigongling and Guanyinzhou; (3) analyze spatial-temporal distribution of bank collapse; (4) quantify the driving relationship between low-flow channel erosion and bank collapse. The results provide a scientific basis for bank collapse early warning, navigation channel regulation, and flood safety in the Jingjiang reach.

2. Study Area and Methods

2.1 Study Area

The Jingjiang reach of the middle Yangtze River extends from Zhicheng to Chenglingji, with a total length of approximately 347.2 km, divided into upper and lower Jingjiang by the Ouchi Estuary. The Xiongjiashou – Chenglingji reach is located at the tail of the lower Jingjiang, composed of three reverse bends: Xiongjiashou, Qigongling, and Guanyinzhou (Fig. 1). The reach length is 43.8 km, but the straight-line distance is only 16.5 km, with a sinuosity of 2.65, representing a typical meandering reach. Due to the thalweg impinging on the banks, local bank sections are subjected to long-term mainstream attack, steepening the bank slopes and keeping the river regime in constant adjustment. Considering that the Xiongjiashou bend is a bifurcated channel type, this paper focuses on the two reverse bends of Qigongling and Guanyinzhou.

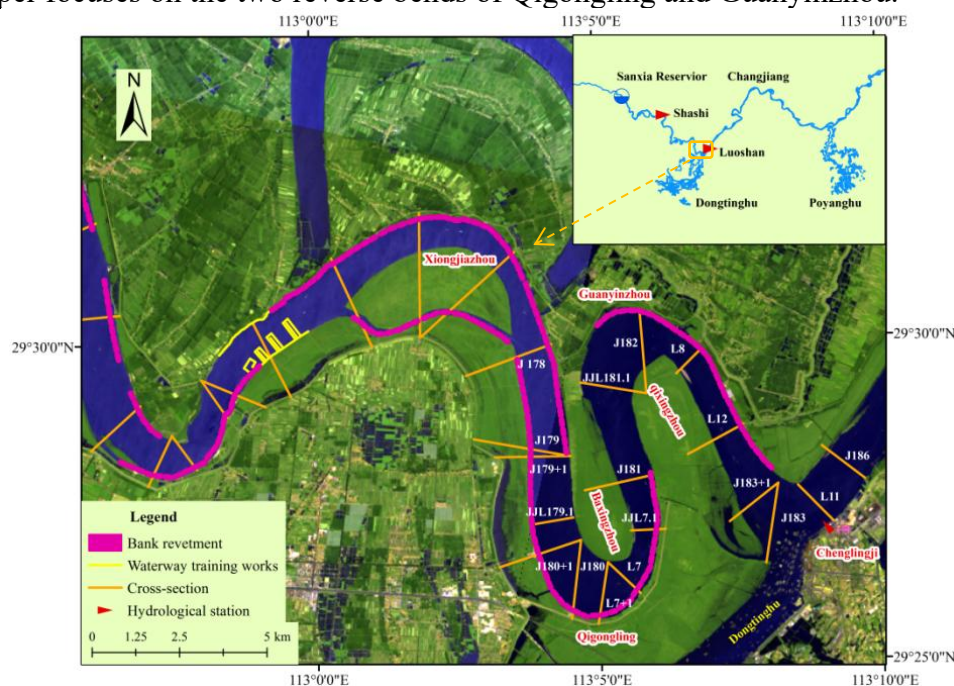


Fig. 1 Sketch Map of the study area

2.2 Data Sources and Methods.

The datasets include: (1) daily discharge and water level series at Shashi and Luoshan stations (1987-2023); (2) seven sets of dry-season Landsat imagery (1987 – 2017); (3) measured topography

of eight fixed cross-sections in the study reach (2003 – 2024); (4) bank collapse records including occurrence time, frequency, and type. Mann-Kendall non-parametric tests were used to analyze long-term trends in runoff and water levels, defining dry season as December-February and flood season as June-September, with $|Z| > 1.96$ indicating significant trends. Based on Google Earth Engine, MNDWI and NDWI indices were calculated to extract water boundaries. ArcGIS overlay analysis identified areas of shoal-to-water conversion (erosion) and water-to-shoal conversion (deposition). Cross-sectional analyses were conducted using characteristic water levels to quantify morphological parameters of the low-flow channel and bankfull channel, including thalweg elevation, were statistically analyzed

