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Severely Declining Suspended Sediment Concentration in the Heavily Dammed Changjiang Fluvial System

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Key Points:

- Suspended sediment concentration of the Changjiang River has decreased by an order of magnitude in recent 3 decades from ~1.0 to ~0.1 kg/m^3
- Sediment source/sink reverse partially and downstream recovery capacity decrease exponentially under the reservoir operation
- Predicted by a new sediment modeling framework, the river-lake relationship in the fluvial system will change considerably in 2030s

Supporting Information:

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

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Abstract

As a key component of global change, dam-induced sediment reduction occurs in large rivers worldwide, which has profound implications on the fluvial systems. However, the systematic change of suspended sediment concentration (SSC) and its dynamic processes are not well known. We summarize typical SSC changes and propose a new sediment modeling framework for heavily dammed fluvial systems with the Changjiang (Yangtze River) as a background. We find that the fluvial SSC has declined by an order of magnitude, i.e., from ~1.0 to ~0.1 kg/m^3, and even to ~0.01 kg/m^3 locally. The SSC distribution pattern along the mainstream has changed remarkably, with the sediment source/sink being partially reversed. Downstream of the Three Gorges Dam, the SSC recovery capacity gradually decreases with the sediment erosion quantity accumulated over time, and the SSC contribution rate of a linked large lake (Dongting) will change from negative (ca. −39%) to positive (ca. 17%), in the coming decades.

Plain Language Summary

Suspended sediment plays a key role in fluvial nutrient transport and aquatic ecological processes. Globally river damming has led to sediment discharge reduction to the sea, yet the systematic riverine concentration (SSC) changes and their mechanisms remain poorly understood. Herein, we propose a new modeling framework for reproducing and forecasting suspended sediment processes for dammed fluvial systems with the Changjiang as a reference. Results show a sediment source/sink reverse, downstream recovery capacity decrease and a change in river-lake relationship under severe SSC decline. These findings offer essential guidelines for river management subject to super reservoirs, which have been built (e.g, the Three Gorges Reservoir) or planned in large rivers, such as the Congo and Amazon River.

1. Introduction

Worldwide fluvial sediment reduction is a key component of global change (Best, 2019; Golosov & Walling, 2019; Walling, 2009). In recent decades, a significant declining trend in sediment discharge has been identified in many large rivers, e.g., the Nile, Colorado, Mississippi, Indus, Changjiang, and Yellow Rivers, which used to be the major carriers of sediment on Earth (Golosov & Walling, 2019; Milliman & Farnsworth, 2011; Syvitski et al., 2005; Vorosmarty et al., 2003; Wang et al., 2016). Dams play a dominant role in the sediment transport reduction in numerous fluvial systems, although soil erosion of the land surface and sand excavation are also severe and important for sediment budget in various scales (Grill et al., 2019; Mouyen et al., 2018; Syvitski & Kettner, 2011; Syvitski et al., 2005). The change in sediment regime can further affect riverine environments and ecosystems by altering the nutrient distribution, light penetration, aquatic habitat, etc (Beechie et al., 2010; Milliman, 1997; Wohl et al., 2015; Zhou et al., 2015). Therefore, the fluvial sediment variation attracts the increasing attention of not only hydrologists and geologists but also biologists and environmentalists.

In existing studies, much effort has been focused on the sediment budget, aiming to estimate the total sediment discharge to the sea and to understand delta subsidence and shrinkage due to sediment starvation (Dai et al., 2018; Elsey-Quirk et al., 2019; Giosan et al., 2014; Nienhuis et al., 2020; Syvitski et al., 2009; Tessler et al., 2015). However, limited investigations have been conducted on the suspended sediment concentration (SSC) distribution in large rivers (Dai et al., 2016). For instance, when the Amazon River was investigated, a 20% decrease in surface SSC has been found in a tributary, named Madeira River, downstream of the Santo Antônio Dam (Latrubesse et al., 2017), whereas in that study a proposed index of dam environmental vulnerability was still based on the sediment flux instead of the SSC. There is no doubt that flux budget is useful when estimating total sediment discharge to an estuary or a marine, as well as the sediment exchange between the river channel and floodplain (Forsbert et al., 2017; Rudorff et al., 2018). Nevertheless, the large-scale SSC value and its variation are fundamental and important for large fluvial systems, and the SSC-related dynamic processes and interactions among the mainstream, tributaries, subsidiary lakes, etc., yet remain unclear.

For a river system undergoing a sediment decrease, self-adjustment of the sediment regime is activated through water and sediment exchange with tributaries and subsidiary lakes and sediment recruitment from bed/bank erosion, i.e., SSC recovery downstream of dams (Williams & Gordon, 1984; Xia et al., 2016). Both regression- and physics-based methods have disadvantages in modeling sediment transport. The former, as an empirical method based on historical data, usually presumes that the river self-adjustment capacity is constant (Griffiths & Topping, 2017; Hassan et al., 2010; S. L.Yang et al., 2014), but this is not always true for the long-term SSC variations in large rivers. Particularly in heavily modified systems, such as river reaches downstream of a large dam, empirical approaches are usually not effective, because boundary conditions usually have significant changes over time. Regarding the latter method, although it is attractive to establish a fine-grid numerical model, which potentially account for the physics of processes under adjusting conditions, to predict the detailed SSC and sediment transport. However, it is difficult to set up in practice and may be over-parameterized, and reliable prediction is hard to achieve for large-scale and long-term modeling, due to the complexity of the turbulent flow, sediment movement and bed material distributions (Dey, 2014; Le et al., 2019; Lodhia et al., 2019; Mohan et al., 2019; Wu, 2008). Therefore, a hybrid method, which is capable of coupling the primary characteristics of physics and the conciseness of empirical models, is deemed to be a more effective choice for analyzing the long-term variation in the sediment regime in large dammed rivers.

The Changjiang River (also known as the Yangtze River) is one of the world's largest rivers and has undergone a significant sediment reduction in recent decades, as shown in Figure 1. Its annual discharge is ~900 km^3, ranking fifth in the world (Avijit, 2007). About 450 million people are living in its catchment, and along the mainstream 3 mega cities and 16 large cities are located with a population of more than 134 million (data, 2018). The river provides water, food, transportation, energy and other life necessities for such a large population. In order to obtain a stable material/energy source from the river and ensure the security of riparian residents, a large number of infrastructure projects have been implemented, or planned to be conducted, on this river. To date, more than 50,000 dams have been built in the river basin, and among them, the largest hydropower project in the world, i.e., the Three Gorges Dam (TGD) is located at the end of the mountain reach of the mainstream, which began to operate in 2003 (S. L. Yang et al., 2011; Z. Yang et al., 2006). The dams have regulated the water flow and altered the transport of sediment and nutrients (Hassan et al., 2010; Zhou et al., 2013, 2015), and the river-lake relationships are changing (Mei et al., 2018; Yu et al., 2018). The dam-induced environment and ecosystem disturbances will potentially affect the water security and life quality of the people relying on the river.

