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Can Reservoir Regulation Along the Yellow River Be a Sustainable Way to Save a Sinking Delta?

Xiao Wu[1,2], Naishuang Bi[1,2], Jaia Syvitski[3], Yoshiki Saito[4,5], Jingping Xu[2,6], Jeffrey A. Nittrouer[7], Thomas S. Bianchi[8], Zuosheng Yang[1], and Houjie Wang[1,2]

[1]College of Marine Geosciences, Key Laboratory of Submarine Geosciences and Prospecting Technology, Ocean University of China, Qingdao, China, [2]Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and Technology, Qingdao, China, [3]Community Surface Dynamics Modeling System, INSTAAR, University of Colorado, Boulder, CO, USA, [4]Estuary Research Center, Shimane University, Matsue, Japan, [5]Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan, [6]Department of Ocean Science and Engineering, Southern University of Science and Technology, Shenzhen, China, [7]Department of Earth, Environmental, and Planetary Sciences, Rice University, Houston, TX, USA, [8]Department of Geological Sciences, University of Florida, Gainesville, FL, USA

Key Points:
- The impact of reservoir regulation along the Yellow River on delta evolution was systematically evaluated
- The man-made experiment through reservoir regulation along the Yellow River did mitigate delta erosion by scouring the lower river bed
- With sediment coarsening of lower riverbed, bed scouring through reservoir regulation is not a sustainable way to nourish delta lobe

Correspondence to:
H. Wang,
hjwang@mail.ouc.edu.cn

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Author Contributions:
Writing – original draft: Xiao Wu
Writing – review & editing: Naishuang Bi, Jaia Syvitski, Yoshiki Saito, Jingping Xu, Jeffrey A. Nittrouer, Thomas S. Bianchi, Zuosheng Yang, Houjie Wang

Abstract Today's deltas are impacted negatively by (1) accelerated subsidence (e.g., from ground fluid extraction), (2) global eustatic sea level rise, and (3) decreased sediment supply, which increasingly starves these landforms of sediment necessary to sustain their footprint. This growing vulnerability threatens many megacities that have developed due to the rich resources offered by deltas and therefore urgently calls for efforts to maintain sustainability. The Yellow River of China is classic example of such a landform under threat and which requires human intervention to maintain its resilience. Since 2002, the Yellow River Conservancy Commission has enacted an annual water and sediment regulation scheme (WSRS) by coordinated operation of three large reservoirs in the mainstream. Here we evaluate the efficiency and sustainability of this man-made experiment on delta evolution. The impulsive delivery of muds and sands, within ~20 day intervals (averaged duration of the WSRS), did indeed move the present Yellow River delta from a destructive phase to an accretion phase. With continuous scouring, however, the downstream riverbed erosion efficiency has decreased, due to coarsening of surface bed material sediment. Concomitantly, sediment delivery has decreased, resulting in the present delta once again entering an erosive (destructive) phase, since 2014. From a perspective of delta restoration, the WSRS on the Yellow River is effective but potentially unsustainable. Restoring delta resilience necessitates an enhanced, coordinated effort, relying upon new sciences advances, rather than simply assuming channel scour will address the sediment deficit of the delta.

Plain Language Summary Deltas are highly dynamic systems which lie on the interface between rivers and oceans. Due to accelerated sea level rise and terrestrial sediment decrease, over half of global deltas are presently under a growing risk of being submerged. How best to protect these important terrestrial surface has become an urgent problem to be resolved. With our manuscript, we describe the successes and unintended consequences learned from one of the largest man-made experiments in the world. Since 2002, the Yellow River Conservancy Committee started to release flushing water from the Xiaolangdi Reservoir annually to remove accumulated sediment from the reservoir and to erode the lower riverbed of the Yellow River. This man-made experiment did increase the quantity and particle size of sediment reaching the sea, and thereby nourishing the Yellow River delta successfully. With gradually eroding, however, the enhanced particle size has armored the lower riverbed, making it progressively difficult to be eroded by reservoir-released flushing water. Consequently, the sediment delivery from the Yellow River to the sea declined, resulting in that the Yellow River delta, has once again retreated landward since 2014.

