

Article

Emphasizing the Role of Human Activities and Extreme Floods in Riverbed Evolution: Inspiration from Hainan Island

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Abstract: Riverbed morphology is in dynamic change due to the influences of both natural and human-induced factors. However, there is a knowledge gap in distinguishing the components caused by human activities as well as extreme flooding from the total riverbed evolution. The current study evaluated the water depth variation in the Nandu River (NR) and Wanquan River (WR) in Hainan Island in response to diverse driven factors. The results showed that the average water depth of both rivers significantly increased, but the spatial-temporal variation patterns were different. In the NR, the dominant spatial-temporal water depth variation was driven by extreme flooding, which contributed 59% to the total variance. Then, water–sediment conditions accounted for 30%, followed by direct human activities for 3.6%. However, the main spatial-temporal water depth variation patterns in the WR were 77%, driven by water–sediment conditions, 10% driven by extreme flooding, and 3.9% driven by direct human interventions, respectively. Considering the indirect effects of human activities on the water–sediment process, the total contributions of human activities on the water depth variation were 6.9% and 42.9% in the NR and WR, respectively. Due to the poor riverbed stability and worse resistance, island rivers are more fragile to extreme floods and human interventions. Our findings suggest that extreme floods usually lead to a significant increase in sediment carrying capacity, followed by severe erosion of the riverbed. In addition, combining with the decrease in sediment concentration and grain size caused by human activities, the rebuilding effect on riverbeds would be magnified. These results highlight the important role of human activities and extreme floods in the evolution of island rivers, which can provide new insights and recommendations for river management and restoration engineering.



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Keywords: riverbed evolution; water depth; extreme floods; human interventions; Hainan Island

1. Introduction

Riverbed morphology shows different characteristics in the river evolution process, driven by both natural (e.g., precipitation and wind) and human-induced (e.g., reservoir construction and sand excavation) factors [1,2]. With the advent of the Anthropocene, many studies have reported that human factors have made the evolution of riverbed morphology deviate from the original natural process [3,4]. Understanding the evolution mechanism, as well as further distinguishing and quantifying human influence, will enable us to better develop rivers, which is currently lacking.

From the perspective of river dynamics, the major characteristics of riverbed morphology can be accurately described by the cross-sectional area, width, water depth, width–depth ratio, and thalweg. These riverbed characteristics are continuously adjusted by the incoming water discharge and sediment load, which are fundamental boundary conditions for controlling river dynamics [4]. Mueller and Pitlick [1,2] correlated the sediment supply to riverbed patterns, demonstrating the importance of sediment supply in riverbed evolution. Similarly, Nelson et al. [5] observed that river channel width is sensitive to sediment supply in the laboratory experiments. Moreover, the sediment supply of tributaries also made significant contributions to the mainstream riverbed evolution [6]. The long-term evolution has led to the formation of a stable hydraulic geometric relationship between the riverbed and the water–sediment conditions [7].

Currently, human interventions (e.g., dam construction and water-soil prevention) have strongly affected the riverbed evolution via altering the water–sediment condition. According to incomplete statistics, more than 50,000 large dams (with heights > 15 m) have been built for flood control and water supply. The average annual sediment flux to the global coastal ocean is reduced by about 1.4 billion metric tons due to human interventions, mainly reflected in reservoir construction [8]. Li et al. [9] also reported that the sediment flux of the world's large rivers has decreased by 20.8% driven by human activities (e.g., reservoir operation and irrigation). Therefore, it has brought about some chain reactions, namely, an insufficient river sediment supply leading to global riverbed erosion [3]. Moreover, some human activities (e.g., sand excavation and channel dredging) even transform the riverbed directly, causing dramatic changes in local riverbed. For example, the sand excavation caused broadscale and uneven riverbed erosion in the Pearl River, forming several excavation pits more than 20 m deep, and destroying the original pool-riffle structure along the river channel [10,11].

In addition, anabatic climate change in recent years is also having a profound impact on riverbed evolution. On the one hand, there is a trend of change in water–sediment discharge due to global warming causing the snowmelt and the change in precipitation and evapotranspiration, which further deforms the riverbed [12]. For example, the high flow frequency contributed significantly to the formation of alternate bars, and the variability of high flow frequency caused by climate change is triggering profound adjustments in the river bar morphology around the world, such as the Alpine Rhine River [13]. In addition, extreme flood caused by weather events such as El Nino has played a nonnegligible role during the formation of the riverbed [14,15]. In the Yangtze River estuary channel, an extreme flood could result in about 20 cm of riverbed erosion [15].

Hainan Island, located at the southernmost end of China, with an area of 35,000 km², is the second largest island in China after Taiwan. Hainan Island is also one of the most promising areas with the second fastest GDP and population growth rate in China [16], due to the Hainan Free Trade Port policy proposed by the Chinese government. The combination of geo-strategic value, economic potential and human-induced environmental stress makes the Hainan Island particularly worthy of concern and study. Previous studies have provided some insights into the river evolution of Hainan Island, mainly focusing on the changes in water–sediment condition, hydrodynamics and the water environment [17,18]. However, there is a knowledge gap regarding the abnormal changes in the riverbed caused by human intervention and extreme flooding, both of which are generally difficult to distinguish from the perennial riverbed evolution. To fill this gap, the current study attempts to quantify the evolution mechanism of riverbeds driven by different factors based on the long period of riverbed measured data in Hainan Island. Combined with the hydrological data of the same period, the roles of human activities and extreme flooding in riverbed evolution will be further revealed.

2. Materials and Methods

2.1. Study Area

The Hainan Island has a humid climate, with an annual mean temperature of above 22 °C and an annual mean precipitation between 1200 and 2000 mm. The distinct wet season in the island is from May to October, accounting for 80% of total annual precipitation, while the dry season is from November to April of the following year with only 20% of total annual precipitation [17]. Notice that the Hainan Island is located on the typhoon corridor, so tropical cyclones (July–October) bring copious precipitation, equivalent to ~30% of the total annual precipitation of Hainan Island [17]. Moreover, the heavy precipitation brought by tropical cyclones is also an important inducing factor of extreme floods in Hainan Island.

