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Fluvial Sediment Load Characteristics from the Yangtze River to the Sea During Severe Droughts

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Abstract: Most river deltas worldwide are located in well-developed, densely populated lowland regions that face challenges from accelerated sea level rise. Deltas with morphological equilibrium are the foundation for associated prosperous economies and societies, as well as for preserving ecological fragile environments. And for deltas to be in morphological equilibrium, sufficient fluvial sediment supplies are fundamental. Severe droughts have significant impacts on the sediment load discharged to the sea, but this is considerably less studied compared to flooding events. This study examines the characteristics of Yangtze River sediment flowing toward the East China Sea during severe droughts. The effect of the Three Gorges Dam (TGD) was investigated by comparing the difference before and after its construction in 2003. Results indicate that the sediment load from the Yangtze River to the sea has experienced a more pronounced decrease during severe drought years since 2003. The primary cause is a substantial reduction in sediment supply from the upper reaches, resulting from the impoundment of the Three Gorges Reservoir created in 2003 and the construction of additional major reservoirs in the upper reach thereafter. Simultaneously, this is accompanied by the fining of sediment grain size. The fining of sediment and considerably reduced sediment load discharged to the sea during severe droughts after 2003 are likely to accelerate the erosion of the Yangtze subaqueous delta. The rating parameter values during severe drought years fall within the range observed in normal years, indicating that these drought events do not align with extreme rating parameter values. Less than 30% of the average discrepancy between measured and reconstructed sediment loads in severe drought years before 2003, and approximately 10% of the discrepancy after 2003, demonstrate the feasibility of reconstructing sediment loads for severe drought events using a sediment rating curve. This rating curve is based on daily water discharge and sediment concentration data collected during the corresponding period. These findings indicate that the rating curve-based reconstruction of sediment load performs well during severe droughts, with relative error slightly exceeding the average error of normal years prior to 2003 and approaching that observed after 2003. This study provides insights on sediment management of the Yangtze River system, including its coastal zone, and is valuable for many other large river systems worldwide.

Keywords: severe drought; sediment load; sediment rating parameter; Yangtze River; Three Gorges Dam

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1. Introduction

Most river deltas in the world are located in well-developed, densely populated regions and fulfill important economic and ecological functions. Replenishing the deltaic coasts and their hinterlands with fluvial sediments is important to overcome local sea level rise due to global warming [1–5]. Riverine sediment load plays a significant role in the evolution of deltas. Critical fluvial sediment loads for keeping the delta in equilibrium with sea level change have been assessed by various studies [1,2,6,7], and they are closely related to the grain sizes of the riverine sediment load [8]. As an important mechanism for moving organic carbon from river basins to the sea [9], fluvial sediment transport is also responsible for the majority of total riverine flux of elements, such as P, Ni, Mn, Pb, Al, and Cr [10].

Numerous studies have investigated the changes in the quantity, composition, and grain size of sediment load discharged into the sea [11,12] and established sediment rating curves ($C_s = aQ^b$), which are capable of revealing the sediment transport regime and are used to reconstruct or extrapolate fluvial sediment loads [13–17]. Results show that human activities, especially dam emplacement, have resulted in a significant reduction in fluvial sediment load discharged to the sea [2,12], which is captured in the sediment rating parameters, i.e., a decrease in the rating coefficient *a* of the sediment rating curve and an increase in the rating exponent *b* [13–15]. A severe reduction in fluvial sediment load discharged to the sea can lead to erosion, subsidence, and shoreline retreat in many deltas [3,18,19].

Extreme hydrological events induce considerable variations in fluvial sediment load discharged to the sea, whereas both large and small rivers deliver great amounts of sediments to the sea during major flood years [20,21]. Conversely, a historically low amount of suspended sediment was discharged into the sea during the severe drought year of 2006 for the Yangtze River—amplified significantly by the TGD [22,23]. A mega-drought in central Chile in 2010 induced a decrease in annual sediment fluxes, causing a seasonal shift in maximum sediment transport and associated variation in the rating parameters within the Itata River Basin [24]. Hydroclimatic events can cause sediment rating parameters to deviate from general trends for a short period. For example, extreme high *b*-values and low log(*a*)-values typically indicate drought events [13]. However, drought events mentioned by Yang et al. [13] refer to events with water discharges lower than average, rather than severe droughts. Under global warming, previous studies have shown a significant increase in drought frequency, duration, and severity in Eastern Asia for 1951–2010 [25,26]. As such, drainage areas upstream of deltas could be more vulnerable to severe drought events in the future. Compared to studies on sediment loads associated with flooding events, only a few drought events have been studied thoroughly. Consequently, the long-term characteristics of fluvial sediment discharge to the sea during severe droughts remain poorly understood. In this study, gradations in hydrological drought in river watersheds are assessed as normal ($-0.5 < \text{SRI} < 0.5$), mild drought ($-1 < \text{SRI} \leq -0.5$), moderate drought ($-1.5 < \text{SRI} \leq -1$), severe drought ($-2 < \text{SRI} \leq -1.5$), and extreme drought ($\text{SRI} \leq -2$) based on the standardized runoff index (SRI) [27].

The Yangtze River delta, one of China's most economically developed regions, faces several challenges: accelerated sea level rise [28]; ongoing erosion driven by a significant reduction in sediment supply from the Yangtze River, which has fallen below the critical threshold needed for delta stability since 2003, primarily due to large dams in the upper reaches [2,11,29]; and an increase in both the frequency and severity of drought events in the middle and lower reaches of the river [30]. Many studies have revealed the characteristics of sediment load and rating parameters of Yangtze River sediment discharged into the East China Sea [2,11,29], among which some are focused on major floods [21,31] or the specific severe drought event of 2006 [22,23]. However, the general characteristics of the fluvial sediment load discharged to the sea during severe and extreme drought events have rarely been studied. Since the 1950s, eight severe to extreme drought events (1959, 1960, 1972, 1978, 1986, 2006, 2011, and 2022) have occurred within the Yangtze Basin [32,33], causing significant hardship for residents in the watershed. These events are documented in the long-term hydrological records of the Yangtze River. Among these events, the 1978 event was an extreme drought. For simplicity, all of the events are described as severe drought events from here on. This study addresses three primary objectives concerning Yangtze River sediment: (1) to characterize the quantity and grain size of the sediment load discharged to the sea during severe drought years, (2) to analyze the properties of sediment load rating parameters during these drought years, and (3) to assess the feasibility of reconstructing the sediment load discharged to the sea during these drought years using a sediment rating curve.

2. Study Area

With its length of ~6300 km, the Yangtze River is the longest river in China. Its upper, middle, lower, tidal, and estuarine reaches refer to the section above Yichang, from Yichang to Hukou, from Hukou to Datong, from Datong to Xuliujing, and from Xuliujing to the river mouth, respectively (Figures 1 and 2). The upper reach is dominated by a hinterland that drains the mountainous region and plateau, whereas the middle and lower reaches comprise areas mostly characterized by plains. The upper Yangtze River was the main sediment source area before the construction of the TGD in 2003 [34]. The Yichang gauging station, located at the junction of the upper and middle reaches, monitors the runoff and sediment loads supplied by the upper reach. The Hankou station is the main gauging station for the middle reach. The Datong station, as the most downstream hydrological gauging station along the main stream, monitors the runoff and sediment loads discharged into the tidal river reach.