1. Introduction

As one of the most valuable terrestrial surfaces on Earth, deltas are relied upon to nourish hundreds of millions of people worldwide (Syvitski & Saito, 2007; Tamura et al., 2012). Yet deltas are highly dynamic environments, ever changing form, as they lie at the interface of rivers and oceans and are therefore impacted by

both fluvial and coastal processes (Day & Giosan, 2008). Anthropogenic impacts have taken a toll: recent decreases in delivery of riverine sediment to the sea, along with accelerated land subsidence and relative sea level rise, have moved most deltas from a constructive to destructive phase (Blum & Roberts, 2009; Vörösmarty et al., 2009). A multibillion-dollar question then emerges: How best to protect, sustain, and restore these important coastal systems?

Rising sea level as a consequence of global warming is inevitable and predicted to accelerate over the coming decades, while subsidence is an intrinsic property of deltas (Brown & Nicholls, 2015; Goodwin et al., 2017; IPCC, 2007). Replenishing a diminished sediment load and enhancing the land-building ability is considered to be the best exercisable approach to saving drowning deltas (Giosan et al., 2014). Efforts to maintain and even enhance sediment delivery have included using controlled floods to scour sediment from the bed, along with implementing engineered river diversions in combination with vegetation seeding to optimize the sediment trapping on deltas (Edmonds & Slingerland, 2010; Giosan et al., 2014; Kondolf et al., 2014). Indeed, while the effectiveness of these efforts is well conceived via theoretical analysis and numerical modeling, their performance in practice remains unclear. Given that such efforts are planned for other systems globally (Edmonds, 2012; Lauzon & Murray, 2018), it is prudent to evaluate their effectiveness where evidence exists.

In this regard, the Yellow River delta (YRD) is a perfect candidate: well known for its fast growth due to its sufficient sediment supply and history for frequent channel avulsions (Xue, 1993), the system has claimed over 5,800 km^2 of new land from the Bohai Sea since the last major channel migration in 1855. However, over the past few decades, increasing pressure of human modifications, including construction of reservoirs, landscape engineering, and terracing in the Loess Plateau (the dominate sediment source for the Yellow River), has cut delivery of sediment to the Bohai Sea by over 90% (Wang et al., 2016). Correspondingly, delta growth has slowed until finally transitioning into an erosional phase (Wu et al., 2017), with a maximum retreating rate of 0.4 km/year (Wu, Wang, Bi, Nittrouer, et al., 2020). The impacts of unchecked erosion of landscape are potentially devastating to the estimated ~2 million people that reside on the delta, adding urgency to the challenge of managing this landscape.

In July 2002, an official administrative department for the Yellow River (the Yellow River Conservancy Committee, YRCC) initiated the water and sediment regulation scheme (WSRS) through a coordinated regulation of three large reservoirs (Wanjiazhai, Sanmenxia, and Xiaolangdi reservoirs; Figure 1a) located along the mainstream. Since then, the WSRS has been generally operated every summer and used to boost sediment delivery, including sand through bed erosion, by unleashing artificial flood waves (Wang et al., 2017). Consequently, the present lobe of the YRD began a phase of seaward progradation (Wu et al., 2017). Such a large-scale regulation of a river system in an effort to maintain deltaic resilience is unprecedented and therefore necessitates scientific assessment. Seventeen years since implementation of the WSRS, a systematic evaluation of its effectiveness in terms of delta sustainability is now addressable.

2. Operation of the WSRS

The goals of the WSRS were twofold: scour the lower river channel, so as to increase flood carrying capacity of the downstream channel, and to remove accumulated sediments from the Xiaolangdi Reservoir and thus prolong its operational life expectancy. Consequently, a yearly WSRS event is designed to have two chronological phases: a water discharge period, followed by a sediment discharge period.

