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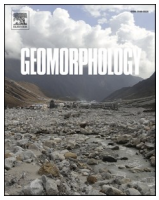
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Dam-induced changes in multi-fraction sediment recovery in the middle-lower Yangtze River

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A B S T R A C T

Hydropower dams induce downstream sediment starvation, influencing fluvial morphology. With the focus commonly on morphological changes, an aspect of sediment starvation that has received much less attention is the impact of changes in the sediment grain size distribution (GSD) on these morphological changes. In this study, we investigate the effects of the Three Gorges Dam (TGD) on the multi-fraction sediment transport and bed recovery in the middle-lower Yangtze River. Based on long-term field data (1987–2021), we evaluate how fine ($d < 0.031$ mm), medium (0.031–0.125 mm), and coarse ($d > 0.125$ mm) fractions differentially respond to dam regulation. Our findings reveal a progressive coarsening of suspended sediment and identify three distinct dam-induced sediment regimes: static armored gravel bed, active bed armoring, and strong erosion. Within the first ~350 km downstream of the TGD, erodible sediments, especially fine and medium fractions, have been almost entirely depleted. In contrast, the subsequent 750 km reach has emerged as the dominant sediment source, increasingly characterized by medium and coarse fractions over time. In addition, tributaries now supply fine-grained sediment during the wet season, whereas lakes, acting as long-term sediment storage zones, release previously deposited material during the dry season. Both sources are playing an increasingly important role in modulating the GSD of the middle-lower Yangtze. These findings shed lights on the dam-induced multi-fraction sediment recovery, offering valuable guidance for the sustainable management of river systems influenced by upstream dams.

1. Introduction

Dams have been constructed in many river systems across the globe, serving hydropower generation, flood control, and water storage (Best, 2019; Lucas-Borja et al., 2021; He et al., 2024). Currently, over 58,000 large dams (over 15 m high) capture approximately 25–30% of the global sediment flux (Poff and Schmidt, 2016; Vörösmarty et al., 2003), significantly altering downstream hydraulic regime and sediment transport processes. This disruption drives riverbed erosion (Graf, 2006; Zheng et al., 2018), channel instability (Graf, 2006; Morais et al., 2016), and coastal degradation (Anthony et al., 2015; Bussi et al., 2021; Syvitski and Saito, 2007). Therefore, understanding the impact of dams on downstream sediment dynamic is essential for dam regulation and sustainable river management.

Sediment trapping in reservoirs reduces downstream sediment load and alters channel morphology (Dethier et al., 2022; Syvitski et al., 2005; Vörösmarty et al., 2003), which has been a main focus of most studies examining the impacts of dams. However, the effects of dams on sediment grain-size distribution (GSD) have received far less attention. In the Mekong and Yellow River, for instance, coarse-grained sediment is preferentially trapped in reservoirs and finer sediments are released downstream (Anthony et al., 2015; van Maren et al., 2013; Wang et al., 2017). A similar phenomenon is observed in the Colorado River, where dam-induced reductions in sand supply have led to bed armoring and associated ecosystem shifts. Likewise, in the Mississippi River, post-dam coarsening of bedload sediments has exacerbated bank erosion (Grams et al., 2007; Meade and Moody, 2010). Despite recognition of the GSD's role in sediment dynamics (Antoine et al., 2020; Fu et al., 2023; Kondolf et al., 2014), few studies explicitly link multi-fraction sediment transport to morphological adjustments, leading to large uncertainties in predicting long-term river responses to transitions in sediment regimes.

The Yangtze River, Asia's largest fluvial system, has experienced a 70% decline in sediment load since the Three Gorges Dam (TGD) began in operation in 2003, resulting in extensive downstream erosion (Tian et al., 2021; Yang et al., 2023). Fine sediments dominate suspended sediment loads, and coarser fractions are increasingly sourced from channel erosion (Dai et al., 2018; Chen et al., 2022; Deng et al., 2022; Zhou et al., 2023a). Consequently, progressive riverbed coarsening has

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been widely observed downstream of the TGD, particularly in the upper reaches of the middle Yangtze River, leading to shifts in erosion intensity and spatial patterns (Lai et al., 2017; Luo et al., 2012). Understanding changes in the GSD and multi-fraction sediment transport is therefore critical for predicting long-term downstream morphological evolution. Earlier studies on sediment decline mainly relied on sediment budgets based on annual mean sediment loads measured in the main channel (Yang et al., 2002; Yang et al., 2006; Zhang et al., 2006; Chen et al., 2008; Dai and Liu, 2013; Dai et al., 2018). These studies focused on the effect of the TGD only, evaluated for the main stem of the Yangtze River, and not accounting for granulometric changes. Since then, several studies have advanced our understanding of several aspects of this response. Luo et al. (2012) was probably the first to address the impact of the TGD on the grain size distribution. They documented channel erosion and riverbed coarsening but provided limited insight into the recovery of the suspended load through channel erosion. Fractional sediment transport and recovery processes were evaluated for several regional river reaches (Deng et al., 2022; Zhou et al., 2023b), including the buffering effects of the large lakes along the Yangtze River (Guo et al., 2018; Yang et al., 2022; Zhu et al., 2022; Zhu et al., 2023). In the past decade, the sedimentary response is further complicated by the construction of reservoirs upstream of TGD (Yang et al., 2018a; Wu et al., 2018; Li et al., 2023). We identify two aspects in this sedimentary response which has received limited attention so far. First, the sediment grain size of the Yangtze and its tributaries are seasonally varying, and understanding the granulometric response of the river therefore requires an assessment of the seasonal variability in suspended load transport. Secondly, and probably most importantly, a comprehensive framework that integrates non-uniform sediment transport, channel erosion, tributary and lake contributions, and downstream recovery processes is missing.

In this study, we aim to investigate the effect of dams on multi-fraction sediment transport and morphological changes in the middle-lower Yangtze River, with a focus on associated sediment recovery regime transitions. We specifically address: (1) the role of GSD adjustments in multi-fraction sediment transport and their influence on riverbed erosion, and (2) the compounded impacts of the TGD, tributaries, and lakes on sediment recovery. By synthesizing suspended and bed sediment GSD data, hydrological records, and findings from two field surveys, we quantify how sediment load decline, riverbed erosion, and inputs from tributary and lakes collectively modulate post-dam sediment dynamics. The paper is organized as follows: Section 2 describes the study area, datasets, and methods; Section 3 presents changes in sediment GSD and recovery, including interannual and recent seasonal variations; Section 4 discusses the sediment regimes associated with GSD changes, the distinctive contributions of tributaries and lakes, and broader global implications; finally, Section 5 concludes with the key insights.

2. Study area and materials

2.1. The Yangtze River basin

The Yangtze River ranks the third, fourth, fifth globally in terms of length (~6300 km), sediment load (351 Mt/yr during1950–2020) and river discharge (9×10^{11} m^3/yr during 1950–2020) (Milliman and Farnsworth, 2013; Changjiang Water Resources Commission (CWRC), 2002–2022). From the Qinghai–Tibet Plateau (>3000 m), through mountainous regions (~1000 m), to the Eastern China Plain (~100 m), the river exhibits a three-step topography before entering the East China Sea (Wang et al., 2013). Therefore, it is conventionally divided into three sub-reaches: upper, middle, and lower. Defining the TGD as 0 km, the middle-lower Yangtze River basin extends around 1050 km from Yichang to Datong (45–1100 km, see Fig. 1), transiting from low foothills to a vast alluvial plain.

Governed by the East Asian monsoon system, the mean annual precipitation ranges from ~1000 mm in the upper basin to 1100–1800 mm in the middle-lower basin, of which more than 70% occurs during the wet season (May–October) (Ma et al., 2025). This seasonal rainfall variability results in wet-season flows exceeding 40,000 m^3/s in the middle-lower Yangtze, while dry-season flows generally remain around 10,000 m^3/s. Besides, strong seasonal rainfall, combined with steep topography in the upper basin, historically promoted high soil erosion rates and efficient hillslope-channel sediment connectivity prior to

