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Geophysical Research Letters

RESEARCH LETTER
10.1029/2025GL119137

Reservoir Regulation has Brought a Classic River-Dominated Delta Under Human Control

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Abstract Damming of wild rivers has trapped vast quantities of sediment that would otherwise nourish deltas, causing severe sediment deficits and accelerating delta erosion worldwide. The Yellow River Delta (YRD), once prograding seaward at ~10 km^2/yr, began retreating at −5.6 km^2/yr following completion of the Xiaolangdi Reservoir. Implementation of the Water and Sediment Regulation Scheme (WSRS)—a reservoir flushing program—fundamentally reversed this trend. By mobilizing trapped sediment and enhancing downstream channel scouring, the WSRS increased sediment delivery to the sea from 17.6 Mt/yr before its initiation to 178.5 Mt/yr during operation years. This renewed sediment flux restored delta growth, producing subaerial expansion of 6–7 km^2/yr and significant subaqueous deposition near the estuary. These results demonstrate that the YRD has entered a new phase of evolution under active human management and highlight that sediment trapped behind dams can become a potentially important source for restoring sediment-starved deltas worldwide.

Plain Language Summary River deltas are critical to human society, yet they are increasingly threatened by intensified human activities. Dam construction in river basins has resulted in the trapping of huge amounts of sediment that rivers once carried to the sea, reducing sediment supply to deltas and aggravating widespread delta erosion around the world. This study focuses on the Yellow River Delta (YRD), once one of the fastest-growing deltas on Earth. In 1999, a large dam called Xiaolangdi was built on the middle reach of the Yellow River. The dam has since trapped nearly all incoming sediment, causing the delta to shrink. However, the implementation of a major reservoir management project—the Water and Sediment Regulation Scheme—allowed reservoir flushing and downstream riverbed scouring and increased sediment delivery to the sea. This reversed the sediment deficit in the delta allowing for sustained growth. The YRD's evolution is now largely under human control, showing that sediment stored behind dams—often seen as a liability—can become a vital resource for delta restoration when strategically released.

Key Points:

- Reservoir regulation dominates the Yellow River's sediment delivery to the sea
- Yellow River Delta's evolution is driven by human-managed reservoir operations
- Sediment trapped in dams can support delta survival if strategically released

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Wu, X., Wang, H., Syvitski, J., Saito, Y., Bi, N., & Nittrouer, J. (2026). Reservoir regulation has brought a classic river-dominated delta under human control. *Geophysical Research Letters*, *53*, e2025GL119137. https://doi.org/10.1029/2025GL119137

Received 29 AUG 2025
Accepted 9 DEC 2025

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1. Introduction

River deltas are among the most productive and economically vital environments on Earth, yet they are also among the most dynamic landforms, situated on the interface of land and sea (Day et al., 2016; Shaw et al., 2016; Tessler et al., 2015). The formation and maintenance of a delta fundamentally depend on a continuous sediment supply from upstream river basins to offset marine erosion, natural and human-induced subsidence, and sea-level rise (Edmonds et al., 2023; J. Syvitski, Anthony, et al., 2022). Over recent decades, however, the riverine supply to delta experienced a sharp decrease with intensified human activities substantially altering pre-industrial sedimentary stores and fluxes (Dethier et al., 2022; J. Syvitski, Ángel, et al., 2022). Among these, widespread dam construction in the 20th and 21st centuries represent one of the most powerful interventions, trapping an estimated 25%–30% of the total land-to-ocean sediment flux (J. Syvitski, Ángel, et al., 2022; Vörösmarty et al., 2003). Starved of sediment, most of world's deltas have been facing unprecedented challenges of degradation, leading to severe environmental consequences, coastal retreat, and growing risks to populations and infrastructure. These challenges underscore the urgent need for maintenance strategies that can reverse deficits in estuarine sediment budgets and ensure delta sustainability (Anthony et al., 2024; Chan et al., 2024; Hoitink et al., 2020).

