Quantifying sediment storage on the floodplains outside levees along the lower Yellow River during the years 1580–1849

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ABSTRACT: The lower Yellow River channel was maintained by artificial levees between 1580 and 1849. During this period, 280 levee breaches occurred. To estimate sediment storage on the floodplains outside the levees, a regression model with a decadal time step was developed to calculate the outflow ratio for the years when levee breaching occurred. Uncertainty analysis was used to identify the likely outflow ratio. Key variables of the model include annual water discharge, a proxy for levee conditions, and potential bankfull discharge of the channel before flood season. Uncertainty analysis reveals an outflow ratio of 0.35–0.56. We estimate that during this period, 18.8–30.1% of the total ~312 Gt of sediment load was deposited on the floodplains outside the levees. Human-accelerated erosion in the Loess Plateau caused a 4-fold increase in sediment delivery to the lower Yellow River, which could not be accommodated by channel morphodynamic changes. As a result, 21.2–27.5% of the total sediment load was deposited within the levees, creating a super-elevated channel bed that facilitated an unusually high breach outflow ratio. Hence, the factor of a large super-elevation relative to the mean main channel depth should be considered when designing diversions to restore floodplains. © 2018 John Wiley & Sons, Ltd.

KEYWORDS: Sediment budget; Yellow River; Levee breaches; Floodplain sedimentation; Bankfull discharge

Introduction

Rivers are sediment transport features in the landscape that run from a source to the coastal ocean (Allen, 2008; Bracken et al., 2015). In alluvial rivers, a significant fraction of the sediment eroded within a drainage basin is deposited within its channel belts, floodplains or wetlands, often outside the levees, rather than being delivered to an ocean (Walling, 1983; Milliman and Syvitski, 1992; Allison et al., 1998; Dunne et al., 1998; Goodbred and Kuehl, 1999). Since pre-industrial times, through changing land use and levee construction, humans have unintentionally affected sediment fluxes through river systems, resulting in substantial modifications to the geomorphic evolution of rivers, floodplains and receiving coastal zones (Wolman, 1967; Kesel, 1988; Gregory, 2006; Walling, 2006; Syvitski and Kettner, 2011; Pietsch et al., 2015; Bergillos et al., 2016; Levin et al., 2017). By managing intentional levee breaks or engineered diversion structures, modern societies are purposefully affecting sediment fluxes through river systems for the sake of building land or restoring floodplain ecosystems (Florsheim and Mount, 2002; Wang et al., 2003; Florsheim and Dettinger, 2015; Kesel and McGraw, 2015; Ollero et al., 2015).

The Rhine Delta was an efficient sediment trap before an embankment was constructed between 1100 and 1300 AD. As of today, 94.4% of the total floodplain area has been cut off by levees from overbank sedimentation. As a result, only ~13% of the sediment delivered to the delta can be trapped by the embanked floodplains (Middelkoop et al., 2010). On the lower Mississippi River, since 1927, little sediment has been stored in the floodplains outside the levees, as the levee system was upgraded to prevent overbank flooding and crevassing (Kesel et al., 1992; Kesel, 2003). Notable coastal wetland losses have subsequently occurred over the last century (Kesel, 1989; Day et al., 2007). To rebuild these wetlands, diversion structures are being used to deliver sediment and freshwater to the surrounding wetland areas (Kesel and McGraw, 2015; Meselhe et al., 2016; Esposito et al., 2017).

The lower Yellow River is an ideal area for studying the impacts of human activities, particularly the impact of embankments, on floodplain sedimentation processes. The Yellow River is a large river system in terms of sediment loads and the area of its alluvial plain. In the early 20th century, the annual average sediment load of the lower Yellow River reached 1.6 Gt (Ren, 2015). The extensive alluvial plain covers an area of ~250,000 km² (Figure 1). Historically, the lower Yellow River
has shifted its course >30 times, discharging into either the Bohai Sea or Yellow Sea; its levees were breached >1000 times and large volumes of sediment were distributed and deposited on the alluvial plain.

Ninety percent of the sediment supplied to the lower Yellow River originates from the Loess Plateau, which is located in the middle basin (Figure 1). Over two millennia, human-accelerated erosion in the Loess Plateau has caused an estimated 3- to 10-fold increase in sediment load to the lower river (Milliman et al., 1987; Ren and Zhu, 1994; Chen et al., 2015). Over these two millennia, unparalleled resources have been devoted to preventing floods by placing embankments along the lower river. Management climaxed between 1580 and 1849, when the river channel was secured in the Old Yellow River location by an artificial levee system (Figure 1). Humans persisted in repairing levees and in plugging breaches to prevent the Yellow River from shifting its course (Xu, 1993; Chen et al., 2015).

For the Old Yellow River, sediment accumulated within the artificial levees, eventually forming an elevated channel belt ~10 m higher than its surrounding area (Figure 2). At the same time, large amounts of sediment were bypassing the levees and being deposited on the floodplains as a result of significant and frequent breaches, given the super-elevation of the channel belt and the weakness of the earthen levees (Chen et al., 2015). In 1841, the Yellow River breached its levee close to the city of Kaifeng (Figure 2); the river flowed through this breach for 8 months, depositing a volume of 3 m-thick silt on the floodplains that extended ~8 km beyond the levees.

The breach events on the Old Yellow River were characterized by a high frequency of outflows of unusually high magnitude and long duration (Shen et al., 1935). Studies on human-influenced sediment flux to the floodplains beyond the levees along the lower Yellow River in historical times offer insight for assessing the risks of levee breaches, managing intentional levee breaks and engineering diversion structures on rivers.

After embankment, the sediment input to the lower Yellow River from the upper and middle basins could be trapped by three depositional features: 1) the channel belt and floodplains within the artificial levees, 2) the floodplains outside the levees, and 3) the river delta and its associated basin. Ren (2015) estimated that between 1550 and 1855, the annual sediment load for the lower Yellow River was 1.1 Gt, of which 12%, 34% and 54%, respectively, were distributed across the abovementioned depositional features. Ye et al. (1983) estimated that from 1494 to 1855, the annual sediment load of the lower Yellow River was 1.3 Gt, of which 44% was sequestrated on the first two mentioned depositional features and 56% delivered to the river delta and beyond. These sediment budgets are based on analyses of geomorphological maps of alluvial fans, limited stratigraphic cross sections, sparse core data, comparisons with modern conditions, and expert opinions (Ye et al., 1983; Ren, 2015).