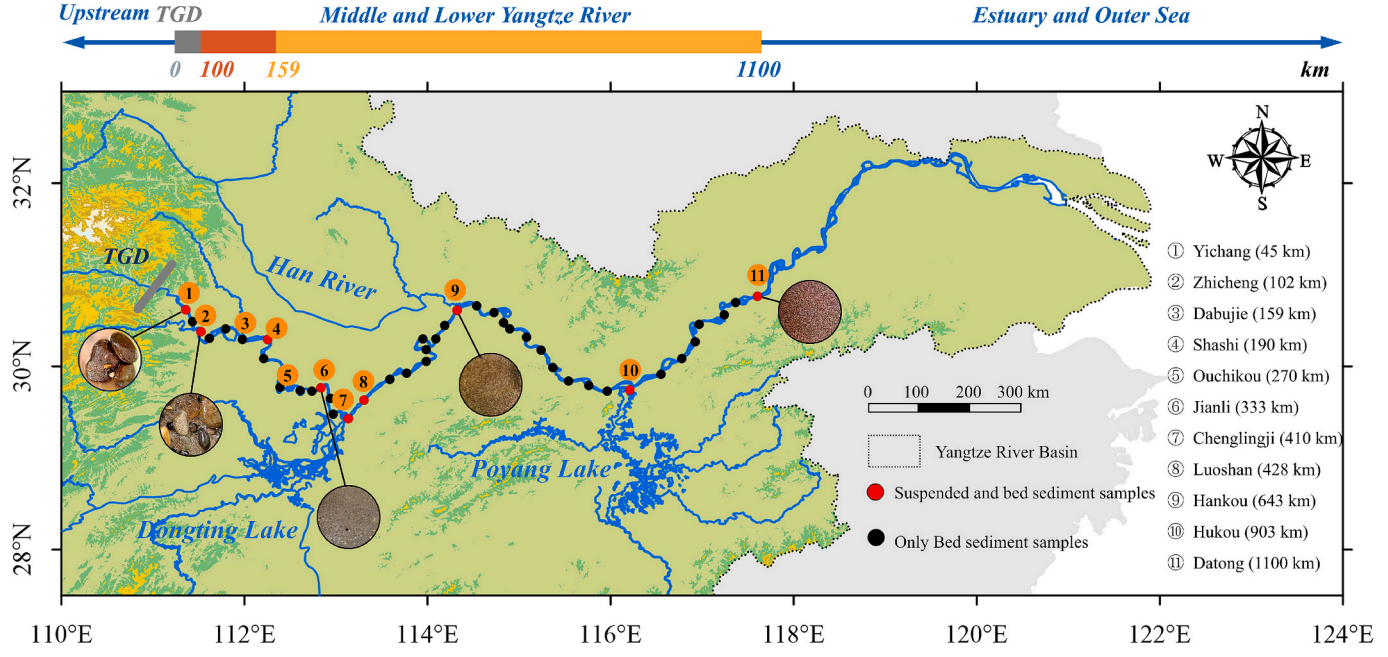


Fig. 1. Map of the middle and lower Yangtze River, illustrating major tributaries, lakes, gauging stations, and sediment sampling locations. The photos depict riverbed sediment samples collected in December 2022. The grey, red and orange regions of the axis on top of the map represent the pre-TGD sand-gravel, transitional, and sandy reaches, respectively. The locations of the gauging stations are indicated by the distances downstream of the TGD (defined as 0 km). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

large-scale dam construction. Moreover, the upper Yangtze River basin is dominated by sedimentary rocks, while the middle-lower basin is characterized by thick alluvial deposits formed under long-term fluvial aggregation (Yan et al., 2011; Liu et al., 2022). This lithological contrast leads to spatially variable sediment grain-size supply, with coarse material mainly sourced from the mountainous upper basin and finer sediment generated from weathering and floodplain reworking downstream, regulated by dam constructions (e.g., TGD). Specifically, prior to the construction of the TGD, the riverbed was primarily composed of gravel and sand within the initial ~100 km downstream of the TGD and predominantly sandy between Zhicheng to Datong (102–1100 km). Note that the Zhicheng-Dabujie reach (102–159 km) transitioned from sand-gravel to sandy, and no bedrock is exposed further downstream (Yang et al., 2018b).

The middle-lower Yangtze River fed by several major tributaries and lakes, e.g., the Han River, Dongting Lake and Poyang Lake, is nowadays strongly impacted by the TGD located at Yichang. The TGD is one of the largest dams in the world, with a crest elevation of 185 m above mean sea level and a normal pool level of 175 m (Freer, 2001; Niu, 2016). Since its initial impoundment in 2003, the TGD has experienced three major operational stages, with water levels rising from 135 to 139 m (2003–2006) to 144–156 m (2006–2008), and finally to 145–172 m since 2008. Since 2010, the reservoir has been operated to reach its maximum post-flood level around September 10 each year (Zheng, 2016). Water is stored during the wet season and released during the dry season for hydropower generation and flood control (Chen et al., 2016). As a result, the annually averaged sediment load at Datong station sharply decreased from ~430 Mt during 1950–2002 to ~160 Mt during 2003–2014 (Guo et al., 2018; Yang et al., 2018a).

Apart from the TGD, more than 14,000 dams with individual storage capacities exceeding 10,000 m^3 have been constructed in the upper Yangtze basin for flood control and hydropower generation (Guo et al., 2020). Large cascade reservoirs with storage capacities exceeding 2 km^3, including Xiluodu, Jingping-1, Xiangjiaba, Guanyinyan, Tingzikou, and Ludila, were mainly completed between 2010 and 2014, substantially enhancing sediment trapping efficiency at the basin scale (CWRC, 2015). The combined storage capacity of the Xiluodu and Jingping-1 reservoirs alone exceeds half of that of the TGD. These reservoirs have dramatically reduced longitudinal sediment connectivity, causing sediment supply from the upper Yangtze River to approach zero in recent years (Tian et al., 2021; Yan et al., 2022). Consequently, sediment load at Datong station further declined to ~120 Mt after 2014 (CWRC, 2015).

2.2. Datasets

We collect river discharge, suspended sediment concentration (SSC), suspended and bed sediment grain size, morphology in the middle-lower Yangtze River from different datasets (Table 1). Long-term hydrological and sediment data were collected by the Changjiang Water Resources Commission (CWRC, https://www.cjw.gov.cn/zwzc/zjgb/cjnsgb) and China Three Gorges Corporation (CTGC, https://www.ctg.com.cn/sxjt/xzzx37/jtnb/index.html) at main gauging stations downstream of the TGD during 1987–2021. Detailed riverbed sediment grain size data downstream of the TGD are available before its construction (Wang, 2006) and after 2008 (Luo, 2013). Daily river discharge and suspended sediment concentration (SSC) were recorded, with particle size measurements conducted over 30 times annually. Notably, the sediment load from May to October (the wet season) constitutes more than 85% of the total annual sediment load. During this period, the suspended sediment exhibits a slightly coarser composition compared to the dry season (Guo et al., 2018; Li et al., 2021; Zhou et al., 2023b). The annual sediment GSD, shown in Table 1, was calculated by weighting the monthly averaged GSD with the corresponding monthly sediment load (Deng et al., 2022).

As part of this study, field measurements were conducted in September 2021 and December 2022 to measure the river discharge, SSC, suspended and bed sediment GSD in the middle and lower Yangtze River (Fig. 1). The discharge was measured with ADCP cross-sectional observations, and sediment sampling was done in the central part of the river channel. Before GSD analysis, all carbon, carbonates, and flocs were removed by pre-treating all samples following standard protocols with (chronologically) H_2O_2, dispersant $(NaPO_3)_6$ and ultrasonic treatment. However, it is worth noting that an LS-100Q Coulter Counter was used to measure the GSD in 2008 while an LS 13320 Coulter Counter was employed in other years. Different instruments are known to influence the GSD (Jacobs, 2011), but we are not sure to what extent the use of these specific Coulter versions influenced the GSD. In this study, sediment load specifically refers to suspended sediment transport. We exclude bed load because it constitutes less than 4% of the total sediment load in the Yangtze River (Xia et al., 2016; Guo et al., 2018).

Table 1
Source of hydrological and sediment data downstream of the TGD.

Data type	Sampling station	Description	Sources
Daily discharge, annual and monthly runoff and sediment load	Yichang, Zhicheng, Shashi, Jianli, Luoshan, Hankou, Datong	1987–2021 annual averages	CWRC
Median size of suspended sediment	Yichang, Zhicheng, Shashi, Jianli, Luoshan, Hankou, Datong	1987–2021 annual averages	CWRC
Fine, medium, coarse fraction of suspended sediment	Yichang, Zhicheng, Shashi, Jianli, Luoshan, Hankou, Datong	1990–2015 annual averages	CWRC
Fine, medium, coarse fraction of suspended sediment	Yichang, Zhicheng, Shashi, Jianli, Luoshan, Hankou, Datong	2016–2021 annual averages	CTGC
Channel erosion volume	Zhicheng to Ouchikou reach and Ouchikou to Chenglingji reach	2011–2020 annual total erosion	CWRC
Longitudinal thalweg profiles in the middle reaches of the Yangtze River	Yichang to Hankou	October 2002, October 2008, October 2017	CWRC
Bed sediment grain size	Along each cross-channel transect, two or three samples were collected with one of them at deeper channel	April 2000 to May 2003, January 2008	Wang (2006) Luo (2012)
Suspended sediment concentration (SSC) Suspended sediment grain size Bed sediment grain size	SSC and suspended grain size data are obtained at main station (Fig. 1). Bed sediment samplings are conducted every 20 km.	September 2021, December 2022	This study

In the Yangtze River basin (upstream of Datong), a particle size of 0.125 mm is commonly used to distinguish wash load ($d < 0.125$ mm) and suspended bed material ($d > 0.125$ mm) (Chien and Wan, 2003; Dai et al., 2018; Guo et al., 2023). For the Yangtze Estuary and adjacent coastal area (downstream of Datong), fluvial sediments with a particle size smaller than 0.031 mm drive morphodynamic changes (Chen et al., 2003; Yun et al., 2003). Therefore, existing long-term datasets typically distinguish between a fine sediment fraction ($d < 0.031$ mm), medium sediment fraction ($d = 0.031$–0.125 mm) and coarse sediment fraction ($d > 0.125$ mm). For consistency, the more recent observational data (2021, 2022) are presented following this classification scheme.