Here, we investigate the systematic SSC variation in the mainstream of Changjiang. We reconstruct the SSC distributions along the river based on the latest data set and propose a new hybrid empirical-theoretical modeling framework for estimating the fluvial sediment variations. That model is later used to make various inferences and predictions about the behavior of the fluvial system. Combining the data and models allows us to understand the systematic changes in the sediment regime, quantify the contributions from the mainstream, tributaries and lakes, and predict the changing river-lake relationship in the future.

2. Materials and Methods

2.1. Data Collection and Reconstruction

Large quantities of field data are required to investigate the fluvial sediment regime and its long-term systematic variation, especially for a large river. For the Changjiang fluvial system, we compiled an integrated data set of dam/reservoir parameters and measured water discharge and sediment discharge at 20

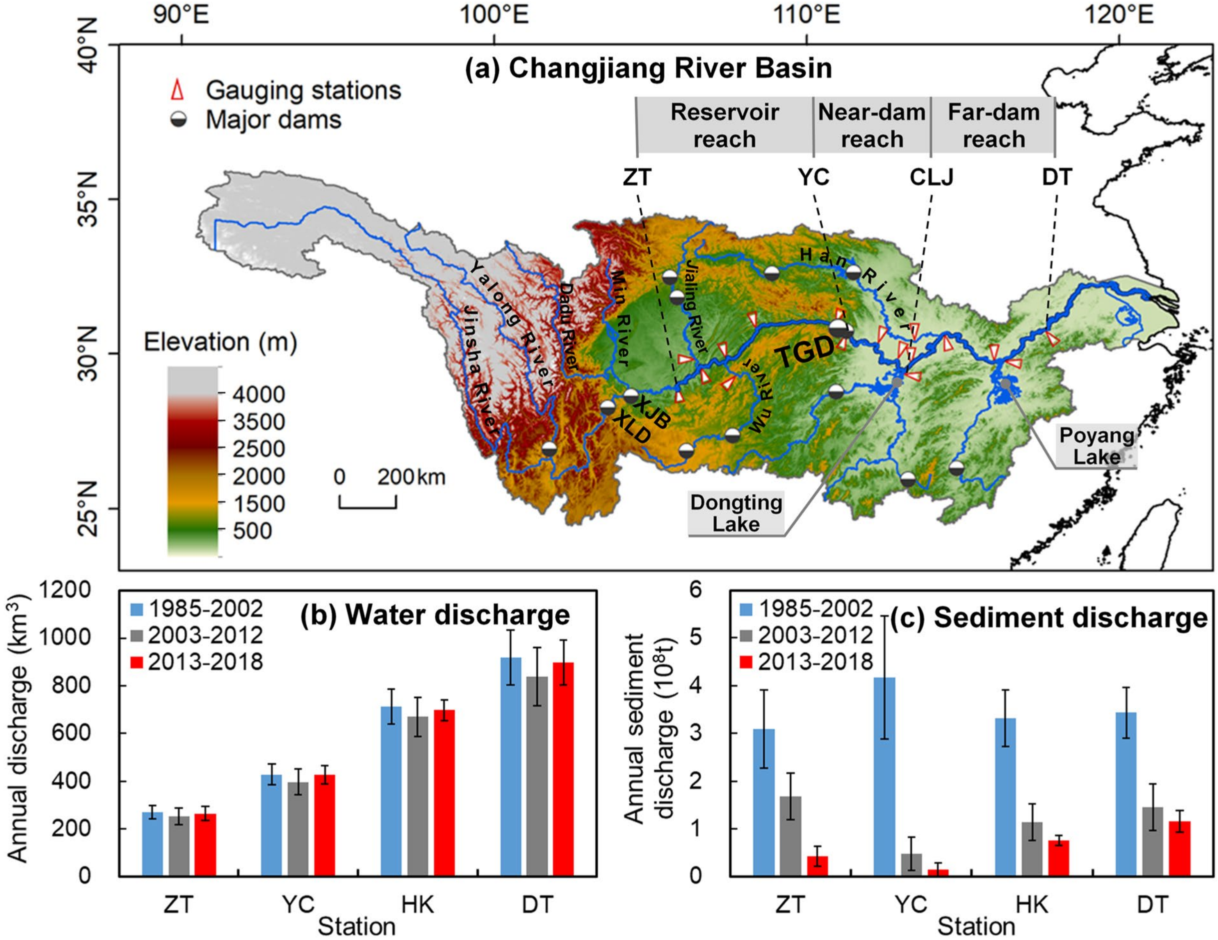

Figure 1. The Changjiang River Basin with gauging stations (a), annual water discharge (b), and annual sediment discharge (c) at four major hydrological stations, namely Zhutuo (ZT), Yichang (YC), Hankou (HK) and Datong (DT). The tributaries, lakes and hydrological stations in this study are labeled in panel (a), as well as three main dams including the Three Gorges Dam (TGD), the Xiangjiaba (XJB) and the Xiluodu (XLD). In panels (b and c), the error bars indicate twice the standard deviation of the water and sediment discharges, respectively, and the three periods represent the pre-TGD period (1985–2002), post-TGD period I (2003–2012) and post-TGD period II (2013–2018). The post-TGD periods I and II are divided by the impoundments of the upstream large dams of XJB and Xiluodu XLD. The water and sediment discharges at ZT station represent the accumulated values from the upstream rivers; the Jialing and Wu Rivers are two tributary rivers upstream of the TGD, whereas the Han River, Dongting Lake and Poyang Lake are located downstream of the TGD. The mainstream from the ZT station to the tidal limit station (DT) is divided by the TGD (represented by the YC station) and Dongting Lake confluence (represented by the Chenglingji (CLJ) station) into three sub-reaches: the ZT-YC reach (the mountain reach covering the Three Gorges Reservoir, TGR), the YC-CLJ reach (i.e., the near-dam reach) and the CLJ-DT reach (i.e., the far-dam reach). Detailed information on the dams and stations are provided in Tables S1 and S2 in Supporting Information S1, respectively.

hydrological stations, covering both the mainstream and tributaries/lakes, as summarized in Table S2 in Supporting Information S1. The water and sediment data were collected by the Changjiang Water Resources Commission (CWRC) during the period from 1985 to 2018, because the monitoring network did not cover the major tributaries and lakes before the mid-1980s. The data after 2001 are available in the published Changjiang Sediment Bulletin (CWRC, 2000–2018). With this data set, we reconstructed the annual SSC distributions along the Changjiang by interpolation and considered discontinuity due to the tributary/lake confluences. In the longitudinal distributions, sediment and water discharge conservation is fully maintained. The details of reconstruction of annual SSC distributions are shown in Supplementary Information. Systematic changes in the sediment concentration can be holistically revealed through the reconstructed SSC distributions.