There are 214 rivers on Hainan Island, of which the Nandu River (NR) and the Wanquan River (WR) are the two rivers with the largest water flux flowing into the sea (Figure 1). The NR has a total length of 334 km, with the entire catchment occupying 7033 km². The statistical data of the Longtang station (LT, 26 km upstream from the mouth) show that the average water discharge is 176 m³/s, and the average suspended sediment load is 8.4 kg/s, between 1973 and 2021. The total length of the WR is 157 km, and its entire catchment is 3683 km². According to the statistical data of the Jiaji station (JJ, 18 km upstream from the mouth), during the time period of 1973–2021, the average water discharge was 152 m³/s, and the average suspended sediment load is 10.4 kg/s. The Songtao Reservoir (STR), with a total storage capacity of 33.45×10^8 m³, was built in 1967 in the upper reach of the NR. The Niululing Reservoir (NLLR) and Hongling Reservoir (HLR), located at the upper reaches of the WR, were built in 1986 and 2015 with a total storage capacity of 7.78×10^8 m³ and 6.62×10^8 m³, respectively. These large reservoirs have strong regulating effects on the river runoff. In addition, the dynamics in the estuary of the NR and WR are controlled by the upstream runoff and the downstream tide, with the tidal influence range traced back 12~15 km and 13~16 km upstream from the mouth (Figure 1), respectively.

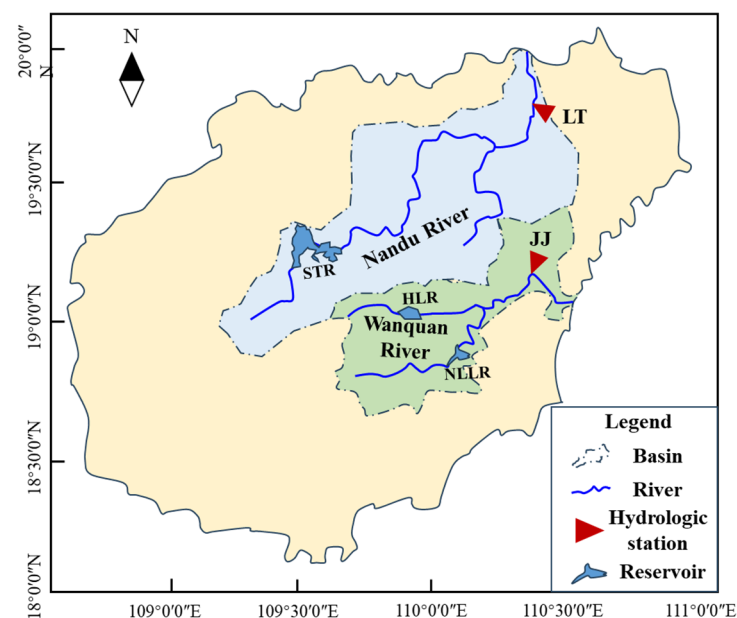


Figure 1. Map of Hainan Island displaying the rivers, hydrological stations and large reservoirs focused in this study.

2.2. Data Set

The riverbed morphology is represented by the cross-sectional elevation data, which were measured at the LT (period: 1994–2017) and JJ (period: 1994–2021) stations after the flood season by the Water Resources Survey Bureau of Hainan Province. These cross-

sectional elevation data were used to calculate the depth at each point along the cross-section, one of the key characteristics of riverbed morphology (Figure 2). Firstly, the heights of the datum line at the LT and JJ cross-sections were given as 8 m and 5 m, which are almost the same heights as the bankfull water level of the two cross-sections. Then, starting from the left bank, the difference between the height of the datum line and the riverbed elevation was calculated every 5 m as the depth at that point, excluding points where the difference was less than 0.

In addition, the annual water and sediment data from 1980 to 2021 were collected from the hydrological yearbook and the Hydrology and Water Resources Survey Bureau of Hainan Province. And the precipitation data on Hainan Island provided by the Hainan Meteorological Service were used to identify the extreme weather during the study period. The quality and reliability of the above data were checked and calibrated by the relevant department before publication.

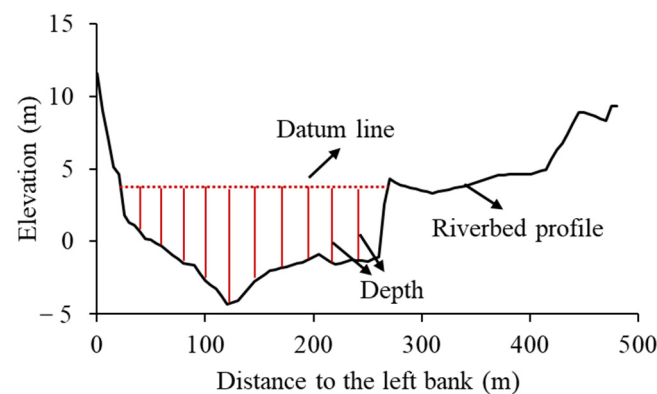


Figure 2. Calculation of depth characteristics at each point of the riverbed cross-section, taking the cross-section of the JJ station in 2021 as an example.

2.3. Data Analysis

One of the main tasks of this study is to test the trends and mutations of the collected hydrological series. For the hydrologic time series (e.g., cross-sectional mean depth in this paper), a t test was used to analyze the linear variation trend, and a sliding t test was used to identify the mutations in the series. Moreover, the correlations between the two hydrological series (e.g., precipitation and sediment load in this paper) may also change. Such changes are tested by the double cumulative curve (DCC), whose significances are judged by the Pettitt test [19].

To further explore the spatial-temporal variation in hydrological series, the Empirical Orthogonal Function (EOF) analysis was used in this study. The idea of (EOF) analysis is to assume that a physical process is responsible for most of the variability, and the corresponding eigenfunction will be related to that phenomenon [20]. The space-time field $D(x, t)$ of hydrological variables (e.g., depth at each cross-sectional point in this paper) can be decomposed into multiple linear combinations of spatial-temporal orthonormal functions using EOF analysis:

$$d_i(x, t) = C_i(x)L_i(t) \quad (1)$$

$$D(x, t) = \sum_{i=1}^n d_i(x, t) = \sum_{i=1}^n C_i(x)L_i(t) \quad (2)$$

where C_i represents the spatial eigenfunctions, indicating the main spatial variation patterns of depth; while L_i represents the temporal eigenfunctions, containing the long-term trend of depth variation. n is the number of EOF modes, which is related to the cross-section

width in this study. Notice that d_i reflects the i th EOF mode in the total variance, whose relative contribution (η_i) is calculated as follows:

$$\eta_i = \frac{\lambda_i}{\sum_{i=1}^n \lambda_i} \times 100\% \quad (3)$$

where λ_i is the eigenvalue corresponding to the i th eigenfunction. Generally, the eigenvalues of the first few largest eigenvectors contain most of the space-time signals with high relative contribution, representing the dominant spatial-temporal patterns of the depth variation. The spatiotemporal field $D'(x, t)$ can be reconstructed with m' ($m' \leq m$) dominant eigenvectors to explain the variance of specified EOF modes [21]:

$$D'(x, t) = \sum_i^{m'} C_i(x) L_i(t) \quad (4)$$

2.4. Establishment of Hydraulic Geometry

Riverbed evolution is affected by the incoming water and sediment from the basin, so there is a close relationship between the channel geometry and the water–sediment condition [4,22]. Moreover, previous studies reported that the riverbed evolution has a lag effect on the variation in water–sediment conditions. The channel geometry is generally related to water discharge and sediment load in the previous 5 years [4,22]. To establish the hydraulic geometry, the relationship between the current channel geometry and previous water–sediment condition is derived as follows:

$$G = \alpha f(Q, S)^\beta \quad (5)$$

$$f(Q, S) = \frac{1}{5} \sum_{i=1}^5 Q_i^a S_i^b \quad (6)$$

where G is the channel geometry parameter (cross-sectional average depth in this paper), $f(Q, S)$ is the function of water discharge (Q) and suspended sediment concentration (S), calculated by the average values for the last 5 years, α is the coefficient, and β , a , and b are the exponents. Based on the regression tests of measured data, the parameter values were determined according to the optimal correlation ($\alpha = 2.44$, $\beta = 0.08$, $a = 1.5$, and $b = -0.1$ in the LT station; $\alpha = 0.19$, $\beta = 0.55$, $a = 0.9$, and $b = -0.3$ in the JJ station).

2.5. Differentiation of Human Activity Factors

Riverbed evolution is a comprehensive long-term change process driven by nature factors and human interventions. However, the interaction of various factors makes it difficult to quantitatively peel off their respective impacts. To address this issue, a series of analysis methods are introduced in this paper to gradually distinguish the human factors in the total variance of riverbed (Figure 3).

Firstly, EOF analysis was introduced to decompose the total variance of the riverbed into different EOF modes, which represent the changes in the riverbed driven by different factors. Then, the EOF mode (D_i) driven by human factors was identified, which reflects the direct deformation of the riverbed caused by human activities (e.g., sand excavation). However, human activities (e.g., reservoir construction) also change the water–sediment conditions, which indirectly affect the riverbed evolution. Therefore, this part of human factors needs to be further distinguished from the EOF mode (D_j) driven by water–sediment conditions. The double accumulation curve is applied to eliminate human interventions from the water–sediment trend. The riverbed evolution ($d_{j,2}$) dominated by the natural water–sediment trend was calculated based on the hydraulic geometry relationship. Com-

pared with D_j , the difference ($d_{j,1}$) is the human-induced variance. To quantify relative contribution of $d_{j,1}$ to D_j , the dimensionless parameter σ is introduced as follows [23]:

$$\sigma = \frac{\sum |d_{j,2} - D_j|^2}{\sum (|d_{j,2} - \bar{D}_j| + |D_j - \bar{D}_j|)^2} \times 100\% \quad (7)$$

The value of σ ranges from 0 to 1. The closer the value is to 0, the lower the relative contribution of $d_{j,1}$ to D_j . And the relative contribution of $d_{j,1}$ in the total variance is further calculated as follows:

$$\eta_{j,1} = \eta_j \cdot \sigma \quad (8)$$

Finally, the comprehensive human factors (D_i and $d_{j,1}$) were distinguished from the variance of the riverbed, with the total relative contribution ($\eta_i + \eta_{j,1}$).

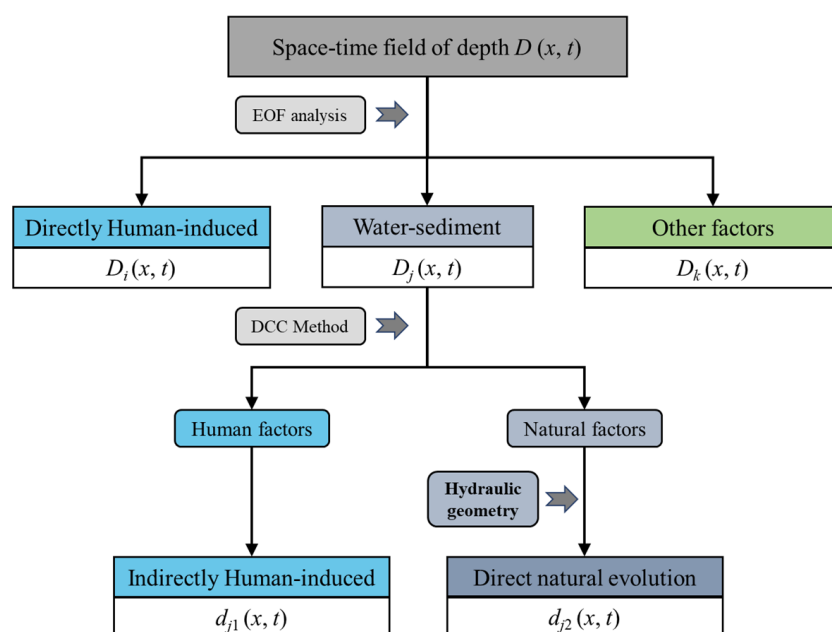


Figure 3. Basic framework of distinguishing human factors in the total variance of the riverbed.

3. Results

3.1. Interannual Variation in Cross-Sectional Depth

Cross-sectional depth is a key parameter that can characterize riverbed evolution. In order to comprehensively depict the riverbed evolution trends at the LT and JJ stations, box plots are applied to reflect variations in depth distribution (Figure 4). The elongation of the box indicates that the differences in depth along the cross-section at the two stations are both increasing. Specifically, at the LT station, the low value of depth (25th percentile) has little change, while the high value (75th percentile) increases greatly. In addition, the difference between the maximum and minimum depth increased from 5 m in 1994 to 9 m in 2017. This reflects erosion occurring in the pools of cross-section, causing the higher differences in elevation between shoals and pools. Being different from the LT station, the high value and the low value both change markedly at the JJ station, with high value increasing and low value decreasing, indicating erosion in the pools but deposition in shoals. The differences between high/low values and maximum/minimum values of depth increase from 1.5/4.8 m in 1994 to 5/8.5 m in 2021, respectively.

As shown in Figure 5a, without considering the drastic adjustment of cross-sectional depth during the 2008–2010, it can be found that both the average depths at LT and JJ stations show a significant increasing trend before 2008 ($p < 0.01$). After 2010, the increasing

trend of depth at the LT station slowed down greatly ($p > 0.1$), while the depth at JJ station continued to increase ($p < 0.01$). Moreover, the results of the sliding t -test show that the average depth of the LT station has two significant mutations ($\alpha < 0.001$), respectively, in 2000 and 2010. Meanwhile, there is only one significant mutation in 2010 at the JJ station, with a relatively low confidence level ($\alpha < 0.01$). Hence, the interannual variation in depth at the LT station is more sudden, but that at the JJ station displays a more continuous trend.

