

2024 Bank Stability Assessment and Early Warning for Typical Riverbank Sections of the Jingjiang Reach (Hubei Section), Yangtze River

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Abstract: In response to the frequent bank collapses in the Jingjiang reach of the Yangtze River caused by "clear water discharge" after the impoundment of the Three Gorges Reservoir, this paper proposes a bank stability assessment and collapse early warning method based on the Analytic Hierarchy Process (AHP), taking 49 typical monitoring bank sections in this reach as the study objects. First, an evaluation system comprising six indicators—bank line status, bank geological conditions, revetment integrity, river regime changes, degree of near-bank riverbed change, and bank slope ratio change—is established. The bank stability is classified into three risk levels: red (<60 points), orange (60–80 points), and blue (≥80 points). On this basis, a discriminant matrix for bank collapse warning levels is developed by comprehensively considering the probability of collapse and the degree of hazard (including the distance from the bank to the embankment, threats to river regime stability, navigation conditions, and the safety of existing engineering structures). The warning levels are classified into Grade I (highest), Grade II, and Grade III. Applying this method to the monitoring bank sections in the Jingjiang reach in 2024, nine red-risk sections (totaling 14.3 km) and 35 orange-risk sections were identified. Post-assessment shows that all red-risk sections experienced bank collapse in 2025, achieving a 100% accuracy rate, while the accuracy rate for orange-risk sections was 71.4%. Using the 2024 measured data, early warnings for 2025 indicate that the total length of Grade I warning sections is 4.46 km, Grade II 17.62 km, and Grade III 39.89 km. Among these, Grade I warning sections such as Changjiangcun, Nongfengcun, and Lianxinyuan all experienced bank collapse in 2025. These results verify the reliability of the proposed early warning method, providing a scientific basis for bank collapse prevention and engineering management in the middle and lower reaches of the Yangtze River.

Keywords: bank collapse; Analytic Hierarchy Process (AHP); stability assessment; bank collapse early warning

1. Introduction

Bank collapse is a common phenomenon of riverbank, lake bank, or coastal bank failure and sliding under the action of hydrodynamic forces such as water flow and waves during river evolution. Bank collapse may lead to the undermining of embankment foundations and even cause embankment breaching, representing one of the most significant safety hazards during flood seasons. At the same time, large amounts of riparian land collapsing into the water results in severe soil erosion. Extensive bank collapse may alter the main flow direction of the river, obstruct navigation channels, and threaten shipping stability. It may also damage infrastructure such as wharves and water intakes along the river. From October 2002 to October 2024, the cumulative scour volume of the bankfull channel in the Jingjiang reach reached 1.35 billion m³, with an average annual scour of 61 million m³. In the Honghu reach, the riverbed experienced alternating erosion and deposition between years, but overall showed a net erosion trend. From October 2001 to October 2024, the scour volume of the bankfull channel was 384.9 million m³, with an average annual scour of 16.7 million m³[1、2]. Intense scour has led to frequent bank collapses, seriously threatening the safety of people's lives and property along the river. Therefore, understanding the current stability of riverbanks and conducting early warning for bank collapses is of great importance.

Since the 20th century, many scholars at home and abroad have carried out research on bank collapse prediction. Models such as the Osman-Thorne model, the Swedish arc method, and the BSTEM model have proposed bank stability analysis methods for typical cross-sections based on the concept of safety factor in soil mechanics[3、4]. Xia Junqiang et al. combined river dynamics and soil mechanics to propose a numerical simulation and assessment method for bank retreat.[5] He Guangshui, Deng Caiyun, et al. employed the Analytic Hierarchy Process (AHP) to establish a method for monitoring, analyzing, and assessing riverbank stability [6-8]. Given that some bank sections have a high probability of collapse but cause relatively minor losses, and that some collapses are even beneficial from the perspective of overall river regime adjustment, it is necessary to comprehensively consider the impacts and potential losses of bank collapse based on prediction results, and to develop early warning systems for bank collapse accordingly.

Based on the analysis of flow and sediment data, revetment data, bank collapse records, and measured topographical data, this paper adopts the Analytic Hierarchy Process (AHP) to analyze bank stability. On this basis, considering the hazards caused by bank collapse in different sections, a method for bank collapse early warning is proposed and applied to the Jingjiang reach of the Yangtze River in Hubei Province in 2024.