2.3. Methods

To systematically investigate the spatial and temporal development of the fine, medium, and coarse sediment fractions (as defined above), the annual sediment load per sediment fraction (S_f) is calculated at all major gauging stations using:

$$S_f = S_{total}\overline{P_f} \quad (1)$$

where f = 1–3 represents the fine, medium and coarse sediment composition; S_{total} is the annual total sediment load at the station and $\overline{P_f}$ is the annually averaged contribution per sediment fraction. Using such an annual average to identify individual fraction is a valid approach because these annual averages were computed with the exact opposite approach (the annual sediment grain size was calculated as the average value of monthly-averaged fraction, weighted by the corresponding sediment load of that month (Deng et al., 2022).

The sediment loads per fraction were subsequently used to develop a sediment budget to compute erosion/accumulation of the three sediment fractions in each river section. The relation can be briefly described with the following equation:

$$\Delta S_f = S_{fin} - S_{fout} \tag{2}$$

where a positive ΔS refers to the sediment accumulation in the riverbed while a negative value reflects sediment recovery from the riverbed. The S_{fin} and S_{fout} are the sediment loads per fraction at the inlet and outlet stations of the study reach.

The formula for evaluating the contribution of the Han River (η_H), Dongting Lake (η_D) and Poyang Lake (η_P) to the sediment recovery in the Yangtze River is as follows:

$$\eta_* = \frac{(SSC_* \times Q_*)}{(SSC_{DT} \times Q_{DT} - SSC_{YC} \times Q_{YC})} \times 100\% \tag{3}$$

where SSC and Q are suspended sediment concentration and water discharge. When * represents *H*, *DT*, and *PY*, it corresponds to the data collected at the stations where the Han River, Dongting Lake, and Poyang Lake connect to the Yangtze River, respectively. Note that Dongting Lake receives flow from four secondary tributaries and joins the Yangtze River at Chenglingji (410 km); Poyang Lake is fed by five secondary tributaries and supplies water and sediment to the Yangtze River at Hukou (903 km). Therefore, these stations refer to Chenglingji for Dongting Lake and Hukou for Poyang Lake, respectively. The subscripts of DT and YC refer to the corresponding data collected at Datong station and Yichang station, respectively.

3. Results

3.1. Suspended sediment load and grain size changes

This section introduces the interdecadal variation in suspended sediment characteristics in terms of suspended sediment load, median diameter (D_{50}) and three sediment fraction contribution. The study period (from 1987 to 2021) are divided into four periods according to the operational schedule of the TGD: (1) before the closure of the TGD (1987–2002); (2) the TGD was impounded with a top water level of 139–156 m (2003–2007); (3) the top water level of the TGD was further raised to 172 m or 175 m (2008–2014); and (4) additional mega-reservoirs upstream of the TGD began operating (2015–2021).

Prior to the closure of the TGD in 2003, the annual average SSC at Datong station was only half that recorded at Yichang station (see Fig. 2a), indicating that the middle-lower Yangtze River historically acted as a sediment-sink, with an estimated annual deposition 65 Mt. However, post-2003 observations reveal a reversal in this pattern (Fig. 2a & b). This shift is attributed to large-scale riverbed erosion in the Yichang-Datong reach since TGD operation. As the eroded sediment mass far exceeding the sediment load at Yichang, the downstream channel is established as the primary source of sediment transported to the estuary via Datong station, marking its transition into an erosional system.

The suspended sediment grain size has shown a coarsening trend

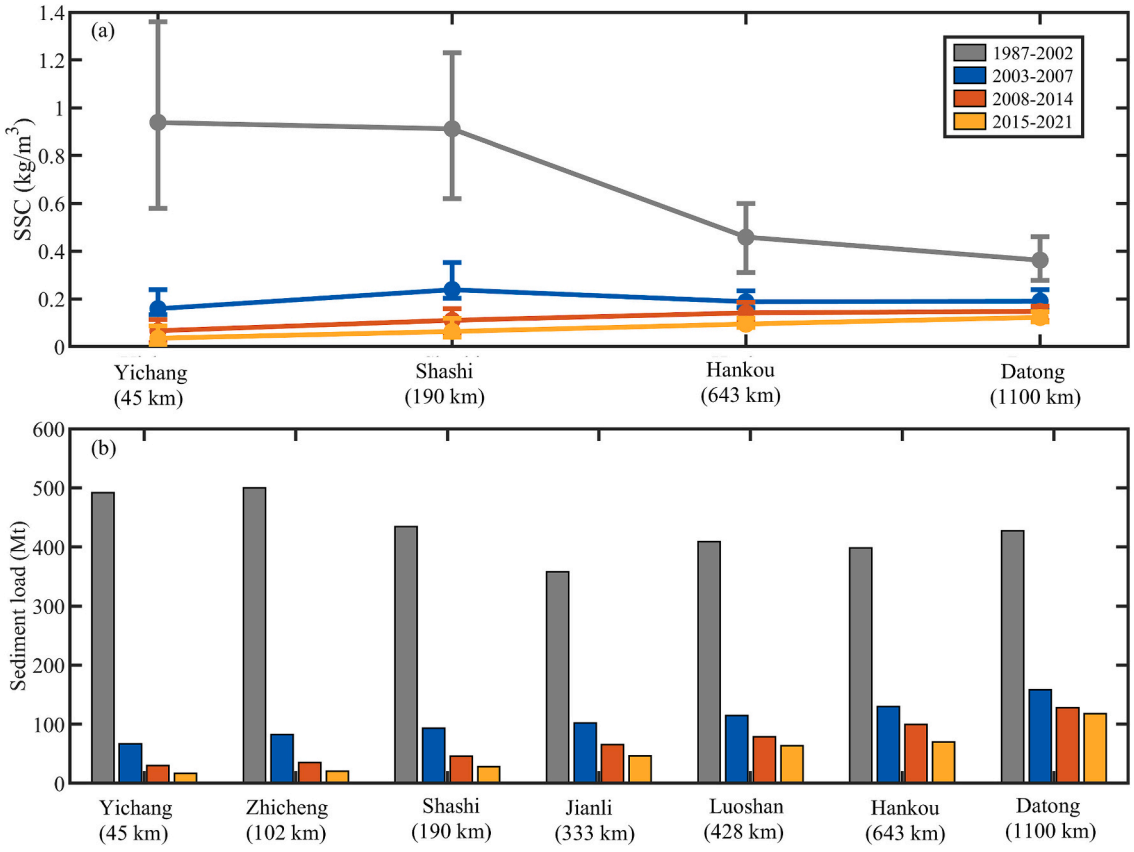


Fig. 2. Variation in annually averaged (a) suspended sediment concentration (SSC) and (b) sediment load at major gauging stations during 1982–2002, 2003–2007, 2008–2014, and 2015–2021.

over time in response to dam operation (Fig. 3a & b). At Yichang, near the TGD, the D_{50} has gone up from 0.005 mm to 0.009 mm, whereas at Datong, the farthest from the dam, it has risen from 0.009 mm to 0.016 mm. Jianli station recorded the largest increase, with D_{50} exceeding 0.02 mm and reaching 0.2 mm in 2017. The downstream fining from Jianli to Luoshan (Fig. 3a & b) is influenced by the decreasing riverbed slope and flow velocity, despite the overall bed erosion (Chen et al., 2007; Lai et al., 2017). The coarse sediment fraction at Yichang has declined from 9% pre-dam to below 2% post-dam (Fig. 3b). This reduction highlights that the mega-dams upstream of the TGD function as nearly complete traps for the coarse-grained sediment. This argument is supported by the decreasing D_{50} in the upper reaches of the TGD and the difference in sediment particle size between inflow and outflow in the TGD (Li et al., 2018; Liu et al., 2020; Yang et al., 2014; Yang et al., 2018a).

3.2. Changes in multi-fraction sediment recovery

Over the past two decades, the entire middle and lower Yangtze River witnessed continuously decreased both fine and medium sediment fraction load (Fig. 4 & Fig. 5), with reduction ratios decreasing downstream, ranging from 96% at Yichang to 77% at Datong for fine sediments, and 98% to 67% for medium sediment. This trend closely mirrored the overall reduction in total sediment load (Fig. 2b). In contrast, the coarse fraction displays a more complex spatial pattern. Notably, during the first 5 years following the TGD's closure, the coarse sediment load increased from Yichang to Jianli, nearly returning to pre-dam levels at Jianli station (Fig. 4c). Downstream Jianli, particularly between Jianli and Luoshan, the coarse sediment load decreased, likely due to sediment retention in Dongting Lake and extensive sand mining (Ma et al., 2022). Further downstream, beyond Luoshan, coarse fraction load has partially recovered, as ongoing channel adjustments and sediment redistribution continue (Fig. 4c).

The multi-fraction sediment load at Yichang (Fig. 2 & Fig. 4) reflects the impact of dams upstream beyond the TGD. Sedimentation in the TGR traps 77% sediment finer than 0.032 mm (Li et al., 2018) and the additional upstream dams similarly reduce the supply of fine sediment fraction to the middle and lower Yangtze River. However, their impact on medium and coarse sediment fractions appears limited, as these were already negligible during the 2008–2014 period. Recently, the annual fine sediment load at Yichang has decreased by only 10 Mt, suggesting further retention of fine sediment by upstream dams.