During the water discharge period, sluice gates skim clear water, devoid of sediment (Figure 1b), and discharge increases from hundreds of m^3/s to over 3,000 m^3/s within 2 to 3 days; this is maintained over ~10 days (Figure 1d). As the artificial flood wave maintains enhanced sediment transport capacity, downstream bed scour removes bed material (Bi et al., 2019). The water discharge period concludes with partial closure of the sluice gates, wherein the water discharge decreases sharply to <1,000 m^3/s (Figure 1d). Subsequently, sediment gates at the base of the dam are opened, marking the initiation of the sediment regulation period. As the water level in the Xiaolangdi Reservoir is decreased by the preceding water release, a significant source of trapped sediment here, as well as in the upstream Wanjiazhai and Sanmenxia reservoirs, is subject to erosion. As a result, highly turbid water with suspended sediment concentration of 60–100 kg/m^3 is discharged from the Xiaolangdi Reservoir (Figure 1c) and travels downstream via artificial hyperpycnal flow (Li et al., 2017). Compared to the water discharge period, sediment exported from the

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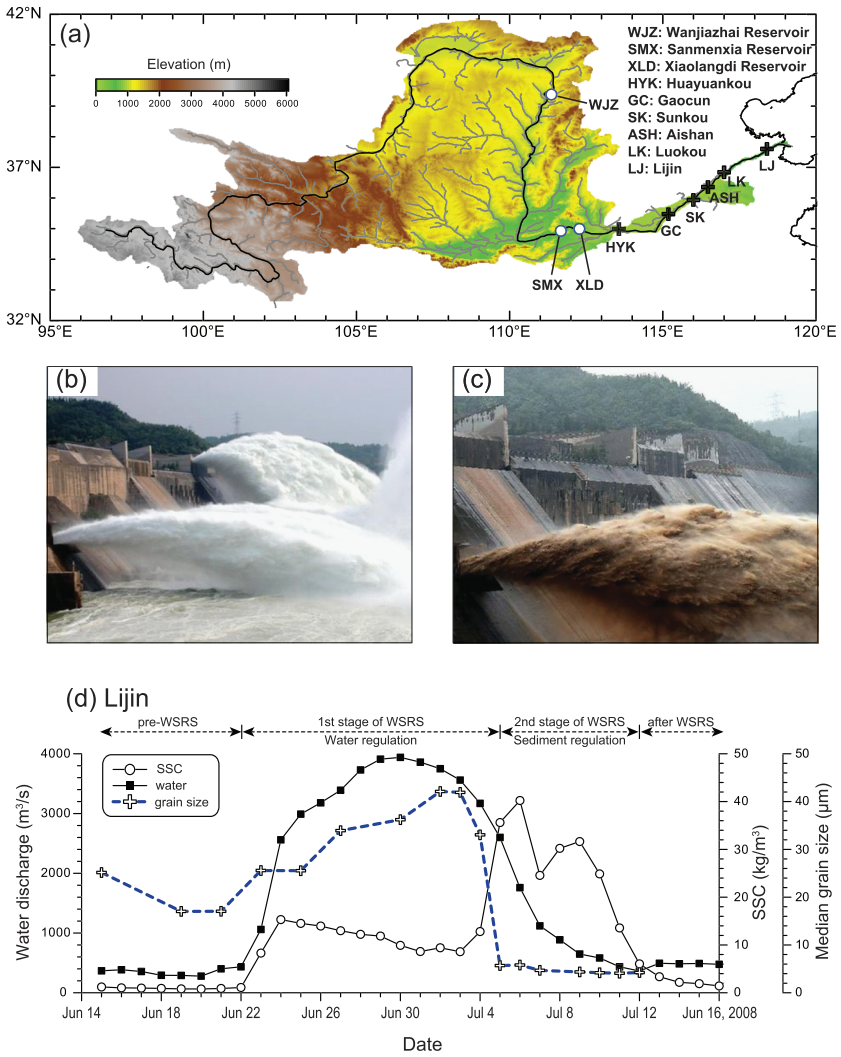

Figure 1. (a) Drainage catchment map of the Yellow River, showing the locations of reservoirs operated during the WSRS and downstream gauging stations; (b and c) clear flood and turbid water released from the Xiaolangdi Reservoir in 2013 (from http://www.xinhuanet.com/); (d) daily river flow, suspended sediment concentration, and median grain size of suspended sediment before, during and after the WSRS at Station Lijin in 2008.

Xiaolangdi Reservoir is much finer, and therefore, a drastically smaller grain size is delivered to the delta (Figure 1d). After completion of the WSRS, water discharge and sediment concentration return to normal values of <500 m^3/s and <5 kg/m^3, respectively (Figure 1d).