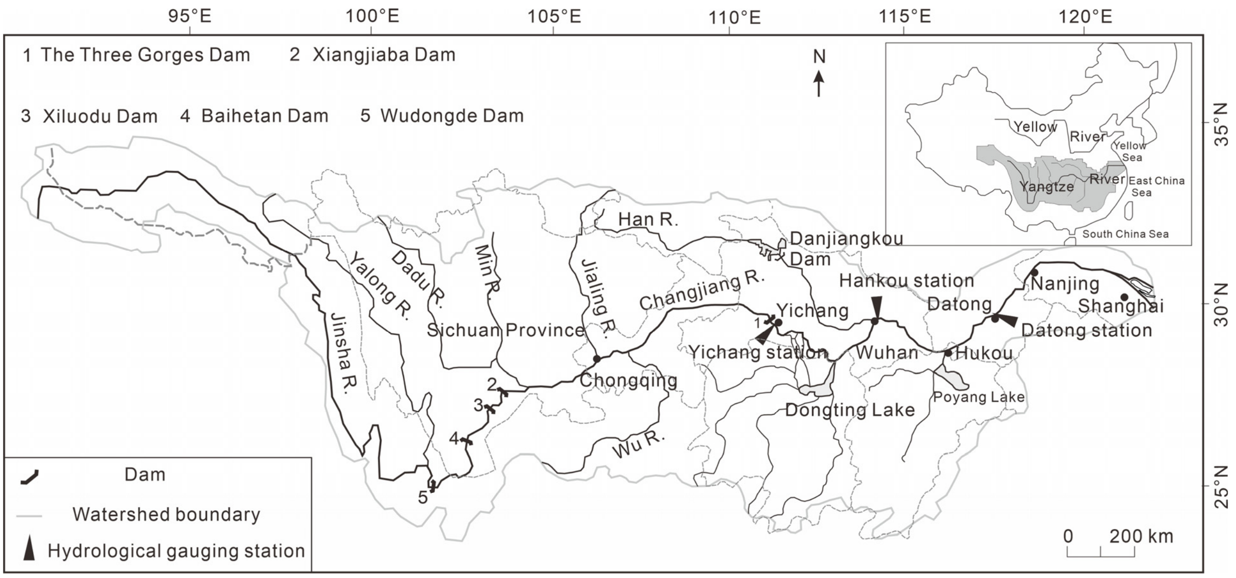

Figure 1. Overview of the study area.

The Datong gauging station, as the most downstream hydrological station, is located 528 km upstream of the Yangtze Estuary. There are no large tributaries or major lakes downstream of the Datong gauging station. Before 2002, siltation used to occur in the tidal river reach as a response to abundant fluvial sediment supply. This resulted in a decrease of no more than 10% in the sediment load of this reach during two distinguished periods, 1958–1992 and 1992–2002 (Figure 2) [35–37]. However, after 2002, a regime shift from siltation to erosion occurred in the tidal river reach due to a significant reduction in sediment load upstream. The erosion led to an increase of 14% and 23%, respectively, in the sediment load leaving the estuary reach compared to what was delivered by the upper reach during two periods of 2002–2012 and 2007–2019 (Figure 2) [37,38]. When analyzing the sediment fluxes in and out of the estuary reach domain, studies show a decrease of 8%, followed by an increase of 10%, another increase of 2%, and a decrease of 10%, respectively, during 1958–1992, 1992–2002, 2002–2012, and 2007–2019 due to siltation or erosion (Figure 2) [36–38]. As a result, the difference in sediment load between Datong and the river mouth decreased by 18% during 1958–1992 and increased by 2%, 16%, and 13% during the periods of 1992–2002, 2002–2012, and 2007–2019, respectively (Figure 2). Water and sediment measured at the Datong station are generally considered fluxes discharged from the Yangtze River into the sea. Accordingly, when referring to "water" and "sediment" discharged from the Yangtze River into the sea, from here on, we refer to water and sediment measured at the Datong station.

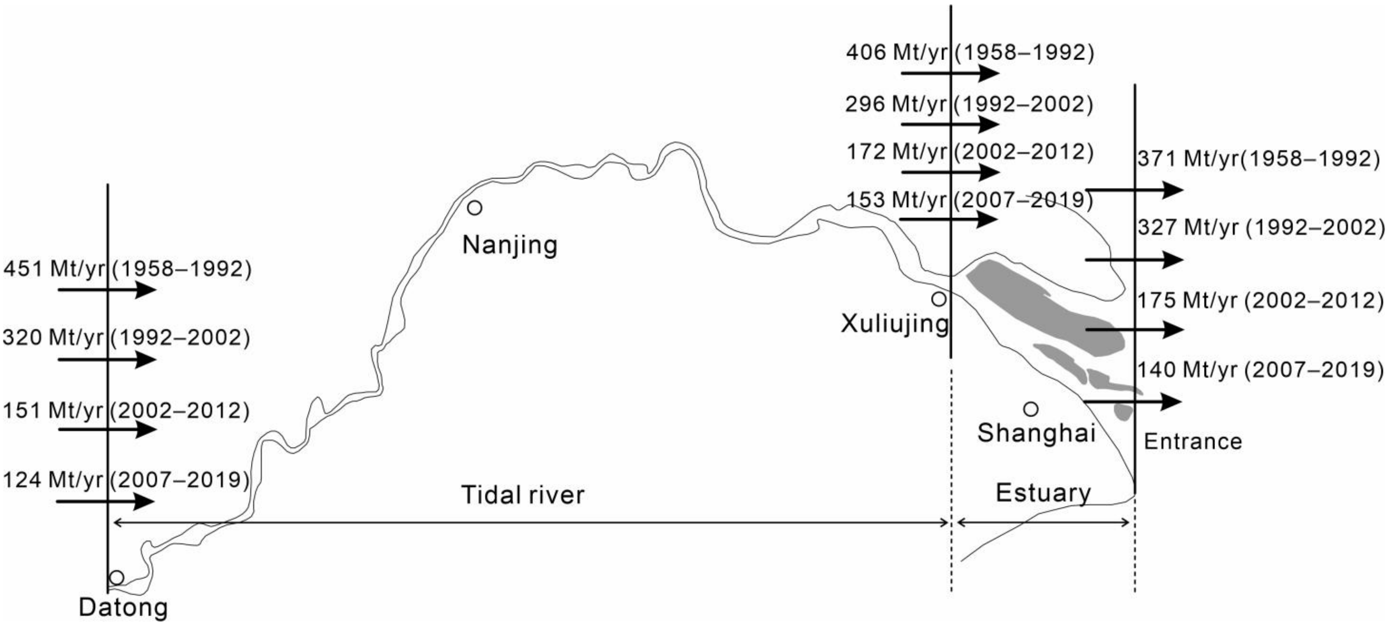

Figure 2. Sediment budgets within the tidal influenced reach and the estuary of the Yangtze River. Data for 1958–1992 are from Wu et al. [36], those for 1992–2002 and 2002–2012 are from Yang et al. [37], and those for 2007–2019 are from Guo et al. [38].

The annual sediment load at the Yichang station showed a significant decrease from 1990 to 2003 and in 2014 (Figure 3a). Two-thirds of the reduction in sediment load at Yichang since the mid-1980s was attributed to hydropower dams, and 65% of the decline since 2003 was caused by the TGD [39]. Sediment load at Yichang decreased further in ~2014 when the Xiangjiaba and Xiluodu Dams became operational in 2012 and 2014, respectively. And this reduction in sediment load was most likely further exacerbated by the construction of the Wudongde and Baihetan Dams in 2020 and 2021, respectively (Figure 1). The change in sediment load at the Hankou and Datong stations was smaller than that at Yichang due to the buffering capacity of the middle reach (Figure 3b,c). The upper reach supplied abundant sediment to the middle reach before ~2002. As a result, fluvial sediments were temporarily deposited in the middle reach until the sediment supply of the upper reach significantly decreased after ~2002. And even with the sediments that now erode from the middle reach, since 2003, the amount of sediment load discharged to the sea has been less than the critical amount needed to sustain the Yangtze Delta as it is known. As a result, part of the subaqueous delta has transformed from a depositional to an erosional environment [2]. Therefore, since 2003, the sediment load from the Yangtze River to the sea has been experiencing a deficit to sustain the Yangtze Delta.