2.2. Modeling Framework for SSC in Dammed River

To analyze and predict the SSC distributions in dammed rivers, we propose a new modeling framework, which consists of three types of models to address (a) sediment trapping in reservoirs, (b) near-dam downstream sediment recovery and (c) far-dam SSC changes. The systematic SSC changes in dammed rivers are the combined result of these dynamic processes.

2.2.1. Trap Efficiency Model

The SSC reduction in reservoirs is modeled by applying the concept of the trap efficiency (TE), which is defined as the percentage of trapped sediment to the total sediment inflow (Brune, 1953; S. L. Yang et al., 2014). The TE attenuates over time with the reservoir storage being reduced due to sediment deposition. The outflow SSC from a dam (S_{dam}) can be calculated by the total sediment discharge (Q_{s}) flowing into the reservoir, the TE value and the outflow discharge passing through the dam (Q_{dam}), i.e.:

$$S_{\mathrm{dam}} = Q_{\mathrm{s}} \times \left(1 - \mathrm{TE}\right) / Q_{\mathrm{dam}} \tag{1}$$

where TE is estimated based on the ratio of the reservoir storage capacity (C) to its annual water inflow (I), i.e., TE ~ C/I (Brune, 1953; Grill et al., 2019). In this study, a power function characterizes the relationship between TE and C/I in the TGR (S. L. Yang et al., 2014). The capacity C varies over time due to sediment trapping, which is updated through the known TE and I values at the previous calculation step in the model.

2.2.2. Hybrid Model

The reaches downstream of a dam are divided into two categories, i.e., near- and far-dam reaches, according to the geographical feature and sediment transport dynamics (Hassan et al., 2010; Mei et al., 2018; Yu et al., 2018). The near-dam reach is defined as the YC-CLJ reach, while the far-dam reach is CLJ-DT reach, as shown in Figure 1. In the near-dam reach, a low SSC can be partially recovered through bed/bank erosion along the channel, while the erodibility gradually decreases over time due to erosion development and coarsening (Lai et al., 2017). Here, we propose a new hybrid empirical-theoretical model for the SSC distribution and variation in near-dam reaches based on the longitudinal SSC recovery process (Chien, 1985; Lai et al., 2017; Williams & Gordon, 1984) and the non-equilibrium sediment transport concept (Han et al., 2015). Along a near-dam reach, the SSC (S_x) increases from a low level of S_{dam} to a characteristic SSC value (S_∞) at a longitudinal recovery rate (k), defined as follows:

$$S_x = S_\infty + \left(S_{\mathrm{dam}} - S_\infty\right) \cdot \mathrm{e}^{-k \cdot x} \tag{2}$$

where x is the distance downstream of the dam, parameter S_∞ is defined as the saturated SSC under no-erosion condition, and it depends closely on the water discharge (Q). The value of S_∞ is calculated by using the following equation:

$$S_\infty = S_\infty^{\mathrm{m}} \left(Q / Q^{\mathrm{m}}\right)^\gamma \tag{3}$$

where S_∞^{m} and Q^{m} are measured SSC and discharge in the post- TGD period, before the reach is notably eroded, and γ is a coefficient. According to a joint analysis of various suspended sediment transport equations (Zhang et al., 2007) and hydraulic geometry relationships (Qian et al., 1987; Singh et al., 2003), the value of γ is found to range from 0.6 to 1.8 under general conditions, with 1.1 being used in this study through trial and error. The details of the joint analysis are shown in Supporting Information.

The longitudinal SSC recovery rate k is a time-dependent variable that reflects the SSC recovery capacity within a near-dam reach. Here, we propose a relationship between k and the post-dam cumulative sediment erosion quantity (E_{s}) in the near-dam reach, i.e.:

$$k \sim E_{\mathrm{s}} \tag{4}$$

that can be used to represent the cause and effect of near-dam erosion and to forecast the k value. Historical data are used to calculate the k and E_{s} values for the post-TGD period, i.e., from 2004 to 2016 (data from 2017 to 2018 are incomplete for the near-dam reach). The k value is determined using Equations 2 and 3, and the E_{s} value is computed through the local sediment budget. Through regression analysis, it is found that an exponential function performs well for the near-TGD reach in Changjiang, i.e.:

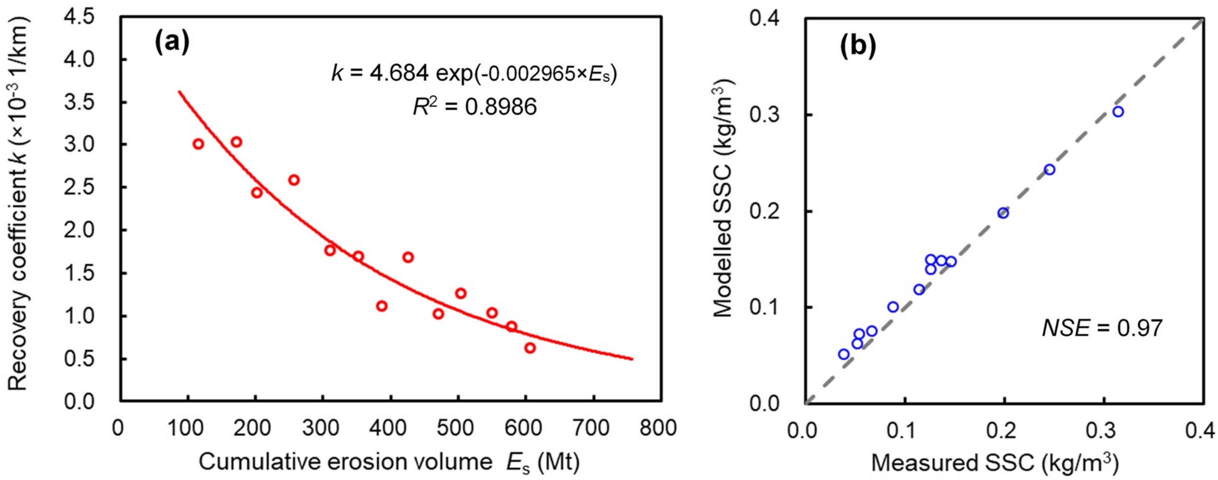

Figure 2. Exponential regression relationship between the longitudinal recovery rate (k) and cumulative sediment erosion amount (E_s) for the near-TGD reach (a), and comparison between the modeled and measured SSCs for verification (b).

$$k = 4.684 \times e^{-0.002965 E_s} \tag{5}$$

with $R^2 = 0.8986$ (as shown in Figure 2a, where k is in 1/km and E_s is in Mt). The best-fit curve reveals an exponential relationship of $k \sim E_s$, indicating that the SSC recovery capacity gradually decreases with the sediment erosion amount accumulated over time in the near-dam reach.