3. Effectiveness of the WSRS

Since the implementation of the WSRS, the monsoon-fed Yellow River has been substantially altered from its natural state. The flood peaks, which were previously (naturally) fed by monsoon rains, are now largely controlled, replaced by man-made flood peaks (Wang et al., 2010). During the 1950s when the Yellow River was less fragmented by dams, high water discharge (over 3,000 km^3/s) was usually found in rainy season (once every month from July to September), with a duration of 15–25 days (Wang et al., 2017). After 2002, the duration of high water discharge was greatly shortened to be less than 10 days (Figure 1d), corresponding to dam-releasing events. The short-term discharge pulses during the WSRS have caused significant changes in the delivery regime of Yellow River water and sediments. The duration of WSRS has averaged only ~20 days per year (5%) but accounts for 28% and 54% of total annual water and sediment delivery to the sea, respectively (Wang et al., 2017).

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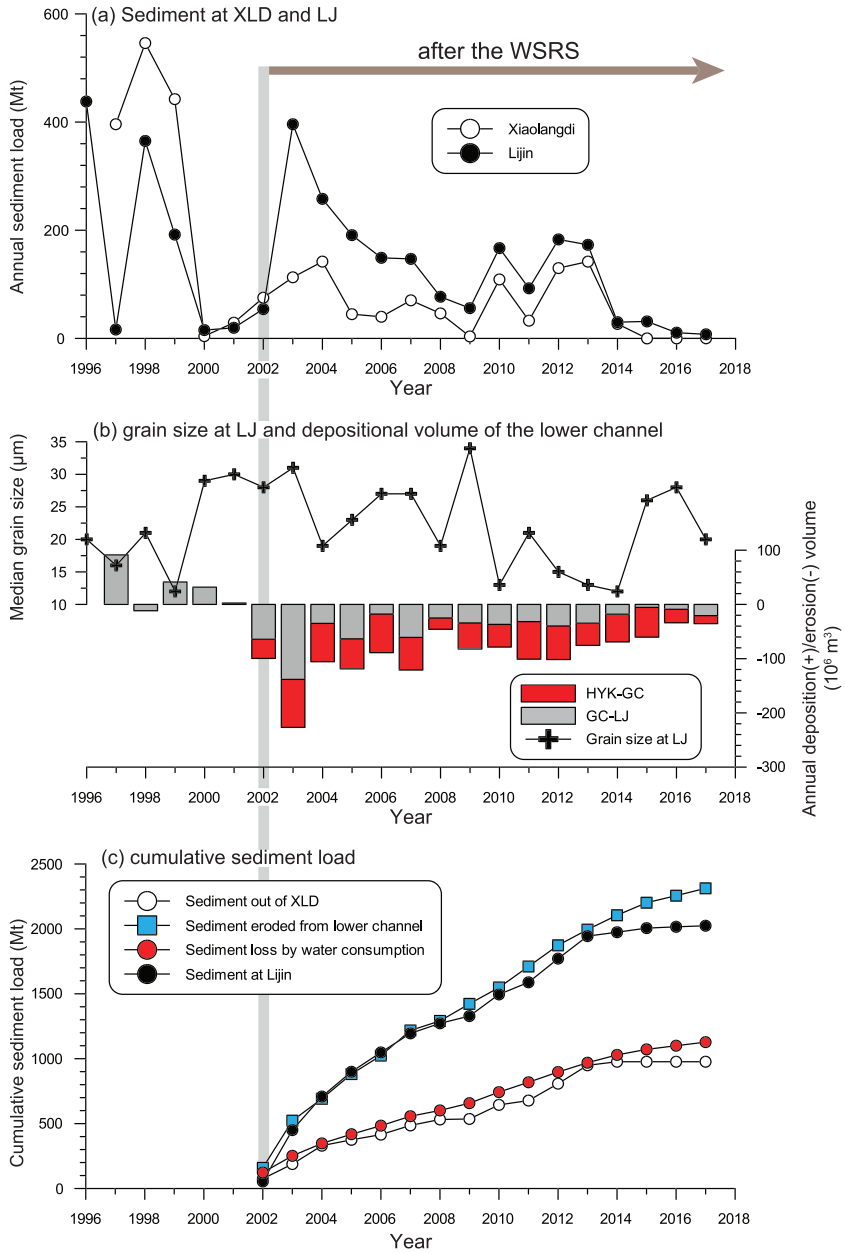