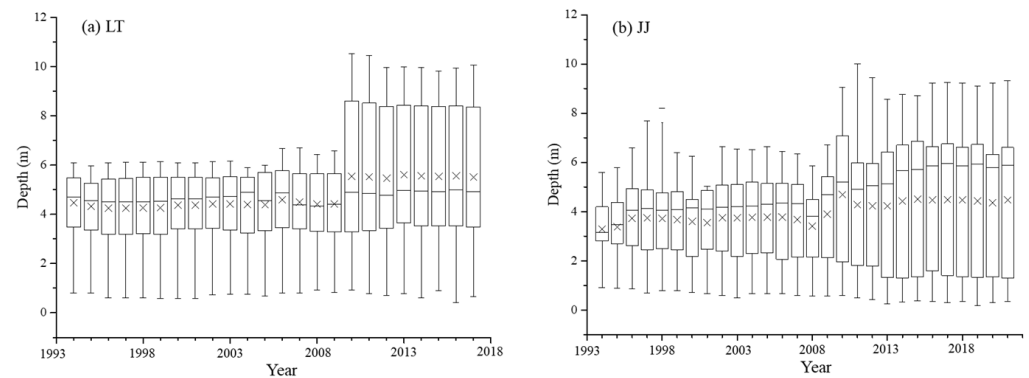


Figure 4. Box plots of depth along cross-sections at (a) the LT station and (b) the JJ station. The lower and upper lines of the boxes are the low value (25th percentile) and high value (75th percentile) of the depth, the center line is the median value, and the $\times$ sign is the average value. The lowermost and uppermost segments are the minimal and maximal depth, respectively.

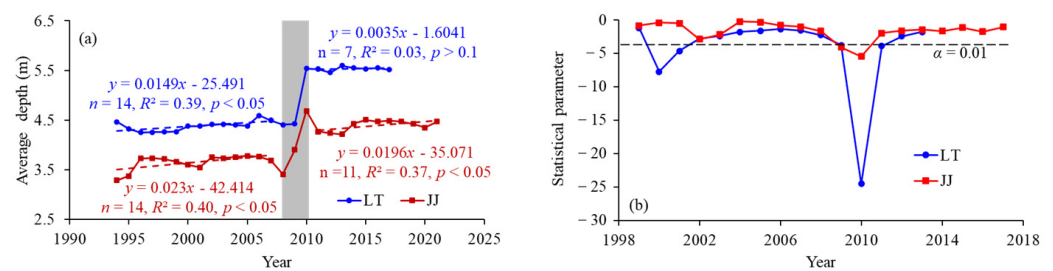


Figure 5. The average depth of the cross-sections: (a) interannual variations; and (b) sliding t -test.

3.2. Spatial-Temporal Patterns of Depth Variation

To understand the dominant spatial-temporal patterns of depth variation at the LT and JJ stations, the datasets of spatial-temporal variation in depth along the cross-sections are decomposed with the EOF method (Figures 6 and 7). Notice that the relative contributions of the first four modes are $>92\%$ and $>90\%$ at the LT and JJ station, respectively, indicating that these modes can explain most of the depth variation. Therefore, the following analysis will focus on these four modes, with the remaining modes ignored.

At the LT station, the first mode is the main evolution mode, accounting for 59% of the total variance. The variation in the depth in space showed a conformable increase along the cross-section (Figure 6a), indicating that the riverbed underwent overall erosion. The corresponding temporal variation displayed a sharp increase in depth around 2000 and 2010 (Figure 6d), which was consistent with the time of extreme floods in the basin (Figure 8a). Therefore, the first mode is regarded to be driven by extreme floods, which also explains the mutation in the result of the sliding t -test in Figure 5b. Here, the second and third modes are combined for analysis, with 30% of the total variance. The spatial variation in the second and third modes reflect that the depth in the middle of the cross-section decreases while increasing on both banks (Figure 6b), which is a typical riverbed evolution pattern of deposition in pools and erosion in shoals. On the other hand, the depth showed a certain periodic variation in time (Figure 6e), and the reconstructed depth of the second and third modes formed a good correlation with the water–sediment condition (Figure 8c),

i.e., the hydraulic geometry relationship. This finding suggests that the dominant driving force of the second and third modes is the water–sediment condition. As for the fourth mode ($\sim 3.6\%$), the spatial-temporal changes in depth were relatively random (Figure 6c,f), which could reflect the direct transformation of the riverbed by human activities (e.g., sand excavation and channel dredging).

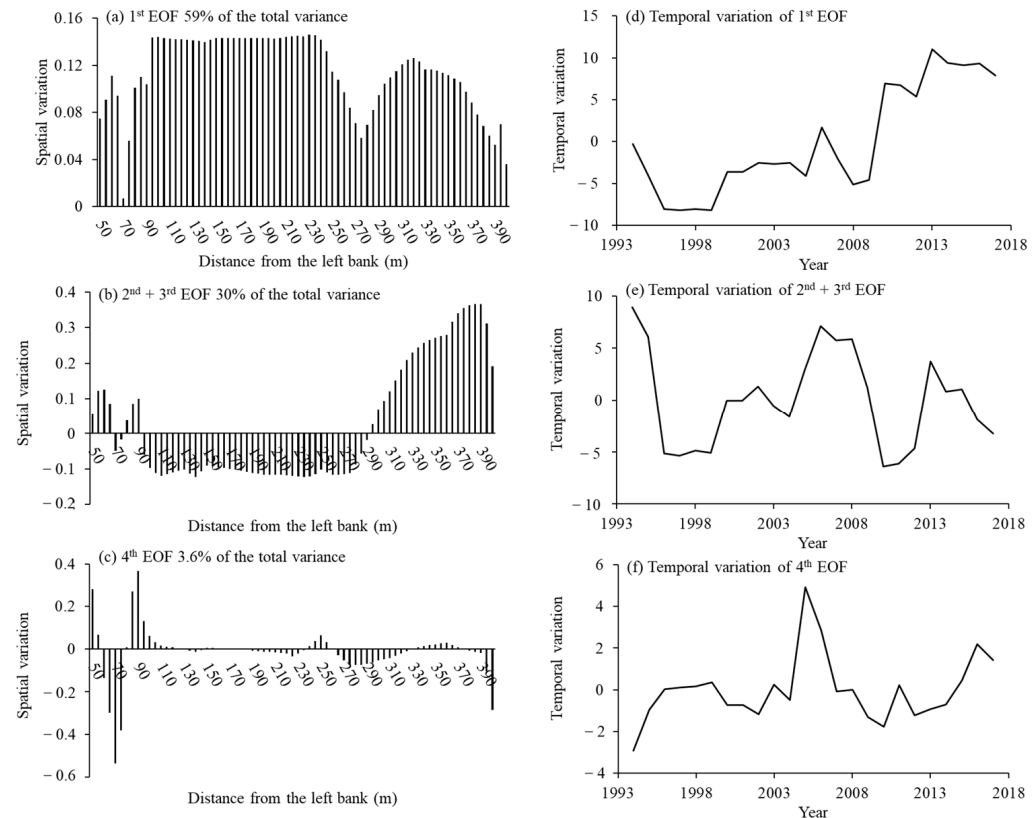


Figure 6. First four EOF modes of the depth along the LT station: (a–c) display the 1st, 2nd + 3rd, and 4th spatial modes, respectively, indicating the spatial variation patterns of the depth; (d–f) show the corresponding temporal modes, respectively, representing the long-term evolution patterns of the depth.