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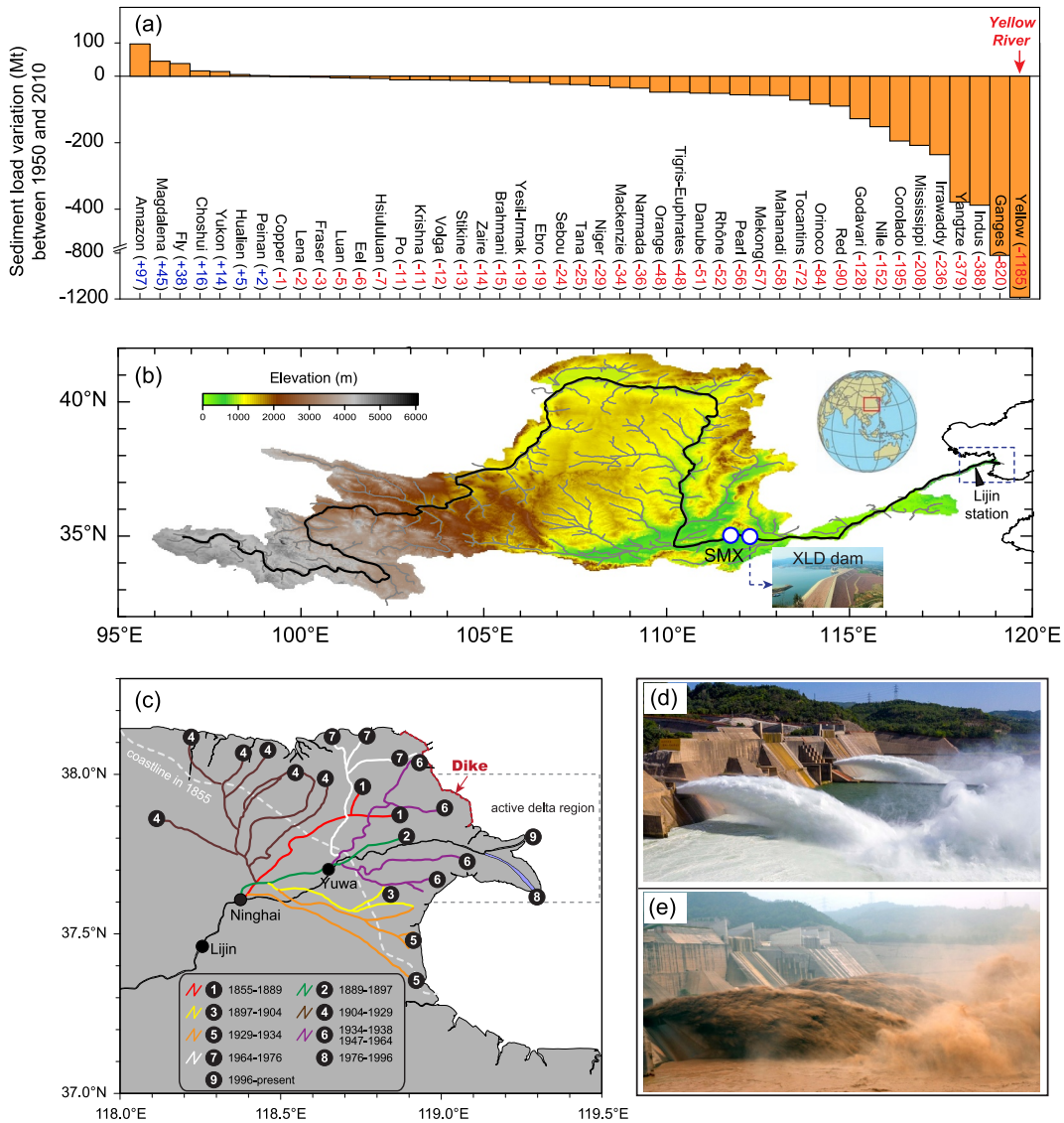

Figure 1. (a) Changes in sediment supply to the sea from 45 representative rivers globally between 1950 and 2010 (modified from J. Syvitski, Ángel, et al., 2022). (b) Overview of the Yellow River drainage basin showing the locations of key stations, including Sanmenxia Reservoir (SMX), Xiaolangdi Reservoir (XLD) and the Lijin station. (c) Historical deltaic channel shifts within the Yellow River Delta since 1855. The white dashed line marks the 1855 coastline, while the red dashed line indicates the position of constructed dikes. (d) Clear water discharge and (e) turbid water release from the Xiaolangdi Reservoir during water regulation and sediment regulation phases of the WSRS in 2011, respectively.

Among global river systems, the Yellow River in China provides a striking example of how human interventions can reshape a large river system (Besset et al., 2019; J. P. M. Syvitski et al., 2009). Basin-scale activities, such as dam construction, land use change and upstream water withdrawals, have drastically reduced sediment delivery to the sea by more than 1,100 Mt from peak levels, marking the most drastic sediment decline among the world's major rivers (Figure 1a; Chen et al., 2015). As a consequence of this sharp decline, the Yellow River Delta (YRD), once famous for its fast growth due to sufficient sediment supply and frequent channel avulsions, lost strong ability of seaward accretion (Figures 1b and 1c; Wu et al., 2017; Xue, 1993). In particular, one mega-reservoir named Xiaolangdi (XLD), built downstream the river's main sediment source region (i.e., the Loess Plateau) in 1999, further decreased the sediment with trapping efficiency of over 95% and thereby posed higher sediment deficit on delta region (Wu et al., 2023). A basin-wide reservoir regulation project called Water and Sediment Regulation Scheme (WSRS; Figures 1d and 1e and Figure S1 in Supporting Information S1) initiated in 2002 and operated annually since, helped excavate sediment from the XLD reservoir and the lower Yellow River channel

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(H. Wang et al., 2017). The WSRS has since exerted dominant control over the river's sediment delivery regime, rendering the Yellow River one of the most highly regulated fluvial systems in the world.