Therefore, the SSC along the near-dam reach (YC-CLJ reach) can be specifically modeled as:

$$S_x = S_{\text{dam}} + \left(0.356 \times \left(\frac{Q}{Q^m}\right)^{1.1} - S_{\text{dam}}\right)\left(1 - e^{-kx}\right) \tag{6}$$

In Figure 2b, the hybrid model-predicted SSCs are compared with the measured values at an independent gauging station, i.e., Shashi (SS) station. The SS station is located in the middle of the near-dam reach, ~204 km downstream from the TGD. The data series at the verification station were measured during the post-TGD period from 2004 to 2016 with values ranging from 0.05 to 0.3 kg/m^3. It can be seen that a high Nash-Sutcliffe model efficiency coefficient (*NSE*) of 0.97 is obtained, which indicates a good performance of the model (Nash & Sutcliffe, 1970).

2.2.3. Regression-Based Model

Regarding the far-dam reach, the degree of erodibility would not be notably influenced by the dam, mainly due to the long distance from the dam. Therefore, it is appropriate to model the longitudinal varying SSC process by using a regression-based approach against field measurements. Both linear and nonlinear functions were applied to build the relationship between the inflow SSC (S_{in}) and outflow SSC (S_{out}) for a river reach, i.e., $S_{\text{out}} \sim S_{\text{in}}$ (Hassan et al., 2010; S. L. Yang et al., 2014; Z. Yang et al., 2006). Here, a long-distance river reach can be divided into successive sub-reaches bounded by nodes, such as tributary/lake confluences. The data are generally available in 1985–2002 for the pre-TGD period and in 2004–2018 for the post-TGD period, except for some missing data in certain reaches. Therefore, there are up to 18 data points for the pre-TGD period, 15 data points for the post-TGD period, but the real numbers could be less than those due to the missing data. In the present study on the Changjiang River, regression-based linear models have been built as Equations 7–9 (Figure 3):

$$S_{out} = 0.8266 S_{in} + 0.0216 \left(\text{CLJ - HK reach}\right) \tag{7}$$

$$S_{out} = 0.8611 S_{in} + 0.0035 \left(\text{HK - JJ reach}\right) \tag{8}$$

$$S_{out} = 0.9416 S_{in} + 0.0428 \left(\text{JJ - DT reach}\right) \tag{9}$$

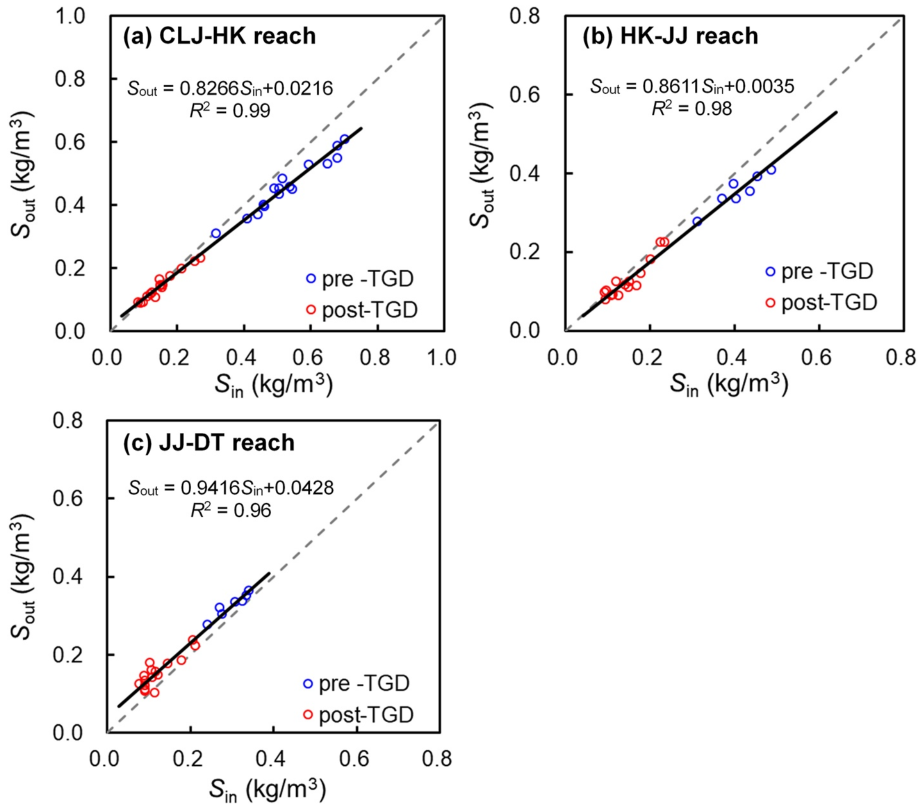

Figure 3. Regression relationships between the inflow SSC (S_{in}) and outflow SSC (S_{out}) for the far-TGD sub-reaches. The long-distance far-TGD reach is divided into three successive sub-reaches bounded by the confluence nodes of the Han River and Poyang Lake, i.e., the CLJ-HK (a), HK-JJ (b) and JJ-DT reaches (c). These relationships are obtained from measured data covering both the pre- and post-TGD periods, represented by the blue and red circles, respectively.

where S_{in} denotes the integrated SSC value representing all sediment sources to the reach, including the tributary/lake confluences, whereas S_{out} is the SSC value at the outflow gauging station. For these three far-dam sub-reaches, the R^2 values of 0.99, 0.98, and 0.96 indicate the reliability of the regression-based model for the SSC.

The proposed modeling framework is then applied to the Changjiang fluvial system to analyze and predict its systematic sediment changes, including the decrease in SSC recovery ability and the changing relationships between the mainstream and subsidiary lakes. At each boundary (the uppermost station and lake/tributary confluences), the measured SSC and discharge have been recorded over the past decades. In determining the model predictions, a set of boundary values is adopted according to recent field data and the dam construction plan for the Changjiang River Basin. The measurement data has shown that the river discharge, which is dominated by precipitation, do not have a significant change, whereas sediment load reduction is mainly impacted by dams built in the catchment (Yan et al., 2021). Upstream of the TGR, two large reservoirs (XJB and XLD, as shown in Figure 1) began to operate in 2012 and 2013, which is the main reason for the sediment reduction of the incoming flow in recent years. However, for the future long-term dam construction plan, it is certain that no additional large dam will be built between the TGR and the upstream reservoir (XJB) due to the lack of suitable sites. Therefore, at the upstream boundary station (ZT), the average values between 2013 and 2018 are used to define its boundary conditions. For the main confluences of the three tributaries (the Jialing, Wu and Han Rivers) and two lakes (Dongting and Poyang Lakes), the contemporaneous SSC and discharge data are used to set up their boundary conditions.

2.3. Quantifying Tributary/Lake Contributors

Based on the reconstructed SSC in Changjiang, we quantify the contributions from the tributaries and lakes to the mainstream by calculating the confluence-induced SSC increments, ΔS_t and ΔS_l, respectively (the subscript t stands for the tributaries, and l represents the lakes). Along the mainstream, the SSC also changes due to sediment deposition or erosion from the bed, banks, floodplains, and other local sediment supplies. Therefore, the contribution of a mainstream sub-reach is defined as the longitudinal concentration increment, ΔS_r, analogous to the contributions from tributaries and lakes. According to the above definition, the following conservation equation holds for the river system:

$$\Delta S_{\text{tot}} = \sum_t \Delta S_t + \sum_l \Delta S_l + \sum_r \Delta S_r \tag{10}$$

where ΔS_{tot} is the total sediment concentration increment in the mainstream.