The recovery of the three sediment fractions in the middle and lower Yangtze River exhibits distinct spatial and temporal patterns following the commissioning of the TGD (Fig. 4, Fig. 5 & Fig. 6). Between 2003 and 2021, the annual recovery of fine sediment averaged approximately 70 Mt/yr (2003–2007), 73 Mt/yr (2008–2014), and 58 Mt/yr (2015–2021) (Fig. 4a). The majority of this recovery—ranging from 92% to 100%—occurred in the Jianli–Datong reach (350–1100 km), indicating that this section has become the principal source of fine sediment replenishment (Fig. 6a & Fig. 7a). Besides, medium sediment recovery declined upstream of Jianli, from 13.5 Mt/yr (2003–2007) to 9 Mt/yr (2008–2014) and then further down to 3.8 Mt/yr (2015–2021) (Fig. 4b), suggesting the riverbed here becomes depleted of both fine and medium-sized sediments. Conversely, recovery has increased downstream of Jianli, highlighting the increasing importance of this downstream reach as a new sediment source (Fig. 4a, b, Fig. 6a & b). This shift reflects the dynamic adjustment of sediment sources along the river. Coarse sediment erosion has consistently grown, from 3.6 Mt/yr (2003–2007) to 7.8 Mt/yr (2008–2014), and further to 17 Mt/yr (2015–2021) (Fig. 5d & Fig. 6c). The primary zone of coarse sediment erosion is concentrated within the Zhicheng–Jianli reach (Fig. 4c & Fig. 5d), located at ~100–350 km. Notably, the first 100 km downstream of the TGD (Yichang to Zhicheng) is now largely depleted of coarse sediment (Fig. 6c & Fig. 7c), while the Luoshan-Datong reach has emerged as a new source of coarse sediment since 2008 and has become an important

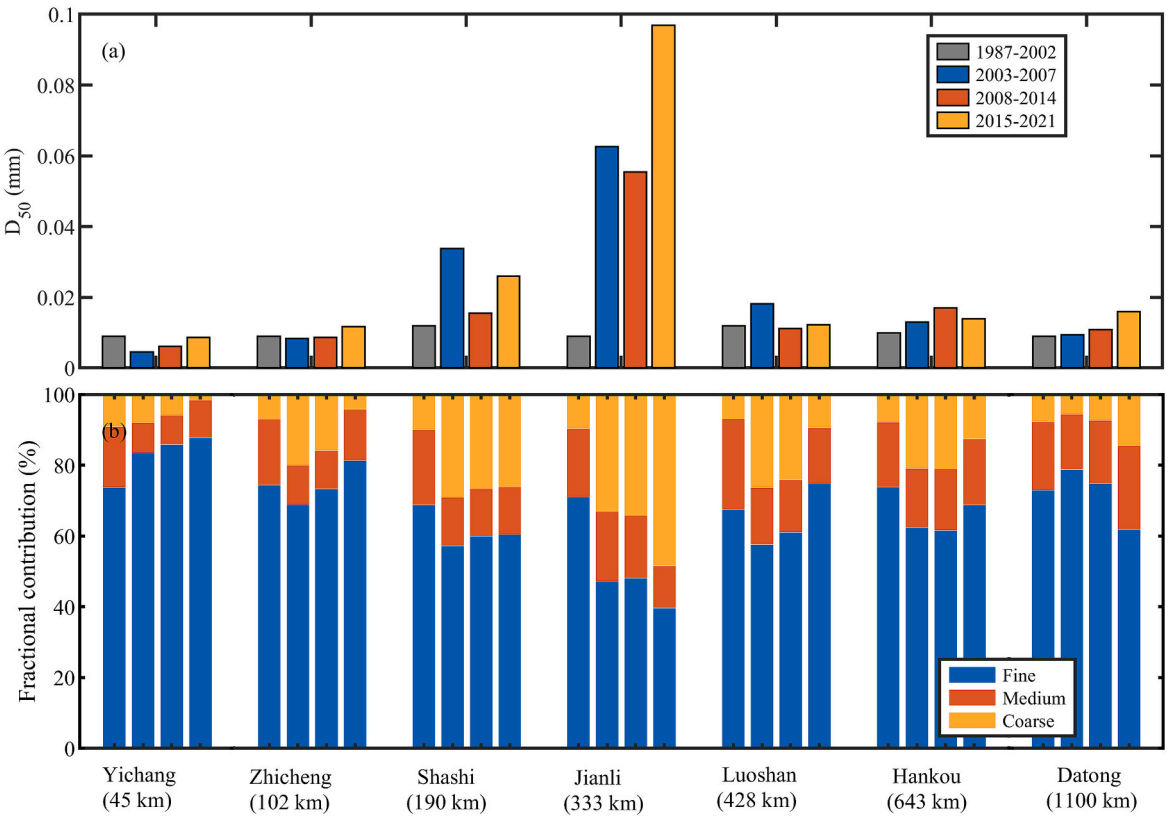


Fig. 3. Temporal variations in (a) averaged median grain size (D_{50}) and (b) contributions of find, medium, and coarse-grained suspended sediment at major gauging stations in the middle-lower Yangtze River during 1987–2002, 2003–2007, 2008–2014, and 2015–2021.

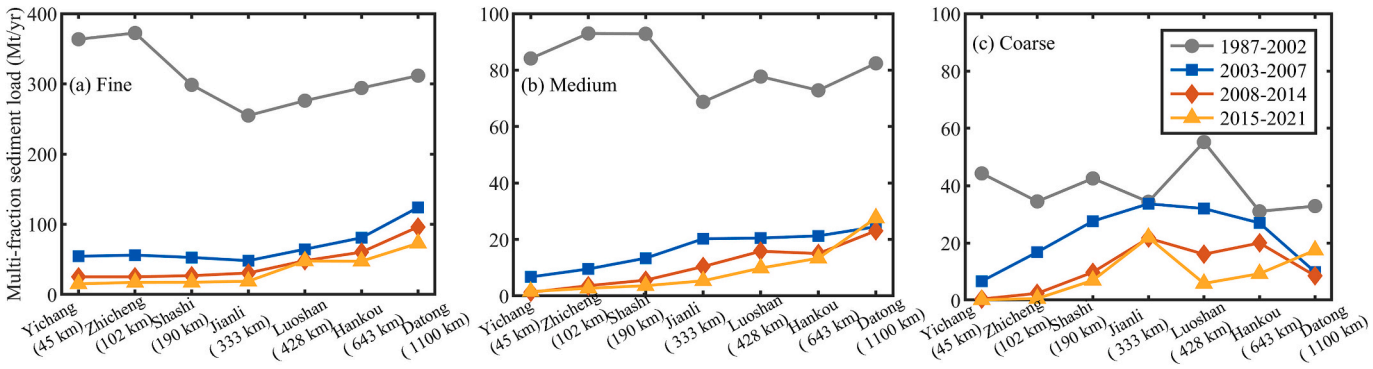


Fig. 4. Changes in annual multi-fraction sediment load during pre-TGD (1987–2002) and post TGD periods (2003–2021) in the middle-lower Yangtze River.

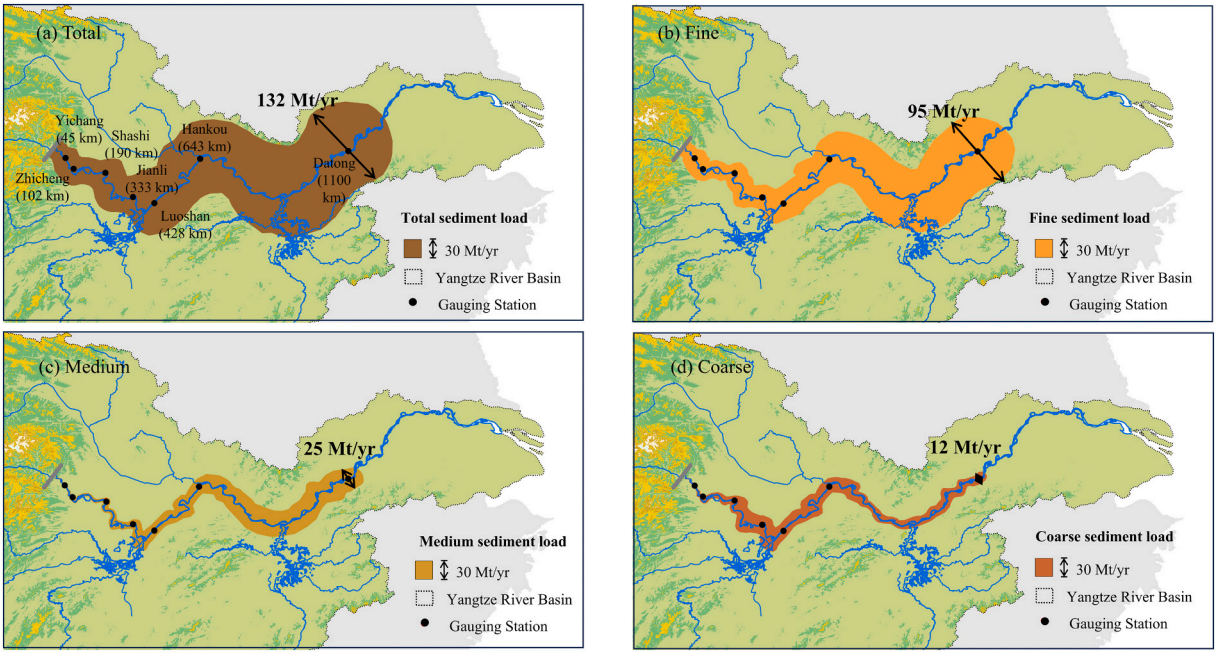


Fig. 5. Variations of total sediment load and multi-fraction sediment load during 2003–2021 along the middle-lower Yangtze River.

contributor to coarse fraction since 2015 (Fig. 6c). Overall, the middle-lower Yangtze River is experiencing suspended sediment recovery, driven by full channel erosion with dams-operations: the section upstream of Jianli (~350 km) is becoming gradually depleted as a sediment source (especially fine and medium sediment fractions) while the reach downstream of Luoshan (~640 km) has become a significant source for all three sediment components (with fine sediment declining and medium and coarse sediment increasing in time).