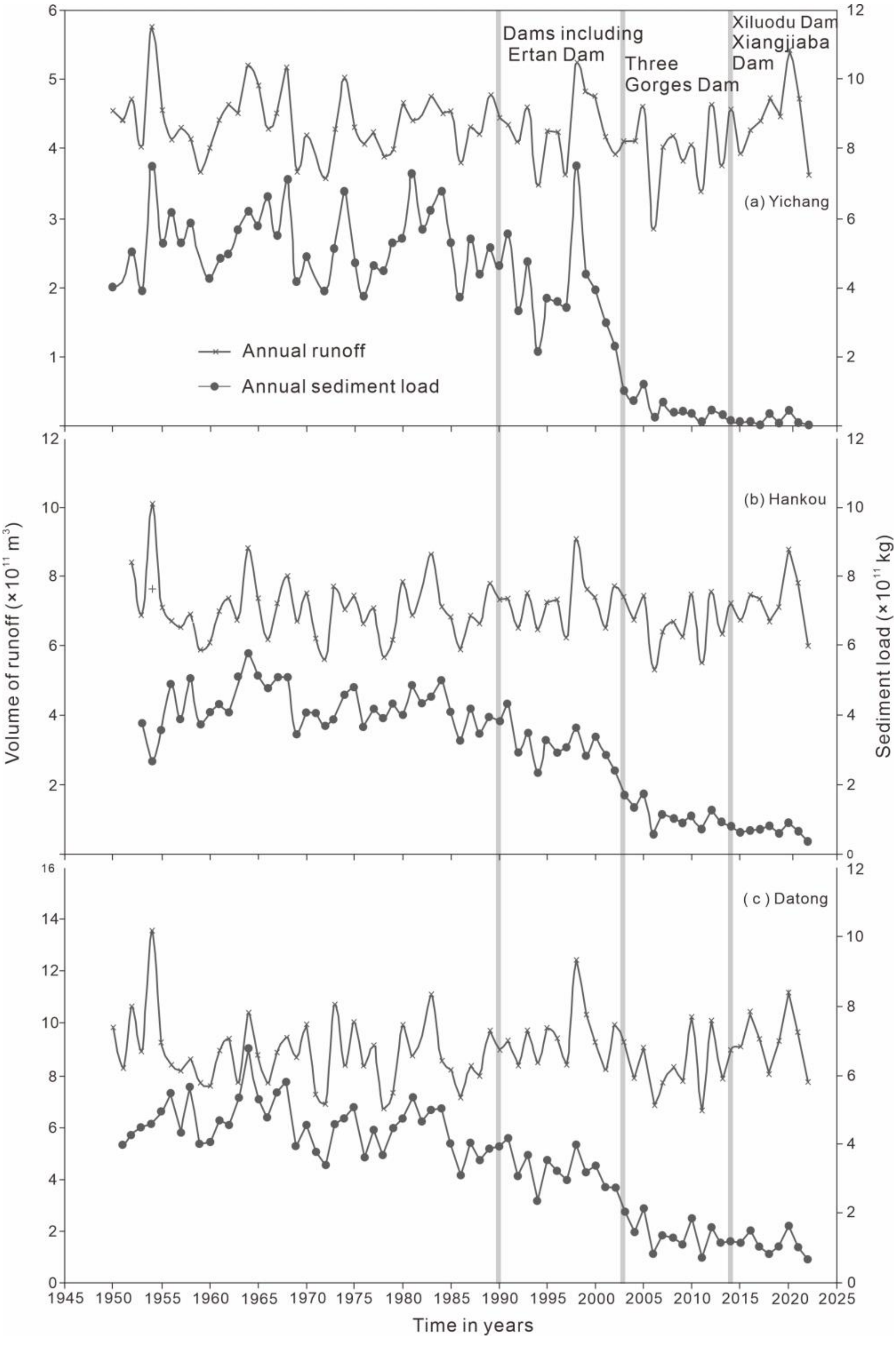

Figure 3. Time series (early 1950s–2022) of runoff and sediment load along the main stream of the Changjiang River and the construction of large dams (gray vertical lines) in the upper reaches for: (**a**) Yichang station, (**b**) Hankou station, and (**c**) Datong station.

The majority of the Yangtze Basin is dominated by a typical sub-tropical monsoon climate, except for a small portion situated in the Tibetan Plateau. As a consequence, up to

~70% of the annual runoff and ~85% of the annual sediment load are transported during the monsoonal flood season (May to October). When a persistent anomaly of atmospheric circulation in East Asia is present, extreme hydrological events, such as severe droughts, can occur within the Yangtze River Basin. Eight severe drought events have occurred since the 1950s. Sediment loads deposited in the sea during these drought years were lower than those during average flow years (Figure 3c).

3. Materials and Methods

3.1. Materials

The hydrological data used in this study were collected from the Annual Hydrological Report P. R. China and from the Hydrology Bureau of Changjiang Water Resources Commission (CWRC). Hydrological measurements at the major gauging stations along the main channel of the Yangtze River began in the early 1950s. The homogeneity and reliability of the hydrological data released by the CWRC has been strictly examined, and the estimated daily error is 16% [40]. These hydrological data include daily water discharge, daily suspended sediment concentration, monthly and yearly particle size distributions, and the median grain size of suspended sediment. The suspended sediment load contributes >99% of the sediment load from the Yangtze River to the sea [41]. Accordingly, the transport of bed load material is not considered in this study. From here on, when we mention "sediment", it represents suspended sediment. Accurate data on the particle size distribution of suspended sediments along the Yangtze River have been released since 1960 [42].

3.2. Estimation of Sediment Components

Different methods have been used to analyze sediment grain sizes during different periods at gauging stations along the Yangtze River. Specifically, particle size apparatuses were used prior to 1986, a combination of a particle size apparatus and a pipette was used during 1987–2009, and laser particle size analyzers have been used since 2010.

Grain sizes analyzed using a particle size apparatus are systematically larger than those conducted using a pipette. A regression equation was proposed to correct this bias [43]:

$$D_a = 0.521 D_p^{0.671} \quad (1)$$

where D_a and D_p are the sediment grain sizes obtained by using a particle size apparatus and a combination of a particle size apparatus and a pipette, respectively. However, a correction has not been developed yet to compensate for any potential measurement bias in grain size distributions measured by a laser particle size analyzer for the Yangtze River sediment. After the correction of bias due to applying different methods, the quantities of clay, silt, and sand within the monthly and yearly sediment loads are recalculated. The grain sizes of clay, silt, and sand are smaller than 0.004 mm, 0.004–0.064 mm, and larger than 0.064 mm, respectively. As such, the quantities of clay, silt, and sand in the seasonal and annual sediments load are obtained. Considering the stages of sediment load deposited in the sea, the time period of 1954–2022 is divided into five stages—1954–1969, 1970–1985, 1986–2002, 2003–2013, and 2014–2022—when referring to the amounts of sediment load. Considering the comparability of sediment grain sizes and components deposited in the sea, the time period of 1960–2021 is divided into five stages—1960–1969, 1970–1985, 1986–2002, 2003–2009, and 2010–2021—when referring to sediment grain sizes and components of the sediment load carried to the sea (the data on sediment grain size for 2022 are not available at present).

3.3. Sediment Budget Analysis

The amount of sediment deposition and erosion in Dongting Lake and the main channels of the middle and lower reaches are estimated based on a sediment budget analysis. More specifically, deposition occurs when the amount of incoming sediment exceeds that of outgoing sediments for a channel or lake, and erosion occurs when the latter exceeds the former. The amount of sediment load supplied by gauged areas are calculated by multiplying the water discharge and the suspended sediment concentration. The amount of sediment load supplied by ungauged areas is estimated by the difference in runoff between upstream and downstream stations multiplied by the minimum suspended sediment concentration among the upstream stations of the study reach. We refer to the details for the computation of sediment load provide by Dai and Lu [44] and Liu et al. [21].

3.4. Sediment Rating Curves

The sediment rating curve is defined as a statistical relationship between suspended sediment concentration (C_m, kg/m^3) and water discharge (Q, m^3/s). It is typically expressed as a power function or a linearized equation:

$$C_m = aQ^b \tag{2}$$

$$log(C_m) = log(a) + b(log(Q)) \tag{3}$$

where a is the rating coefficient and b is the rating exponent.

The rating curve-based sediment reconstruction leads to an underestimation of sediment load [45]. Multiple forms of bias correction factors (CFs) were proposed [45–47]. The one suggested by Ferguson [45] is as follows:

$$\text{CF} = \exp\left(2.651S^2\right) \tag{4}$$

where

$$S^2 = \frac{\sum_{i=1}^{n} (log(C_m)_i - log(C_r)_i)^2}{n-2} \tag{5}$$

denotes the mean square error of the regression, C_r denotes the reconstructed sediment concentration based on the sediment rating curve, and n denotes the number of sediment concentration data points. CF increases with S because the underestimation of measured concentration increases with the scatter degree of the rating curve. Then, the reconstructed sediment concentration after correction is calculated by the following equation:

$$C_{rc} = \text{CF} \times aQ^b \tag{6}$$

4. Results

4.1. Quantity Characteristics of Yangtze River Sediments Carried to the Sea During Severe Drought Years

During all severe drought years, the annual sediment load discharged to the sea observed at the Datong station was less than the corresponding perennial average (Table 1). Before 2003, the amount of sediment supplied by the upper reach during severe drought years was less than the perennial averages. Compared to the perennial average, the annual sediment load discharged to the sea during these years decreased by 19%, 19%, 24%, 17%, and 9%, during respectively 1959, 1960, 1972, 1978, and 1986. After 2003, the amount of sediment supplied by the upper reach during the severe drought years of 2006, 2011, and 2022 was considerably less than the perennial averages. Compared to the corresponding perennial averages, the annual sediment load discharged to the sea decreased by 41%, 50%, and 41%, respectively for 2006, 2011, and 2022. Therefore, severe drought events after 2003 exacerbated the reduction in the amount of Yangtze River sediment carried to the sea.