Similarly, the spatial-temporal variation in depth was decomposed into different modes by applying the EOF method at JJ station (Figure 7). Among the first four modes, the first mode plays an absolutely dominant role in the depth variation, with a relative contribution of 77%. The depth in the middle cross-section increased while decreasing on both banks (Figure 7a), representing a typical riverbed evolution pattern of erosion in pools and deposition in shoals. Moreover, the depth maintained a long-term trend of continuous increase (Figure 7d), and its reconstruction satisfied the hydraulic geometry relationship with the water–sediment condition (Figure 8d), revealing that the water–sediment condition was the dominant factor. The combined second and third modes, accounting for 10% of the total variance, which appear approximately as the complete erosion along the cross-section in spatial variations (Figure 7b), are demonstrated to be closely related to extreme floods due to the consistent timing between temporal changes and extreme flooding (Figures 7e and 8b). Similar to the LT station, the fourth mode ($\sim 3.9\%$) displays spatial-temporal randomness (Figure 7c,f), presenting a strong human-driven characteristic.

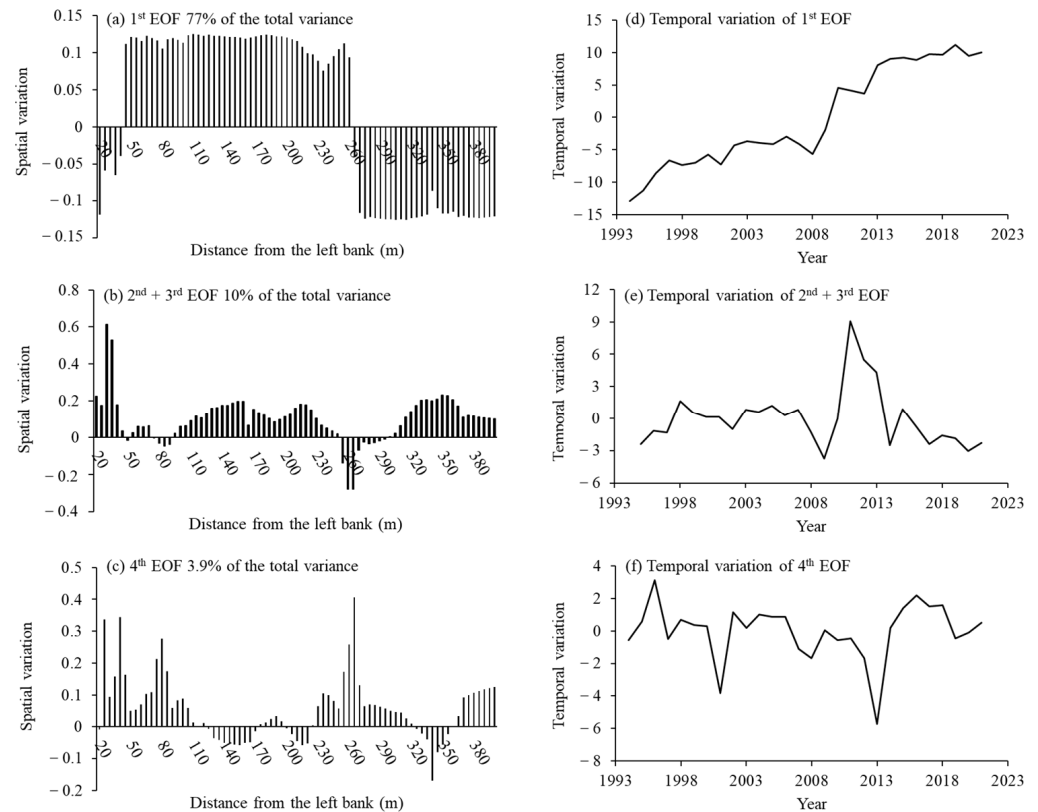


Figure 7. First four EOF modes of the depth along the JJ station. The meanings of each figure here are the same as those in Figure 6.

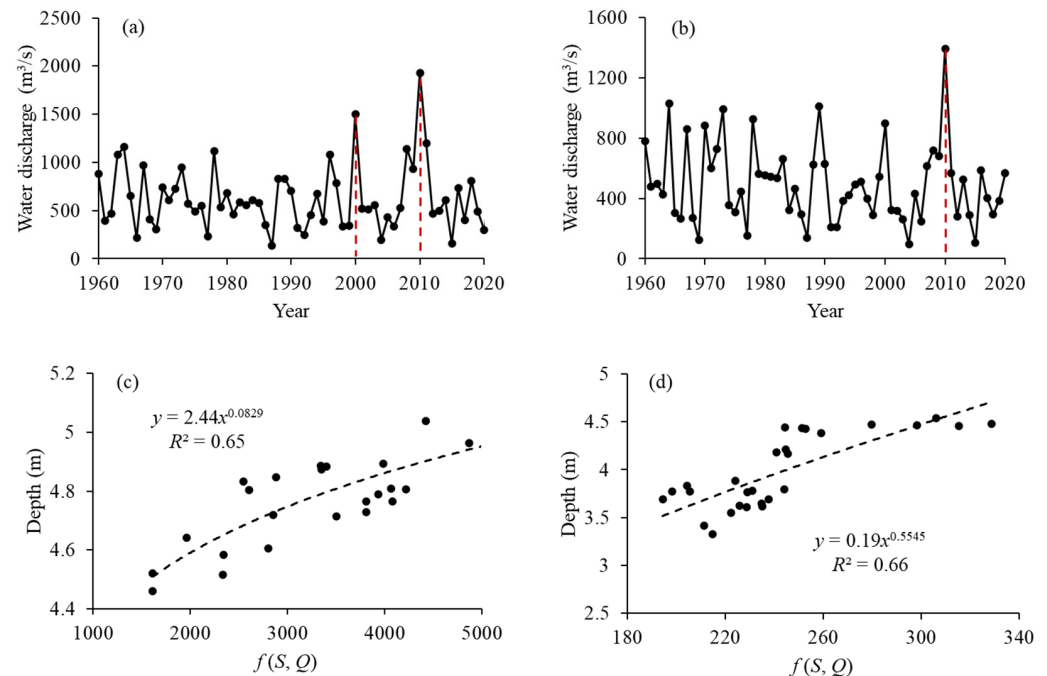


Figure 8. The maximum monthly water discharges of the year at (a) LT station and (b) JJ station. The hydraulic geometry relationships at (c) the LT station and (d) the JJ station. The red dashed line represents maximum monthly water discharge events with a frequency of less than 1%. The dependent variables in the hydraulic geometry relationships are the (2nd + 3rd) and 1st modes reconstructed depths at the LT and JJ stations, respectively.