3.3. Seasonal variation in multi-fraction sediment transport

Suspended sediment transport also exhibits pronounced seasonal variability, as revealed by standard gauging station observations and our field surveys. Erosion is dominant throughout the downstream reaches of the TGD during both high-flow, high-SSC periods and low-flow, low-SSC periods (Fig. 8). Both the 2021 wet season and the 2022 dry season observed a stepwise increase in SSC along the 1100-km long river reach (Fig. 8), rising from 0.017 kg/m^3 to 0.07 kg/m^3 (wet season) and from approximately ~0 to 0.06 kg/m^3 (dry season). The Han River and the two lakes are vital for SSC recovery: the Han River contributes mainly in the wet season, while the lakes supply sediment during the dry season (Fig. 8a & b). Consistent with the decadal patterns in Section 3.2, D_{50} of suspended sediment is relatively high in the Yichang–Jianli reach due to bank and bed erosion, with coarse sediment dominating in the wet season and medium sediment in the dry season. In addition, the primary sediment recovery distance differed — 600 km in the wet season and 400 km in the dry season. Between 400 and 800 km, fine sediment decreases in the dry season and increases in the wet season (Fig. 8). This suggests that fine sediments deposit in the dry season and are eroded during the following wet season.

3.4. Changes in bed sediment grain size with channel degradation

The riverbed of the 1100-km-long Yangtze River downstream of the TGD is continually coarsening with the entire river channel erosion (Fig. 9a & b). Before the closure of the TGD in 2003, the entire middle and lower Yangtze featured a sandy riverbed, with an average bed sediment D_{50} of ~0.25 mm. The bed sediment at Yichang was the most coarse-grained with D_{50} of 0.44 mm (Fig. 9c). The first field measurement conducted after the construction of the TGD (in 2008) reveals a rapid coarsening of riverbed sediment over the first 200 km downstream of the dam, with the D_{50} increasing by two orders of magnitude, from a few millimeters to several tens of millimeters. Specifically, the bed sediment at Yichang became gravel with a D_{50} of 57 mm. According to the bed sediment grain size data obtained in 2022, the section with coarse-grained bed sediments had migrated further downstream to 270

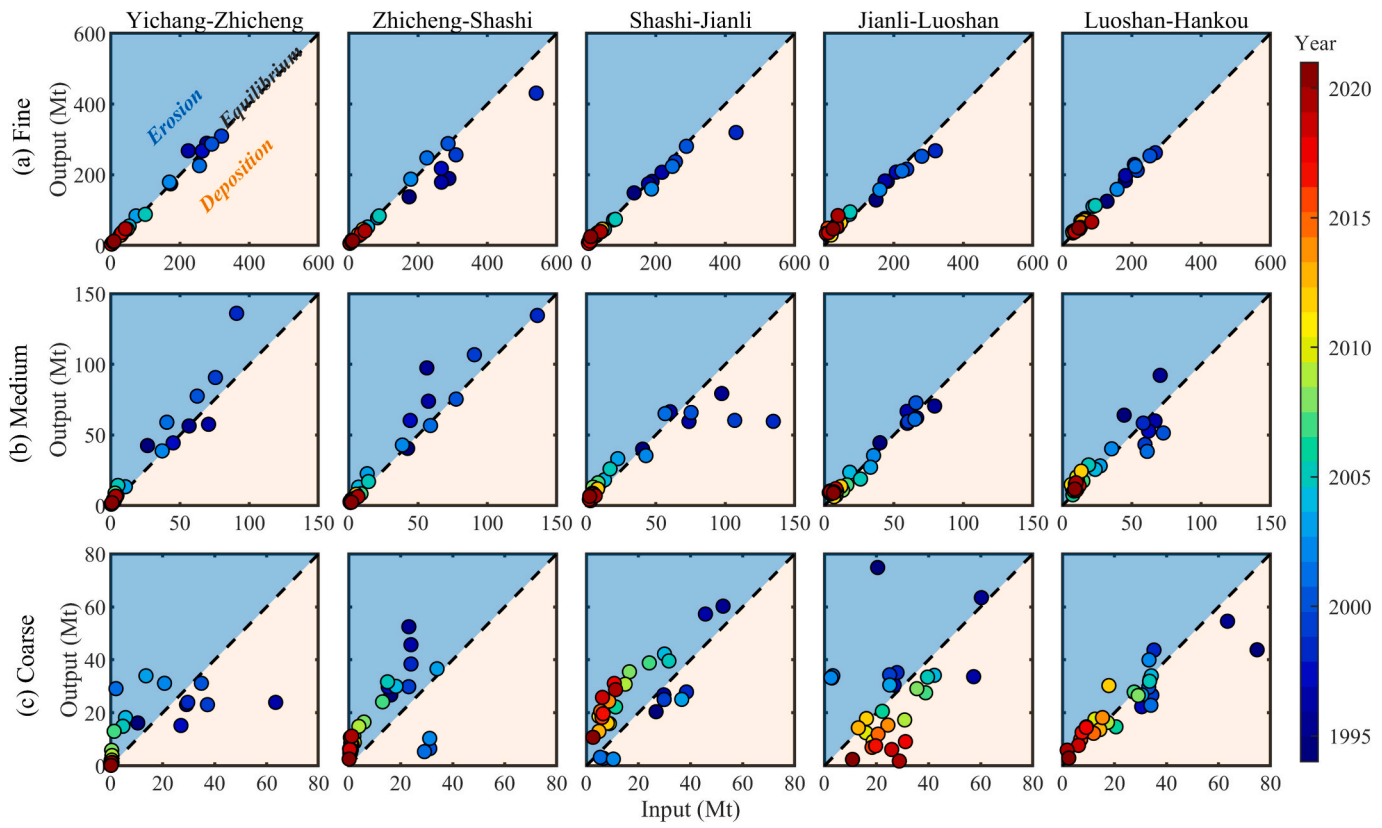


Fig. 6. In-reach multi-fraction sediment input and output correlations from Yichang to Hankou: (a) fine, (b) medium, (c) coarse. An output to input ratio equal to 1 indicates equilibrium, whereas ratios <1 and >1 denotes the intensity of erosion-derived recovery and deposition into storage, respectively.

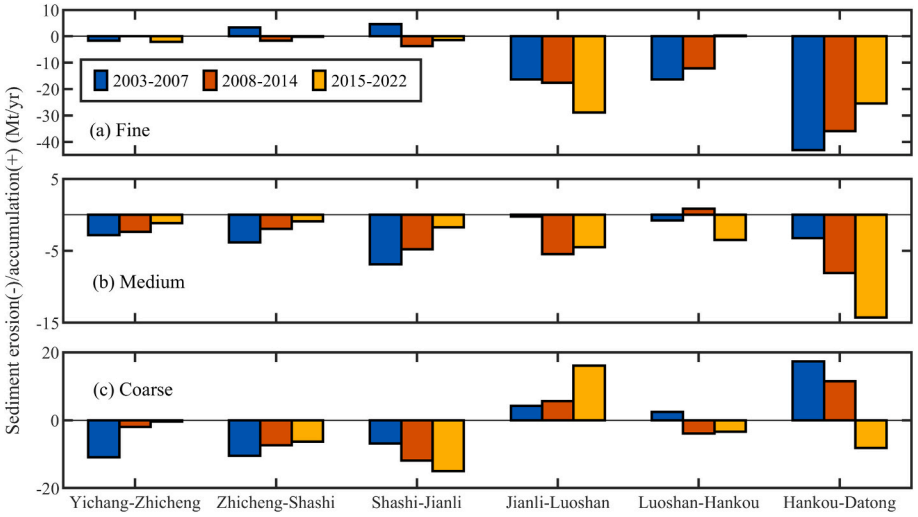


Fig. 7. Spatial-temporal variation of river channel erosion/accumulation intensity of 3 sediment fractions from Yichang to Datong after construction of dams since 2003: (a) fine, (b) medium, (c) coarse.

km, revealing a continuous coarsening response to sediment starvation (Fig. 9c). Overall, the entire riverbed has shown varying degrees of coarsening compared to 2000. Except for Yichang, the average D_{50} for all samples in 2022 was 0.27 mm. Following two decades of closure of the TGD, the composition of riverbed sediment is made up of 15% fine, 5% medium, and 80% coarse sediment. And at Yichang, gravel bed samples with a D_{50} up to 84 mm were observed (Fig. 9c).