2. Basic Situation

2.1 Basic Situation of the Study Area

The Jingjiang reach of the Yangtze River within the jurisdiction of Jingzhou City has a total length of approximately 492 km, consisting of the Jingjiang reach (347.2 km) and the Honghu reach. The Jingjiang reach starts at Zhicheng and ends at Chenglingji, and is divided by Ouchikou into the Upper Jingjiang and Lower Jingjiang reaches. Upper Jingjiang (171.7 km) is a slightly curved, braided channel. The Zhicheng–Jiangkou section is a transitional reach from low mountains and hills to alluvial plains, with the riverbed covered mainly by sand, gravel, and cobbles, averaging about 20 m in thickness. The Jiangkou–Ouchikou section is an alluvial plain, where the upper part of the bank consists of 8–16 m thick silty loam. Lower Jingjiang (175.5 km) is a meandering river, with riverbed materials dominated by medium-to-fine sand; the right bank locally features hilly terraces, while the left bank in the alluvial plain has relatively weak erosion resistance. The Honghu reach starts at Chenglingji and ends at Hujiawan, comprising the Yueyang, Luxikou, Jiayu, and Paizhouwan sub-reaches. The banks typically exhibit a dual-layer structure, with cohesive soil and sandy loam in the upper layer and medium-to-fine sand in the lower layer, resulting in poor erosion resistance.

After the impoundment of the Three Gorges Project, the discharge of "clear water" has significantly affected the river channel. According to the Master Plan for River Regulation in the Middle and Lower Reaches of the Yangtze River (2016 Revision), systematic regulation projects have been implemented in the Jingjiang reach, including the emergency river regime control project, the follow-up river training project of the Three Gorges Project, the Jingzhou Phase I to Phase III river training projects, and the key bank collapse control project from Xiongjiazhou to Chenglingji. By December 2024, the lengths of existing revetments in Upper Jingjiang, Lower Jingjiang, and the Honghu reach were 195.804 km, 214.865 km, and 67.513 km, respectively. In 2024, a total of 6.58 km of revetment was constructed at sections such as Longzhou and Nanwuzhou.

Affected by the impoundment of the Three Gorges Reservoir, scour has intensified in the Hubei section of the Yangtze River mainstream, increasing the risk of bank collapse. From 2003 to 2023, a total of 497 bank collapses occurred in the Jingjiang reach, with a cumulative length of 372.51 km. Among these, 221 collapses (145.9 km) occurred in Upper Jingjiang, 276 collapses (226.61 km) in Lower Jingjiang, and 123 collapses (109.72 km) in the Honghu reach[9、10].

In this paper, taking into account factors such as the river regime evolution characteristics, evolution trends, channel patterns, and bank stability of each reach, as well as differences in

historical dangerous sections versus newly added dangerous sections, revetted versus natural banks, and curved concave banks, curved convex banks, and straight transitional reaches, a total of 19 bank sections in Upper Jingjiang, 22 in Lower Jingjiang, and 8 in the Honghu reach were selected as analysis objects, with a total length of 217.5 km.

2.2 Bank Collapse Situation of Typical Bank Sections

According to the field survey conducted in October 2024, the total length of bank collapse and affected areas within Jingzhou's jurisdiction in 2024 was approximately 53.35 km, accounting for 26.0% of the total shoreline length. The bank collapse sections mainly consisted of: 38.20 km of slight collapse (17.72 km of natural banks, 18.88 km of revetted banks including cracks), accounting for 71.6%; 11.73 km of moderate collapse (4.81 km of natural banks, 6.92 km of revetted banks), accounting for 22%; and severe collapse occurred at Changjiangcun (chainage 37+120 to 35+600) and Fuquanjia (chainage 7+300 to 9+200), both natural banks.



(a) Lower Beimenkou

(b) Sunliangzhou Section

Figure 2.2-1 Field survey status of typical bank sections in the Jingjiang and Honghu reaches in October 2024

2.3 Flow and Sediment Conditions

The year 2024 was characterized as moderately dry with below-average flow. The annual runoff at major stations upstream of Chenglingji was slightly lower than the post-impoundment average, with decreases of 6.5% at Zhicheng, 7.3% at Shashi, and 4.8% at Jianli. At the Luoshan station, the annual runoff in 2024 was 5.6% higher than the multi-year average. Sediment discharge decreased by 90% compared to pre-impoundment levels, and also decreased significantly compared to the post-impoundment average, with the reduction being more pronounced at upstream stations.