3. Results

3.1 Intra-Annual Variations of Runoff and Water Level

The Mann-Kendall analysis of monthly runoff and water level at Shashi and Luoshan stations (1990-2023, Table 1) reveals pronounced seasonal differentiation in the middle Yangtze River. During the dry season (Dec-Feb), runoff at Shashi increased significantly, with Z-values exceeding 5 (Dec $Z = 3.17$; Jan $Z = 5.31$; Feb $Z = 5.57$). Luoshan station also showed moderate but significant upward trends ($Z > 2$). In spring (Mar-May), runoff at Shashi station continued to increase, although the trend's significance weakened, whereas trends at Luoshan station remained mostly insignificant. During the main flood season (Jun-Sep) and autumn (Oct-Nov), runoff variations at both stations were generally not significant. Specifically, Shashi station showed a modest declining trend during the flood season (average $Z = -2.14$), whereas Luoshan station did not reach statistical significance. These results collectively indicate a pattern of “significant dry-season flow increase accompanied by an insignificant trend during the flood season”.

In contrast, Shashi water levels declined persistently year-round (dry season $Z = -5.66$; flood season $Z = -3.47$), whereas Luoshan remained relatively stable, declining significantly only in October ($Z = -2.40$). This decoupling indicates that ongoing channel incision at Shashi dominates water level variations, outweighing the effect of enhanced low-season flows. Thus, despite increased dry-season runoff, continuous riverbed erosion drives declining water levels, highlighting the key role of channel incision in regulating hydrological conditions.

Table 1. Mann-Kendall trend test of monthly mean discharge and water level at Shashi and Luoshan stations (1990 – 2023)

Month	Runoff				Water level			
	Shashi Z	Trend	Luoshan Z	Trend	Shashi Z	Trend	Luoshan Z	Trend
January	5.31	↑***	3.2	↑**	-3.71	↓***	1.19	—
February	5.57	↑***	2.67	↑**	-3.59	↓***	0.53	—
March	4.95	↑***	1.51	—	-2.28	↓**	0.19	—
April	3.83	↑***	1.01	—	-1.65	—	-0.06	—
May	1.93	—	1.31	—	-1.19	—	0.62	—
June	-1.04	—	0.03	—	-3.44	↓***	-0.03	—
July	-1.63	—	-1.51	—	-2.4	↓**	-1.42	—
August	-1.07	—	-1.48	—	-2.7	↓**	-1.42	—
September	-1.57	—	-1.28	—	-2.64	↓**	-1.39	—
October	-1.81	—	-1.78	—	-3.77	↓***	-2.4	↓*
November	-0.03	—	-0.28	—	-4.74	↓***	-1.66	—
December	3.17	↑**	1.57	—	-5.81	↓***	-1.96	—
Dry-season average	5.43	↑***	3.41	↑***	-5.66	↓***	-0.03	—
Flood-season average	-2.14	↓*	-1.72	—	-3.47	↓***	-1.6	—

Notes: ↑ increase, ↓ decrease, — no significant trend ($|Z| \leq 1.96$); *** indicates $p < 0.001$, ** indicates $p < 0.01$, * indicates $p < 0.05$

3.2 Dry-Season Remote Sensing Analysis of Shoal-Bar Morphodynamics

Based on daily runoff and water level data from Shashi and Luoshan stations, seven periods of Landsat imagery under comparable dry-season conditions were selected (Table 2). Water boundaries were delineated using MNDWI and NDWI, and shoal-bar scouring–silting dynamics were quantified via ArcGIS spatial analysis (Fig. 2). The results reveal substantial morphological adjustments in the Qigongling and Guanyinzhou reaches, including Baxingzhou, Qixingzhou, and Jinjiangzhou, from 1987 to 2017.