Figure 2. (a) Annual sediment load exported from the Xiaolangdi Reservoir and at Station Lijin. (b) Annual median grain size of suspended sediment gauged at Station Lijin and annual variations in depositional volume of the river channel in the lower Yellow River during the period of 1996–2017. Locations of stations Huanyuankou (HYK), Gaocun (GC), and Lijin (LJ) are shown in Figure 1a. The Xiaolangdi Reservoir was completed in 1999, while the WSRS was initiated in 2002. (c) Cumulative curves of sediment load from Station Xiaolangdi, lower channel erosion, sediment loss in the lower channel due to water consumption, and sediment load at Station Lijin.

After 2002, sediment load exported from the Xiaolangdi Reservoirs averaged 61.03 Mt/year (Figure 2a). The artificial flood strongly scoured the riverbed of the lower Yellow River at an average rate of 90×10^6 m^3/year (Figure 2b), and this erosion contributed ~41% of coarse-grained sediment reaching the YRD (Bi et al., 2019). Combined with turbid water release of the WSRS, the sediment mass reaching the sea both increased and coarsened. These two factors, as well as the impulsive nature by which the sediment was delivered, have played a crucial role in the morphological evolution of the YRD (Ji et al., 2018). For example, during the period of 1996–2002, the delta suffered net erosion of 5.1 km^2/year due to insufficient supply (Figure 3).

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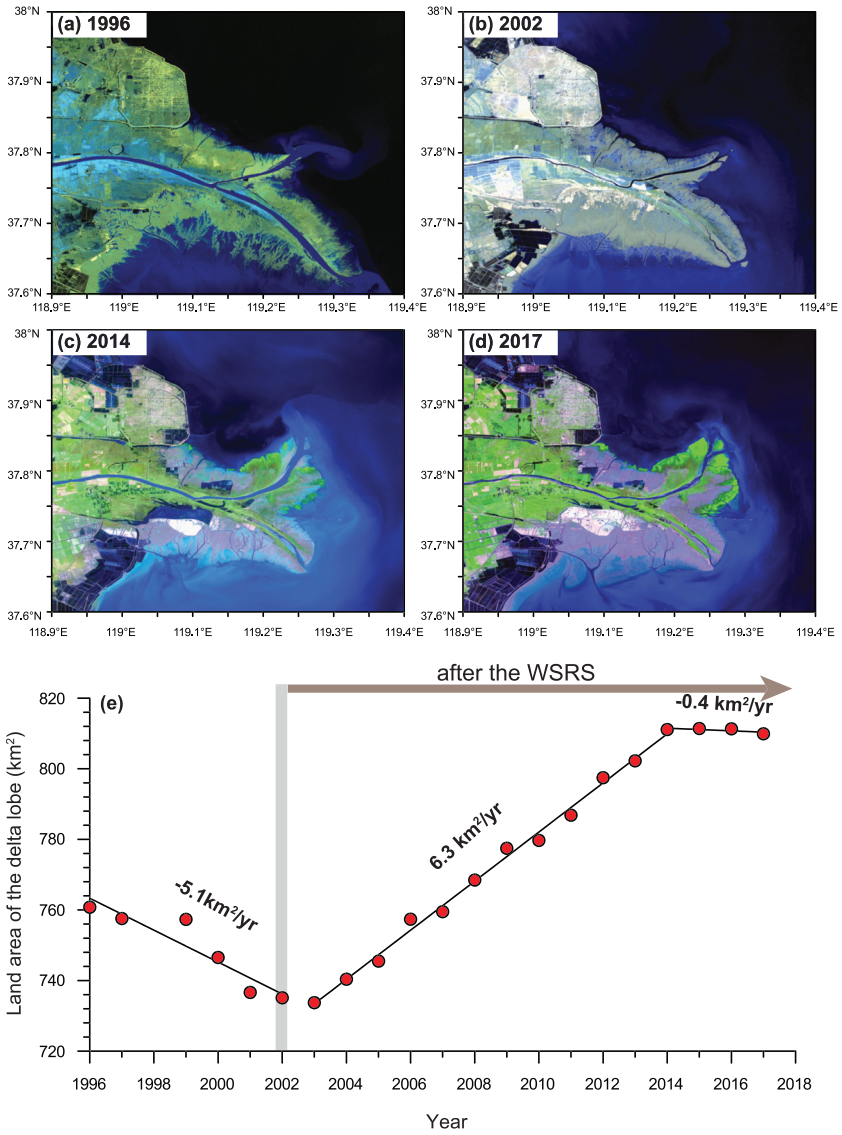