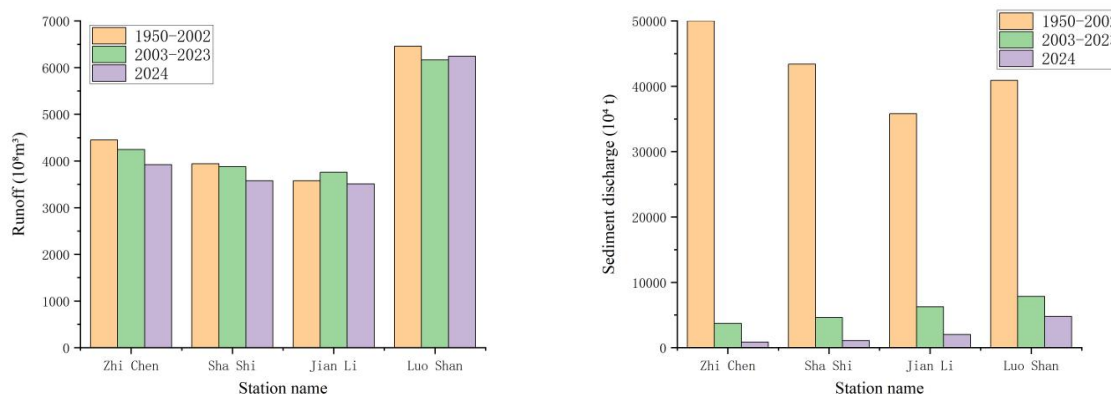


Figure 2.3-1 Variation of mean annual runoff and sediment discharge at major control stations in the Jingjiang reach of the Yangtze River in different periods

The annual distribution of runoff in the Jingjiang reach is uneven: the flood season (May to October) accounts for about 80% of the total annual volume, while the dry season (January to March) accounts for 7%–9%. Since the impoundment of the Three Gorges Project, the annual

runoff at stations in the Jingjiang reach has not changed significantly compared to the multi-year average. However, due to the regulating effect of the Three Gorges Project on the intra-annual runoff distribution downstream of the dam, runoff in the Jingjiang reach from September to October has relatively decreased, while runoff from December to March has relatively increased. Compared with the 2023 flood season (May–October), the changes in flow and water level at the Shashi and Jianli hydrological stations in 2024 were relatively small. At Shashi station, the flood season water level rose by 0.31 m, the average flood season flow increased by 420 m³/s, and the annual water volume increased by about 2.95%. At Jianli station, the flood season water level rose by 1.14 m, the average flood season flow increased by 208 m³/s, and the annual water volume increased by about 1.76%. During the 2024 dry season (January–April), the monthly average water level and flow at Shashi station were essentially the same as those in 2023, while at Jianli station both increased compared to 2023. After entering the main flood season, the water levels and flows at both stations in May, June, and July 2024 were higher than those in the same period of 2023, with significant increases particularly in May and July, and a notable increase in the peak flood flow. During the middle and late flood season (August–October), compared with 2023, the monthly average flows at Shashi and Jianli stations in 2024 decreased significantly; in October, the monthly average flow at both stations decreased by about 7,000 m³/s. In the post-flood period (November–December), the monthly average water levels and flows at Shashi and Jianli stations in 2024 were slightly lower than those in 2023.

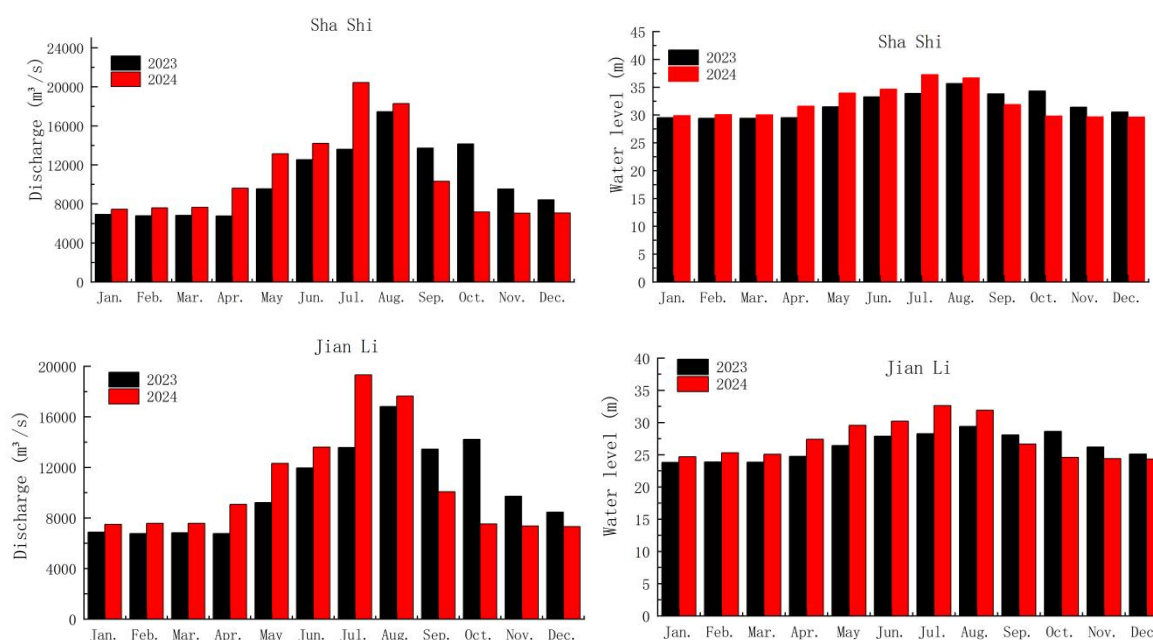


Figure 2.3-2 Comparison of monthly average flow and water level at typical gauging stations