Topographic data from the Yangtze River reveals that the riverbed near Yichang initially eroded, but erosion has now nearly stopped (Lai et al., 2017; Zheng et al., 2023). Presently, the ~320 km reach between Zhicheng and Chenglingji (known as the Jingjiang reach, Yang et al., 2022) is the main erosional area (Fig. 1 & Fig. 9b). In 2011, three times more sediment was eroded from the Upper Jingjiang section (~100–270 km) than the Lower Jingjiang section (~270–410 km), but by 2019, more sediment was eroded from the Lower Jingjiang section (Fig. 10). As a result, the contribution of the Lower Jingjiang section to annual erosion volumes increased from 19% in 2011 to 70% in 2019. The erosion center is currently migrating further downstream, from Upper Jingjiang to Lower Jingjiang. Previous studies suggest that this shift is primarily driven by the progressive downstream propagation of

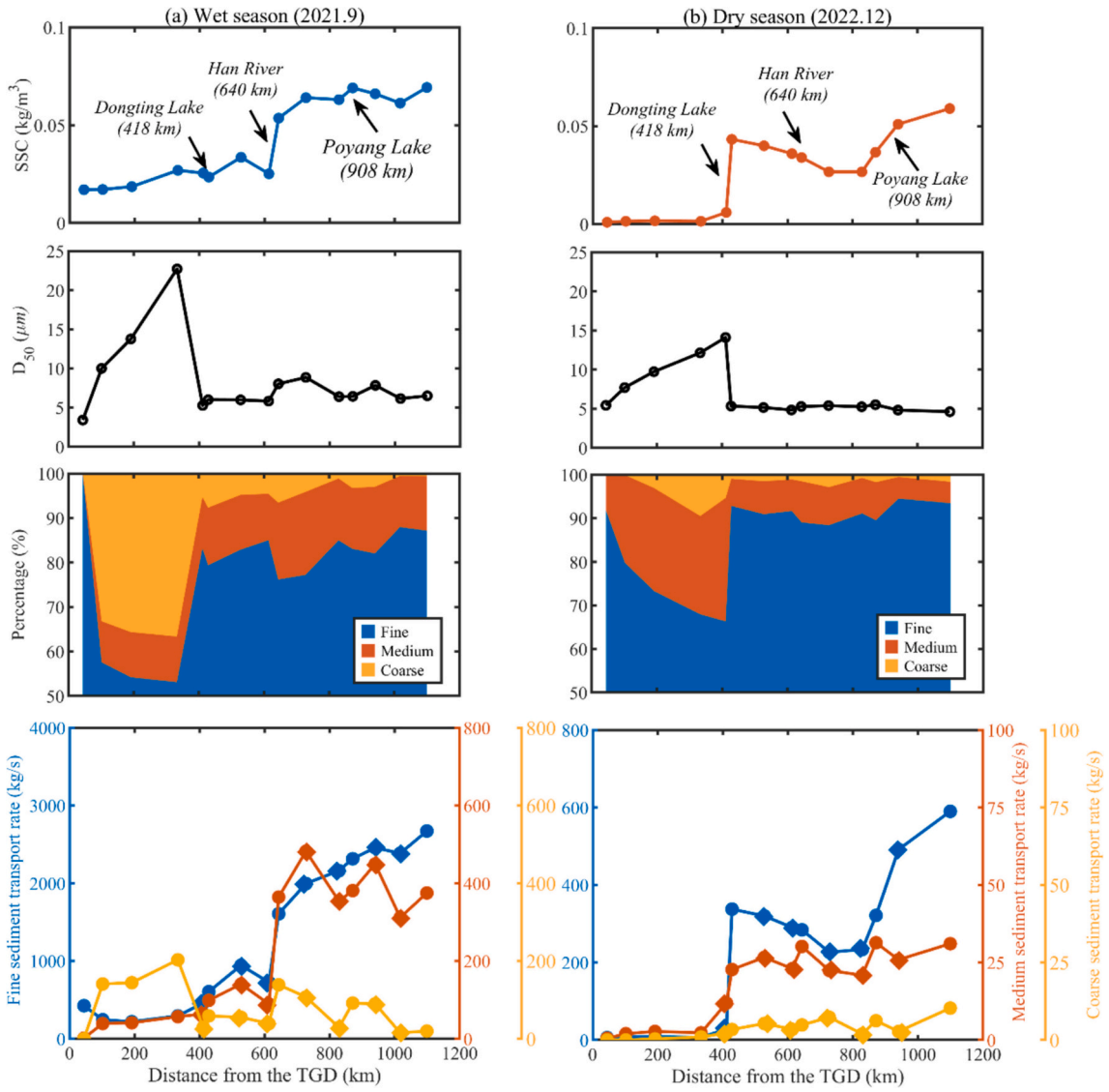


Fig. 8. The suspended sediment concentration (SSC), median diameter (D_{50}), cumulative contribution of fine, medium, and coarse fractions to the total sediment load, and sediment transport rate at representative gauging stations downstream of TGD in (a) September 2021 and (b) December 2022. The circles in the subplots of sediment transport rates indicate data from official gauging stations whereas diamonds indicate estimates from our field survey (using water samples and ADCP measurements).

sediment depletion following dam operation (Lai et al., 2017), whereas adjustments in channel geometry and associated flow energy have remained relatively limited over the same period (Yang et al., 2022; Zheng et al., 2023) and thus play a secondary role in controlling the spatial pattern of erosion in the middle Yangtze River.

4. Discussion

4.1. Sediment regimes of riverbed erosion in response to dams

Adaptation of a riverbed downstream of a reservoir leads to channel erosion and changing bed sediment grain size distribution. Based on our analysis of multi-fraction sediment transport and recovery in the middle-lower Yangtze River, three distinct regimes of riverbed erosion downstream of the TGD are identified (Fig. 11), which the riverbed chronologically experiences. In addition, these regimes can be distinguished using the rate of change of bed sediment D_{50} (dD_{50}/dt) and bed level (dZ/dt) (Fig. 11), as well as bed sediment D_{50} thresholds, which captures sediment recovery processes, sediment coarsening and morphological evolution. Recognition of these regimes therefore allows determination of the adaptation stage and approximate adaptation times.

(a) **Static armored gravel bed**: In the first 100 km downstream of TGD, nearly all sediment finer than 2 mm has been fully eroded, and the bed sediment is largely gravel. In this regime, both dD_{50}/dt and dZ/dt decrease rapidly, suspended sediment shows negligible recovery from the bed, and bed-sediment D_{50} exceeds ~450 mm, with no further bed erosion. In 2008, the transition from gravel to sand in the riverbed progressed 30–50 km downstream of the TGD. By 2011, this transition moved downstream to 110–160 km (Luo et al., 2012), but our field measurements conducted in 2021 and 2022 reveal that the transition to sand now remains stable without further downstream migration (Fig. 1, Fig. 9c, at 100–180 km downstream of the TGD). The remaining gravel accumulated at the bed surface currently prevents further degradation. Additionally, the suspended sediment is sufficiently fine-grained to prevent sedimentation even at low-flow conditions. As a combined result, the riverbed has become morphodynamically static within approximately 8 years of the TGD's operation.

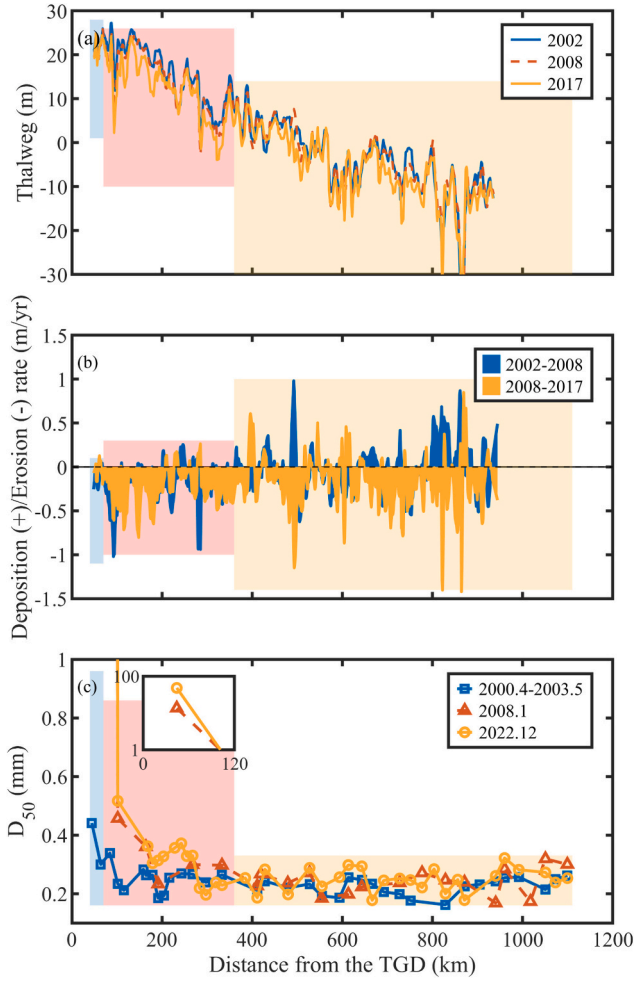


Fig. 9. (a) Changes in the thalweg downstream of the TGD after its construction. (b) Deposition and erosion patterns derived from elevation differences during 2002–2008, 2008–2017, and 2002–2017. (c) Changes in medium grain size (D_{50}) of the riverbed sediment. Grey, red, and orange shades indicate three sediment regimes of static armored gravel bed, active bed armoring, and strong erosion, respectively (see Section 4.1).