Here we systematically analyze the morphological changes of the YRD since the implementation of WSRS using satellite-derived shoreline data and detailed bathymetric records. Our findings reveal how regulation of a mega-reservoir 800 km upstream the river mouth can fundamentally alter the sediment supply to the sea and support delta maintenance or growth. By documenting the transition of the YRD from a classic river-dominated delta to a human-controlled system, this study provides crucial insights that inform future restoration and sustainability strategies for sediment-starved deltas worldwide.

2. Data and Methods

2.1. Water and Sediment Data

Daily records of water discharge and suspended sediment concentration at XLD and Lijin Station, compiled by the Yellow River Conservancy Committee (YRCC), were used to calculate sediment fluxes (tonnes/day). The data were sourced from the Yellow River Hydrological Annuals and the Bulletin of Chinese Rivers and Sediments. Additionally, during WSRS operations, suspended sediment samples from Lijin were collected for grain-size analysis, with a Malvern Mastersizer 2000 in the Ocean University of China, with a measurement range of 0.02–2000 μm and a relative error of less than 2% in repeated measurement.

2.2. Channel Erosion and Deposition

Since the 1970s, annual bathymetric surveys along the lower River have been conducted by YRCC using SDH-13D echo sounders with vertical accuracy of ±5 cm ± 0.4% of the measured water depth. Given that channel evolution typically occurs on the meter scale, this level of precision is sufficient for quantifying bed erosion and deposition through repeated cross-sectional measurements. Data were sourced from the Yellow River Hydrological Annuals.

2.3. Delta Morphology

Shoreline positions from 1999 to 2020 were extracted from cloud-free Landsat images after flood seasons. To minimize tidal influence, images were selected to similar water levels at the time of acquisition. After geometric correction, a histogram thresholding and band ratio model (Alesheikh et al., 2007) was used to delineate high water lines, achieving ~30 m accuracy. These derived shorelines were subsequently used to quantify changes in the subaerial delta area.

Since 1976, the bathymetric survey on the subaqueous delta was conducted annually along 10 cross-shore transects spaced approximately 5 km apart (Figure S2 in Supporting Information S1), using SDH-13 echo sounders in conjunction with a UHF-547 microwave positioning system and Differential Global Position System. Tidal fluctuations were removed based on tidal records at gauging stations along the coast, and the bathymetric data were referenced to the sea level of the Yellow Sea datum. The resulting bathymetric data sets achieved vertical accuracy of ±5 cm and horizontal positioning accuracy of <2 m. The bathymetric transects were fixed in position to ensure consistency across surveys and covered the full extent of the subaqueous region. Bathymetric records in 1999, 2002, 2014, 2017 and 2020 were used in this study to evaluate patterns of accumulation and erosion across the subaqueous portion of the YRD.

3. Results and Discussions

3.1. Stepwise Variation of Sediment Delivery and the Delta Evolution

The XLD Reservoir is located at the terminus of the final gorge in the middle Yellow River (Figure 1b) and controls approximately 92% of the basin's drainage area (0.69×10^6 km^2). With no major tributaries downstream, the XLD Reservoir effectively governs the entire sediment flux to the lower Yellow River and ultimately to the sea (Wu et al., 2023). In particular, the implementation of the WSRS since 2002 has further underscored the reservoir's control over downstream sediment delivery. The WSRS consists of two distinct chronological phases—water regulation (Figure 1d) and sediment regulation (Figure 1e)—aimed at releasing clear water to scour sediment from the downstream riverbed and flushing trapped sediment from the reservoir to extend its

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operational lifespan, respectively. Since its initiation in 2002, the WSRS has typically been conducted annually between late June and mid-July, a period strategically selected to optimize reservoir storage in advance of the rainy season (Table S1; Figure S3 in Supporting Information S1). This engineering effort fundamentally altered the Yellow River's natural hydrological regime, replacing the historic pattern of gradual seasonal wet and dry signals with abrupt, artificial high-flow events (H. Wang et al., 2017). On average, each WSRS operation accounts for approximately 27.8% of the river's annual water discharge and about 53.8% of its annual sediment flux to the sea (Wu et al., 2020).