Table 2. Information of available Landsat images under low flow conditions (Path 124/Row 40)

Date	Shashi discharge (m ³ /s)	Shashi water level (m)	Luoshan discharge (m ³ /s)	Luoshan water level (m)
1987/12/31	4490	32.54	7080	19.27
1993/12/31	5750	32.47	8820	20.45
1996/12/23	4990	31.86	7330	19.54
2003/12/27	5660	31.9	6870	19.44
2007/4/10	6010	31.6	9590	20.25
2011/3/14	6490	31.52	9370	20.29
2017/2/16	7090	30.76	10100	19.62
Maximum	7090	32.54	10100	20.45
Minimum	4490	30.76	6870	19.27

1987-2003 (Pre-impoundment): At Qigongling bend, minor silting occurred on the left bank near the entrance, while the right bank experienced slight scouring; pronounced continuous scouring affected the convex bank upstream of the bend apex. Guanyinzhou exhibited a “left-bank silting, right-bank scouring” pattern, driving an overall rightward channel migration. In Jinjiangzhou, scouring dominated the left bank and silting the right. Overall, this period was marked by convex bank retreat and rightward channel shift. 2003-2017 (Post-impoundment): The river regime stabilized but local adjustments persisted. Between 2003 and 2007, scouring occurred on Qigongling’s left bank, both banks at Guanyinzhou apex, and the convex left bank at Jinjiangzhou apex. From 2007 to 2011, minor localized convex bank scouring continued. Between 2011 and 2017, silting appeared on Qigongling’s right bank and the concave right bank upstream of Jinjiangzhou apex, while convex banks at Guanyinzhou and Jinjiangzhou apexes experienced slight scouring. Cumulatively, the period was characterized by concurrent silting and scouring patterns, with ongoing convex bank erosion and local concave bank accretion shaping channel morphology.