Figure 3. Landsat images of the present Yellow River delta in (a) 1996, (b) 2002, (c) 2014, and (d) 2017; (e) variations in land areas in the present delta during the period of 1996–2017. The land area data were derived from landsat images based on the method described in Alesheikh et al. (2007).

However, after the implementation of the WSRS in 2002, the delta lobe transitioned to an accretion phase with an average progradation rate of 6.3 km^2/year (Figures 3c and 3e). Although the initial design of the WSRS had no regard for downstream delta evolution, the result was nevertheless a satisfactory morphological evolution. Reservoir regulation in the drainage catchment of the Yellow River offers important new insights into the global battle to solve delta drowning (Xu et al., 2019).

4. Sustainability of the WSRS

Although the WSRS alleviated the rate of sediment filling of the Xiaolangdi Reservoir, 85% of the incoming sediment from the Loess Plateau is still trapped in the upstream reservoirs (Chen et al., 2012). Until October 2017, the total sediment retention in the Xiaolangdi Reservoir had reached 3.4×10^9 m^3, about 27% of the total capacity of the reservoir. This material occupies the reservoir in the form of a shallow lacustrine delta that progrades downstream toward the dam (Figure 4a). However, this delta deposit gradually limits the

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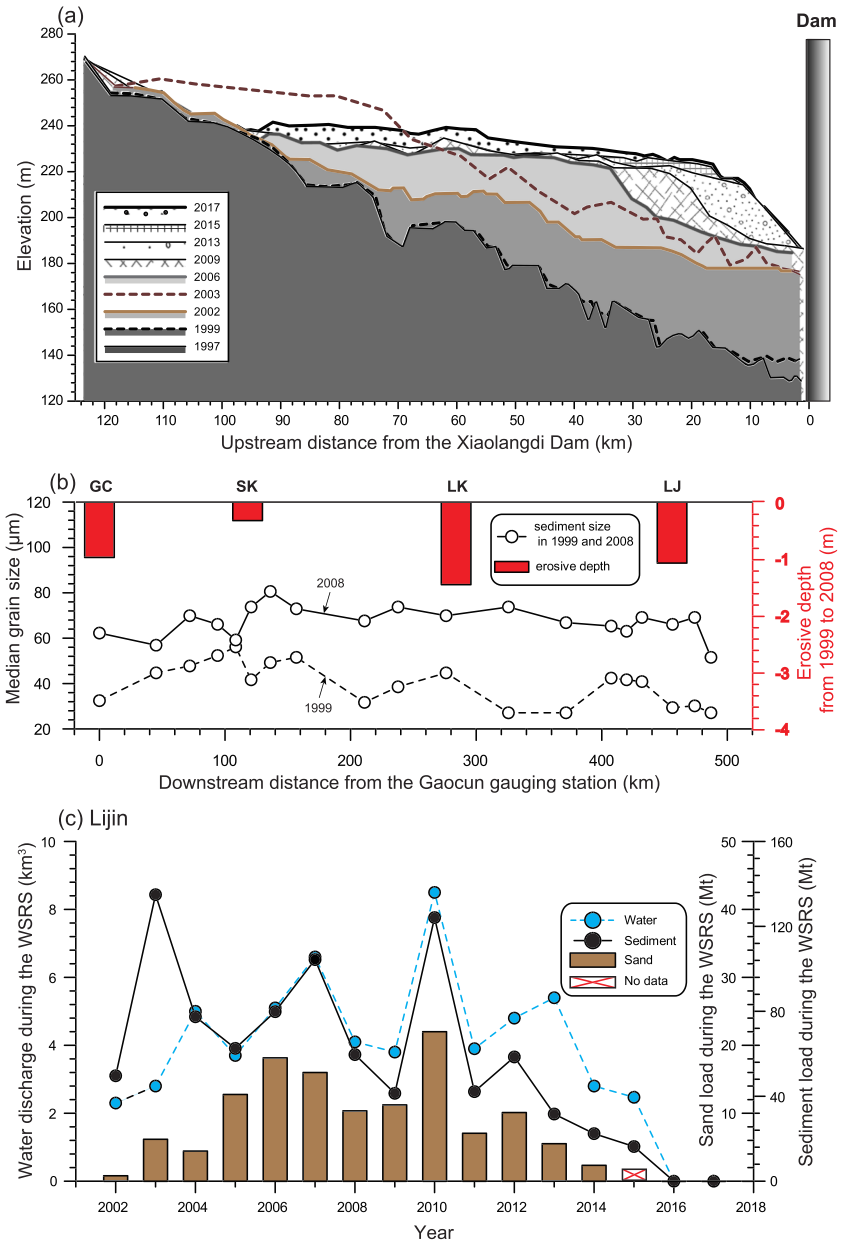