Before WSRS implementation (2000–2001), the XLD Reservoir trapped 618.1 Mt of sediment, with a trapping efficiency of 94.5% (Figure 2a). Only 16.6 Mt of sediment was able to pass downstream annually, representing less than 4.5% of the average sediment discharge during the preceding decade (390 Mt/yr between 1990 and 1999). As a result, the sediment flux reaching the sea dropped sharply to 17.6 Mt/yr (Figure 2d), supplemented with limited erosion of the lower riverbed (Figure 2c). This severe sediment deficit led, for the first time on record, to a transition from delta construction to net erosion, with the subaerial delta losing land at a rate of 5.6 km^2/yr (Figure 3a). Concurrently, widespread erosion occurred across the subaqueous delta, except for a localized depocenter near the river mouth, resulting in a net erosion rate of −0.09 km^3/yr (Figure 3b).

Since 2002, the WSRS substantially boosted sediment delivery to the sea. During the water regulation phase, the artificial release of sediment-free floodwaters from the XLD Reservoir induced significant downstream channel bed erosion (Miao et al., 2016; Figure S4 in Supporting Information S1). From 2002 to 2014, approximately 1315.5 Mm^3 of sediment (equivalent to 1447.0 Mt with a density of 1.1 g/cm^3) were scoured from the riverbed and transported to the sea (Figure 2c). Simultaneously, the joint operation of upstream Sanmenxia Reservoir (SMX; see location in Figure 1b) effectively expelled sediment that would otherwise be trapped in the XLD Reservoir, reducing its sediment trapping efficiency to 74.6% (Figure 2a). Consequently, an average of 75.1 Mt sediment passed downstream annually, restoring the Yellow River's sediment delivery to the sea to 151.9 Mt/yr during 2002–2014 (Figure 2d). This renewed sediment supply, enriched with coarser-grained particles mobilized during scouring, favored nearshore deposition and delta accretion (Edmonds, 2012; Shaw et al., 2016). As a result, the subaerial delta reversed to a constructive phase, with a rate of land area gain of 5.7 km^2/yr (Figure 3a). The subaqueous delta had a net accumulation of 0.05 km^3/yr (Figure 3c).

From 2015 to 2017, however, drought conditions across the basin necessitated prioritization of water storage, leading to the suspension of WSRS operations. During this period, almost all of 276.2 Mt of sediment entering the XLD Reservoir was trapped, pushing the reservoir's trapping efficiency closed to 100% (Figure 2a). This indicates that there was no sediment passing through the XLD Reservoir during the entire 3 years. Meanwhile, the scouring of lower riverbed declined to 43.2 Mm^3/yr due to the absence of artificial flood release, less than 42% of the volume observed during WSRS operation years (Figure 2c). Sediment delivery to the sea plummeted to just 7.7 Mt in 2017 (Figure 2d), the lowest value since record-keeping began in 1950 and less than 1% of the well-cited historical record (1,080 Mt; Milliman & Meade, 1983). This dramatic sediment reduction forced the subaerial delta back into a destructive phase, with an average land loss of 0.4 km^2/yr (Figure 3a). It is noteworthy that this erosion rate was notably lower than that observed during 2000–2001, despite similar sediment load (16.7 Mt/yr in 2015–2017 vs. 17.6 Mt/yr in 2000–2001). This may be attributed to increased vegetation coverage, particularly the invasion of the exotic species Spartina alterniflora (J. Wang et al., 2024, Z. Wang et al., 2024), which acted as a buffer zone that attenuate the wave energy and trap sediments, thereby mitigating subaerial delta erosion (Edmonds, 2012; Li et al., 2025). Despite vegetation-induced stabilization of the subaerial delta, the subaqueous delta continued to experience widespread erosion at an average rate of −0.07 km^3/yr under sediment-starved conditions (Figure 3d).

Since 2018, the WSRS was reinstated with an enhanced operational mode. Favorable precipitation conditions allowed the XLD Reservoir to release substantial volumes of impounded freshwater during water regulation phase, leading to prolonged low-water-level conditions (Wu et al., 2023). Between 2018 and 2020, the WSRS duration increased to an average of 54.7 days annually (Figure 2b), with low-water-level periods (water level of XLD Reservoir <230 m) lasting 39.7 days, significantly longer than during 2002–2014 (19.8 days of total duration and 8.5 days of low-water-level periods, respectively). This operational adjustment greatly improved sediment flushing (Kondolf et al., 2014), reducing the XLD Reservoir's trapping efficiency to 5.1% in 2018 and 4.7% in 2020, substantially lower than the 74.6% observed during 2002–2014 (Figure 2a). Notably, in 2019, the operating water level of the XLD Reservoir during the WSRS dropped to 209.0 m—the lowest since