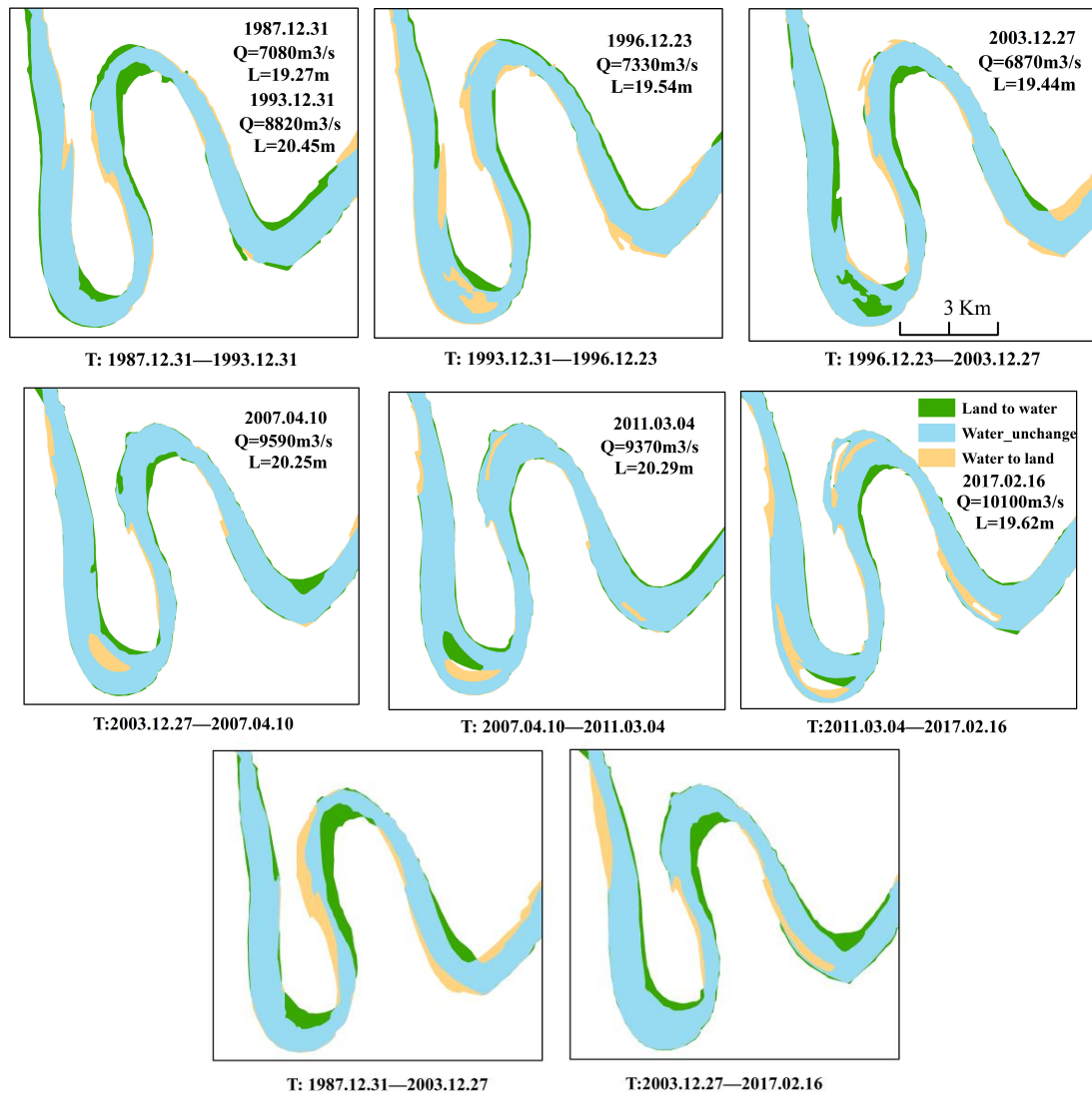


Fig. 2 Shoal-bar scouring-silting dynamics

3.3 Channel Cross-sectional Morphological Adjustment

Four representative cross-sections were selected to investigate the morphological evolution of the channel: the Qigongling bend entrance sections (Jing178 and JLL179.1), the Guanyinzhou bend apex section (Jing182), and the reach outlet section (Li11) (Fig. 3). The analysis revealed pronounced bank-specific differences and an overall trend of channel scouring. At the Jing178 and JLL179.1 sections, continuous left-bank erosion was observed, with the bankfull shoreline retreating by over 100 m and nearly 200 m, respectively. Notably, the thalweg elevation at the Jing178 section declined markedly from 13.5 m to 2.6 m, accompanied by a substantial lateral shift from the right bank toward the left bank (approaching less than 100 m from the left low-water bank by 2024), indicating a “left-bank scouring, right-bank deposition” pattern and an overall leftward channel migration. At the Jing182 section, continuous retreat occurred along the right bank, with a cumulative erosion of 1200 m between 2001 and 2024. Concurrently, the river width expanded from 1250 m to 2500 m, and the thalweg migrated from the left-bank margin to the central-right portion of the channel. The Li11 section was dominated by left-bank retreat (approximately 800 m), resulting in a river width increase to 1800 m, while the right bank and thalweg remained relatively stable. These substantial cross-sectional adjustments directly contributed to bank slope instability.