The unconfined and super-elevated lower Yellow River has extensive floodplains (Figures 1 and 2); thus, it is expensive and time-consuming to collect a large amount of stratigraphic data to quantify spatial heterogeneities in floodplain sedimentation. Here, we construct a multiple regression model that determines the decadal-averaged probability of levee breaches to predict sediment flux to the floodplains outside the levees for 1580–1849, which is made possible by the detailed historical records available for this period. Further, we determine the uncertainty range for the prediction and construct a sediment budget for the Old Yellow River. Sediment budgets for other historical periods are also investigated to better understand human impacts on sediment fluxes and their geomorphic consequences from 1580 to 1849.
Our model suggests that risks of levee breaches on rivers around the globe can be altered by climate change and human activities in the future, which is addressed in the discussion. We explain why the Old Yellow River, though embanked, still transferred a high ratio of sediment to its floodplains beyond the levees and the implication for managing self-sustainable diversions.

**Study Area**

**Channel Conditions**

In 1128, an artificial avulsion allowed the lower Yellow River to capture the Huai River, and for the following 700 years, the Yellow River drained south-eastwards into the Yellow Sea (Xu, 1989). From 1128 to 1577, due to a laissez-faire attitude towards levee breaches, the main course of the Yellow River shifted among tributaries of the Huai River. In 1578–1579, an extensive levee system was constructed along the Bian River, a tributary of the Huai River. As a result, no major avulsions occurred from 1578 to 1855. In 1855, a northward avulsion diverted the Yellow River back to the North China Plain and Bohai Sea (Chen et al., 2012; Figure 1).

The Old Yellow River, or the lower Yellow River from 1578 to 1855, which includes relic super-elevated channel belts and floodplains within levees that can be easily identified from SRTM imagery, was ~800 km long from the alluvial fan apex close to the Huayuankou gauging station to the apex of the subaerial delta close to Yuntiguan (Figure 2). The distance between the opposing levees decreased from ~14 km upstream to <5 km farther downstream as the river’s channel pattern shifted downstream from braided to meandering.

**Water and Sediment Discharges**

The confluence of the Old Yellow River and the main stream of the Huai River was located at Qingkou, which is positioned approximately 120 km upstream from the delta apex (Figure 2). As the channel bed of the Huai River was much lower than that of the Yellow River, a substantial proportion of Huai River
discharge was forced southward to the Changjiang River or Yel-
low Sea; only a small portion of the flow was captured by the
Yellow River at Qingkou (Pietz, 2002; Figure 2). Therefore, dis-
charge from the Old Yellow River mostly originated from the
upper and middle basins of the Yellow River, upstream from
Huayuankou.

The mean annual water discharge of the Old Yellow River
at Huayuankou was slightly larger than that at Sanmenxia,
which was 268 km upstream (Figure 1) and had a long-term
annual water discharge of 52 km³ between 1580 and 1849
(Wang et al., 1999). The mean annual sediment discharge
of the Old Yellow River at Huayuankou was 1.0–1.3 Gt, as
soil erosion in the Loess Plateau was exacerbated by exces-
sive reclamation from 1580 to 1849 (Ye et al., 1983; Shi
et al., 2009; Ren, 2015). The median grain size of suspended
sediments in the lower Yellow River was 0.02 mm (Chien and
Zhou, 1965).

Floods and Landscape Evolution

Long-term sedimentation rates for the channel belt and flood-
plains within the levees are estimated to have been 20–
30 mm yr⁻¹ (Xu, 1998). In the 1850s, before the channel belt
of the Old Yellow River was abandoned, its elevation above
the adjacent floodplain reached >10 m, as measured from the
extracted elevation profiles (Figure 2).

Super-elevated rivers are prone to breach levees. Historical
documents show that from AD 1580–AD 1849, the Old Yellow
River experienced 280 levee breaches (Supporting Material
Table S1). We mapped these levee breach sites onto SRTM
90 m topography images and found that the levee breach sites
are evenly distributed along the Old Yellow River (Figure 2).
The breaches diverted impressive and long-lasting flows from
the main channel. From 1580 to 1849, at least 34 major
breaches resulted in the drying-up of the Yellow River down-
stream and simultaneously in siltation of the channel down-
stream. Most breaches were not repaired until the following
spring or even longer (Shen et al., 1935; Chen et al., 2015), so
that a large amount of water and sediment diverged onto the
floodplains outside the levees.

The active floodplains of the Old Yellow River have a total
area of ~136,000 km² and can extend 100–200 km from the le-
vees (Figure 2). Stratigraphic data show that the thickness of
flood deposits on crevasse splays varies from 1 to 15 m (Chen,
The dry bulk density of flood deposits is 1.24–1.70 g cm⁻³ (Ma
et al., 1997; Shi et al., 2002).

The Hongze Lake did not exist before the Huai River was
captured by the Yellow River in 1128 (Figure 3). The lake de-
veloped as the Huai River was dammed by the super-elevated
channel belt of the Old Yellow River (Ren, 1992). A subaerial
delta started to develop in 1128, and a large amount of sedi-
ment discharge was deposited on the coastal plains to the south
of the delta (Figure 3; Zhang, 1984; Ren, 1992). Only a small
amount of sediment was dispersed into the outer shelf and
ocean (Milliman et al., 1989; Ren, 2015).

From 1580 to 1849, 657 levee maintenance and breach clo-
cure projects were implemented (Shen et al., 1935). In 1855,
the levee system was overwhelmed by a major avulsion event,
and the Yellow River shifted to its present course. Since 1950,
no levee breaches have occurred upstream of the delta apex.