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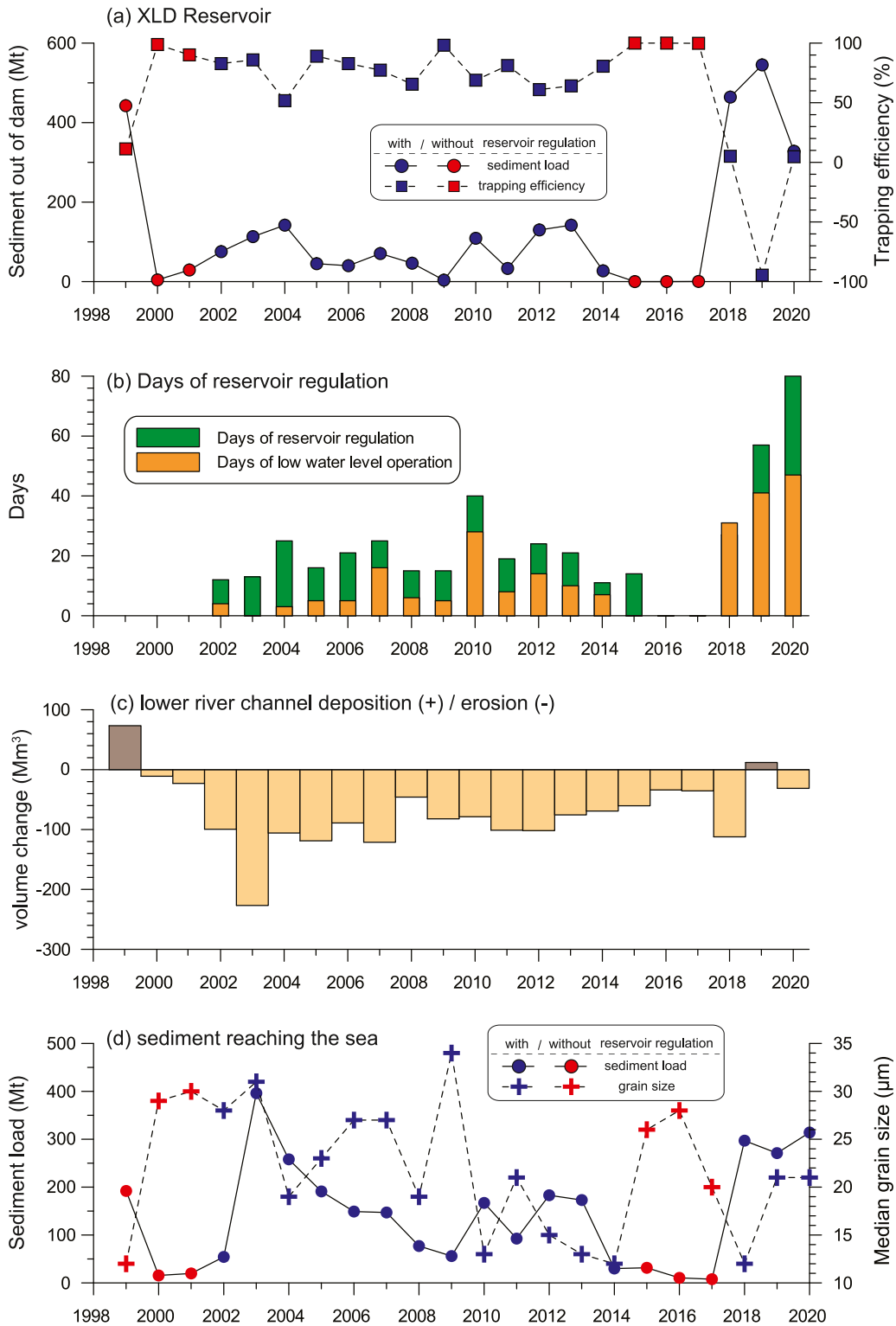

Figure 2. (a) Time series of annual sediment outflow and trapping efficiency of Xiaolangdi Reservoir since impoundment in October 1999. (b) Days of reservoir regulation and low water level operation during the WSRS. (c) Annual channel deposition (+ve) or erosion (−ve) and in the lower Yellow River (Huayuankou-Lijin). (d) Annual sediment load and median grain size of suspended sediment reaching the sea from 1999 to 2020.

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2003—greatly enhancing sediment flushing. Consequently, the reservoir released 545 Mt of sediment while only receiving 208 Mt, achieving net sediment removal for the first time since its commissioning (Figure 2a). Consequently, the sediment discharge into the sea rebounded sharply to 294 Mt/yr, 17.6 times higher than that during the suspension period of 2015–2017 and exceeding levels recorded in the 1990s (Figure 2d). This dramatic increase in sediment delivery allowed the delta to not only halt erosion but also transition back into rapid net accretion, with subaerial land expanding at 6.8 km^2/yr from 2018 to 2020, reaching a total area of 830.2 km^2 (Figure 3a). Meanwhile, the subaqueous delta experienced significant deposition, averaging 0.22 km^3/yr—an rate and spatial extents unprecedented in the past two decades—forming an oval-shaped depocenter with sediment accumulate rates exceeding 1 m/yr near the estuary (Figure 3e).