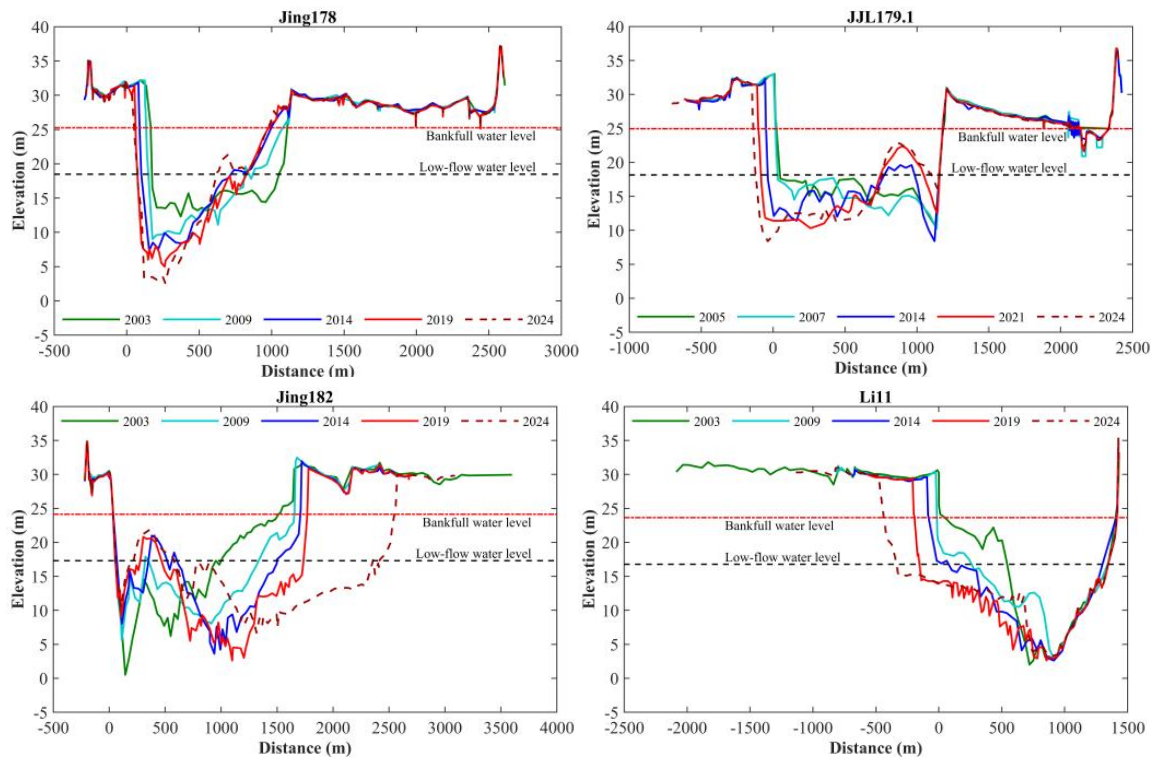


Fig. 3 Cross-sectional evolution in typical meandering reaches

Based on topographic data from eight fixed cross-sections, the morphological evolution of both the low-water and bankfull channels at the reach scale was analyzed for the period following the impoundment of the Three Gorges Reservoir (2003-2024). The results indicate significant scouring and lateral expansion: the low-water channel area increased by 2600 m^2 , and the bankfull channel area increased by 4050 m^2 ; corresponding river widths widened by 260 m and 270 m, respectively; and water depths increased by 0.52 m and 0.51 m, respectively. These findings consistently demonstrate that the low-water and bankfull channels experienced substantial vertical incision and lateral widening across the reach, leading to a progressive enhancement of channel area.