3.3. Human-Induced Depth Variation

Human activities can not only directly transform the riverbed evolution but also have indirect effects by changing the water–sediment input. How to distinguish these indirect effects of human activities on the depth is the focus of this study. The double accumulation curves show that the relationships between precipitation and sediment load have changed at the LT ($p = 0.129$) and JJ ($p = 0.065$) station (Figure 9a). Considering the sequence data before mutation, the relationships between precipitation and sediment load under quasi-natural conditions are obtained by regression analysis (Figure 9a). Now that the natural trends of water and sediment input can be calculated by these relationships, the theoretical calculation values of depth are further obtained based on the hydraulic geometry relationships (Figure 8c,d). Compared with the reconstructed depth of the corresponding EOF mode (Figure 9b), the difference between the calculation and the reconstruction is small at the LT station, indicating that the indirect effects of human activities are insignificant, with 11% of the proportion to the mode and 3.3% of the relative contribution to the total variation. However, a large difference between the calculation and the reconstruction appears at the JJ station (Figure 9b), contributing 50% to the mode and 39% to the total variation, which reveals the significant indirect effects of human activities on the riverbed evolution. Combining the direct and indirect effects of human activities, the relative contribution of human-induced depth variation to the total variation is 6.9% (3.6% and 3.3%) at the LT station, whereas that is 42.9% (3.9% and 39%) at the JJ station.

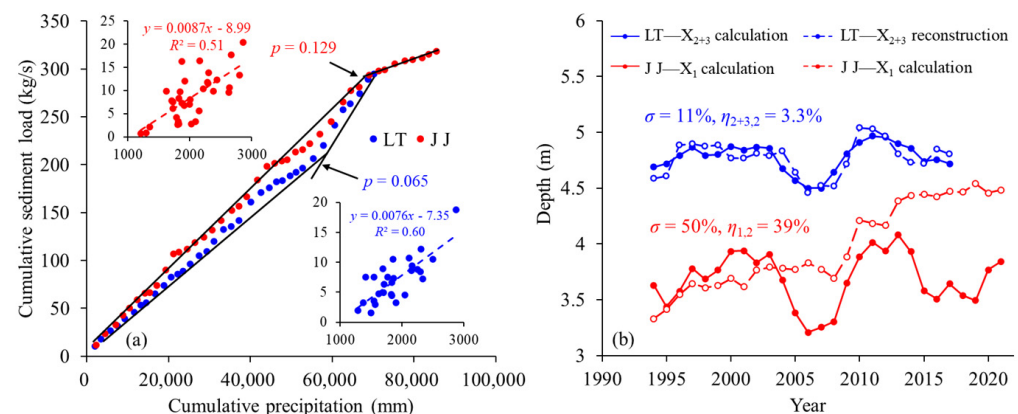


Figure 9. Distinguishing human impacts: (a) relationships between precipitation and sediment load; and (b) differences between depth calculation and reconstruction. The p values represent the significant confidence levels of the mutation test for the slopes of the double accumulation curves by the Pettitt test. The small scatter plots show the relationships between precipitation and the sediment load before the mutations, where x , y represent precipitation and sediment load, respectively.

4. Discussion

4.1. Rebuilding Effect of Extreme Floods

The riverbed is in a state of dynamic variation under the interaction with water flow. The key factor affecting this interaction is the relationship between the suspended sediment transport capacity (S^*) and the actual suspended sediment concentration (S). It is well known that the water discharge (Q) and water depth (h) together with other factors (e.g., river channel width B and sediment setting velocity ω) determine the S^* [24]:

$$S_* = k \left(\frac{v^3}{gh\omega} \right)^e \xrightarrow{Q=vBh} k \left(\frac{Q^3}{gB^3h^4\omega} \right)^e \quad (9)$$

where k is a coefficient; e is an exponent, reported to be between 0.5 and 1.5 [25]. Moreover, the suspended sediment concentration (S) and water level (H) depend on the water dis-

charge (Q) in the river channel [25,26]. Figure 10a,b shows the relationships between Q - S and Q - H at the LT station, where S is proportional to $Q^{0.4}$. Moreover, H is proportional to $Q^{0.14}$ when the discharge is lower than the bankfull discharge, and H is proportional to $Q^{0.23}$ when the discharge is higher than the bankfull discharge. Hence, S and H will increase with the increase in Q , but the increase rates are not as large as that of Q . Assuming other factors remain unchanged, S^* is proven to be proportional to $Q^{1.0\sim3.1}$. Here, a parameter ε is defined to compare the suspended sediment transport capacity with the actual suspended sediment concentration:

$$\varepsilon = \frac{S_*}{S} = \frac{k_1 Q^{1.0\sim3.1}}{k_2 Q^{0.4}} = k_3 Q^{0.6\sim2.7} \quad (10)$$

where k_1 , k_2 , and k_3 , are all proportional coefficients. If $\varepsilon > 1$, this means that the suspended sediment transport capacity is greater than the suspended sediment concentration, with more sediment erosion and less sediment deposition, resulting in riverbed erosion. Conversely, it will lead to riverbed deposition. Now a conceptual model is introduced to qualitatively study the effect of extreme flooding on the sediment dynamic processes in the riverbed (Figure 11). Before the flood, the suspended sediment transport capacity and the suspended sediment concentration are in balance with the moderate flow strength within the river channel, resulting in equal probabilities of sediment deposition and erosion; hence, the riverbed is in a state of dynamic equilibrium (Figure 11a). When extreme flooding occurs, water discharge within river channel rapidly increases, causing the suspended sediment transport capacity to significantly magnify. Although suspended sediment concentration of the water also increases, its increase is much smaller than the suspended sediment transport capacity, lead to a high probability of erosion and low probability of deposition, with significant erosion occurring in the riverbed (Figure 11b). Notice that the suspended sediment transport capacity will magnify exponentially with discharge, meaning that extreme flooding can markedly rebuild the riverbed. However, the relationship obtained by our study can only reflect a qualitative correlation between water discharge and sediment transport. A short time process, such as field or laboratory observations, needs to be studied to obtain a more accurate quantitative relationship.