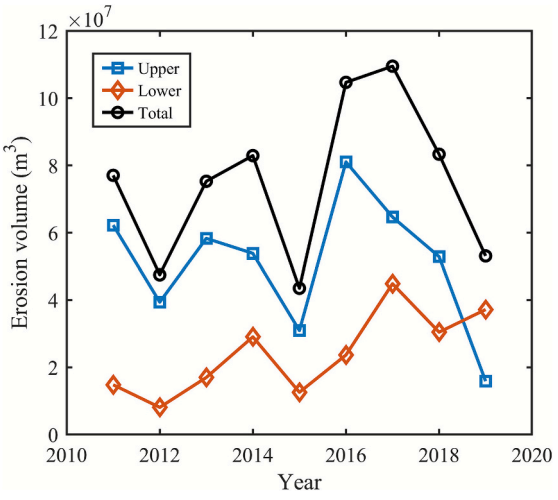


Fig. 10. The annual volume of channel erosion in the Zhicheng-Chenglingji reach over the past decade. The upper reach refers to the Zhicheng-Ouchikou reach, and the lower reach is the Ouchikou-Chenglingji reach.

(b) **Active bed armoring**: The riverbed is presently actively armoring in the section ~100–350 km downstream of the TGD (the Jingjiang Reach). In this regime, both dD_{50}/dt and dZ/dt increase, and bed-sediment D_{50} exceeds ~300 mm. Coarse-grained sediment is actively eroded into suspension, resulting in pronounced channel erosion, coarsening of both suspended and bed sediment and the formation of a coarse surface layer. The main erosion center within this reach is migrating downstream, with the Upper Jingjiang reach almost depleted of fine to medium-sized sediments (Fig. 7a, b) while erosion of coarse sand is increasing (Fig. 7c); probably the sediment bed is depleted of sediment within several years. The Lower Jingjiang section has not yet developed an armoring layer, and as a result, it is experiencing progressively increasing erosion (Fig. 10) and a rapid increase in the D_{50} of the sediment transported in suspension (Jianli station in Fig. 3). Suspended sediment transport in this area is (different from the upstream section) not only determined by the upstream sediment supply, but also by local sediment availability in the bed.

(c) **Strong erosion**: Downstream of Chenglingji (400 to 1100 km downstream of the TGD), no gravel layer exists, and both dD_{50}/dt and dZ/dt remain small due to ample sediment availability and the large channel volume. Bed-sediment D_{50} is generally <~300 mm. Riverbed erosion is strong, especially of fine and medium-sized sediments. Herein the erosion rate of the finest fraction is decreasing, while those of the medium and coarse-sized sediments began increasing after the construction of upstream mega-dams in 2015 (Fig. 6 & Fig. 7), revealing a coarsening trend of the river's sediments (in suspension and according to the sediment budgets in Fig. 6 & Fig. 7), even though such a coarsening is not yet evident from the bed samples (Fig. 10).

Erosion (as described in Fig. 12) is the result of the reduction of the Yangtze river's sediment load reduction, which is mainly the result of sediment trapping by the TGD. All medium to coarse-sized sediment is deposited in the reservoir, while fine-grained sediments are released (primarily during the wet season). Our findings suggest that sediment trapping in newly constructed dams upstream of the TGD has further decreased the release of fine-grained sediments from the TGD, from 20 Mt/y between 2008 and 2014 to 10 Mt/y after 2015 (Fig. 2a). However, this additional decline may not have the biggest impact of the upstream reservoirs. In river systems carrying large amounts of sediments, reservoirs may fill up over time and eventually release sediment downstream, as observed in Sanmenxia reservoir in the Yellow River (Wang et al., 2005). In time, and without upstream sediment trapping, some of the sediment load released from the TGD could potentially be restored. However, ongoing construction of upstream reservoirs continues to diminish sediment loads entering the TGD, making restoration of downstream sediment release from the TGD highly improbable in the coming centuries.

4.2. *Other factors affecting sediment recovery*

The Han River was one of the major sediment sources to the Yangtze River before the Dangjiangkou Dam (the largest dam in the Han River) began operation in 1968 (Yang et al., 2018b). Despite the Danjiangkou Dam intercepting 99% of the incoming sediment, 24 Mt of sediment is annually discharged into the Yangtze River due to the erosion of the channel and bed in the Lower Han River (Yang et al., 2006). This erosion process is concentrated in the wet season, constituting over 90% of the annual transport (Bai et al., 2021). Our short-term field observations (Fig. 8) reveal that the Han River (η_H) can contribute 60% to the recovery of SSC in the Yangtze River in the wet season of 2021 (predominantly supplying fine sediments), but only ~2% in the dry season of 2022.

A typical feature of the Yangtze River sediment load is its modulation

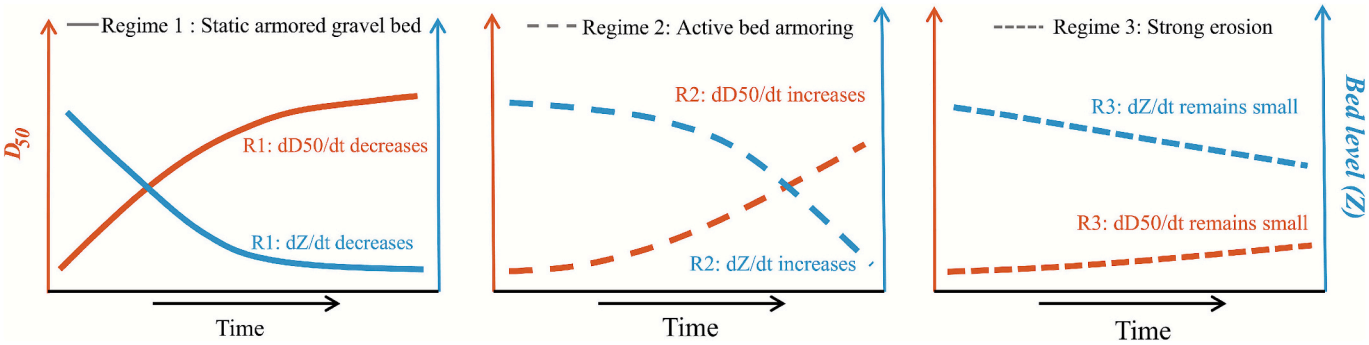


Fig. 11. A theoretical framework for identifying three sediment erosion regimes in the middle and lower Yangtze River.