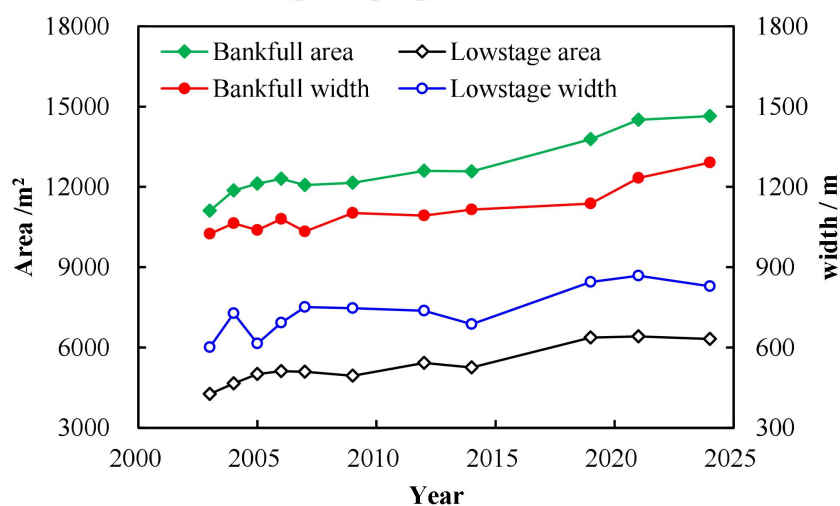


Fig. 4 Temporal evolution of reach-scale channel morphology

3.4 Driving Relationship between Channel Scouring-Silting and Bank Collapses

Based on statistical data obtained from key cross-sections, including Jing179 to Jing181, Li7, Li8, Li11, and Li12 (Table 3), bank collapse events exhibited pronounced spatial heterogeneity and temporal clustering. Spatially, right-bank collapses were predominantly concentrated at the Jing179

to Jing181 and Li7 sections. Notably, the right bank of Jing181 experienced the highest frequency of collapse events (16 occurrences), spanning two distinct active periods: 2003-2009 and 2015-2021. The right bank of Jing179 recorded seven events, primarily strip-type collapses occurring between 2003 and 2009, while the right bank of Li7 experienced four bowl-shaped collapses during 2014-2016, indicating localized intensive erosion. In contrast, left-bank collapses were mainly observed at Li8, Li11, and Li12, with cumulative event counts of 10, 3, and 8, respectively, and active periods primarily concentrated between 2011 and 2022. Furthermore, channel-bar collapses at Jing179 and Jing180 occurred frequently (9 and 10 events, respectively, from 2015/2016 to 2023), reflecting weak local bank resistance. Temporally, bank collapse events exhibited characteristics of short-term high frequency and phased clustering. Representative sections, such as the right bank of Jing181, demonstrated an alternating pattern of “active period-relatively stable period”.

Table 3. Information of available Landsat images under low flow conditions (Path 124/Row 40)

Cross-Section	Bank	Number of Collapses	Year(s) of Occurrence	Collapse Type
Jing179	Left	1	2013	—
Jing179	Channel-bar	9	2016, 2017, 2018, 2019, 2020, 2021, 2022 (2 events), 2023	—
Jing179	Right	7	2003, 2004, 2005, 2006, 2007, 2008, 2009	Strip
Jing180	Left	1	2013	—
Jing180	Channel-bar	10	2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022 (2), 2023	Strip
Jing180	Right	1	2003	Bowl
Li7	Right	4	2014, 2015, 2016 (2)	Bowl
Jing181	Right	16	2003, 2004, 2005 (2), 2006 (2), 2007, 2008, 2009, 2015, 2016 (2), 2017, 2018, 2019, 2021	Strip
Li8	Left	10	2011, 2012, 2013, 2014, 2015, 2018, 2020, 2021, 2022 (2)	—
Li12	Left	8	2012, 2015, 2016, 2017, 2018, 2019 (3)	—
Li11	Left	3	2021, 2022, 2023	Strip

To elucidate the intrinsic relationship between channel scouring-silting and bank collapse processes, a correlation analysis was conducted using measured data of scouring-silting volumes and corresponding bank collapse lengths in the Lower Jingjiang reach (Fig. 4ab). The analysis demonstrated a significant positive relationship. The correlation was stronger for the low-water channel than the bankfull channel, indicating that lateral scouring and thalweg migration of the low-water channel exert a more direct control on bank slope instability. Further, the cumulative bank collapse length showed a highly linear positive correlation with cumulative low-water channel scouring volume ((Fig. 4c, $R^2 = 0.84$), confirming that long-term continuous channel scouring is the primary hydrodynamic driver of bank collapse accumulation and spatial expansion. Collectively, these results indicate that progressive low-water channel morphological adjustments directly drive the destabilization of riverbanks and the evolution of bank collapse patterns.