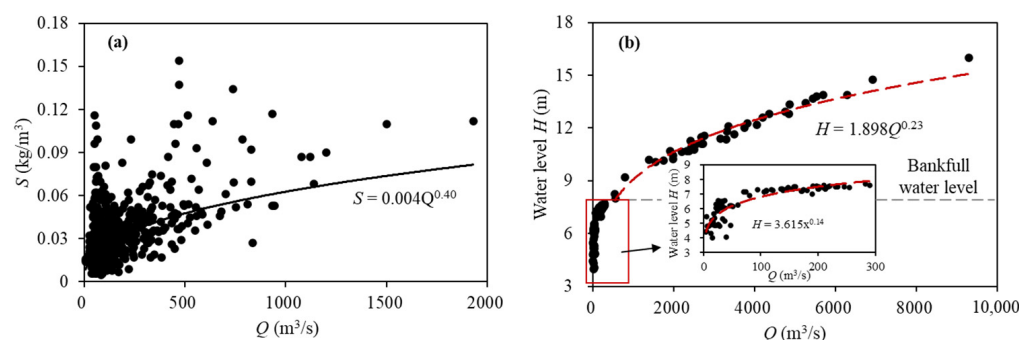


Figure 10. Relationships between (a) Q - S ; and (b) Q - H at LT station.

4.2. Characteristics of Island Rivers

As mentioned above, human activities and extreme floods play important roles in the riverbed evolution of Hainan Island. Compared with the effects of these factors on other large alluvial rivers [27], the rivers on Hainan Island seem to be more susceptible. Therefore, the common characteristics of island rivers and other alluvial rivers are combined for analysis to further reveal why island rivers are more vulnerable to extreme flooding and human activities.

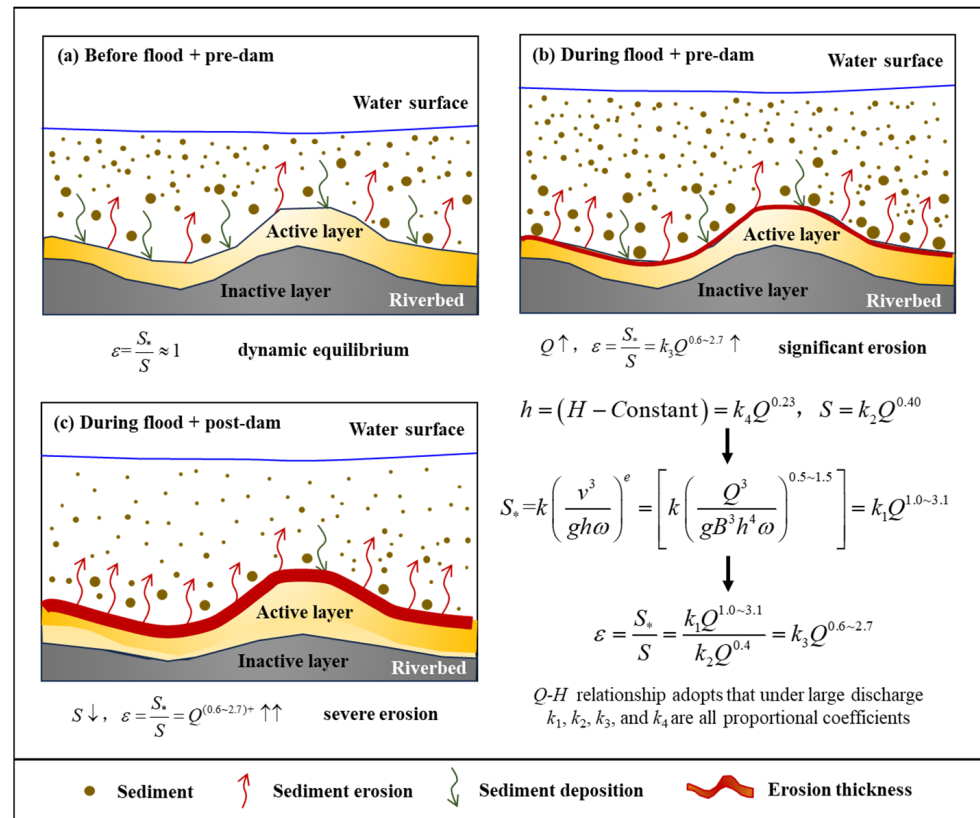


Figure 11. Conceptual model showing the sediment dynamic processes in riverbed: (a) before flood and reservoir construction; (b) during flood and before reservoir construction; and (c) during flood and after reservoir construction.

4.2.1. More Fragile Riverbed

Riverbed stability directly determines the resistance of riverbed to external disturbance (e.g., extreme flooding and human activities). Many previous studies have reported that riverbed stability is closely related to riverbed material size m_s [28], river slope J [29], bankfull river width B_b [30], bankfull discharge Q_b [31], and bankfull water depth h_b [32]. To quantitatively compare the riverbed stability of Hainan Island and other large alluvial rivers, a riverbed stability index φ is introduced as follows [32]:

$$\varphi = \frac{m_s}{h_b J} \left(\frac{Q_b}{J^{0.2} B_b} \right)^2 \quad (11)$$

where the first term represents vertical stability, and the second term represents lateral stability. Among the parameters, the m_s and Q_b are positively related to the riverbed stability, and the influence of Q_b is greater. Meanwhile, h_b , J , and B_b are negatively related to the riverbed stability, with the greatest influence of J . The comparative results of riverbed parameters and stabilities (Figure 12) indicate that the riverbed stabilities of Hainan Island (LT and JJ) characterized by the higher J and the lower Q_b are lower than those of other alluvial rivers (MK, SS, and DT). It is well known that island rivers are commonly characterized by higher slopes than large alluvial rivers because of the shorter distance flowing into the sea [33]. In addition, the water discharge of island rivers is usually smaller than large alluvial rivers due to their narrower catchment basins [34]. These two parameters of island rivers and alluvial rivers can even differ by several orders of magnitude, resulting in the riverbed of island rivers becoming more fragile.