Table 1. Sediment budget in the Yichang–Datong reach during the different periods and drought years.

Period/Year	Annual Sediment Load at Yichang Station	Annual Sediment Load from Han River	Sediment Deposition at Dongting Lake	Sediment Deposition in the Main Channel of the Middle Reach	Annual Sediment Load at Hankou Station	Annual Sediment Load from Poyang Lake	Sediment Deposition in the Main Channel of the Lower Reach	Annual Sediment Load at Datong Station
	$\times 10^{11}$ kg	$\times 10^{11}$ kg	$\times 10^{11}$ kg	$\times 10^{11}$ kg	$\times 10^{11}$ kg	$\times 10^{11}$ kg	$\times 10^{11}$ kg	$\times 10^{11}$ kg
1954–1969	5.61	1.12	−1.38	−0.98	4.42	0.11	0.43	4.99
1959	4.77	0.31	−0.92	−0.47	3.72	0.15	0.10	4.02 (19%)
1960	4.19	0.86	−1.14	0.09	4.02	0.13	−0.13	4.06 (19%)
1970–1985	5.25	0.28	−0.77	−0.53	4.27	0.14	0.02	4.46
1972	3.86	0.25	−0.31	−0.11	3.74	0.05	−0.39	3.40 (24%)
1978	4.42	0.04	−0.47	−0.10	3.92	0.11	−0.35	3.70 (17%)
1986–2002	4.11	0.08	−0.45	−0.47	3.30	0.08	−0.0011	3.40
1986	3.61	0.03	−0.36	−0.07	3.25	0.16	−0.34	3.11 (9%)
2003–2013	0.47	0.07	0.08	0.48	1.12	0.12	0.16	1.43
2006	0.09	0.03	0.14	0.31	0.58	0.14	0.13	0.85 (41%)
2011	0.06	0.05	0.13	0.43	0.69	0.08	−0.06	0.72 (50%)
2014–2022	0.15	0.04	0.11	0.38	0.67	0.07	0.36	1.13
2022	0.028	0.01	0.12	0.20	0.36	0.05	0.24	0.67 (41%)

Note: For channels and lakes, "−" denotes siltation, and omitted "+" denotes erosion. The values in parentheses in the rightmost column denote degree of reduction in the annual sediment load at the Datong station.

4.2. Seasonal Characteristics of Yangtze River Sediments Transported to the Sea During Severe Drought Years

During severe drought years, the sediment loads carried toward the sea during the flood season and the dry season were nearly all less than the perennial averages (Table 2). Before 2003, the contributions of sediment load transported during the flood season to that of the entire year were 83%, 89%, 87%, 93%, and 90%, respectively, in 1959, 1960, 1972, 1978, and 1986. These are consistent with the perennial averages, with slight variations. After 2003, the contributions of sediment load transported during the flood season to that of the entire year were consistently smaller than the perennial averages. These findings indicate that a stronger reduction in sediment load discharged to the sea during severe drought years occurred during the flood/dry season before 2003 and during the flood season after 2003, accompanied by a decrease in the contributions of runoff during the flood season after 2003.

The year 2003 was clearly a turning point for the seasonal characteristics of runoff and sediment load delivered from the Yangtze River to the sea. Specifically, this turning point was caused by redistributing the water discharge within a year due to reservoir regulation, rather than a sudden weather change. Scheduling the outflow from reservoirs has reduced the peak flow, resulting in a decrease in runoff during the flood season and an increase in runoff during the dry season. As a result, the sediment load decreases during the flood season, while it increases during the dry season. This phenomenon has been observed in other studies as well [48,49].

4.3. Grain Size and Composition Characteristics of Yangtze River Sediment Transported to the Sea During Severe Drought Years

Before 2003, during severe drought years, the median grain sizes of the sediment load discharged to the sea were higher or lower than the perennial averages, and the quantities of sand were all lower than the perennial averages, accompanied by similar or lower contents of sand. Moreover, the quantities of clay were lower or higher than the perennial averages, accompanied by lower or higher contents of clay (Table 3). After 2003, during severe drought years, the median grain sizes of sediment load discharged to the sea were lower than the perennial averages, and the quantities of sand were all significantly lower than the perennial averages, accompanied by slightly higher or lower contents of sand. Moreover, the quantities of clay were lower than the perennial averages, accompanied by higher contents of clay.

Table 2. Seasonal characteristics of runoff and sediment load discharged to the sea measured at the Datong station during severe drought years.

Period/Year	Annual Runoff	Runoff During Flood Season	Runoff During Dry Season	Contribution of Runoff During Flood Seasons	Annual Sediment Load	Sediment Load During Flood Season	Sediment Load During Dry Season	Contribution of Sediment Load During Flood Season
	$\times 10^{11}$ m^3	$\times 10^{11}$ m^3	$\times 10^{11}$ m^3	%	$\times 10^{11}$ kg	$\times 10^{11}$ kg	$\times 10^{11}$ kg	%
1954–1969	8.96	6.51	2.45	73	4.99	4.35	0.64	87
1959	7.73	5.13	2.60	66	4.02	3.32	0.70	83
1960	7.67	5.55	2.12	72	4.06	3.61	0.45	89
1970–1985	8.81	6.30	2.51	72	4.46	3.95	0.51	89
1972	6.95	4.60	2.35	66	3.40	2.96	0.44	87
1978	6.76	4.80	1.96	71	3.70	3.43	0.27	93
1986–2002 *	9.28	6.56	2.71	70	3.28	2.90	0.38	88
1986	7.16	5.04	2.12	70	3.11	2.79	0.32	90
2003–2013	8.33	5.71	2.62	69	1.43	1.15	0.28	80
2006	6.89	4.42	2.47	64	0.85	0.60	0.25	71
2011	6.67	4.26	2.41	64	0.72	0.55	0.17	76
2014–2022	9.31	6.21	3.10	67	1.12	0.88	0.24	79
2022	7.71	4.84	2.87	63	0.67	0.50	0.17	75

Note: *: Daily suspended sediment concentration data from the Datong station for 1988–1996 are not available. Therefore, the statistical results during the period of 1986–2002 exclude data from 1988–1996.

Table 3. Grain size and components of sediment load discharged to the sea measured at the Datong station during severe and extreme drought years.

Period/Year	Median Grain Size	Quantity of Clay	Content of Clay	Quantity of Silt	Content of Silt	Quantity of Sand	Content of Sand
	μm	$\times 10^{11}$ kg	%	$\times 10^{11}$ kg	%	$\times 10^{11}$ kg	%
1960–1967	11.7	1.56	30	2.82	57	0.69	13
1960	16.8	0.62	15	3.02	74	0.42	11
1971–1985 *	12.6	1.28	29	2.60	58	0.60	13
1978	6.1	1.44	39	2.02	55	0.24	6
1986–2002 **	9.5	1.26	38	1.67	50	0.42	12
1986	15.2	0.75	24	1.96	63	0.40	13
2003–2009	9.9	0.49	34	0.73	48	0.26	18
2006	8.0	0.31	36	0.38	44	0.17	20
2010–2021	14.0	0.24	19	0.71	57	0.29	24
2011	9.0	0.19	26	0.46	64	0.07	10

Notes: *: Sediment grain size data from the Datong station for 1972–1973 and 1975 are not available. Therefore, the statistical results for the period of 1971–1985 exclude data for 1972–1973 and 1975. **: Yearly sediment grain size data from the Datong station for 1988–1996 and 2001 are not available. Therefore, the statistical results for the period of 1986–2002 exclude data from 1988–1996 and 2001.