Methods and Data

Procedure for Prediction

To estimate the amount of sediment that was stored on the
floodplains outside the levees from 1580 to 1849, we predict

Figure 3. Historical (AD 943, 1208, 1582 and 1820) changes in the course of the lower Yellow River, in the drainage network of the Huai River, in
lakes in the floodplains and in coastlines shaped by sediments of the Yellow River on the basis of historical maps shown in (Tan, 1982). HYK: Huayuankou, QK: Qingkou, YTG: Yuntiguan; 1: Hongze Lake, 2: Gaojia Dike. Coastlines shown as dotted lines are current coastlines together with the Fanggang Dike built in the 11th century and serve as a frame of reference in terms of coastline changes.
the long-term averaged outflow ratio of breaches for this period ($R_o$), as $S_i$ is calculated by:

$$S_i = R_o \times \frac{Q(i)}{Q_{bf}}$$

(1)

where $I$ is the sediment input to the Old Yellow River at Huayuankou, which is estimated to have been 1.0 to 1.3 Gt yr$^{-1}$ (Ye at el., 1983; Shi et al., 2009). Here, the outflow ratio for sediment discharge approximates that of water discharge, as the sediment concentration in flows through a breach is close to that in river flows assuming that the bottom of the breach reaches the riverbed. This situation is very likely for the breaches of the super-elevated Old Yellow River. Historical documents record a breach erosion depth as large as 23–27 m during this period (Shen et al., 1935). $R_o$ is calculated as follows:

$$R_o = \frac{\sum_{i=1}^{270} Q_o(i)}{\sum_{i=1}^{270} Q(i)}$$

(2)

where $\sum_{i=1}^{270} Q(i)$ is the volume of annual water discharge at Huayuankou from 1580 to 1849. $\sum_{i=1}^{270} Q_o(i)$ is the sum of annual breach outflows for 1580–1849, and $i$ indicates the years from 1580 to 1849. Assuming an annual outflow ratio $r_{oa}$ that is equal for all breach years, $Q_o(i)$ for breach years can be calculated as:

$$Q_o(i) = r_{oa} Q(i)$$

(3)

To estimate $r_{oa}$, we construct a model for the probability of levee breaches on the Yellow River, including $r_{oa}$ as a model parameter. We then apply an automatic calibration that uses an uncertainty analysis to identify its most likely value (Chen et al., 2015). Two additional uncertainty analyses are applied to investigate the full uncertainty range.

Regression Model for the Probability of Levee Breaches

Two key factors affecting the occurrence of a levee breach are 1) the water level above the channel bed (as jointly controlled by the ratio of water discharge to the bankfull discharge of a channel) and 2) the condition of the levees. We formulate a multi-exponential regression model for the decadal average probability of a levee breach on the Old Yellow River from 1580 to 1849 as follows:

$$P = X_1 \left( \frac{Q}{Q_{bf}} \right)^{X_2} L_{v}^{X_3}$$

(4)

All variables are decadal-averaged time-series either reconstructed from historical observations or calculated using empirical equations, as explained in the following section. $P$ is the annual probability of breach occurrence, $Q$ is the annual water discharge at Huayuankou, $L_v$ is a proxy for levee conditions in a given year, and $Q_{bf}$ is bankfull discharge of the channel before the flood season with its magnitude depending on $r_{oa}$ (see below). $X_1$, $X_2$, and $X_3$ are model parameters, which are estimated using a least squares fit model and thus vary with $r_{oa}$.

The data sources used and the construction of variables in Equation (4) are as follows:

$P$ and $L_v$ are based on records from The Chronicle of the Yellow River (Shen et al., 1935). All events noted as “breach” and “avulsion” in the written chronology are counted as breach events. The annual probability of breach occurrence for a given year is calculated by dividing the sum of breach events occurring in a given year by 365. Levee construction, maintenance and repair projects are noted as “construction” in the chronicle. We assume earthen levees during this period had a lifetime of $T$ years, and we take the sum of “construction” projects for the previous $T$ years as a proxy for levee conditions in a given year. As the lower Yellow River had been fixed to the course of the Old Yellow River since AD 1546, the sum of “construction” projects is set to 0 for years prior to AD 1546.

$T$ ranges from 10 to 90, and by sampling $T$ at equal intervals of 10, we draw nine discrete likely values for $T$, that is, $T = \{10, 20, \ldots, 80, 90\}$. For every likely value of $T$, the coefficient of determination ($R^2$) is calculated to estimate to what extent the decadal sum of breach event occurrence is correlated with $T$. As $R^2$ reaches its maximum value 0.29 at $T=40$ (Figure 4), we estimate that earthen levees have a lifetime of 30-50 years.

Figure 4. Changes in the correlation between the decadal sum of breach events and the proxy of levee conditions ($L_v$) with the lifetime of levees ($T$). The coefficient of determination $R^2$ peaks at $T=40$, suggesting that earthen levees have a lifetime of ~40 years.
Q is constructed from the time-series of annual discharge at the Sanmenxia station (Figure 1), which is an estimated time-series by Wang et al. (1999) using several historical data correlations. Long-term annual water discharge at Huayuankou is approximately 1.1 times that observed at Sanmenxia in modern times. Therefore, annual water discharge at Sanmenxia is multiplied by 1.1 to obtain an estimate of discharge at Huayuankou, which is denoted as Qa. Averaging Qa decadal yields Q.

For the lower Yellow River between 1950 and 2003, Chen et al. (2006) formulated an empirical relationship between annual water discharge at Huayuankou Qa and the magnitude of post-flood bankfull discharge for a given year Qbfa:

\[ Q_{bfa} = -0.0117Q_a^2 + 20.5Q_a - 733.3 \quad (150 \leq Q_a \leq 876) \]  (5)

where the units of Qa and Qbfa are 0.1 km\(^3\) yr\(^{-1}\) and m\(^3\) s\(^{-1}\), respectively. We assume that for the Old Yellow River, Qbfa can be calculated similarly using Qa in a quadratic function but with three coefficients different from those of the current Yellow River.

Our prediction of the three coefficients is based on reasoning as follows: how would the equation for Qbfa of the lower Yellow River from 1950 to 2003 deviate from Equation (5) if there were no human-induced reduction of water discharges during flood seasons. Since the 1960s, river diversion and regulation have significantly reduced water discharges both annually and during flood seasons, particularly the proportion of discharges during flood seasons, resulting in a remarkable narrowing of the channel for the lower Yellow River (Chen et al., 2006; Wang et al., 2007; Wu et al., 2008). The bankfull discharge decreased from 7000 to 8000 m\(^3\) s\(^{-1}\) in the 1950s to 2200–2800 m\(^3\) s\(^{-1}\) in the 2000s (Chen et al., 2006).