To express the relative importance of each tributary, lake or mainstream sub-reach, we define a dimensionless metric of the contribution rate d_i as the ratio of the SSC increment ΔS_i to a characteristic concentration S_i^*:

$$d_i = \frac{\Delta S_i}{S_i^*} \times 100\% \tag{11}$$

where the index i stands for the sediment source, i.e., a tributary (t), a lake (l), or a mainstream sub-reach (r). The value of S_i^* is quantified as the maximum SSC within the neighborhood of the i contributor. Taking a tributary confluence as an example, when $\Delta S_t > 0$, the downstream SSC of the confluence is used, and when $\Delta S_t < 0$, the upstream value is adopted.

In this study, there are three tributaries (t = JLR, WR, or HR) and two lakes (l = DTL or PYL), as shown in Figure 1. A positive contribution, i.e., $\Delta S_t > 0$ or $\Delta S_l > 0$, represents an increase in the mainstream SSC due to the tributary/lake confluence with a higher SSC, whereas a negative contribution represents an SSC decrease. In the mainstream, there are three sub-reaches (r = ZT-YC, YC-CLJ or CLJ-DT).

3. Results

3.1. Multistage SSC Reduction and Distribution

Reconstructed SSC distributions (Figure 4) enable us to investigate holistically the sediment regime and multistage variations in the Changjiang fluvial system before and after the Three Gorges Reservoir (TGR) began to impound in 2003. Both the SSC values and longitudinal pattern have changed substantially in the past decades (S. L. Yang et al., 2011), and the sediment regime has undergone three stages, namely: (a) the pre-TGD period (1985–2002), (b) the post-TGD period I (2003–2012), and (c) the post-TGD period II (2013–2018, after additional impoundment of the upstream dams of Xiangjiaba (XJB) and Xiluodu (XLD) with more details being provided in Table S1 in Supporting Information S1). During the pre-TGD period, there was a decreasing SSC trend along the whole river. Upstream of Dongting Lake, the mean SSC was high and decreased slightly from ~1.1 kg/m^3 (ZT station) to ~0.9 kg/m^3 (JL station), while downstream of the lake, it ranged from 0.3 to 0.5 kg/m^3, i.e., a moderate level. In particular, a remarkable SSC decrease of ~0.4 kg/m^3 occurred at the confluence of Dongting Lake due to dilution.

After the TGD began operation, the longitudinal SSC changed remarkably from a decreasing trend to a non-monotonic trend, as shown in Figure 4. Near the dam, the SSC reduced substantially to a much lower level of ~0.15 kg/m^3 in the post-TGD period I. Moreover, an extremely low SSC level of ~0.01 kg/m^3 occasionally occurred during the post-TGD period II. This significant decline in the SSC was caused by both the sediment trapping effect of the TGR and the incoming sediment reduction due to the upstream cascade reservoirs and soil conservation projects (Guo et al., 2019; H. F. Yang et al., 2018; Z. Yang et al., 2006). At ZT station (the main inflow station of the TGR), the SSC dropped to ~0.65 kg/m^3 during the post-TGD period I and reduced further to ~0.15 kg/m^3 during the post-TGD period II, which was mainly caused by the operation of the two large reservoirs, XLD and XJB, in the upstream reach. The representative SSC distributions (bold lines in Figure 4) for the three stages show that the suspended sediment regime has substantially changed with the SSC decreasing typically by an order of magnitude.

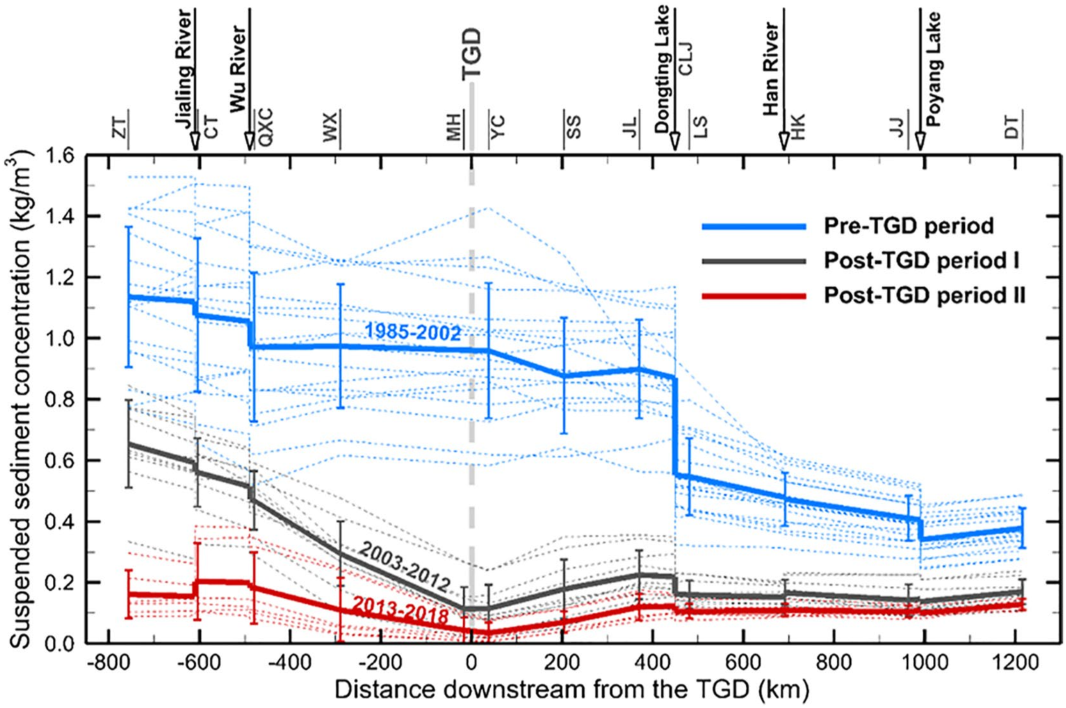

Figure 4. Longitudinal SSC distributions in Changjiang indicate a multistage SSC reduction over recent decades. The annual SSC distributions (dashed lines) are categorized into three stages, colored in blue, gray and red for the pre-TGD period, post-TGD period I and post-TGD period II, respectively, which are driven by the combined effects of upstream sediment influx reduction, reservoir sediment trapping, downstream SSC recovery, tributary/lake confluences, etc. Solid lines are multi-year average SSC values in each stage, and error bars on the lines indicate twice the standard deviation of the SSC. The hydrological stations (ZT to DT) and the tributaries (rivers and lakes) are shown along the top horizontal axis. The full names of gauging stations are provided in Table S2 in Supporting Information S1 with more detailed information.