3.2. Control of Reservoir Regulation on Delta Evolution

Sediment is the life-nourishing resource to any delta as it provides essential material base to combat erosion and relative sea-level rise (Nittrouer & Viparelli, 2014; Zhu et al., 2025). However, sediment trapping behind dams has emerged as a dominant cause of sediment starvation for deltas worldwide (Besset et al., 2019; Blum & Roberts, 2009). By the 2010s, reservoirs globally trapped approximately 65 billion tonnes of sediment annually, 22 times more than that in the 1950s (J. Syvitski, Ángel, et al., 2022). The delta regions of these rivers have thus become sediment starved. For example, the Mississippi River Delta has lost over 4,800 km^2 of land, primarily due to reduced sediment supply (Blum & Roberts, 2009). With the construction of ∼50,000 dams throughout the drainage basin over the past 60 years, the Yangtze River's sediment load to the sea dropped by 65%, inducing net erosion of its subaqueous delta at rates of 152–200 Mm^3/yr (Yang et al., 2011). Therefore, at a global scale, the natural evolution of most deltas has been largely disturbed by direct and indirect effects of human activities such as reservoir construction.

The Yellow River represents one of the most striking examples of human control over delta evolution. In particular, the operation of the WSRS has fundamentally altered sediment delivery patterns. Direct manifestation of this human intervention is the variation in downstream sediment discharge, which can be clearly observed by examining the sediment load at two stations, the SMX and its ∼100 km downstream XLD. With no major tributaries between these two stations, the sediment load measured at SMX and XLD were nearly identical (determination coefficient >0.99) from 1950 to 1998 (Figure S5 in Supporting Information S1). After the completion of the XLD Reservoir in 1999, however, this relationship broke down due to intense sediment trapping and controlled releases linked to WSRS operations (Figure S5 in Supporting Information S1). During non-WSRS years, especially in 2015–2017 when the WSRS was suspended, the Yellow River's sediment to the sea declined by one to two orders of magnitude, lower than the Niger, Rhône, and Danube rivers which are not known for high sediment loads (Figure 4a). While in the operation years of the WSRS, especially in 2018–2020 when the WSRS was operated in a longer period of low water level (Figure 2b), the Yellow River has restored its characteristics of high sediment delivery (Figures 2d and 4a).

With the fluctuations of sediment load, the YRD has experienced a stepwise evolution process over the past two decades (Figure 3). Typically, a time lag exists between variations in riverine sediment supply and the resulting geomorphic response of the delta, as deltas often require extended periods to adjust to changes in external drivers (Huang, 2011; Ritchie et al., 2018). The duration of this response lag varies among deltas and is influenced by factors such as sediment availability, delta size and hydrodynamic setting (J. Wang et al., 2025). Large river deltas with ample sediment supply can respond more rapidly to shifts in fluvial sediment flux (J. Wang et al., 2025), which was confirmed by the rapid response of the YRD evolution to riverine sediment variation (Figures 2d and 3a).

In addition to sediment input, delta evolution is also strongly governed by coastal processes including sea-level rise, tidal dynamics and wave action (J. Wang et al., 2020). The regional sea level rise has risen at an average rate of approximately 3.6 mm/yr (Cheng et al., 2015). Tidal currents near the YRD flow parallel to the shoreline with mean velocities of 0.5–1.0 m/s, while wave activity is primarily driven by the East Asian Monsoon, producing seasonal variability. Under normal weather conditions, significant wave heights typically remain below 0.8 m (Wu et al., 2017). Due to the weak tidal regime and wave action, the YRD fell well into the river-dominated delta following the Galloway's classification, even in the year 2017 with the lowest sediment load since record-keeping (Figure S6 in Supporting Information S1). From the perspective of construction or destruction, however, the evolution of YRD has been completely dominated by human activities. The delta, either the subaerial component or the subaqueous component, only can survive during the years when the WSRS was effective operated