A near-pristine relationship between annual water discharge and post-flood bankfull discharge can be calculated using two equations. One equation is the correlation between water discharge in flood seasons from July to October Qf (0.1 km\(^3\) yr\(^{-1}\)) and annual water discharge at Huayuankou Qa (0.1 km\(^3\) yr\(^{-1}\)) for the lower Yellow River from 1949 to 1957 when there was no flow regulation and the diversion was insignificant (Figure 5a):

\[ Q_f = 0.6113Q_a \]  (6)

The second equation is an empirical relationship between Qf and Qbfa, a companion equation of Equation (5) from Chen et al. (2006):

\[ Q_{bfa} = -0.0219Q_f^2 + 26.745Q_f + 518.12 \quad (90 \leq Q_f \leq 611) \]  (7)

Merging the above two equations, we have the relationship between Qa and Qbfa for an ideal lower Yellow River whose water discharges experience no modern human interventions:

\[ Q_{bfa} = -0.00818Q_a^2 + 16.349Q_a + 518.12 \quad (150 \leq Q_a \leq 999) \]  (8)

According to Equation (8), when Qa > 999, Qbfa decreases as Qa increases, which is unnatural. Therefore, Qbfa is extrapolated further using a linear equation with a value of slope equal to that at Qa = 990:

\[ Q_{bfa} = 0.1504Q_a + 8533.38 \quad (99 < Q_a \leq 1011) \]  (9)

As shown in Figure 5b, if there were no river diversion and regulation, the magnitude of bankfull discharge would be larger than that calculated by Equation (5). The differences are largest when annual water discharge is very high or extremely low, which are due to intense reservoir regulations in high-flow years and substantial river diversions in the 1990s, respectively. The differences are close to 0 when Qbfa ranges between 7,000 and 8,000 m\(^3\) s\(^{-1}\). This result occurs because during the 1950s, Qbfa was within this range while the Yellow River was in a near-pristine state (Chen et al., 2006).

We assume that Equations (8) and (9) hold for the Old Yellow River. For non-breach years during 1580–1849, Equations (8) and (9) are used to calculate the post-flood bankfull discharge. For breach years during this period, two modified functions (Equations 10–11) are used to account for the effects of breaching, ra, on the bankfull discharge downstream from a breach:

\[ Q_{bfa} = 0.00818[(1 - ra)Q_a]^2 + 16.349(1 - ra)Q_a + 518.12 \quad (150 \leq (1 - ra)Q_a \leq 999) \]  (10)

\[ Q_{bfa} = 0.1504(1 - ra)Q_a + 8533.38 \quad (99 < (1 - ra)Q_a \leq 1011) \]  (11)

The reduction in bankfull discharge downstream from a breach can be inferred from Equations (10) and (11). It is
evident that after a breach is repaired, the smaller bankfull discharge is a key controlling factor that shapes the occurrence of levee breaches during the impending flood season. Therefore, this post-flood bankfull discharge $Q_{bf}$ is taken as the bankfull discharge before the flood season for the next year. $Q_{bf}$ is further decadaly averaged to yield $Q_{bf}^0$.

Figure 6 shows decadal changes in water discharge at Huayuankou $Q$, bankfull discharge $Q_{bf}^0 (r_{oa}=0.45)$, and $Q_{bf}$ levee conditions ($T=40$ yrs) and frequencies of levee breach events.

**Uncertainty Analyses for $r_{oa}$**

The most likely range of $r_{oa}$ is estimated by an automatic calibration for the regression model expressed as Equation (4) (Muleta and Nicklow, 2005; Reisgaard et al., 2007; Chen et al., 2015). An uncertainty analysis is employed for the calibration. First, we need to determine a likely range for $r_{oa}$ that is as realistic as possible to guarantee an accurate calibration. As $r_{oa}$ is mainly controlled by the long-term average duration of a breach $T_b$ and the long-term average outflow ratio of the duration of a breach $r_{oa}$, we compile all relevant historical accounts of major breaches during 1580–1849 that include dates of breach initiations, breach durations, and outflow ratios of breaching flows (Supporting Material Table S1). Among the 143 breaches, 76% initiated between July and September, and the average date of initiation was mid-August. For the sake of simplification, we assume all breaches initiate on August 15. According to historical accounts, the average duration of 115 breaches was 9.1 months from their initiation date to their repair date. For the breaches that lasted for years, a new channel could form to reroute flows back to the main channel downstream (Shen et al., 1935). We assume that the average duration of these breaches would be somewhat smaller, say, 8.5 months. That is, we assume all breaches are repaired on the following May 1. According to historical documents, the average outflow ratio for 40 breaches was 0.83. As people tended to record data as the beginning of a month, we assume that the long-term average outflow ratio during the interval of a breach $r_{oa}$ ranged from 0.2 to 0.8. By sampling $r_{oa}$ at equal intervals of 0.1, we draw seven discrete likely values of $r_{oa}$ that is, $r_{oa} = \{0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8\}$.

We further assume that long-term monthly means for water discharge during 1580–1849 were similar to those during 1949–1957 (Figure 7), when water discharge was near-pristine and had a long-term annual mean (57 km$^3$ yr$^{-1}$) very close to those during 1580–1849 (57.1 km$^3$ yr$^{-1}$). Hence, seven discrete likely values of $r_{oa}$ that correspond to the above seven values of $r_{oa}$ are computed; that is, $r_{oa} = \{0.13, 0.19, 0.26, 0.32, 0.39, 0.45, 0.52\}$ for breaches that initiate on August 15 and are repaired on the following May 1 (Figure 7a).

For every likely value of $r_{oa}$, non-linear least squares fitting is applied to estimate the three parameters $X_1$, $X_2$, and $X_3$ in Equation (4). The performance of this fitting is evaluated by $R^2$ and RMSE (Willmott, 1982). $R^2$ measures the proportion of total variation in the observed probability of a breach explained by the fitted equation. RMSE is a measure of accuracy (Willmott et al., 1985); here, it is designed to measure the average difference between predictions and observations of the decadal frequency of levee breach events.