2.4 Near-Bank Riverbed Changes

In recent years, the near-bank riverbed of the monitoring sections in Upper Jingjiang has remained relatively stable. However, as the riverbed scour effect caused by sediment trapping at upstream reservoirs continues to migrate downstream, the overall stability of the monitoring sections in Lower Jingjiang and the Honghu reach has declined to some extent. At the Shishou Lianxinyuan monitoring section, the bank slope below the dry-season water level exhibits a scouring trend, with the toe being eroded and deepened, resulting in a significant steepening of the bank slope in recent years, thereby affecting bank line stability. At the Jianli Baxingzhou monitoring section, the submerged toe and the front near-bank riverbed show a scouring trend, and bank collapse continues to develop in the unprotected sections. In the Honghu reach, the Yanwo and Xiazigou sections have experienced the main flow running close to the bank in recent years,

with the near-bank riverbed generally showing a scouring and downcutting trend; bank collapse has occurred in unprotected sections, increasing the risk to bank stability.

Among the 49 monitoring sections within the study area in 2024, a total of 95.925 km of near-bank riverbed experienced scour, accounting for 46.39% of the total monitored shoreline length. Among these, eight sections (total length 12.69 km) had an average scour depth of 2.0 m or more at the front of the near-bank toe. These sections are: Qing'an Ershengzhou section (chainage 10+400–9+600, average scour depth 5.88 m), Lingguanmiao to Chongheguan section (chainage 722+000–720+800, average scour depth 2.31 m), Sikouyao section (chainage 40+900–40+370, average scour depth 2.41 m), Lianxinyuan section (chainage 1+600–0+000, average scour depth 2.19 m), Xiongjiashou section (chainage 16+300–14+800, average scour depth 3.17 m; chainage 14+800–13+500, average scour depth 2.14 m), Sunliangzhou section (chainage 7+400–6+000, average scour depth 2.41 m), and Upper Guanyinzhong section (chainage 564+860–563+020, average scour depth 2.94 m; chainage 563+020–562+600, average scour depth 4.18 m).

3. 2024 Bank Stability Assessment

3.1 Bank Stability Assessment Method

This assessment adopts the Analytic Hierarchy Process (AHP). The bank collapse risk evaluation system consists of three levels and six specific indicators[6-8]. Following the principle of assigning higher scores to conditions favorable to bank stability and lower scores to conditions unfavorable to bank stability, scores are assigned to the six indicators: bank line status, bank geological conditions, revetment integrity, river regime changes, degree of near-bank riverbed change, and bank slope ratio change. Based on the weight coefficients of each indicator, a weighted sum is calculated to obtain a comprehensive score. According to the score range of 0–100, three assessment levels are defined: red (<60 points), orange (60–80 points), and blue (≥ 80 points). Blue sections refer to riverbank segments with relatively stable bank conditions; orange sections refer to segments with a risk of bank collapse but a relatively low probability of occurrence in the near future; red sections refer to segments with an obvious risk of bank collapse and a relatively high probability of occurrence in the near future.