In the near-dam reach from the TGD to the JL station, as shown in Figure 4, the SSC was partially recovered because of the sediment supply from riverbed/bank erosion (Xia et al., 2016). Further downstream from the confluence of Dongting Lake, the SSC recovery became marginal. During the post-TGD period II, the recovered SSC at JL station was just ~0.1 kg/m^3, which was at the same level as that of the outflow from Dongting Lake. Therefore, the sediment dilution effect of the lake on the mainstream tended to disappear due to the reduced sediment supply from the upstream reach.

To date, The SSC has decreased by an order of magnitude, from a general level of ~1.0 kg/m^3 before the operation of the TGR (1985–2002) to ~0.1 kg/m^3 after the operation of XJB and XLD (2013–2018). In certain years (2015 and 2017), the SSC in near-dam reach was even lower than 0.01 kg/m^3. The spatial distribution of SSC along the mainstream of the Changjiang exhibited a gradually decreasing trend from the mountain area to the plain area before the operation of the TGR, and then transformed into a V-shaped distribution pattern with the site of TGD located at the V-valley. Since 2014, the SSC into the Changjiang Estuary (DT station) was generally higher than the SSC in the mountain area (ZT station).

3.2. Systematic SSC Variations and Contributors

The suspended sediment regime in the mainstream and tributaries has notably changed, with the SSC being reduced due to human activities (Figures 5a–5d), while the SSC values from the two large lakes were maintained at the original levels despite the dams being built in their upper catchment (Figures 5e and 5f). From the mid-1980s to the early 1990s, the SSC in the upstream reach (gauged at ZT station) and the Jialing River was high at 0.8–1.5 kg/m^3 (Figures 5a and 5b), while the Wu and Han Rivers had a moderate SSC of ~0.5 kg/m^3 (Figures 5c and 5d).

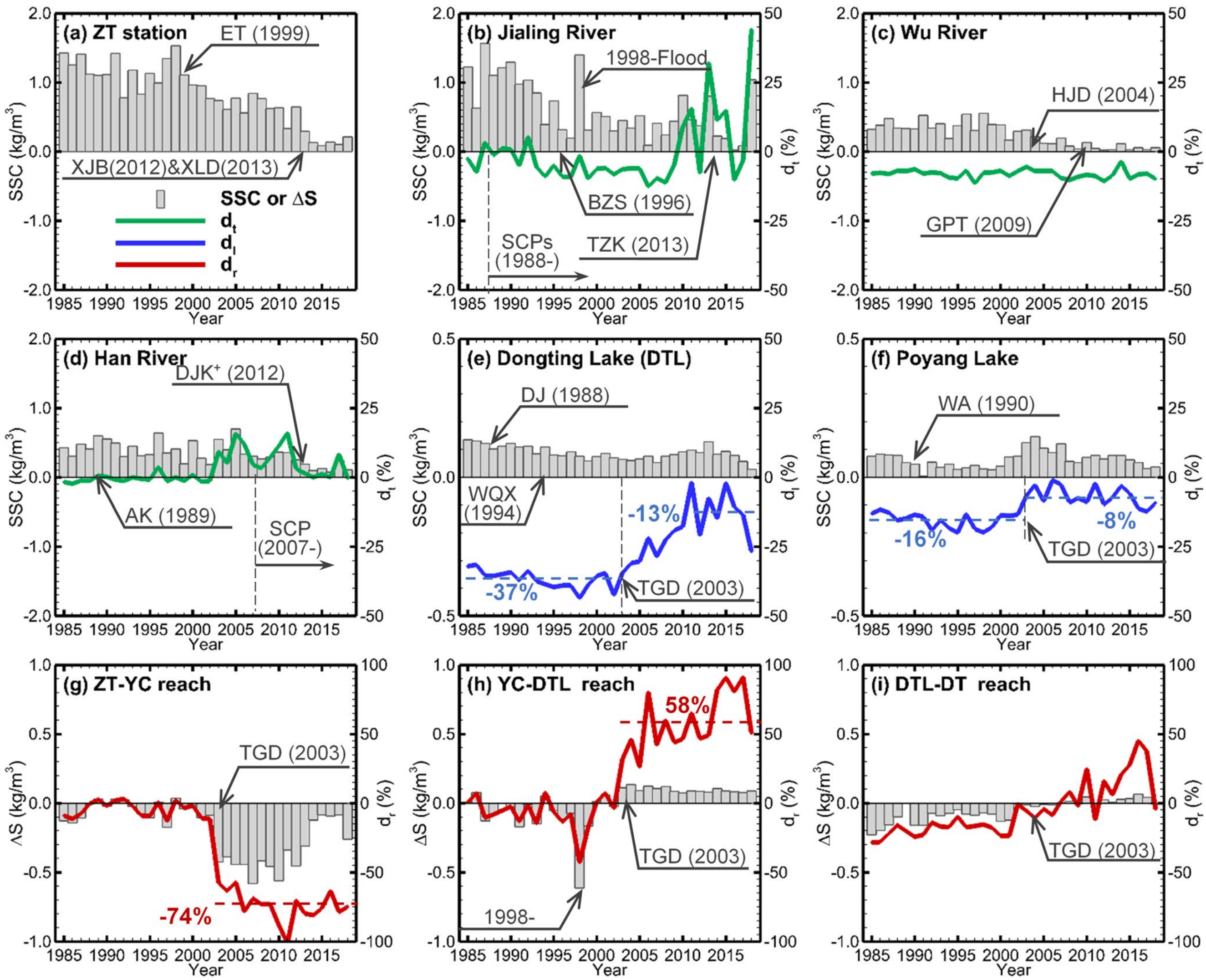

Figure 5. Contributions from the tributaries, lakes and mainstream reaches to the SSC in Changjiang. The colored lines represent the contribution rates of the tributaries (d_t in panels (b–d)), lakes (d_l in panels (e–f)), and the mainstream reaches (d_r in panels (g–i)), and the gray bars represent the corresponding SSC values at the upstream ZT station (panel a) and tributaries (panels (b–f)) and the SSC increment/decrement along the mainstream sub-reaches (panels (g–i)). The SSC at ZT station represents the accumulated sediment from the upstream rivers; the Jialing and Wu Rivers are two tributary rivers upstream of the TGD, while the Han River, Dongting Lake and Poyang Lake are downstream of the TGD. The three mainstream sub-reaches (ZT-YC, YC-CLJ and CLJ-DT) in panels (g–i) are shown in Figure 1. The main human activities and hydrologic events are labeled over time, including large dams (TGD, XJB, XLD, ET, BZS, TZK, HJD, GPT, DJ, WQX, AK, DJK⁺, and WA), large-scale soil conservation programmes (SCPs), and the severe flood event in 1998. The full names of dams and stations are provided in Tables S1 and S2 in Supporting Information S1.