Figure 4. (a) Annual variations of sectional depth in the Xiaolangdi Reservoir. (b) Erosive depth of the lower river channel and changes in median grain size of surface sediment of the lower riverbed from 1999 to 2008 (Bi et al., 2019). Locations of stations Gaocun (GC), Sunkou (SK), Luokou (LK), and Lijin (LJ) are shown in Figure 1a. (c) Water discharge, sediment load, and sand load reaching the sea at Station Lijin during annual WSRS. The percentages indicate the sediment load during the WSRS occupies the annual sediment load.

sediment delivery by flood water from the upstream Wanjiazhai and Sanmenxia reservoirs during the sediment-regulation period, by changing fluvial channel slope and the location of the flood plunge point into the reservoir (Chen et al., 2012).

Since the implementation of the WSRS in 2002, the riverbed of the lower reaches has undergone significant erosion (Figure 2b). The scouring process by artificial floods has largely deepened the riverbed downstream of Gaocun by 0.3–1.4 m, from 1999 to 2008 (Figure 4b). Eroded particles were transported to the sea but with diminishing success: The lower Yellow River bed has coarsened, whereby the median grain size increased by

a factor of 2 to 3 within 10 years of the WSRS (Figure 4b). In essence, the enhanced grain size has "armored" the lower riverbed, making it progressively difficult to erode during subsequent water-regulation periods (Miao et al., 2016).

Due to more reservoir storage (Yang et al., 2020) and coarsening of surface sediment of lower riverbed (Figure 4b), the functional degradation of the WSRS in both water-regulation and sediment-regulation periods has led to visible decrease in both water discharge and sediment load to the sea during the period of the WSRS (Figures 2c and 4c). Since 2006, when the downstream riverbed erosion efficiency began to decrease (Wang et al., 2017), the sand load has dramatically declined (Figure 4c, with exception for 2010 when three WSRS events were unprecedentedly operated). Moreover, in 2015, the implementation of the WSRS failed with no sediment export from the Xiaolangdi Reservoir (Figure 2a). Subsequently, the WSRS stagnated in 2016 and 2017 because of insufficient water storage in the Xiaolangdi Reservoir. All sediment delivered from the Loess Plateau was sequestrated behind the dam. Hence, the only source of sediment delivery to the sea from 2015 to 2017 was the downstream river bed. Combined with sediment coarsening of the lower riverbed, the material flux of the lower Yellow River to its delta fell to 35×10^6 m^3 (Figure 2b), and although the grain size of suspended sediment was relatively elevated, the sediment load decreased to a remarkable 7.7×10^6 t (Figure 2c), which is the lowest since records began in 1950 and even lower than the pristine level of 7,000 cal year BP (Wu, Wang, Bi, Saito, et al., 2020). Furthermore, as a consequence of the declining fine-grained sediment export from the reservoir, particulate organic carbon declined from 4.1×10^{11} g in 2012 to 0.4×10^{11} g in 2015 (Ran et al., 2013; Xue et al., 2017). Since the delivery of nutrients and contaminants has been mainly dominated by the WSRS-released sediment since 2002 (e.g., Hu et al., 2019; Liu et al., 2019), the functional degradation of the WSRS might result in the alteration of coastal biogeochemical cycle.