4.4. Rating Parameters of Yangtze River Sediment Transported to the Sea During Severe Drought Years

The daily water discharge and sediment concentration at the Datong station from 1954 to 2021 (data unavailable for 1988–1996) demonstrate a linear log-transformed relationship with a coefficient of determination of $r^2 = 0.49$ (Figure 4a). The corresponding rating parameters of log(*a*) and *b* are −5.6187 and 1.1196, respectively, which are consistent with the findings of Yang et al. [13] and Hu et al. [15]. Sediment rating curves derived from daily water discharge and sediment concentration during the different periods exhibit a distinct variation with time (Figure 4a). Specifically, the data points for 1954–1969 lie on the upper part of the plot, except for some anomalous data points in July–September from a large, basin-wide flood in 1954 (Figure 4a), followed successively by those in 1970–1985, 1986–2002, 2003–2013, and 2014–2021. That is to say, the data points have continued moving downward in response to the decrease in sediment concentration (Figure 4a, Table 4), mainly caused by the creation of a large number of dams since the period of 1970–1985 [13–15]. Correspondingly, the value of log(*a*) decreases slightly from −6.09 to −6.75, and that of *b* increases slightly from 1.28 to 1.37 before 2003, which is similar to the findings of Hu et al. [15] and attributed to the scale effect of the river sections. Specifically, the magnitude of variations in sediment rating parameters exhibits a decreasing trend from upstream to downstream with the increase in drainage area. Conversely, log(*a*) increases significantly from −6.75 to −4.83 and *b* decreases significantly from 1.37 to 0.90 after 2003 (Table 4). A similar variation is noticed by Hu et al. [15] and attributed to a change in the sediment transport regime, i.e., a decrease in the dominant effect of high water discharge on sediment transport induced by the operation of the TGD.

Table 4. Average water discharge ($\overline{Q}$), sediment concentration ($\overline{Cs}$), and rating parameters of log(*a*) and *b* obtained from daily water discharge and sediment concentration.

Periods	$\overline{Q}$ (m^3/s)	$\overline{Cs}$ (kg/m^3)	log(*a*)	*b*	r^2
1954–1969	28,433	0.56	−6.0666	1.2735	0.7695
1959	24,525	0.52	−5.0961	1.0659	0.5734
1960	24,265	0.53	−6.8108	1.4447	0.8087
1970–1985	28,022	0.50	−6.2062	1.2875	0.766
1972	22,063	0.49	−7.2898	1.5677	0.78
1978	21,431	0.55	−7.779	1.6823	0.7893
1986–2002 *	29,428	0.35	−6.6634	1.3543	0.7281
1986	22,650	0.44	−7.4997	1.5896	0.836
2003–2013	26,398	0.17	−4.916	0.9129	0.6598
2006	21,843	0.12	−4.2691	0.7589	0.667
2011	21,154	0.11	−5.5537	1.0403	0.6531
2014–2021	30,143	0.12	−5.3513	0.9706	0.6394

Note: Data for basin-wide flood years, i.e., 1954, 1998, and 2020 were excluded when obtaining the rating parameters of log(*a*) and *b* during the different periods. * Daily suspended sediment concentration data from the Datong station for 1988–1996 are not available. Therefore, the statistical results during the period of 1986–2002 exclude data from 1988–1996.

The data points for the rating parameters of log(*a*) and *b* during the different periods before 2003 slightly shift downward, although they are close to each other (Figure 4b). The data points of log(*a*) and *b* during two periods after 2003 move further downward. The data points for all severe droughts lie within the range of those of normal years during the different periods. This is not impacted by the construction of the TGD and the subsequent large dams.

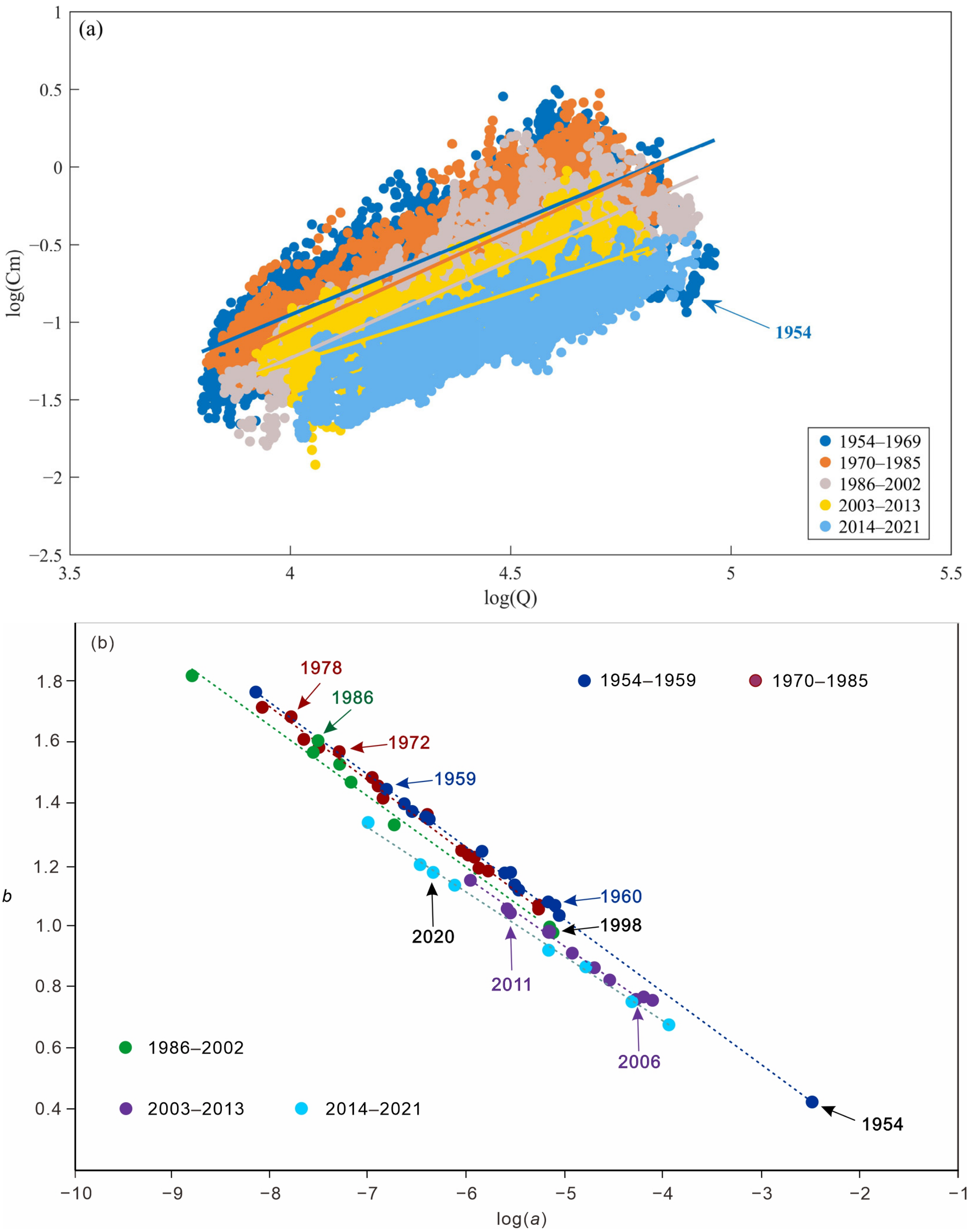

Figure 4. (**a**) Rating curves derived from daily water discharge and suspended sediment concentration data during different periods at the Datong station from 1954 to 2021 (the data from 1988–1997 are excluded, as data for suspended sediment concentration are unavailable), and (**b**) rating parameters obtained from annual sediment load during the different periods.

5. Discussion

5.1. Causes of the Intensified Scarcity of Sediment Flux from the Yangtze River to the Sea During Severe Droughts

During severe drought years, sediment load discharged to the sea was reduced by 9% to 24% from 1954 to 2002, whereas it was reduced by 41% to 50% from 2003 to 2022 (Table 1), indicating that the reduction in the Yangtze River sediment transported to the sea was exacerbated after 2003. In order to explore the causes of this exacerbation of the reduction in Yangtze River sediment carried to the sea, the contribution of each sediment source area to the reduction in sediment load is quantified. The contribution of Poyang Lake to sediment load discharged to the sea ranged from 2% before 2003 to 8% after 2003 (Table 1). The contributions of ungauged areas in the middle and lower reaches to the sediment load at the Hankou and Datong stations are less than 5% and 2%, respectively. Accordingly, the impacts of Poyang Lake and ungauged areas in the middle and lower reaches on the exacerbation of the reduction in sediment load discharged to the sea during severe drought years after 2003 are negligible. Dongting Lake minimizes the variation in sediment load discharged to the sea during severe drought years by decreasing sediment deposition before 2003 and increasing erosion after 2003 (Table 1). Similar to Dongting Lake, the main channel of the middle reach reduces the variation in sediment load discharged to the sea during severe drought years by decreasing sediment deposition before 2003 (Table 1). Therefore, when estimating the impact of each sediment source area, the impacts of Dongting Lake before and after 2003, together with the main channel of the middle reach before 2003, are both negligible. That is to say, only sediment source areas that exacerbated the decrease in sediment load at the Datong station during severe drought years are significant enough to take into account. For example, 0.97×10^{11} kg of sediment reduction at the Datong station in 1959 was induced by the decrease in the main channel of the lower reach (0.33×10^{11} kg) and sediment supply from the middle reach (0.70×10^{11} kg). The decrease in the latter was induced by the decrease in sediment supply from the upper reach (0.84×10^{11} kg) and the Han River (0.81×10^{11} kg) (Table 1). Thus, we can obtain the contribution of each sediment source area to the sediment decrease at the Datong station to estimate the reduction in sediment load discharged to the sea (Table 5).