After the mid-1990s, the effect of intense human activities on suspended sediment reduction gradually emerged. With large dams/reservoirs (ET, XJB, and XLD with capacities of 5.79, 5.16, and 12.67 km^3, respectively, as shown in Figure 5a, and all full names are provided in Tables S1 and S2 in Supporting Information S1) being successively built in the upstream reaches, the SSC at ZT station decreased significantly. For the Jialing River (Figure 5b), large-scale soil conservation programmes (SCPs, area >30,000 km^2) and dam construction (BZS and TZK) in the catchment have caused a substantial SSC reduction, from ~1.2 kg/m^3 (before 1988) to ~0.4 kg/m^3 (after the late 1990s). One exception is the abrupt SSC increase during the severe flood event in 1998 (Xu et al., 2005). For the other two main tributaries, the Wu and Han Rivers (Figures 5c and 5d), similar sediment reduction trends can be seen. In contrast, the SSC did not noticeably change for Poyang and Dongting Lakes (Figures 5e and 5f) with the value remaining at a low level of ~0.1 kg/m^3, even after the operation of the large dams (DJ, WQX and WA) in the upstream catchments.

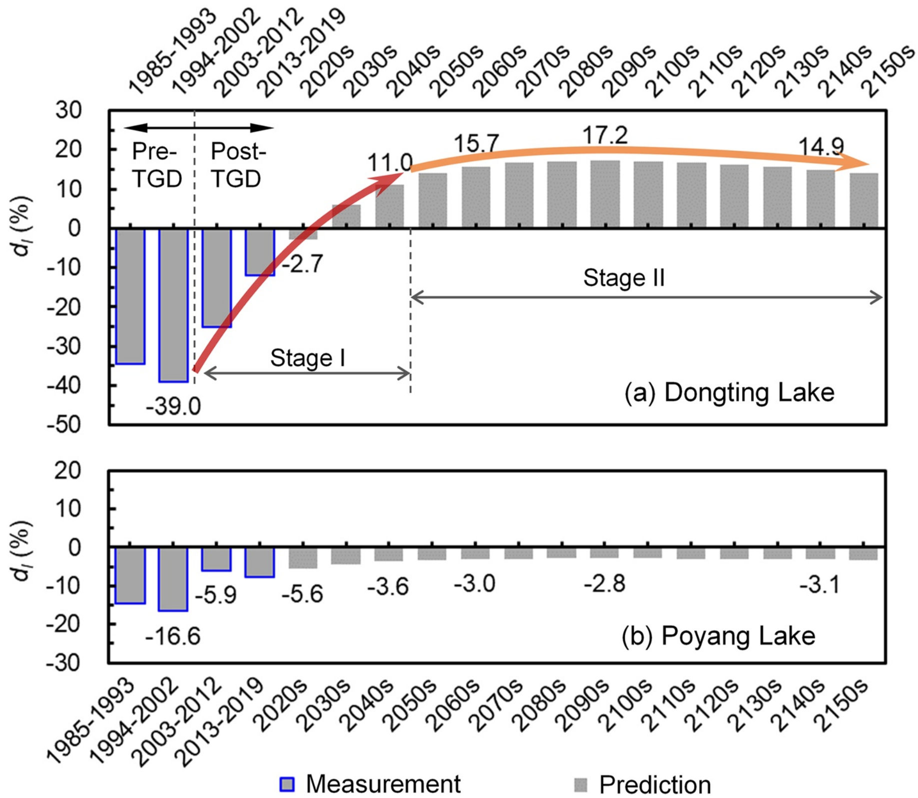

Figure 6. Past and future SSC contribution rates of (a) Dongting Lake and (b) Poyang Lake to Changjiang.

The SSC contributions from the tributaries, lakes and mainstream sub-reaches have changed against the background of sediment source decline, especially after the TGR impoundment. The contribution rates (d_l) of Dongting Lake (Figure 5e) significantly increased from −37% (strong dilution, before 2003) to −13% (weak dilution, after 2010). Weak dilution can also be identified in Poyang Lake, with d_l changing from −16% to −8% (Figure 5e). Regarding the ZT-YC reach (the mountain reach covering the TGR), reservoir trapping resulted in a significant SSC reduction, and the contribution rate of the mainstream reach d_r greatly decreased from nearly zero to −74% (Figure 5g). In the near-dam reach downstream of the TGD (the YC-CLJ reach, as shown in Figure 5h), the negative d_r value represents deposition before the TGD was built in 2003. For example, during the 1998 flood event, the sediment carried by the flood from upstream (Figure 5b) was substantially deposited in this near-dam reach, represented by the remarkable negative increment ($\Delta S \approx -0.6$ kg/m^3) and contribution rate ($d_r \approx -40\%$, Figure 5h). After 2003, the near-dam reach d_r value became positive and increased to as high as ∼58%, indicating a marked SSC recovery due to bed/bank erosion. However, the SSC recovery ability has gradually been depleted since 2003. The decreasing SSC has led to an increasing contribution from Dongting Lake, as shown in the increasing trend of d_l in Figure 5e. In the far-dam reach (CLJ-DT; Figure 5i), the SSC increment changed from negative to positive. Therefore, the mainstream reaches and subsidiary lakes have played an important role in the sediment regime.

3.3. Varying River-Lake Sediment Relationship

Figure 6 shows the past and future SSC contribution rates (d_l) of the two major lakes through measurement data and predictions by using the proposed modeling framework. Under the expected sediment boundary conditions, as described in the Materials and Method section, the d_l value of Dongting Lake will change from negative to positive between the 2020s and 2030s (Figure 6a), and it will gradually increase and exceed 10% by the 2040s and reach up to a peak of ∼17% at the end of the century. In the next century, the contribution will decrease, but at a very slow pace. As a result, a high d_l level (∼15%) will persist for decades, which is in strong contrast to the negative contribution (−39%) recorded during the pre-TGD period. Differently, the contribution rates of Poyang Lake will not reverse (Figure 6b), whereas the d_l value is likely to decrease from −16.6% during the pre-TGD period to approximately −3%.

It can be found that, after the TGD was built, there exist two obvious stages for the river-lake sediment relationship. The first stage is the first five decades, when the SSC contribution rate rises rapidly, especially for the Dongting Lake. In the following century, i.e., the second stage, the rate will keep at a relatively stable level, 15%–17% for Dongting Lake and ~3% for the Poyang Lake. These systematic variations are essentially caused by simultaneous key processes: the decreasing sediment recovery capacity downstream of the TGD and the increasing sediment escape ability through the reservoir. In the first stage, although the near-dam reach can provide sediment to recover SSC partially, the recovery capacity decreases gradually. This caused a decrease in the mainstream SSC, and increase SSC contribution rates from subsidiary lakes. At the same time, the reservoir siltation can enhance the sediment escape rate through the dam, leading to an increase in sediment supply. The two processes are simulated through the proposed hybrid model and the TE model, respectively. The rapid variation of SSC contribution rate in the first stage has been partially reflected through measurement, and the predicted key trends, such as the negative/positive reversal, would be largely expectable. In the second stage, the change of the contribution rates will slow down, indicating a relative equilibrium between the sediment escape ability in the reservoir and the downstream recovery capacity. It should be noticed that the model prediction is based on the presumed boundary conditions as shown in Materials and Methods. Although the boundary conditions are highly expected according to the latest data and current catchment planning, the quantitative results might change to some degree in the future due to other unpredictable factors. One result of this study is to reveal the balance between the reservoir sedimentary and the downstream sediment recovery, which will play an important role in the variation of SSC in mainstream and the river-lake relationship.