Using $R^2$ and RMSE, a search algorithm is designed to identify the most likely values of $r_{oa}$. For the seven fitted equations corresponding to seven values of $r_{oa}$, the maximum value of $R^2$ and the minimum value of RMSE are denoted as $\max(R^2)$ and $\min(RMSE)$, respectively. An equation is identified as the optimal or close-to-optimal equation when its $R^2$ ranges from $0.9 \max(R^2)$ to $\max(R^2)$, and meanwhile, its RMSE ranges from $\min(RMSE)$ to $1.1 \min(RMSE)$. The corresponding value of $r_{oa}$ is identified as the most likely value.

Historical documents indicate that the duration of a breach $T_b$ ranges widely from several days to 72 months (Supporting Material Table S1). To predict a full uncertainty range for $r_{oa}$, a second uncertainty analysis is applied to $T_b$ to obtain the calibration values for $r_{oa}$ when breaches are repaired on April 1 ($T_b = 7.5$ months) or on June 1 ($T_b = 9.5$ months) (Figure 7b, c). Uncertainty analysis is also applied to the lifetime of a levee $T$ that determines $L_c$.

**Constructing the Sediment Budget**

We construct the sediment budget for the Old Yellow River for 1580–1849, which is decomposed into four components (Gt yr$^{-1}$):

$$ I = S_c + S_f + O $$

where $I$ is the sediment input to the Old Yellow River at Huayuankou; $O$ is the sediment output at Yuntiguan, the apex of the delta; $S_f$ is the sediment deposited on floodplains.

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**Figure 6.** (a) Historical data reconstructions of decadal changes in water discharge at Huayuankou $Q$, bankfull discharge $Q_{bf}^0 (r_{oa}=0.45)$, and $Q_{bf}$ levee conditions and (c) frequencies of levee breach event occurrence (observation vs. prediction) on the Old Yellow River for AD 1580–1849.
outside the levees, which is estimated using the methodology described above; and $S_c$ is the sediment flux deposited in channel belts and floodplains within the levees (Figure 2). $S_c$ can be approximated as follows:

$$S_c = S_{\text{ld}} LW \rho_d$$  \hspace{1cm} (13)

where $S_{\text{ld}}$ is the long-term average sedimentation rate within levees estimated from core data (Xu, 1998); $L$ is the length of the channel belt, $W$ is the average distance between two opposing levees, and both geometric parameters can be obtained from SRTM channel belt maps; and $\rho_d$ is the dry bulk density of sediment within levees.

**Results**

**Uncertainty Range for $r_{oa}$**

Table I presents the fitted parameters $X_1$, $X_2$, and $X_3$ in Equation (4) and shows how the performance of the regression model changes with $r_{oa}$ when the lifetime of a levee $T$ is set to 40 years and the duration of a breach $T_b$ is set to 8.5 months. Figure 8 presents how the performance of the regression model changes with $r_{oa}$ and $T_b$ when $T$ is set to 40 years. For all three $T_b$, as $r_{oa}$ increases, $R^2$ increases, and RMSE decreases. However, both measures stabilize when $r_{oa}$ is greater than 0.35. The search algorithm identifies the most likely value ranges of $r_{oa}$ as 0.35–0.47, 0.39–0.52 and 0.42–0.56, for $T_b$ values of 7.5 months, 8.5 months and 9.5 months, respectively, indicating that $r_{oa}$ tends to increase with $T_b$. When $T$ is set to 30 years or 50 years, the calibration value of $r_{oa}$ changes to 0.39–0.56 (Supporting Material Table S2). Hence, overall, $r_{oa}$ ranges from 0.35–0.56. Using Equation (3), $R_o$, the long-term average outflow ratio of breaches for 1580–1849, is found to lie between 0.188 and 0.301.

Table I. Changes in the parameters and performance of the regression model (Equation (4)) with $r_{oa}$ and its corresponding $r_{ob}$ for the case of $T=40$ years and $T_b=8.5$ months

<table>
<thead>
<tr>
<th>$r_{oa}$</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
</tr>
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<tbody>
<tr>
<td>$r_{ob}$</td>
<td>0.13</td>
<td>0.19</td>
<td>0.26</td>
<td>0.32</td>
<td>0.39</td>
<td>0.45</td>
<td>0.52</td>
</tr>
<tr>
<td>$X_1$</td>
<td>147.28</td>
<td>636.50</td>
<td>835.90</td>
<td>243.38</td>
<td>34.38</td>
<td>7.22</td>
<td>1.53</td>
</tr>
<tr>
<td>$X_2$</td>
<td>6.33</td>
<td>7.61</td>
<td>8.25</td>
<td>8.70</td>
<td>6.80</td>
<td>5.93</td>
<td>5.04</td>
</tr>
<tr>
<td>$X_3$</td>
<td>-0.59</td>
<td>-0.60</td>
<td>-0.54</td>
<td>-0.45</td>
<td>-0.35</td>
<td>-0.29</td>
<td>-0.24</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.37</td>
<td>0.49</td>
<td>0.62</td>
<td>0.70</td>
<td>0.75</td>
<td>0.77</td>
<td>0.78</td>
</tr>
<tr>
<td>RMSE</td>
<td>5.26</td>
<td>4.73</td>
<td>4.05</td>
<td>3.61</td>
<td>3.30</td>
<td>3.18</td>
<td>3.12</td>
</tr>
</tbody>
</table>
Sediment Budgets for Different Historical Periods

For 1580–1849, with a sediment input of 1.0–1.3 Gt yr\(^{-1}\) to the Old Yellow River (Ye et al., 1983; Shi et al., 2009) and an \(R_c\) of 0.188–0.301, the sediment flux supplied to floodplains outside the levees is 0.188–0.391 Gt yr\(^{-1}\). \(S_c\), the sediment flux deposited in channel belts and floodplains within the levees, is calculated using Equation (13). Taking \(r_c = 25\) mm yr\(^{-1}\) (Xu, 1998), \(L = 800\) km, \(W = 8.86\) km and \(\rho_d = 2550\) kg m\(^{-3}\) (Shi et al., 2002) yields \(S_c = 0.275\) Gt yr\(^{-1}\). The remaining 0.424–0.781 Gt yr\(^{-1}\) sediment flux is delivered to the deltaic area and beyond.