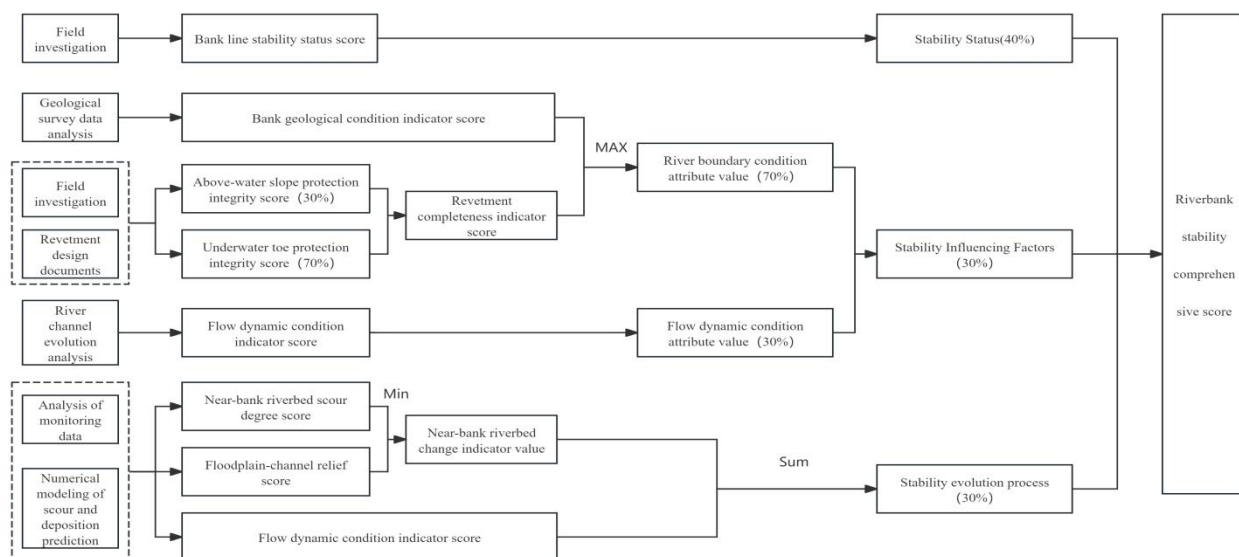


Figure 3.1-1 Roadmap of bank stability assessment

3.2 Assessment Conclusions

In 2024, a total of nine red-risk sections were identified among the monitored bank sections in the Jingjiang reach (Hubei), with a total length of 14.3 km. Based on bank geological conditions, river regime evolution, and near-bank riverbed erosion/deposition characteristics, these sections can be divided into the following three typical categories:

I. The left bank sections of Nanwuzhou (convex bank of the Haoxue bend)

This area includes the Changjiangcun section (37+120–35+600), Zhongmatou section (33+000–32+300), and Nongfengcun section (26+600–25+260), all located on the convex bank of the Haoxue bend, opposite the Long'eryuanji to Tieniu bank line, diagonally downstream of Tieniu, and opposite the Jiaoziyuan bar, respectively. Since 2006, the near-bank riverbed in these sections has shown a continuous scouring trend. Among them, the Changjiangcun section has no revetment, and local bank collapse has approached within less than 10 m of the embankment toe. Affected by the navigation channel regulation project, the mainstream line in the Zhongmatou section has shifted rightward, with the deep groove deepening and expanding; the average scour depth in the chainage range of 33+000–32+300 reached 1.85 m. The Nongfengcun section, despite having revetment, has experienced severe bank collapse. Although some subsections have been included in the post-Three Gorges follow-up treatment project, the works have not yet been implemented, and bank line stability urgently needs to be strengthened.

II. The Tiaoguan bend and the tail of Lower Jingjiang (concave bank scour zone)

This area mainly includes the Shishou Lianxinyuan section (1+600–0+000) and the Jianli Sunliangzhou section (7+400–6+000). The Lianxinyuan section is located on the upper part of the concave bank of the Tiaoguan bend. Affected by bank retreat in the upstream Beimenkou section, the near-bank riverbed has undergone significant scour and downcutting. Between 2022 and 2023, the average scour depth of the dry-season slope in the chainage range of 2+000–1+600 exceeded 3 m, causing the bank slope to steepen and develop subsidence cracks. The Sunliangzhou section is at the tail of Lower Jingjiang. Under the interaction of flow conditions from Dongting Lake and Lower Jingjiang, the near-bank riverbed exhibits interannual scour and intra-annual erosion-deposition alternation. The original riprap revetment has largely been lost. Between 2023 and 2024, the average scour depth at the front of the submerged toe in the chainage range of 7+400–6+000 reached 2.41 m, resulting in severe bank collapse.

III. The transitional reach of the Lower Jingjiang tail and the Chenglingji–Luoshan reach (unrevetted sections and river-regime sensitive zones)

This area includes the Jianli Baxingzhou section (BX2+400–BX4+630), Upper Guanyinzhou section (564+860–563+020), Jianli Hanjiabu section (533+270–531+500), and Honghu Yuanjiadun section (531+600–529+700). The Baxingzhou section is located in the transitional reach between the Xiongjiashou and Qigongling reverse bends, with the deep thalweg pressing against the bank. The bank soil has a dual-layer structure of cohesive soil overlying sand, offering weak erosion resistance. Affected by side bar cutoffs, bank line collapse will continue to develop. The Upper Guanyinzhou section is on the concave bank of a bend; the revetted section has suffered damage, with the submerged toe scoured to a depth of 2.94 m, reducing bank slope stability. The Hanjiabu and Yuanjiadun sections are located on the left bank downstream of Nanyangzhou in the Chenglingji–Luoshan reach. The deep thalweg oscillates near the left bank with flow variations, and the flow diversion ratio of the main channel remains between 60% and 75%. The near-bank riverbed at the front of the submerged toe is severely scoured, and the bank line remains in a natural state without any treatment.

3.3 Post-Assessment of 2024 Bank Stability

All nine red-risk bank sections identified in 2024 experienced bank collapse in 2025. Among the 35 orange-risk sections, 25 experienced collapse. The accuracy rate for red-risk assessment reached 100%, and that for orange-risk assessment was 71.4%, demonstrating the model's outstanding capability in identifying high-risk bank sections.