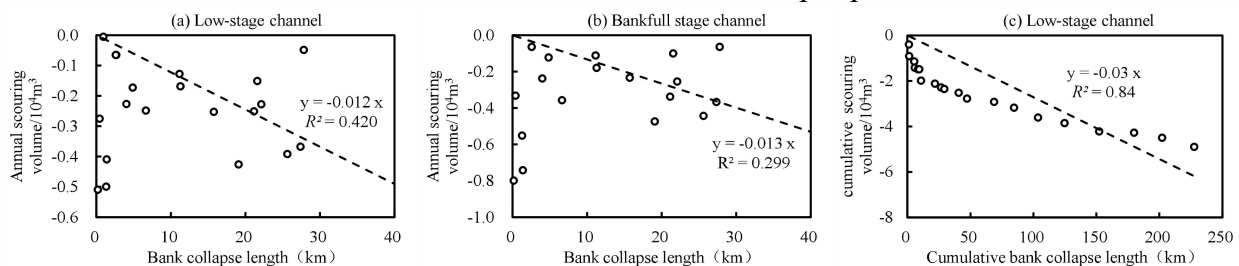


Fig.5 Relationship between channel scouring-silting and bank collapses length

3.5 Discussion

The observed increase in runoff coupled with decreased water levels during the dry season at Shashi station can be attributed to persistent riverbed incision downstream of the Three Gorges Dam following reservoir impoundment. The enhanced flow capacity resulting from incision

outweighs the water level rise associated with increased inflow. Morphological adjustments, including shoal-bar evolution and cross-sectional changes, indicate that convex bank scouring in bends and lateral thalweg migration—such as the Jing178 cross-section thalweg shifting from the right to the left bank—directly trigger bank collapses. Temporal analyses reveal a lag in the active periods of bank collapses between left and right banks: the right bank was predominantly active during 2003-2009, while the left bank experienced concentrated activity after 2011. This lag is closely linked to the delayed response of thalweg migration across the channel. Correlation analyses further demonstrate that scouring-silting volume in the low-water channel has a stronger explanatory power for bank collapse length than the bankfull channel ($R^2 = 0.84$), underscoring that undercutting of the bank slope toe within the low-water channel is the primary controlling factor of bank instability. These findings suggest that bank collapse monitoring and early warning efforts should prioritize the morphological evolution of the low-water channel and the lateral dynamics of the thalweg, which are key drivers of bank failure.

4. Summary

Following the impoundment of the TGR, dry-season runoff increased markedly at Shashi and Luoshan, but water levels declined at Shashi throughout the year due to ongoing riverbed incision. Morphological adjustments, including shoal-bar evolution and cross-sectional changes, show persistent scouring of convex banks in channel bends. At typical cross-sections, such as Jing178, the thalweg elevation dropped by 10.9 m, with the thalweg shifting from the right to the left bank; at Jing182, the right bank retreated cumulatively by 1200 m, doubling the river width. At the reach scale (2003-2024), low-water and bankfull channel areas increased by 2600 m² and 4050 m², respectively, with river widths widening by ~260 m and water depths rising by ~0.5 m. Bank collapse events exhibited pronounced spatiotemporal differentiation, with the right bank most active at Jing181 (16 events) and the left bank at Li8 (10 events), displaying alternating “active” and “relatively stable” periods. Correlation analysis confirms a strong positive relationship between bank collapse length and cumulative low-water channel scouring-silting ($R^2 = 0.84$), demonstrating that lateral scouring and thalweg migration of the low-water channel are the primary dynamic drivers of bank slope instability.

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