Therefore, the total sediment input to the Old Yellow River for 1580–1849 is estimated as 270 – 350 Gt, of which 21.2–27.5% is deposited in the channel belt and in floodplains within levees and 18.8–30.1% is sequestered in floodplains outside the levees, leaving the remaining 42.4–60.0% to enter the delta (Table II). Our estimate for the sum percentage of \(S_c\) and \(S_r\) is 40–57.6%, which is in agreement with estimates by Ren (2015) and Ye et al. (1983) of 46% and 44%, respectively. However, our estimate for \(S_r\) is smaller than that by Ren (2015).

To better understand how floodplain sedimentation for the lower Yellow River basin was affected by human activities, we constructed sediment budgets for an additional three historical periods: 851–350 BC, AD 1128–1546 and AD 1950–1983 (Table II).

The 851–350 BC period was characterized by a pristine and stable Yellow River without human-accelerated erosion in the middle basin and embankment on the lower river (Chen et al., 2015). Using Hydrotrend, a climate-driven hydrological model that incorporates human factors (Kettner and Syvitski, 2008), we estimate the sediment flux supplied to the lower Yellow River as 0.28 Gt yr\(^{-1}\) (Chen et al., 2015). Assuming that the channel belt and natural levees had a sedimentation rate of 2 mm yr\(^{-1}\) (Xu, 1998) and that the length of the channel belt and the distance between two opposite levees were 1500 km and 5 km, respectively, as the lower Yellow River then had three distributaries (Figure 1; Chen et al., 2012), a sediment flux of 0.023 Gt yr\(^{-1}\), or 8.3% of the sediment, was deposited in the channel belt and on the natural levees. Our model estimates that <5% of the sediment was trapped in floodplains behind the levees: the modelled outflow ratio of a major breach was only ~0.02 because the channel bed of the lower Yellow River was lower than its surrounding area (Chen et al., 2015). Thus, in total <13.3% of the sediment was trapped in the pristine lower Yellow River Basin.

The AD 1128–1546 period was characterized by a chaotic lower Yellow River that shifted its course at least 22 times, which was due to a combination of human-induced increases in sediment discharges and no artificial levee system on the lower river (Chen et al., 2012). We assume that during this period, human-accelerated erosion in the middle basin generated a sediment input of 1.0 Gt yr\(^{-1}\) to the lower Yellow River (Ye et al., 1983; Shi et al., 2009). As the river mouth prograded much more slowly during this period than during AD 1580–1849 (Figure 3), we infer that the channel belt close to the delta apex should have had a small sedimentation rate and that it should have been much smaller than the rate on the upper reaches of the lower Yellow River. We assume that the channel belt and levees had an average sedimentation rate of 10 mm yr\(^{-1}\) or approximately half the rate along the upper reaches of the lower Yellow River (Xu, 1998). The length of the channel belt and the distance between two opposite levees were 1200 km and 6 km, respectively, as the unconfined Yellow River then consisted of smaller distributary channels. An estimated 0.112 Gt yr\(^{-1}\) of sediment flux, or 11.2% of the sediment, was deposited in the channel belt and on the natural levees. Meanwhile, as the percentage of sediment that entered the delta during this period was undoubtedly much smaller than that for

### Table II. Changes in source-to-sink sediment transfer over different periods

<table>
<thead>
<tr>
<th>Period</th>
<th>Sediment Flux (Gt yr(^{-1}))</th>
<th>Sediment Flux (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(I)</td>
<td>(S_c)</td>
</tr>
<tr>
<td>851 B.C.–350 B.C.</td>
<td>0.28</td>
<td>0.023</td>
</tr>
<tr>
<td>A.D.1128 – A.D.1546</td>
<td>1.0</td>
<td>0.112</td>
</tr>
<tr>
<td>A.D.1580 – A.D.1849</td>
<td>1.0–1.3</td>
<td>0.275</td>
</tr>
<tr>
<td>A.D.1950 – A.D.1983</td>
<td>1.4</td>
<td>0.34</td>
</tr>
</tbody>
</table>

The performance of the regression model (Equations (6)–(8)), which is evaluated from the coefficient of determination (\(R^2\)) and the root-mean-square error (RMSE), and changes in the annual outflow ratio for breaching years \(r_{oa}\). Optimal or near-optimal performance is achieved when \(r_{oa}\) is between 0.35 and 0.56, as 0.9 \(\max(R^2)\) and 1.1 \(\min(RMSE)\) are set as the choice criteria. [Colour figure can be viewed at wileyonlinelibrary.com]
1580–1849, the percentage of sediment deposited on the floodplains outside the levees was definitely larger than that for AD 1580–1849.

The AD 1950–1983 period was characterized by intense river regulation, levee upgrades, and normalization works involving the construction of meander cutoffs and bank revetment structures. Breach outflows along the current lower Yellow River were eliminated by a levee system that was adequate to prevent breaches. As the sedimentation rate within levees jumped to 20 cm yr\(^{-1}\) (Xu, 1998), 24.3% of the sediment was trapped between levees (Table II).

**Discussion**

**Sources of Error in Predicting \(r_{oa}\)**

A regression model (Equation (4)) was used to predict \(r_{oa}\), the annual outflow ratio \(r_{oa}\) for breach years. There are some unavoidable sources of error, such as the model inputs constructed from historical data, \(Q_{bf}\) calculated using Equations (8)–11, which are adapted from the empirical relationships for the current lower Yellow River, and the arbitrary search algorithm that causes the exclusion of the value of \(\frac{Q}{Q_{bf}}\) when \(\frac{T}{\text{min}}\) is set to 30 years or 50 years (Supporting Material Table S2).