The impact of the declining operation of the WSRS has been felt by the morphological evolution of the delta. After 12 years of land accretion nourished by the WSRS-induced sediment restoration, since 2014, the subaerial YRD has once again transitioned to a degradation phase, with an average erosion rate of 0.4 km^2/year (Figure 3e). The present YRD is now in decline and faces a crisis of massive coastal erosion.

5. Implications for Delta Restoration

Deltas worldwide are under a growing risk of drowning, at rates that are unprecedented for the past 7,000 years (Syvitski et al., 2009). A multitude of initiatives have been initiated in an attempt to save world's river deltas (Best, 2019; Giosan et al., 2014). The WSRS on the Yellow River provides a good reference point by which to understand how to properly nourish sediment-starved coastal landforms. Using the coordinated operation of three large reservoirs in the middle reaches of the Yellow River, sediment export to the delta drastically improved, by both delivering sediment trapped in the reservoirs, as well as provisioning material otherwise trapped on the channel bed of the lower river reaches. The impulsive delivery of sediment during the WSRS moved the YRD to a condition of active growth, illustrating that the sediment when properly managed has the potential to greatly mitigate delta erosion (Bianchi, 2016; Kim, 2012).

In the long run, however, increasing the delivery of both mud and sand via future WSRS could be unsustainable. Dams inevitably block the downstream water discharge and decrease the sediment transport capacity. Sediment retention in the reservoirs remains irreversible and will gradually limit the delivery ratio of sediment out of reservoirs (Chen et al., 2012). If channel erosion continues in the downstream segments, the surface of riverbed will continue to become progressively armored by coarser sediments, and so the erosion efficiency will continue to decrease (Bi et al., 2019). Thus, replenishing diminished sediment loads simply via bed scouring is not a sustainable way to save drowning deltas. (1) To better reduce sediment trapping behind dams, engineering designs and operation managements should be used to optimize removal of accumulated sediment. More well-designed turbidity currents venting from the dam might be a successful measure against reservoir sedimentation and would boost sediment reaching the delta (Chamoun et al., 2016). (2) With gradually scouring by the WSRS-released floods, the bankfull flow in the lower Yellow River has increased (Xia et al., 2014). Enlarging the water discharge during the WSRS in a proper way might be an effective measure to further scour the lower riverbed. (3) To better nourishing deltas, the sediment restoration initiated by the reservoir regulation should jointly collaborated with engineered river diversions and vegetation seeding (Edmonds, 2012; Giosan et al., 2014), rather than simply delivering sediment to the deltaic region.

6. Conclusions

After 17 years of implementation, the efficiency and sustainability of the WSRS on the morphologic evolution of the present YRD necessitates evaluation. The WSRS substantially achieved its objectives, which aim to alleviate siltation in both reservoirs and lower river reaches. Although the initial design of the WSRS had no regard for downstream delta evolution, the WSRS did play a critical role in delta restoration. Sediment scoured from the Xiaolangdi Reservoir, and the lower riverbed, largely nourished the present delta. The land area transitioned from an erosional phase to an accretionary phase, with an average rate of 6.3 km^2/year, from 2002 to 2014. However, this trend was unsustainable. Continuous sediment retention in the Xiaolangdi Reservoir will impede sediment escape from the reservoir. Meanwhile, the lower riverbed has armored due to coarsening. Correspondingly, the sediment delivering ratio and downstream riverbed erosion efficiency has gradually decreased, resulting in a decline of sediment reaching the delta. Consequently, the present YRD has suffered erosion once again due to insufficient sediment supply. To better maintain delta sustainability for a long term, the WSRS on the Yellow River will require continued modification to account for the multitude of unintended consequences. On the one hand, how better to release sediment retention behind the dam and to scour the downstream riverbed, aiming at further boosting the sediment delivery, should be considered in detail. On the other hand, the impulsive delivery of sediment should jointly collaborated with other maintenance strategies, such as engineered river diversions and vegetation planting, to optimize the sediment trapping on deltas.

Data Availability Statement

The hydrographic data sets used in this study could be accessible through Figshare (https://figshare.com/articles/dataset/Wu_et_al_2020/12885572). Multitemporal Landsat Thematic Mapper satellite images from 1996 to 2017 were acquired from the U.S. Geological Survey (https://glovis.usgs.gov/).

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