4. Discussion

A significant SSC decrease in rivers can have complex implications on the fluvial ecosystem, including both the aquatic environmental factors and biota community. The implications are manifold. Most notably, the sediment reduction can change the distribution and transport of biogenic substances. For example, the phosphorus limitation was found to be aggravated downstream of large dams, such as the TGD, the Aswan High Dam etc., due to the decline in particulate and dissolved phosphorus (Akbarzadeh et al., 2019; Conley et al., 2009; Elser et al., 2007; Krom et al., 2004; Nixon, 2003; Zhou et al., 2015). This can lead to a lower primary productivity in downstream reaches and coasts. However, the photosynthesis can be enhanced by the increase in light penetration, which could promote the growth of algae and macrophytes (Bilotta & Brazier, 2008), especially in turbid waters where gross primary production is highly controlled by the limited light (McSweeney et al., 2017; Vaz et al., 2019; Yamamoto et al., 2019). With regard to aquatic benthic invertebrates, the decreasing suspended sediment could reduce the risk of damage to their exposed respiratory organs (Langer, 1980). Moreover, for many resident freshwater fishes, the SSC decrease was found to have positive impacts on feeding and embryo survival, through increasing the foraging efficiency and facilitating oxygen exchange with the gills (Chapman et al., 2014; Redding et al., 1987; Utne-Palm, 2002).

Although the effects of sediment reduction on the hydrological and morphological processes in the world's major dammed rivers have been studied (Golosov & Walling, 2019; Wang et al., 2016), the ecological impacts due to the decreasing SSC have not been fully known. This may be because previous studies mainly focused on the total sediment flux rather than the concentration of suspended sediment. In the future, river managers and scientists need to be more conscious about the remarkable decrease in SSC which can cause potentially severe ecological problems. The aquatic environment and organism changes could be long-lasting and fundamental because of the long-term SSC variation caused by dam operation. As shown in this study, the adjustment process of suspended sediment would take a hundred years or more, especially for large fluvial systems with large dams.

In a large fluvial system, linked lakes and tributaries could act as buffers for mitigating the impacts of dam operation on the mainstream sediment regime. As shown in the present case of the Changjiang fluvial system, when the riverine SSC level is high, the outflow from lakes can dilute it. In contrast, when it is too low in the river due to human interference, the lakes could provide vital sediment sources to avoid extremely low SSC. After the operation of the TGR, Dongting Lake makes a negative and then positive contribution to the mainstream SSC during the decreasing process and this shift reflects the natural self-adjustment capacity to changes in the suspended sediment regime. Therefore, the widely discussed gate constructions on Dongting and Poyang Lakes should be carefully and thoroughly investigated in order to prevent the potential loss of fluvial connectivity (Best, 2019; Grill et al., 2019; Nilsson et al., 2005). Any possible fragmentation would reduce the above self-adjustment capacity of the fluvial system and increase the possibility of an extremely low SSC, which would likely expose the aquatic ecosystem to extremely clear water. It should be noticed that the positive/negative contributions of lakes to the mainstream SSC in the present study is different from the concept of sediment sink/source for the lakes based on sediment budget in previous studies (Dai et al., 2018; S. L. Yang et al., 2014). Take Poyang Lake as an example, the suspended sediment discharge (SSD) into the lake was larger than out of the lake before 2003, thus the sediment deposited in the lake, i.e., it was a sediment sink. However, after then, the SSD into the lake became smaller than out of the lake, i.e., the lake became a source with net sediment erosion. As a result, Poyang Lake has shifted from being a sediment sink to a sediment source. Nevertheless, the SSC in Poyang Lake has always been less than the SSC in the Changjiang mainstream throughout the study period. Therefore, the lake makes a negative contribution to the mainstream's SSC during both the pre- and post-TGD periods. Therefore, it is revealed from this study that the SSC indicates a distinguishing aspect of the river-lake relationship, which is very different from the SSD-based sediment budget. Therefore, the SSC should be paid more attention to the worldwide rivers. What is more, the inherent self-adjustment ability of the SSC varies in different river systems, which mainly depends on the capacity of tributaries or subsidiary lakes and the mainstream length downstream of the dam (Pique et al., 2017). Thus for other dammed large rivers, the unique properties of their tributary networks should be adequately considered for river management.

The proposed modeling framework has been proved capable of reproducing and forecasting the suspended sediment dynamic processes, and this may be a vital solution to analyze and predict the future variation of the riverine SSC. In this modeling framework, empirical analyses are coupled with an understanding of the sediment transfer to build a “data-driven” model of large-scale sediment transfer through the fluvial system. The hybrid model seeks to establish how the transfer of sediment is modulated by local, yet significant, exchange with the major fluvial units, i.e., major reservoirs, tributaries and lakes. This is an important aspect for the fluvial system (Mei et al., 2018; Yu et al., 2018), not least because these sediment exchanges exert a fundamental control on the habits and morphodynamics of river and lake segments, and the scale of these fluvial units is so large that the impacts of such changes can be significant societally. The results and conclusions derived from the modeling framework in this study can provide insights into damming impacts for other fluvial systems, and offer guidelines for sustainable river management and policy making from a systematic and long-term point of view. For instance, plans or concepts of constructing super reservoirs on the Congo River and the Amazon River have been reported (Green et al., 2015; Tundisi et al., 2014), and the output of our study could be a useful reference for their potential SSC regime changes subject to the construction of those dams.

5. Conclusion

In this study, we summarize systematic SSC changes and propose a new sediment modeling framework for heavily dammed fluvial systems with the Changjiang as a background. We find that the SSC value has decreased by an order of magnitude in the recent three decades, from ∼1.0 to ∼0.1 kg/m^3, and even to ∼0.01 kg/m^3 locally. The SSC distribution has changed dramatically from a longitudinal decreasing trend to a non-monotonic pattern with the sediment source/sink being partially reversed. In the near-dam reach, the SSC recovery capacity gradually decreases with the sediment erosion quantity accumulated over time, which will lead to a further decline in the downstream SSC. Under reservoir operation, the river-lake relationship in the fluvial system will change considerably, i.e., the SSC contribution percentage from a large lake downstream (Dongting) will change from negative (ca. −39%) to positive (ca. 17%) in the coming decades.

These findings can improve our understanding of the changing sediment regime in dammed large river systems and provide insight into aquatic eco-system evolution under human interference. The proposed modeling framework can be a useful reference for other dammed rivers and offer guidelines for the river research community and policy makers.

Data Availability Statement

The water and sediment data used in this research are collected by the CWRC (http://www.cjw.gov.cn/zwzc/bmgb/).

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