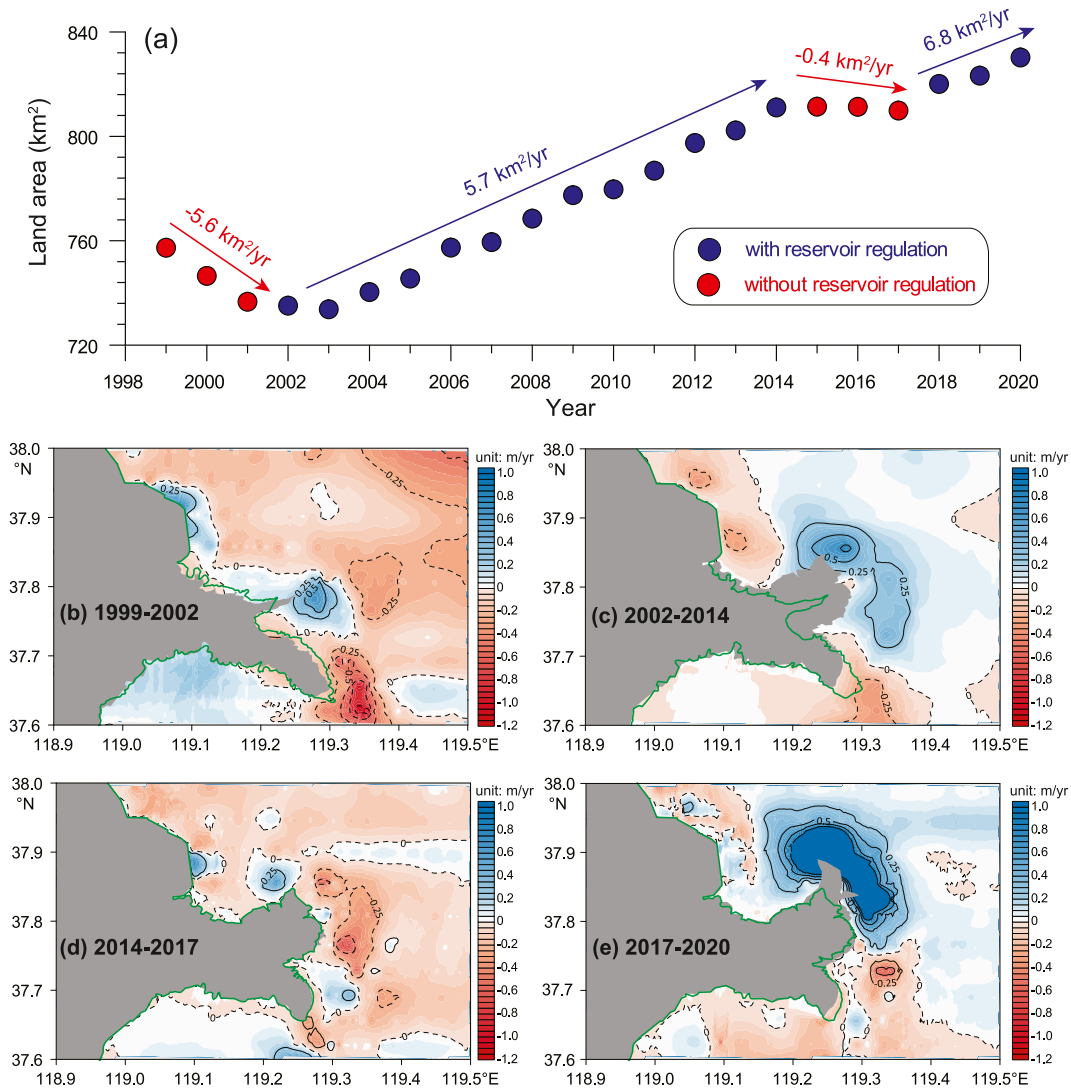

Figure 3. (a) Variations in the land areas in the active Yellow River Delta (YRD) from 1999 to 2020. (b)–(e) Spatial variations of accumulation-erosion pattern of the subaqueous YRD for the corresponding periods. The green lines and gray areas indicate the subaerial delta region in the initial and final years of each period, respectively.

(Figure 4b). Once this reservoir regulation project is suspended or operated ineffectively, the averaged sediment flux reaching the sea sharply declined to below 17 Mt/yr—well below 60–150 Mt/yr threshold required to sustain the delta (Wu et al., 2017). As a consequence, the delta would inevitably transition into a destructive phase due to the severe sediment deficit (Figure 4b).

More and more deltas are moving away from their natural evolution process due to human pressure (Anthony et al., 2024). Many studies have addressed a series of delta erosion due to a marked reduction of sediment supply induced by dam entrapment (Edmonds et al., 2023; Risha & Liu, 2025; J. P. M. Syvitski et al., 2009). There are also presently many examples where human engineering within deltas and their estuaries control the evolution process (Welch et al., 2017). For example, seawall construction and artificial levee diversions are thought to be effective solutions to halt loss (Kim et al., 2009). However, it is still rarely reported that the delta evolution has been remotely controlled through the regulation of reservoir hundreds of kilometers upstream.