To identify major sources of error in the regression model, we constructed three additional exponential regression models for breach probability using different explanatory variables \(Q\), \(Q_{bf}\) or \(\frac{Q}{Q_{bf}}\), and we compared their performances with those of Equation (4), which includes the explanatory variable for the levee condition, \(L_{v}\). Table III shows that Equation (4) performs the best of the four models and can explain 78% of the total variation in observations. \(L_{v}\) contributes very little to its explanatory ability because after it is excluded from the set of explanatory variables, the new regression model:

\[
P = X_{1} \left( \frac{Q}{Q_{bf}} \right)^{x_{1}}
\]

still explains 77% of the total variation in observations. This result is mostly attributed to \(Q_{bf}\) the potential bankfull discharge of the channel before the flood season, as the regression model involving the single variable \(Q_{bf}\):

\[
P = X_{1} Q_{bf}^{x_{2}}
\]

is able to explain 63% of the total variation in observations. Between Equations (14) and (15), the improvement of explanatory ability is due to the addition of \(Q\) to the set of explanatory variables by constructing a variable combination \(Q_{bf}\) as a proxy for water stage. Therefore, in Equation (4), \(Q\) and \(Q_{bf}\) are the influential variables and hence are two major sources of error.

**Table III.** A list of four exponential regression models for the probability of levee breach based on different combinations of the explanatory variables \(Q\), \(Q_{bf}\), and \(L_{v}\) showing changes in model performance based on these models

<table>
<thead>
<tr>
<th>Model</th>
<th>(r_{oa})</th>
<th>(\text{max}(R^2))</th>
<th>(\text{min}(\text{RMSE}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P = X_{1} Q^{x_{2}})</td>
<td>0.02</td>
<td>7.80</td>
<td></td>
</tr>
<tr>
<td>(P = X_{1} Q_{bf}^{x_{2}})</td>
<td>0.39–0.56</td>
<td>0.63</td>
<td>5.52</td>
</tr>
<tr>
<td>(P = X_{1} Q/Q_{bf}^{x_{2}})</td>
<td>0.41–0.56</td>
<td>0.77</td>
<td>3.33</td>
</tr>
<tr>
<td>(P = X_{1} (Q/Q_{bf})^{x_{2}} L_{v}^{x_{1}})</td>
<td>0.35–0.56</td>
<td>0.78</td>
<td>3.11</td>
</tr>
</tbody>
</table>

\(Q\) is, however, less influential than \(Q_{bf}\) but \(Q_{bf}\) is controlled by \(Q\). Ideally, the proxy for mean stage in flood seasons \(\frac{Q}{Q_{bf}}\) that includes water discharge in flood seasons \(Q\) is a more reasonable explanatory variable than \(\frac{Q}{Q_{bf}}\). This difference explains the rather poor correlation found between the probability of breach occurrence and annual water discharge \(Q\) for a given year.

Equations (8)–9 estimate \(Q_{bf}\) for an ideal lower Yellow River whose discharges experience no river diversion or regulation. However, similar to modern river diversions, breachings during 1580–1849 could have had the effect of altering the ratio of water discharge in flood seasons to annual water discharge. To examine whether Equations (8)–9 are a rational approximation to the real relationship between \(Q_{bf}\) and \(Q_{bf}\) for the Old Yellow River, we calculated the ratio \(\frac{Q}{Q_{bf}}\) for all hydrographs for breaching years used in the uncertainty analyses (Figure 7). The ratio ranges from 0.5470 to 0.6764, that is, ±10% from the value of 0.6113 for an ideal lower Yellow River expressed by Equation (6). For a long-term average \(Q\) of 332.4 \(0.1 \text{ km}^3 \text{ yr}^{-1}\), a 10% offset in \(Q\) can generate only a ±6% offset in \(Q_{bf}\), as Equation (7) shows. We therefore assume that the error originating from the altered hydrographs during breach years is negligible for the prediction of \(r_{oa}\).

However, the regression model (Equation (4)) has a non-negligible systematic bias, tending to over-predict when breaches are infrequent and under-predict when breaches are frequent (Figure 9). If breaches tend to be more frequent as \(Q\) increases, this bias can be caused by three factors. First, \(Q\) may be over-predicted when it decreases and under-predicted for larger discharges. Second, \(Q_{bf}\) may be under-predicted when \(Q\) decreases and over-predicted when \(Q\) becomes larger. Finally, we assume an outflow ratio equal for all breach years, regardless of how many breaches occur in a given year. However, for years with a higher breach frequency, the real outflow ratios are likely to be larger than \(r_{oa}\) while a smaller \(r_{oa}\) results in a larger \(Q_{bf}\) and, in turn, a lower breach probability for the following year. Fortunately, as our model is designed to investigate \(r_{oa}\) over the whole period of 1580–1849, these three sources of bias can be reduced in the long term.

![Figure 9](image-url)
Human-Influenced Sediment Transfer and Its Geomorphic Effects

Before the 350 s BC, a pristine Yellow River existed without human-accelerated erosion in the middle basin and embankments on the lower river. As the channel belt had a sedimentation rate of approximately 2 mm yr⁻¹, it would have taken the lower river many centuries to reach its super-elevation threshold for avulsion (Chen et al., 2015). The breach frequency and magnitude were very small, and <5% of the sediment was deposited on the floodplains outside the levees (Table II). Consequently, there were >180 active lakes and swamps in the extensive floodplains of the lower Yellow River (Zou, 1993). More than 86.7% of the sediment was delivered to the delta apex. Such a high delivery ratio is reasonable, considering the fine grain size of the sediment (~0.02 mm) in transport (Chien and Zhou, 1965).

After AD 1128, human-accelerated erosion in the Loess Plateau had distinct off-site geomorphic implications. During AD 1128–1546, as the amount of sediment input to the lower Yellow River increased by >3 times, the sedimentation rate in the channel belt increased 10 times at the apex of the alluvial fans close to Huayuankou. As a result, the lower river became super-elevated within decades, and the breach frequency and magnitude both increased by dozens of times (Chen et al., 2015). Since there was no continuous artificial levee system and few breaches were plugged, the river avulsed frequently and for many years. This period is marked by extensive sediment deposition in the floodplains outside the levees and the lowest delivery rate to the delta (Table II).

During AD 1128–1546, the lower Yellow River was not able to remain super-elevated for a long time, for it shifted its course frequently. However, during AD 1580–1849, when it was maintained along the Old Yellow River by artificial levees, sediments deposited within the levees created an ever-rising channel bed that was eventually elevated ~10 m above its surrounding areas by the 1850s. The high channel belt of the Old Yellow River became a drainage divide in the Huai River Basin. Distributaries in the northern basin joined the Yellow River, while the main Huai River was diverted to join the Changjiang River. The Hongze Lake rapidly expanded to an area of 2069 km² as the Gaojia Dike along the south-eastern lakeshore was raised to store the clear waters of the Huai River in the lake to scour the ever-rising channel bed of the Yellow River (Huai River Commission, 1990) (Figure 3).