Table 5. Contribution of sediment load decrease from each sediment source area to the reduction in sediment load discharged to the sea at the Datong station during severe drought years.

Year	Annual Sediment Load from Upper Reach	Annual Sediment Load from Han River	Sediment Deposition in Main Channel of Middle Reach	Sediment Deposition in Main Channel of Lower Reach
	%	%	%	%
1959	35	33	/	32
1960	35	6	/	59
1972	49	1	/	39
1978	36	10	/	49
1986	12	1	/	87
2006	60	6	27	5
2011	52	3	6	31
2022	25	6	36	26

Note: "/" in the table means that the main channel of the middle reach increased the sediment supply by reducing sediment deposition during these severe and extreme drought years. The contribution (32%) of the decrease in sediment supply by the main channel of the lower reach to sediment reduction at the Datong station in 1959 is calculated as $0.33 \times 10^{11}/(0.33 \times 10^{11} + 0.7 \times 10^{11})$. The contribution of the source areas above the Hankou station is 68% in the same year. The contribution (35%) of the decrease in sediment supply by the upper reach to sediment reduction at the Datong station in 1959 is calculated as $0.68 \times 0.84 \times 10^{11}/(0.84 \times 10^{11} + 0.81 \times 10^{11})$.

Before 2003, the significant decrease in sediment load from the upper reach during severe drought years was regulated by less deposition in Dongting Lake and the main channel of the middle reach, resulting in a lower decrease in sediment load at the Hankou station (Table 1). Consequently, the contributions of the upper reach during severe drought years are less than 50%, whereas those of the main channel of the lower reach range from 32% to 87%, accompanied by the minor contribution of the Han River. After 2003, contributions from the upper reach increased significantly due to a substantial reduction in sediment load caused by large dams, including the TGD, Xiluodu Dam, and Xiangjiaba

Dam. Sediment contributions from the main channel of the middle reach account for approximately one-third, with the exception of 2011 (Table 5). This shift coincided with a transition in the middle reach's main channel from a decreasing sediment reduction trend to an intensified reduction, driven by the marked decrease in sediment supply from the upper reach (Table 1). Simultaneously, sediment contributions from the main channel of the lower reach decreased (Table 5). Accordingly, the exacerbation of sediment load decrease measured at the Datong station during severe drought years was caused jointly by the upper reach and the main channel of the middle reach. A shift in the main channel of the middle reach from siltation before 2003 to erosion after 2003 was caused by a significant decrease in sediment load supplied by the upper reach due to the construction of the Three Gorges Reservoir in 2003 and subsequent major reservoirs in the upper reach. Therefore, a significant decrease in sediment load from the upper reach is the fundamental cause of the exacerbation of the decrease in sediment load discharged to the sea during severe droughts after 2003.

5.2. Consequences of the Intensified Scarcity of Sediment Carried from the Yangtze River to the Tidal Reach During Severe Droughts

For the tidal river reach of the Yangtze River, a shift occurred from a more depositional system to an erosional system in approximately 2003 due to the construction of the TGD [50]. Erosion increased with the further decrease in sediment load entering this river section (Figure 2) [38]. Since 2003, the significantly reduced sediment supply, along with the finer sediment composition during severe drought years compared to normal years, has become a major concern for sediment management in the Yangtze River.

The critical sediment loads for the aggradation of the Yangtze subaqueous delta, proposed based on different methods, range from 218 Mt/yr to 300 Mt/yr [1,2,6,7]. Before 2003, the sediment load discharged to the sea was abundant, and the decrease in sediment load discharged to the sea during severe drought years ranged from 9% to 24% (Table 1). As a result, the minimum sediment load of 311 Mt/yr from the Yangtze River to the sea during these drought years would still exceed the maximum critical sediment load need for aggradation, 300 Mt/yr. Furthermore, the grain sizes of the Yangtze River sediment during most severe drought years are larger than the perennial averages (Table 3), which partially compensates for the reduction in sediment load discharged to the sea. After 2003, the sediment load from the Yangtze River to the sea during severe droughts decreased by 41–50% compared to the perennial averages (Table 1), which is only approximately 50% of the critical sediment load needed for the aggradation of the Yangtze subaqueous delta, implying the intensification of erosion of the Yangtze subaqueous delta. Simultaneously, the grain sizes of the sediment load discharged to the sea during severe drought years after 2003 are smaller than the perennial averages (Table 3). Data-driven models reveal that grain size fractions of the sediment bed are one of key factors affecting the scour depth downstream of sluice gates [51]. We infer that the fining of sediment load discharged to the sea would possibly further amplify the erosion of the subaqueous delta. The potential intensification of erosion in the Yangtze subaqueous delta due to severe droughts warrants thorough investigation, as this would aid in predicting the delta's response to the increasing frequency and intensity of extreme climate events in the context of global warming.

Less variation occurred in the amount of sediment load from Datong to the river mouth from 1950s to 2010s. That is to say that sediment load at Datong is dominant in the sediment flux discharged into the sea at the river mouth. Accordingly, it is reasonable to consider water and sediment measured at the Datong station as the flux discharged from the Yangtze River into the sea. Grain size and components of sediment would change after it is transported for over 500 km from the Datong station to the river mouth due to the inevitable exchange between suspended sediment and bed load material. We consider grain size and components of sediment at Datong as those at the river mouth in this study because of the unavailability of the associated measurements, which induces some uncertainties in our analysis.

5.3. Reconstruction of Sediment Load from the Yangtze River to the Sea During Severe Drought Years

Unlike the data for the large, basin-wide flood of 1954, which deviate from those of normal years, all data for severe drought years across various periods fall within the ranges observed in normal years (Figure 4b). So, extremely high *b*-values and low log(*a*)-values, or the inverse, do not represent severe droughts. This is different from the findings of Yang et al. [13]. The spatial distribution characteristics of the rating parameters of severe drought years provide the possibility for the reconstruction of sediment load during these drought years based on the rating curve.

In order to investigate its feasibility, we reconstruct the annual sediment load from 1954 to 2021 (data from 1988–1996 are excluded due to the unavailability of suspended sediment concentration data) by using the sediment rating curve derived from the daily water discharge and sediment concentration during the corresponding period (Figure 5). Data for the large, basin-wide floods of 1954, 1998, and 2020 are excluded when deriving sediment rating curves in order to eliminate the impacts of these extreme hydrological events. The sediment rating curve represents 79% the variation in annual sediment load for 1955–2021 (Figure 5a). There is a slight bias toward underestimating the reconstructed annual sediment load when using the sediment rating curve method. Also, four of the seven annual sediment loads during drought years fall in or are close to the one-to-one line. The average difference, i.e., the relative error between measured and reconstructed annual sediment loads, decreases from 21% (1955–2002) to 10% (2003–2021) (Table 6). This is partly due to decreased contributions from low and high water discharge caused by seasonal runoff variations after 2003 (Table 2), resulting from the regulation of large reservoirs and partly due to the reduced sediment concentration bias at high water discharge, driven by the significant reduction in sediment load after 2003 (Figure 6). Both decrease the relative error. The middle and lower Yangtze River reaches have changed regimes from being sediment transport limited to being sediment supply limited as a result of a substantial decline in sediment load [29]. Further investigations are needed to explore whether the higher relative error before 2003 and lower relative error after 2003 are representative for sediment-transport-limited and sediment-supply-limited conditions, respectively.

Table 6. Relative errors between measured and estimated sediment loads based on sediment rating curves.

Period/Severe Drought Year	Relative Error Without Correction	Relative Error with Correction
	%	%
1955–2002 *	21	21
1959 **	10	2
1960	15	7
1972	36	32
1978	40	35
1986	43	36
1959, 1960, 1972, 1978, 1986 ***	29	22
2003–2021	10	11
2006	6	12
2011	14	20
2006, 2011	10	16

Note: * The average relative error for 1955–2002, excluding basin-wide flood years. ** Relative error is calculated as 100% × |measured sediment load − reconstructed sediment load|/measured sediment load. *** Average relative error for these severe and extreme drought years.