Under any circumstances, ensuring adequate sediment discharging into the sea is the most important ways to maintain the sustainability of the delta. Reservoir flushing has been proven to be an effective way to mitigate reservoir sedimentation and increase downstream sediment transport in the XLD Reservoir in Yellow River, China and other dams globally, such as: Unazuki Dam in Japan (Sumi et al., 2006), Cachi Dam in Costa Rica

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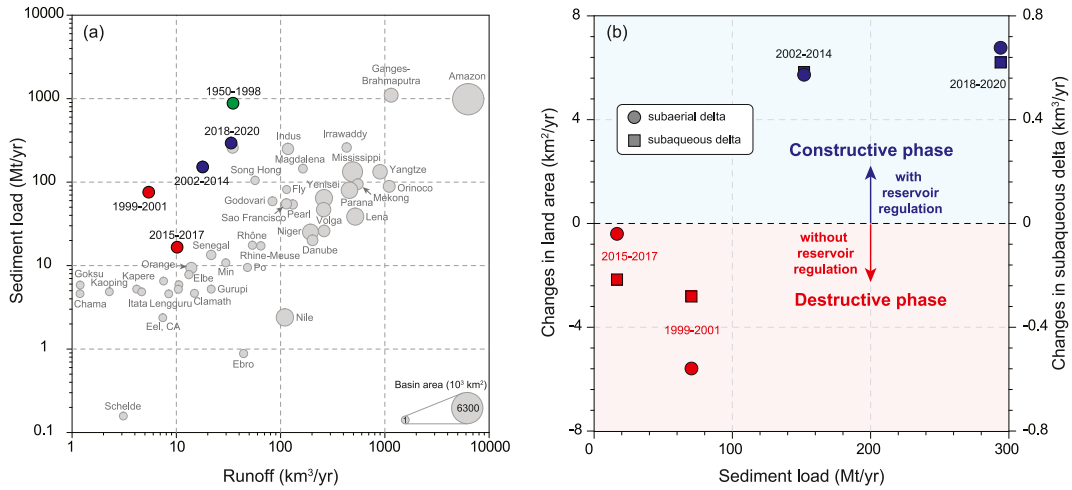

Figure 4. (a) Runoff and sediment load of different rivers (from Das et al., 2021; Higgins et al., 2016; Milliman & Farnsworth, 2011). The green circle indicates the historical data of the Yellow River from 1950 to 1998. The dark blue and red circles indicate the data of the Yellow River with and without WSRS, respectively. (b) Sediment load and active delta evolution in different periods.

(Jansson & Erlingsson, 2000), and Genissiat Dam on the Rhône River in France (Kondolf et al., 2014). While how best to scour the deposited sediment and transport it downstream is still a challenge. The Yellow River provides a good reference point by which to understand how to effective expel sediment behind dams and nourish its delta through the experiences of success and failure during the operation process for over the past 20 years. The best scenario for flushing is to establish low-water-level reservoir conditions, which is favorable for sediment being eroded and resuspended from reservoir deposits, thereby transporting downstream and nourishing the delta regions.

4. Summary

This study reviewed the evolutionary pattern of more than two decades of the YRD, a typical river-dominated delta with rapid accretion throughout history, and discussed the impact of completion and regulation of a mega-reservoir. The construction and regulation of XLD Reservoir completely changed the sediment supply to delta region. No matter how much sediment incoming, there were little to no sediment escaping the XLD Reservoir during non-WSRS years. Sediment trapping efficiency of the dam reached 100%, resulting in a significant decline in sediment reaching the sea and the consequent delta destruction. Operation of the WSRS increased the sediment levels escaping the dam by reservoir flushing and scouring the sediment deposited on the lower riverbed. In particular, during 2018–2020 when the WSRS was operated in a longer period of low water level, the sediment out of the XLD Reservoir increased to 445.7 Mt/yr, even higher than the sediment entering into the reservoir (371.0 Mt in average). This sediment replenishment increased the sediment to the sea by an order of magnitude and nourished the deltaic area, making both the subaerial and subaqueous deltas to prograde seaward. Consequently, the reservoir regulation eight hundred kilometers upstream of the estuary dominated the sediment flux downstream, transitioning the delta's evolution with human control. Lessons learned from the Yellow River demonstrates that sediment deficits caused by dams can, under intentional management, be reversed—offering a paradigm for Anthropocene delta stewardship.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The data set used here are available from the Figshare repository (Wu, 2025).

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Acknowledgments
This research was funded by the National Natural Science Foundation of China (42330407, 42411540024, 42176168, and 42149301), the Science Fund for Distinguished Young Scholars of Shandong Province (ZR2024JQ016), and Taishan Scholar Project of Shandong Province (tsqn202211054).

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