Table 3.3-1 Bank collapse risk assessment for key reaches of the Jingjiang reach in 2024

No.	Warning Bank Section	Chainage Range	Bank Side	Natural/Revetted	2024 Erosion/Deposition (m)	Bank Collapse Occurred in 2024	2024 Bank Collapse Risk Level	Collapse Occurred in 2025
1	Changjiangcun	37+120–35+600	Right	Revetted	1.35	36+500–36+600, 36+900–37+100 (extensive severe)	Red	Yes
2	Zhongmatou	33+000–32+300	Right	Natural	-0.05	Moderate slight collapse on natural bank	Red	Yes
3	Nongfengcun	26+600–25+260	Right	Revetted	3.66	25+730–25+660	Red	Yes
4	Lianxinyuan	1+600–0+000	Right	Revetted	-2.19	Multiple obvious cracks on revetted section	Red	Yes
5	Sunliangzhou	7+400–6+000	Left	Revetted	-2.41	6+350–6+400 (not yet treated)	Red	Yes
6	Baxingzhou	2+400–4+630	Left	Natural	-1.97	Moderate slight collapse on natural bank	Red	Yes
7	Upper Guanyinzhou	564+860–563+020	Left	Revetted	-2.94	Damaged section 565+850–564+000 (treated)	Red	Yes
8	Hanjiabu	533+270–531+500	Left	Natural	1.06	Extensive slight collapse on natural bank	Red	Yes
9	Yuanjiadun	531+600–529+700	Left	Natural	0.5	Extensive slight collapse on natural bank	Red	Yes

4. Early Warning Situation for 2025

4.1 Early Warning Method

Based on the bank stability assessment (blue sections refer to riverbank segments with relatively stable bank conditions; orange sections refer to segments with a risk of bank stability but a relatively low probability of occurrence in the near future; red sections refer to segments with an obvious risk of bank stability and a relatively high probability of occurrence in the near future), and taking into account the impacts caused by bank collapse in each section, the early warning for bank collapse is divided into three levels according to the probability of collapse and the degree of hazard: Grade I (highest) – high probability of collapse and high hazard; Grade II (second highest) – high probability of collapse and relatively high hazard, or relatively high probability of collapse and high hazard, or relatively high probability of collapse and relatively high hazard; Grade III (lowest) – relatively low probability of collapse, but attention should be paid.

The specific criteria are as follows:

Grade I early warning:

- ① Bank collapse risk assessment level is red, and the hazard degree level is medium;
- ② Bank collapse risk level is red, and the hazard degree level is high.

Grade II early warning:

- ① Bank collapse risk assessment level is red, and the hazard degree level is low;
- ② Bank collapse risk assessment level is orange, and the hazard degree level is high.

Grade III early warning:

- ① Bank collapse risk assessment level is orange, and the hazard degree level is low;
- ② Bank collapse risk assessment level is orange, and the hazard degree level is medium.

The division method of the bank collapse early warning judgment matrix established in this study is shown in Figure 3.1-1.

Bank Collapse Risk Level	Low	Medium	High
Red (<60 pts)	II	I	I
Orange ($60\text{--}80$ pts)	III	III	II
Blue (≥ 80 pts)	—	—	—

Figure 4.1-1 Judgment matrix for bank collapse early warning levels

4.2 Early Warning Indicator Construction

The degree of hazard of bank collapse is determined based on the possible consequences after collapse, referring to Table 3.2-1 from three aspects: the distance from the bank line to the embankment, the impact of bank collapse on river regime, and the threat level to navigation channels and existing engineering structures.

Table 4.2-1 Judgment table for the degree of bank collapse hazard

Degree of Hazard	Description
High	The collapse location is relatively close to the main embankment, or the collapse poses a serious threat to river regime stability, navigation conditions, or the safety of existing engineering structures.
Medium	The collapse location is relatively close to a local embankment, and the collapse has a certain impact on river regime stability, navigation conditions, or the safety of existing engineering structures.
Low	The collapse location is far from the embankment, and the collapse has a minor impact on river regime stability, navigation conditions, or the safety of existing engineering structures.

Based on statistical analysis of 365 recorded bank collapse events in the Jingjiang reach of the middle Yangtze River from 2003 to 2023, more than 95% of collapse widths were less than 39 m. After considering a certain safety margin, a distance of less than 50 m from the collapse location to the embankment toe is defined as "relatively close." More than 75% of collapse lengths were less than 140 m, and less than 25% of collapse lengths were less than 27 m. After considering a certain safety margin, a distance of less than 50 m from the collapse location to existing engineering structures is considered a "serious threat," and a distance of less than 200 m is considered as "having a certain impact."