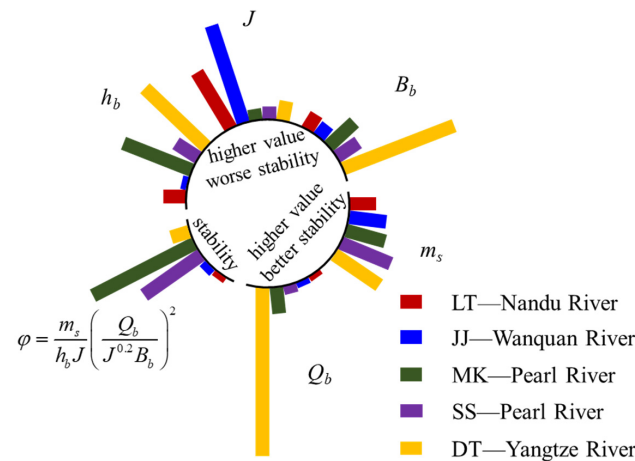


Figure 12. Circular bar chart showing the characteristic parameters and stabilities of the riverbeds in the lower reaches of several rivers with normalized values. The data of Makou (MK) and Sanshui (SS) are collected from Liu et al. [4] and Tan et al. [35], whereas Datong (DT) is derived from Yang et al. [36].

4.2.2. Worse Resistance to Human Intervention

The intensity of human activity highly affects the extent to which riverbed evolution deviates from natural trends. Compared with large alluvial river basins, there are lower water conservancy projects and population density in island river basins [37]. However, the disturbance of human activities on island rivers are still nonnegligible [34]. As shown in Figure 13, the total storage capacities of reservoirs in island river basins (e.g., Nandu and Wanquan River Basins) are much smaller than those in large alluvial river basins (e.g., Yangtze and Pearl River Basins), as well as the total annual runoff. In general, the proportions of the total storage capacity to the annual runoff of island rivers are higher than that of the large alluvial rivers, indicating that the relative regulating ability of reservoirs to runoff in island rivers is stronger than that in large alluvial rivers. This finding suggests that island rivers are under greater pressure from humans, which is not fully recognized by previous studies. It is also important for island river managements to know that a small-scale water conservancy project can make a significant change in an island river with a small water resource quantity.

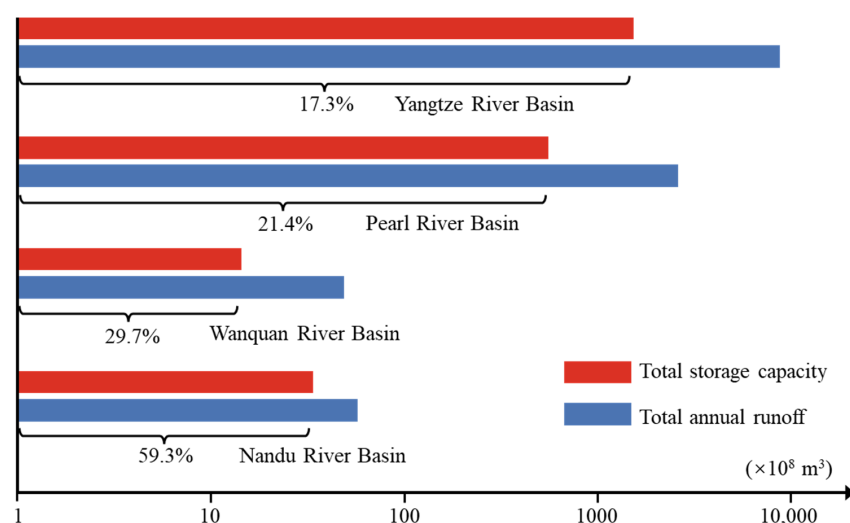


Figure 13. Total storage capacity of large reservoirs ($>10^8 \text{ m}^3$) and river runoff in several river basins, showing the ratios of total storage capacity to annual runoff. The data of reservoirs are derived from China Water Resources Development Bulletin and China Hydrological Annual Report (<http://www.mwr.gov.cn/>, accessed on 5 August 2024).

4.3. Indirect Effects of Human Activities

Although this study has revealed the indirect effects of human activities on the Hainan Island riverbed in terms of water–sediment input, the human intervention in riverbed evolution may still be underestimated.

On the one hand, the disturbance of human activities on water–sediment processes has been underestimated. Due to the lack of monitoring data, the effects of early human activities cannot be estimated. For example, the effects of the STR in the Nandu River Basin, built in 1967 on the riverbed evolution, is not reflected in this study. Since the collected water–sediment data began in 1980, thirteen years after the STR was built, the capacity of the reservoir to intercept river sediment is at a relatively low level [38]. Therefore, double accumulation curve analysis using the water–sediment sequences from 1980 barely reflects the effects of the STR, resulting in a relative contribution of only 3.3% to the indirect effects of human activities. Considering the strong ability (59.3%, Figure 12) of reservoir regulation in the Nandu River Basin, the indirect effects of human activities should have a relatively higher contribution on the riverbed evolution than the current value.

On the other hand, the influence of human activities on sediment grain size has been neglected. It is well known that human activities such as dam construction will intercept the bed load and the coarse fraction of the suspended sediment, thereby changing the size grading of suspended sediment downstream [39]. Considering the suspended sediment transport capacity S^* (see Equation (9)), the decrease in sediment grain size will make sediment setting velocity ω slow down, leading to the increase in suspended sediment transport capacity. Moreover, human activities such as sand excavation will directly excavate the coarse particles of the riverbed as building materials, decreasing the riverbed material size d [10]. Given the positive correlation between riverbed material size and riverbed stability (see Equation (11)), the riverbed stability will decrease, accompanied with sand excavation. The decreasing grain size of both suspended sediment and riverbed material can exacerbate the erosion of the riverbed, which is not further identified in our study due to a lack of sediment grain size data. In addition, when extreme flooding comes, the combination of the decrease in sediment concentration and grain size caused by human activities, combined with the remarkable increase in suspended sediment transport capacity, can lead to a serious erosion of the riverbed (Figure 11c). It is also underexplored in our study but should definitely be taken seriously by river management.

5. Conclusions

In this study, the spatial-temporal depth variations in the NR and WR in Hainan Island were examined to show the significant increasing trend but with different variation patterns. The spatial-temporal depth variation is driven by water–sediment conditions, extreme floods, and direct human interventions, with varying degrees of contribution. Moreover, the indirect effects of human activities were further distinguished from water–sediment conditions. A conceptual model of riverbed sediment dynamics was constructed to understand the rebuilding effect of extreme flooding on the riverbed. The conceptual model reveals that extreme flooding would contribute to an increase in sediment carrying capacity, which leads to the drastic erosion of the riverbed. With the reduction in suspended sediment concentration caused by reservoir construction, this rebuilding effect of extreme flooding on the riverbed will be further amplified. In addition, island rivers are more vulnerable to the extreme floods and human interventions, due to poor riverbed stability and worse resistance. Our findings suggest that human activities and extreme floods play an important role in the evolution of island rivers, which can draw attention to the evolution of island rivers under human pressure and provide scientific guidance for river management.

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