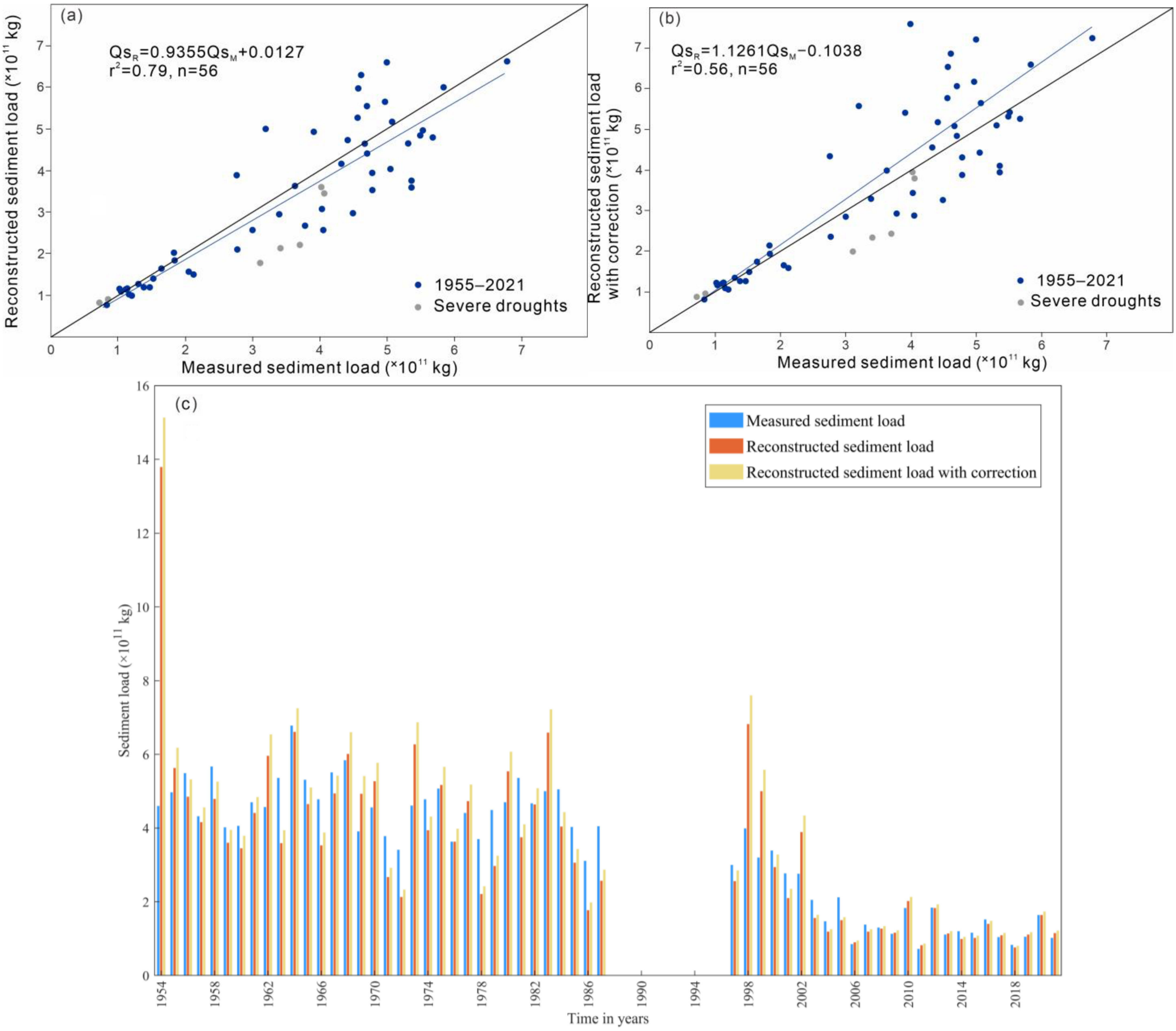

Figure 5. (**a**) Comparison of reconstructed annual sediment load without correction and the measured load at the Datong station from 1955 to 2021, including severe droughts; (**b**) comparison of the reconstructed annual sediment load after correction and the measured load at the Datong station from 1955 to 2021, including severe droughts; and (**c**) measured annual sediment load, reconstructed load without correction, and reconstructed load with correction from 1954 to 2021.