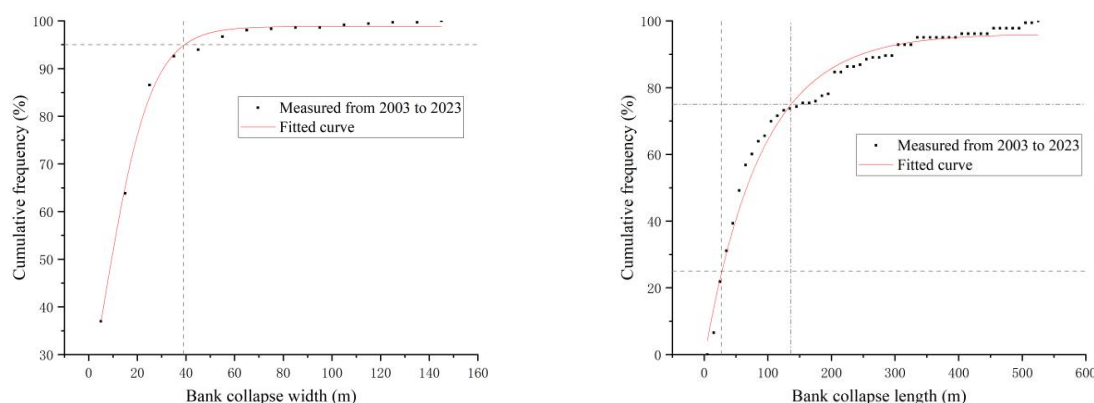


Figure 4.2-1 Frequency curves of collapse length and width in the study area (2003–2023)

Based on the distance between the deep thalweg line and the flood-season water edge line from 2021 data, and after considering a certain safety margin, it is considered that if collapse occurs in a section where the distance from the deep thalweg to the bank slope is within 100 m, it will pose a serious threat to river regime stability and navigation conditions. For sections where this distance is between 100 m and 150 m, collapse will have a certain impact on river regime stability and navigation conditions.

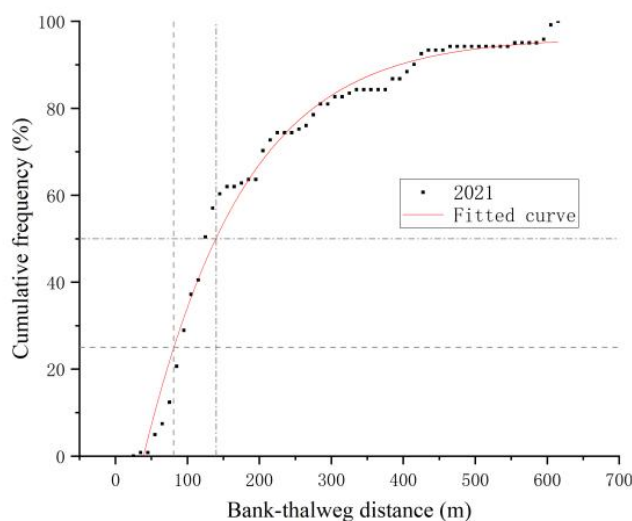


Figure 4.2-2 Frequency curve of distances between thalweg and flood-season water edge line in near-bank thalweg sections (2021)

4.3 Early Warning Results

Based on the analysis of near-bank riverbed topographic changes, river channel evolution, and field survey results of key monitoring bank sections in the Jingjiang reach of the Yangtze River in Hubei Province in 2024, and following the above early warning indicators and methods, a graded early warning for bank collapse risk in 2025 was conducted. The results show that the total length of bank sections with red and orange risk levels is 62.77 km. Considering both the probability of bank collapse and its hazard, the total length of Grade I early warning sections is 4.46 km, Grade II 17.62 km, and Grade III 39.89 km.

Table 4.3-1 Proposed early warning for bank collapse in the Jingjiang reach of the Yangtze River in Hubei Province, 2025

County/City /District	Warning Bank Section	Chainage Range	Bank Side	Natural/ Revetted	2025 Bank Collapse Early Warning Level	Collapse Occurred in 2025
Gong'an	Changjiangcun	38+000–37+120	Right	Revetted	II	No (new revetment implemented in Jan 2025)
Gong'an	Changjiangcun	37+120–35+600	Right	Revetted	I	Yes
Gong'an	Zhongmatou	35+000–32+300	Right	Natural	II	Yes
Gong'an	Nongfengcun	27+800–26+600	Right	Revetted	II	No
Gong'an	Nongfengcun	26+600–25+260	Right	Revetted	I	Yes
Gong'an	Nongfengcun	25+260–22+700	Right	Revetted	II	Yes
Shishou	Lianxinyuan	1+600–0+000	Right	Revetted	I	Yes
Jianli	Sunliangzhou	7+400–6+000	Left	Revetted	II	Yes
Jianli	Baxingzhou	2+400–4+630	Left	Natural	II	Yes
Jianli	Upper Guanyinzhou	564+860–563+020	Left	Revetted	II	Yes
Jianli	Hanjiabu	533+270–531+500	Left	Natural	II	Yes
Honghu	Taokou	458+640–457+500	Left	Revetted	II	No (new revetment implemented in Jan 2025)