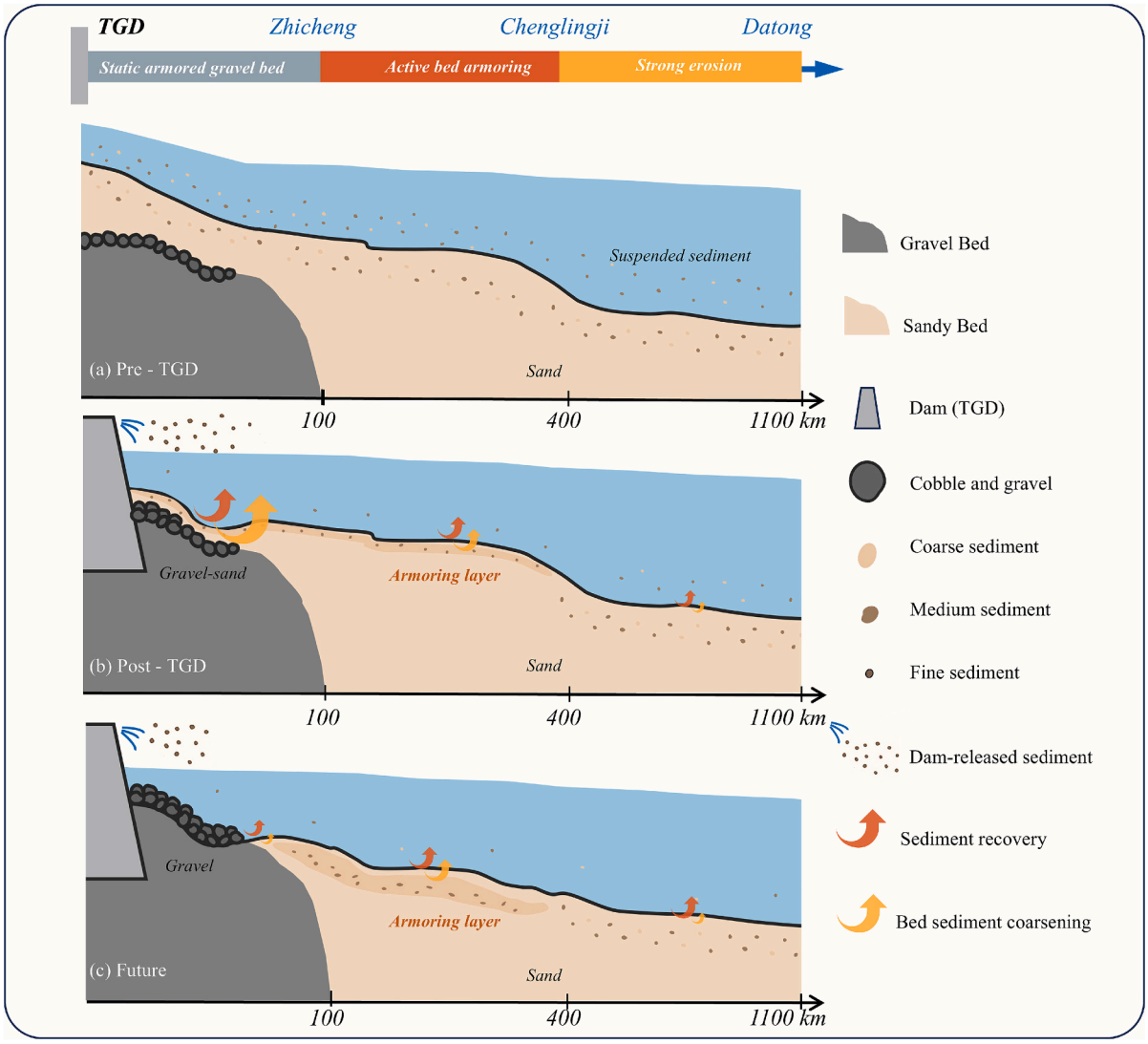


Fig. 12. Three riverbed-erosion regimes in the middle and lower reaches of the Yangtze River in response to the construction of the dams: resulting in (a) a static armored gravel bed, (b) active bed armoring, and (c) strong erosion.

by two large lake systems. Before the construction of reservoirs, these lakes seasonally stored water and acted as sediment sinks. But with the substantial decrease in sediment load after the closure of dams, they are now releasing sediment (Guo et al., 2018; Zhu et al., 2023), i.e. acting as sediment sources. Dongting Lake (η_D) and the Poyang Lake (η_P) especially contribute to the sediment load of the Yangtze River in the dry season (for 45% and 48% of the total Yangtze sediment load, respectively), while they contribute only 5% and 1% during the wet season. In the wet season, the grain size of the sediments declines after passing Dongting lake (Fig. 8), suggesting the lakes trap sand while releasing fine-grained sediments deposited there earlier. The suspended sediment supplied by the two large lakes is similar to that of the Han River, primarily consisting of fine sediment ($d < 0.031$ mm).

Sand mining takes place in the riverbed of the Yangtze River and its

connected lake systems. The sediment loss induced by sand mining on the sediment budget has been largely ignored in earlier works (Dai and Liu, 2013; Guo et al., 2018; Zhu et al., 2023). While its amount is relatively small compared to the total sediment flux of the Yangtze River, its impact is highly selective toward coarse sediment fractions (mean particle size ~0.1 mm; Xu and Xu, 2012). A comparative analysis of sand mining volumes versus natural riverbed erosion rates reveals its important role. In the middle Yangtze reach (Yichang to Hukou), the natural net erosion rate was approximately 35 Mt/yr during 2003–2019 (Deng et al., 2022), while the lower reach (Hukou to Datong) experienced a rate of about 17 Mt/yr for 1992–2013 (Zheng et al., 2022). In contrast, reported sand mining in the middle and lower Yangtze was substantial, averaging ~45 Mt/yr prior to 2014 and ~21.6 Mt/yr from 2015 to 2021 (CWRC, 2002–2022). This magnitude is comparable to the amount of coarse sediment ($d > 0.125$ mm) supplied by riverbed erosion in the same reach, indicating that sand mining represents another non-negligible loss for coarse sediment during the post-dam period. In the linked lakes, net erosion in Dongting Lake and Poyang Lake post-TGD (2003–2019) was ~1.9 Mt/yr and ~4.3 Mt/yr, respectively (Zhu et al., 2023), yet their recent sand mining activities have reportedly exceeded 48 Mt/yr and 38 Mt/yr (CWRC, 2002–2022). This stark contrast—where mining rates are an order of magnitude higher than natural erosion—underscores that sand mining is not merely a secondary factor but a primary driver of coarse sediment deficit in the lake systems. Consequently, the net loss of coarse sediment in the middle and lower Yangtze River reflects the combined effects of sediment supply reduction, hydrodynamic adjustment, and intensive sand mining.

4.3. Implications for anthropogenically modified river system

Many large-scale fine-grained river systems have been transformed by upstream dam construction since the 20th century (Brandt, 2000; Nilsson et al., 2005; Padmalal and Maya, 2014; Best, 2019; Giosan et al., 2014; Syvitski et al., 2022). In some extreme cases such as the Colorado River (Carriquiry et al., 2011), the Ebro River (Ibàñez et al., 1996), and the Nile River (Stanley and Warne, 1993), dam construction has effectively blocked all suspended sediment. Beyond reducing sediment load, dams hinder natural sediment sorting processes, particularly in fine-grained systems where sand, silt, and clay fractions respond differently to hydrodynamics (Brandt, 2000). This leads to riverbed coarsening and degradation, as documented in the Colorado River (Grams et al., 2007) and the Lower Yellow River (Chien, 1985).

The Yangtze River provides an example of a large, fine-grained, heavily regulated river system with extensive long-term data on both sediment loads and sediment GSD. Our findings reveal that decomposition of the sediment loads over different fractions is crucial to capturing its morphodynamic response, the corresponding bed coarsening and channel degradation, which are essential for navigation and flooding management. Most large rivers worldwide lack systematic GSD monitoring, constraining the ability to assess how broadly the sediment recovery regimes identified in the Yangtze may apply elsewhere (e.g., Red, Mekong, and Ayeyarwady Rivers; Dang et al., 2010; Kondolf et al., 2014; Latrubesse et al., 2021). However, our analysis of the Yangtze River's response to the upstream reservoirs highlights the need for consistent sediment GSD monitoring to understand morphodynamic adjustments downstream of dams, the role of tributaries and lakes (e.g. Tonle Sap Lake along the Mekong River, Sok et al., 2021), as well as human activities such as sand mining. In this sense, while specific thresholds and rates observed in the Yangtze may not directly apply elsewhere, the conceptual framework for distinguishing sediment recovery regimes is broadly relevant to similar anthropogenically modified river systems.

5. Conclusions

Sediment trapping by dams profoundly changes the downstream sediment load and grain size, influencing fluvial sediment dynamics, river morphodynamics and delta formation. Based on long-term time series of suspended sediment load and sediment grain size data from 1987 to 2021 and new field surveys in 2021 and 2022, we assess the impact of dam construction (particularly the TGD) on the downstream changes in multi-fractional sediment recovery in the Yangtze River. We identify three distinct sediment recovery regimes: a static armored gravel bed, active bed armoring, and strong erosion. The recovery of fine, medium and coarse sediment fractions downstream of the TGD spatially varies and undergoes dynamic adjustments over time. The reach from Yichang to Jianli (45–350 km from the TGD) has consistently served as a significant source of coarse-grained sediment, whereas erodible sediments in riverbed (for fine and medium sediment fractions) is gradually depleting as erosion progresses. The shift in the source of coarse sediment and the coarser riverbed material both indicate a downstream migration of the erosion center. The reach downstream of Luoshan (428 km from the TGD) is currently the dominant source for all three sediment components, especially for fine-grained sediment ($d < 0.125$ mm). With declining fine sediment availability in the riverbed, medium and coarse sediment fractions will progressively dominate as the primary fractions of erosion over time. Moreover, tributaries, lakes, and other human interventions (such as sand mining) additionally influence sediment loads and GSD. The Han River plays a key role in restoring the sediment concentration and altering the suspended sediment GSD during the wet season, while the impact of Dongting Lake and Poyang Lake is more pronounced during the dry season. Both the lakes and the Han River primarily supply fine-grained sediment.

Our study highlights the significant role of dam construction in altering sediment grain size, which in turn affects morphological changes. We believe that such knowledge is not only crucial for interpreting the historic (and future) changes in the Yangtze River but also is applicable to other large fine-grained river systems influenced by upstream dams.

CRediT authorship contribution statement

Jiamin Chen: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chunyan Zhu:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Investigation, Funding acquisition, Conceptualization. **Dirk Sebastiaan van Maren:** Writing – review & editing, Visualization, Validation, Supervision, Conceptualization. **Leicheng Guo:** Writing – review & editing, Supervision, Resources, Investigation, Funding acquisition. **Weiming Xie:** Writing – review & editing, Supervision, Resources. **Fan Xu:** Writing – review & editing, Supervision, Resources. **Yuan Xu:** Writing – review & editing. **Zheng Bing Wang:** Writing – review & editing, Supervision, Resources, Conceptualization. **Qing He:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The hydrological and sediment data used in this study are publicly available through the Changjiang Water Resources Commission (CWRC) at https://www.cjw.gov.cn/ and the China Three Gorges Corporation (CTGC) at https://www.ctg.com.cn/. Field survey data, including suspended and bed sediment grain size measurements, are archived at the State Key Laboratory of Estuarine and Coastal Research, East China Normal University, and can be accessed upon requests.

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