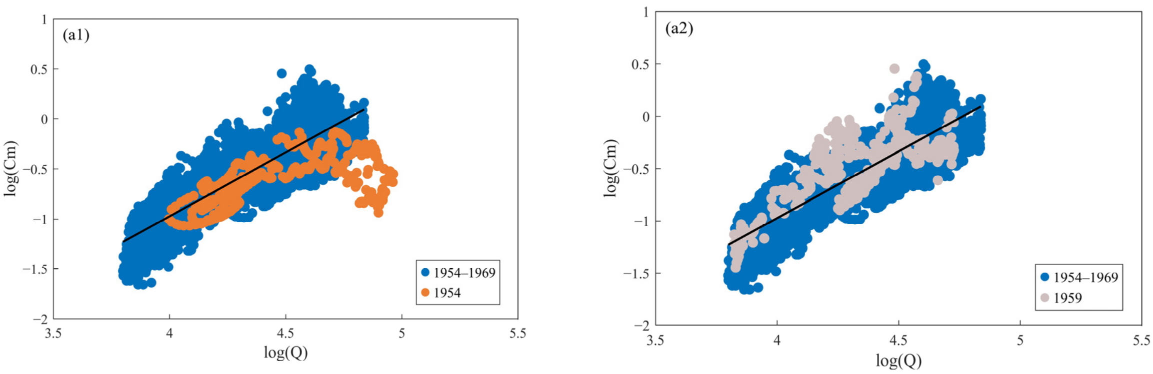

Figure 6. *Cont.*

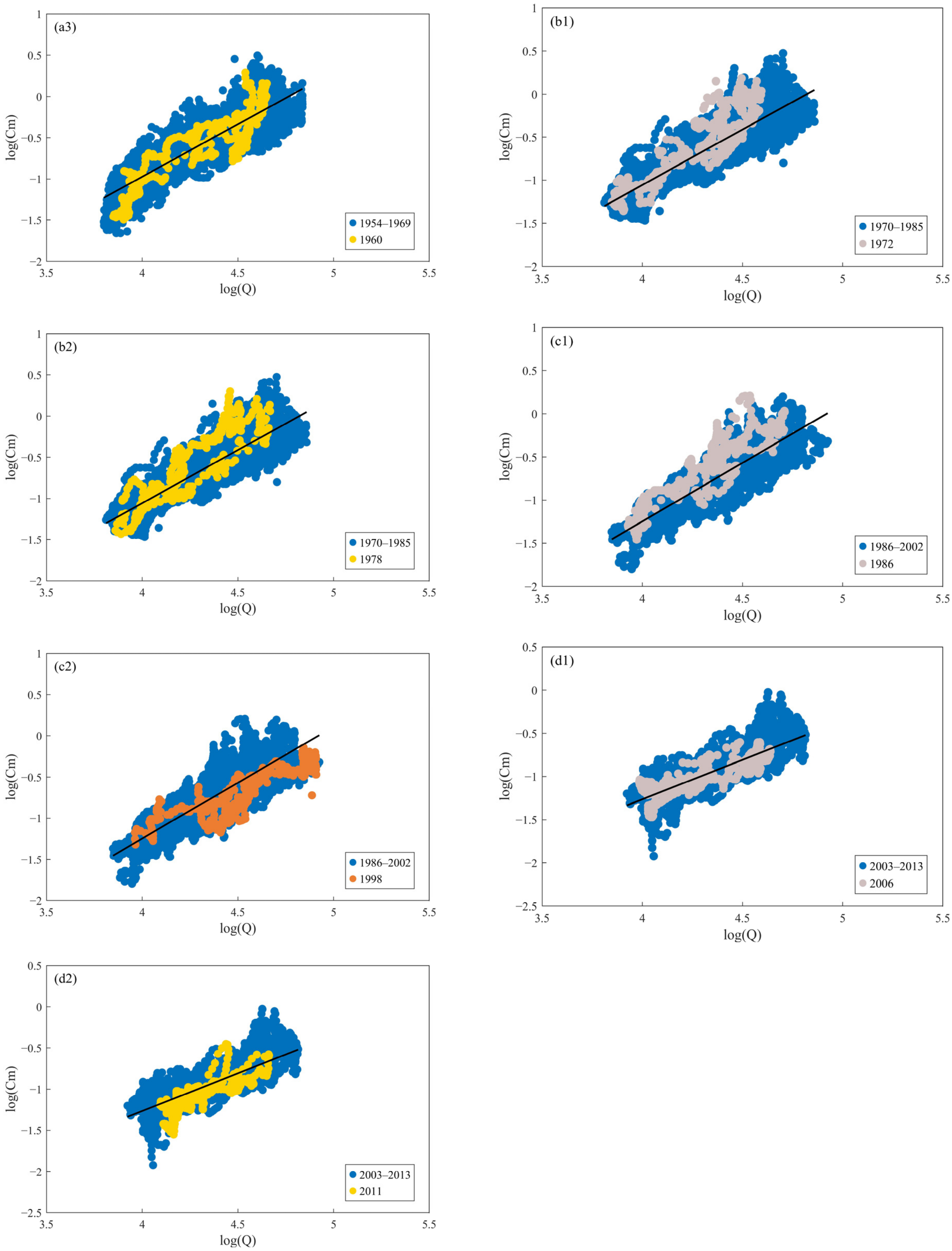

Figure 6. (**a**) Log daily water discharge vs. log daily suspended sediment concentration from 1955 to 1969 and for 1954 (**a1**), 1959 (**a2**), and 1960 (**a3**); (**b**) log daily water discharge vs. log daily suspended sediment concentration from 1970 to 1985 and for 1972 (**b1**) and 1978 (**b2**); (**c**) log daily water discharge vs. log daily suspended sediment concentration from 1986 to 2002 and for 1986 (**c1**) and 1998 (**c2**); and (**d**) log daily water discharge vs. log daily suspended sediment concentration from 2003 to 2013 and for 2006 (**d1**) and 2011 (**d2**).

Before 2003, the average difference between measured and estimated annual sediment loads for five severe drought years was 29%, approximately one-third higher than that between measured and estimated annual sediment loads for the non-drought years of 1955–2002. The average relative error for the two severe drought years after 2003 is similar to that for the non-drought years of 2003–2021 (Table 6). The comparison of the measured sediment loads and estimated loads of the corresponding periods from 1955 to 2021 demonstrates that using this method is effective for estimating sediment loads during severe droughts. However, it is less accurate to use for large, basin-wide floods before 2003, as the reconstructed sediment loads are considerably higher than the measured loads (Figure 5c).

The data from severe drought years can be categorized into two types based on their spatial distribution characteristics. The first type is consistent with data from normal years during the corresponding periods such as 1959, 1960, and 2006 (Figure 6(a2,a3,d1)). The second deviates from those data during the corresponding periods such as 1972, 1978, 1986, and 2011 (Figure 6(b1,b2,c1,d2)). Specifically, for the first type, data from these drought years are centered on the regression line of the corresponding periods and relatively evenly distributed on both sides of the line, resulting in less relative error in the reconstructed annual sediment load for these drought years (Table 6). For the second type, most data from these severe droughts fall above the regression line, as in 1972, 1978, and 1986 (Figure 6(b1,b2,c1)), or below the line, as in 2011 (Figure 6(d2)), which causes a larger relative error for these drought years (Table 6). Furthermore, an extreme negative bias from the regression line occurs for the large, basin-wide floods of 1954 and 1998 (Figure 6(a1,c2)), inducing an abnormally large difference between the measured and reconstructed sediment loads for these two years (Figure 5c).

We use Equations (3)–(5) to correct the reconstructed sediment concentration and obtain a corrected annual sediment load. The data in the plot shift upward after correction (Figure 5b), resulting in their even distribution on both sides of the 1:1 line. The correction reduces the relative error of reconstructed annual sediment loads for five severe drought years before 2003, whereas it increases that for two severe drought years after 2003 (Figure 5c, Table 6). Furthermore, it does not reduce the mean relative error of the reconstructed sediment load before and after 2003. This implies that the correction based on the CF hardly improves the reconstruction of sediment load for both severe drought years and normal years. This finding, which is based on nearly 50 years of hydrological data plus five severe droughts before 2003 and 20 years of data plus two severe droughts after 2003, reveals the limitation of the method of correction used in this study for improving sediment load prediction. Therefore, further analysis is needed to investigate the applicability of our findings, potentially on a longer time scale.

5.4. General Application of This Study

The Yangtze River is among world's largest rivers and has experienced dramatic sediment flux decreases due to intensive human interference. Sediment trapping caused by dams has been widespread in the global hydrologic north, especially in Asia and Europe [12]. The resilience of sediment downstream of the dams occurs as a response to an upstream sediment decrease. The level of resilience of sediment depends on multiple factors such as the distance between a dam and the delta, the availability of sediment downstream from dams, and the magnitude of river flow, among others [8,11,29]. For example, Nittrouer and Viparelli [52] did not find a significant decrease in the sand load of suspended sediment in the lower 1100 km of the Mississippi River since dam construction in the upper reach due to sediment supplement (mostly sand) from bed scouring. Similarly, Gao et al. [11] also found that the mean grain size of the suspended sediment discharged from the Yangtze River into the sea did not change considerably during the different periods from 1956 to 2010 due to sediment recruitment from bed erosion in the middle and lower reaches. However, the sediment fluxes to the sea from the Mississippi and Yangtze Rivers are both much lower than those before dam construction due to the limit of availability of sediment downstream of the dams, which results from the massive construction of levees and revetments [11,53]. The degree of sediment recovery is much smaller when a dam is near the delta, such as the Aswan Dam in the Nile River. As a result, fluvial sediments replenishing the delta from the Nile River have nearly vanished [54]. The impact of river flow on sediment recruitment downstream of dams can be illustrated by the Yellow River. The implementation of a water–sediment regulation scheme (WSRS) using the coordinate operations of three large reservoirs in the middle reaches since 2002 has resulted in artificial flood waters annually, which produce high river flow and cause the erosion of coarser sediments from the lower riverbed. These coarser sediments have become a new sediment source supplied to the delta [55]. This has led to an increase in the average median grain size of suspended sediment discharged by the Yellow River since 2002 [8].

Overall, the variation in sediment load downstream of dams for the Mississippi River is similar to that for the Yangtze River, while the variation for the Nile River is different from that for the Yangtze River. Therefore, it is reasonable to generalize that our research results are representative for large rivers with sufficient opportunity for sediment recovery by a long distance between the dams and the delta, such as for the Mississippi River. Regarding large rivers in which the sediment load downstream of the dam is controlled by the regulation of a reservoir, such as the Yellow River, whether our research results are representative or not probably depends on the degree of reservoir regulation during severe droughts. For small rivers impacted by dams, the sediment recovery is most likely limited by the short distance between a dam and the delta. Therefore, we acknowledge that our research results may not represent the conditions of smaller rivers impacted by dams.

6. Conclusion

(1) The degree of reduction in sediment load from the Yangtze River to the sea during severe drought years has increased significantly since the construction of the TGD in 2003. Before 2003, the sediment load discharged to the sea decreased by less than 25% during severe drought years compared to the perennial average. After 2003, sediment load toward the sea decreased by 41% to 50%. The primary cause of the intensified reduction in sediment load discharged to the sea during severe drought years after 2003 is a substantial decrease in sediment supply from the upper reach.

(2) Before 2003, the median amounts of sediment load discharged to the sea during most severe drought years were larger than the average levels of the corresponding periods. After 2003, the median amounts of sediment load are smaller than those of the corresponding periods. The sand fraction content of the sediment flux to the sea during severe drought years are nearly at or below the average levels of the corresponding periods.

(3) Remarkable variations in sediment load discharged to the sea during severe droughts can have a profound impact on the evolution of the tidal river reach and the subaqueous delta, promoting the acceleration of erosion in the Yangtze subaqueous delta.

(4) Estimated rating parameters of log(a) and b for severe drought years fall within the range of those for normal years, implying that these severe droughts do not correspond to extreme rating parameters, such as extreme high b-values and low log(a)-values or the inverse.

(5) The rating curve-based reconstruction of sediment load is effective for severe droughts, where the relative error is slightly larger than the average of normal years before 2003 and close to those after 2003. However, the accuracy of sediment load reconstruction is insignificantly improved when applying a CF correction.

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