5. Summary

This study takes the Jingjiang reach of the Yangtze River (including Upper Jingjiang, Lower Jingjiang, and the Honghu reach) as the research object. Based on the Analytic Hierarchy Process (AHP), a bank stability assessment system comprising six indicators—bank line status, bank geological conditions, revetment integrity, river regime changes, degree of near-bank riverbed change, and bank slope ratio change—is established. The bank stability is classified into three risk levels: red (<60 points), orange (60–80 points), and blue (≥ 80 points). On this basis, a discriminant matrix for bank collapse early warning levels is developed by comprehensively considering the probability of collapse and the degree of hazard (including the distance from the bank line to the embankment, threats to river regime stability, navigation conditions, and the safety of existing engineering structures). The warning levels are divided into Grade I (highest), Grade II, and Grade III.

Applying the above method to the 49 monitoring bank sections in the Jingjiang reach in 2024, a total of nine red-risk sections (totaling 14.3 km) and 35 orange-risk sections were identified. Post-assessment results show that all red-risk sections experienced bank collapse in 2025, achieving a 100% accuracy rate; among the orange-risk sections, 25 experienced collapse, yielding an accuracy rate of 71.4%. The model demonstrates strong capability in identifying high-risk sections and can effectively support bank collapse early warning efforts.

Based on the measured topography, riverbed erosion/deposition changes, and field survey data from 2024, a graded early warning for bank collapse risk in 2025 was conducted. The results indicate that the total length of Grade I early warning sections is 4.46 km, Grade II 17.62 km, and Grade III 39.89 km. Among these, sections such as Changjiangcun (37+120–35+600), Nongfengcun (26+600–25+260), and Lianxinyuan (1+600–0+000) were classified as Grade I early warning. Actual observations show that all these sections experienced bank collapse in 2025, further validating the reliability of the proposed early warning method.

Acknowledgements

Funding: This research was funded by the National Key Research and Development Program of China (Grant No. 2023YFC3209505), the National Natural Science Foundation of China (Grant Nos. 52509085 and 52409081) and the Changjiang Water Science Research Joint Fund of the National Natural Science Foundation of China (Grant No. U2240206).

References

- [1] Three Gorges Follow-up Work. (2024). Analysis report on river channel observation (Yichang-Hukou) for the impact treatment of the middle and lower reaches of the Yangtze River (Technical report). (In Chinese)
- [2] Xu, Q. X., Dong, B. J., Yuan, J., et al. (2023). Characteristics and impacts of channel scour in the middle and lower reaches of the Yangtze River after the operation of the Three Gorges Project. *Journal of Lake Sciences*, 35(2), 650-661. (In Chinese)
- [3] Osman, A. M., & Thorne, C. R. (1988). Riverbank stability analysis. I: Theory. *Journal of Hydraulic Engineering*, 114(2), 134-150.
- [4] Darby, S. E., & Thorne, C. R. (1996). Development and testing of riverbank stability analysis. *Journal of Hydraulic Engineering*, 122(8), 443-454.
- [5] Xia, J. Q., Deng, S. S., & Zhou, M. R. (2017). Bank collapse mechanism and multi-scale simulation method in the Jingjiang reach. *Yangtze River*, 48(19), 1-11. DOI: 10.16232/j.cnki.1001-4179.2017.19.001 (In Chinese)
- [6] Deng, C. Y., Li, L. Y., & Zhu, Y. H. (2019). A preliminary study on the assessment index system of riverbank stability. *Journal of Yangtze River Scientific Research Institute*, (10). (In Chinese)
- [7] Zou, J., Deng, C. Y., & Wang, H. Y. (2024). Stability evaluation of typical dangerous sections in the Jingjiang reach in 2022. *Yangtze River*, 55(S2), 1-6. DOI: 10.16232/j.cnki.1001-4179.2024.S2.001 (In Chinese)
- [8] Li, L. Y., Deng, C. Y., Chen, F., et al. (2025). Comprehensive risk assessment and influencing factors analysis of bank collapse in the Jingjiang reach of the Yangtze River in 2024. *Journal of Yangtze River Scientific Research Institute*, 42(8), 10-19. (In Chinese)
- [9] Zhang, Y. B., Sun, Q. H., Zhang, X. Y., et al. (2025). Temporal-spatial distribution and formation characteristics of pocket collapses in the middle and lower reaches of the Yangtze River. *Waterway Engineering*, (10), 100-109. DOI: 10.16233/j.cnki.issn1002-4972.20251010.016 (In Chinese)
- [10] Xia, J. Q., Liu, X., Deng, S. S., et al. (2022). Temporal and spatial distribution of bank collapses in the Jingjiang reach and its impact on riverbed adjustment after the operation of the Three Gorges Project. *Journal of Lake Sciences*, 34(1), 296-306. (In Chinese)