During AD 1580–1849, the outflow ratio for the duration of a breach ρₒ was larger than that during AD 1128–1546 (Chen et al., 2015) as the super-elevation of the channel bed was beyond its threshold for avulsion. However, during AD 1580–1849, people were much more active in repairing breaches, and the breach duration decreased from several years to less than a year. Consequently, the annual outflow ratio during breach years ρₒ decreased, and less sediment was deposited outside the levees (Table II). The sediment delivery ratio to the delta increased, resulting in a progradation rate for the river mouth that increased from ~70 m yr⁻¹ during AD 1128–1546 to 110–1,540 m yr⁻¹ during AD 1580–1849. The total area of the subaerial delta and coastal plains created by the Yellow River reached ~13,000 km² before the river shifted to its current course (Figure 3).

Implications for Alluvial River Management

The regression model that calculates the probability of levee breaches has implications for flood hazard management. Equation (4) indicates that, in addition to depending on the levee condition, the probability of levee breach depends on both the water regime and channel morphodynamics, which are related to the water and sediment regimes of the river basin. River diversion and regulation reduce flood flows, leading to a narrowing of the channel and a decrease in bankfull discharge. Many global rivers, such as those in California and in the Southern Uplands of Scotland, are undergoing these anthropogenic channel changes (Gilvear et al., 2002; Kondolf and Batalla, 2005) that can raise flood stages and thus exacerbate flood hazards.

Moreover, future precipitation regimes are predicted to become more unfavourable to flood defences around the globe. Modelling and observations have revealed that precipitation events will be more intense, shorter, less frequent, and less widespread in response to global warming (Giorgi et al., 2014). Consequently, peak flows of rivers will change in frequency, and their magnitudes will often increase (Kettner et al., 2018). As the magnitude of bankfull discharge before a flood season depends on the flow regimes of the preceding years (Pickup and Warner, 1976), a larger variability in annual water discharge means that the channel before a flood season is less likely to have an adequate discharge-carrying capacity in an impending flood event and thus more vulnerable to flood hazard. Meanwhile, the predicted precipitation regimes will exacerbate water resource scarcity for some regions, and as a result, people are very likely to increase diversions on many rivers.

Hence, flood hazard management in the future needs to develop a more holistic vision and to integrate concepts and knowledge from hydrogeomorphology (Buffin-Bélanger et al., 2017). Rivers in semiarid climate zones and rivers with high sediment loads and erosive banks should be monitored more carefully in the future, for they show significant interannual variabilities in water discharge and bankfull discharge.

Changes in the sediment budget for the lower Yellow River over historical times provide implications for the construction of diversion structures, which is a common practice for floodplain restorations. The Old Yellow River, though embanked, still had an uncommonly high breach outflow ratio (ρₒ) of 0.35–0.56 and deposited 18.8–31.1% of the sediment on the floodplains outside the levees (Table II). Regarding rivers in the Rhine Delta, after they were embanked, sediment discharges to the floodplains outside the levees decreased by an order of magnitude during AD 1300–1850 (Middelkoop et al., 2010). For the embanked lower Mississippi River from AD 1880–1911, only 10% of the sediment flux to the river could be trapped behind the levees (Kesel, 1988; Kesel et al., 1992).

Three conditions along the Old Yellow River favoured a high breach outflow ratio. First, the sediment composing the channel bed was dominated by fine sand and silt, which was most prone to entrainment and which thus facilitated rapid breach expansion. In comparison, riverbanks in the Rhine Delta consist predominantly of sand and gravel (Middelkoop et al., 2010), and those along the lower Mississippi below the Red River consist of coarse sand or clay (Kolb, 1963).

Second, a positive feedback acted that tended to increase the frequency of breaches in the long term. As a breach on the Old Yellow River could capture a large ratio of flow, the river stream power was substantially reduced in the main channel, resulting in rapid channel aggradation downstream from the breach, which in turn increased the probability of breach occurrence in the following flood season (Chen et al., 2012).

Third, super-elevation was high relative to the mean main-channel depth, or the normalized super-elevation was large. Here, we define super-elevation of a natural levee or of embanked floodplains as its relative height above adjacent
flood basins (Chen et al., 2015). Normalized super-elevation controls the breach lip height, which is defined as the height of a breach throat bottom relative to the main channel depth (Singerl and Smith, 1998). As shown in Figure 2b, the entire lower Old Yellow River had a normalized super-elevation greater than 1, suggesting that even the bed of the main channel was super-elevated and that the breach throat bottom could be lower than the bed of the main channel, thus producing a high breach outflow ratio.

The normalized super-elevation is estimated to have been ~3 from AD 1580–1849 on the upper reaches of the lower Yellow River, which was characterized by a braided, wide and shallow channel (Chen et al., 2015). For comparison, normalized super-elevations of distributaries of the Rhine Delta and lower Mississippi River are by no means close to 3 and perhaps do not even approach 1, as denoted by cross sections in Middelkoop et al. (2010) and Hudson et al. (2008). An underlying cause is the amount of sediment input to these rivers. Levees can concentrate flows and thus shape a deeper channel with a higher sediment transport capacity. However, for the Old Yellow River, an increase in sediment input from 0.28 Gt yr⁻¹ (its pristine state) to 1.2 Gt yr⁻¹ was so significant that it could never have been accommodated by channel morphodynamic changes alone. As a result, sediment was deposited on both the channel bed and its floodplains within the levees at a high rate. In contrast, sediment delivered to the Rhine Delta is <0.25% of that of the Old Yellow River (Middelkoop et al., 2010). Flows restricted by artificial levees should be able to carve deeper channels that can accommodate a higher sediment transport capacity; thus, the increase in normalized super-elevation can be subdued.

For the Mississippi River below the Red River from AD 1880–1911, sediment delivered to the reach was 0.71 Gt yr⁻¹, of which ~7.6% is estimated to have been deposited in the channel bed as upstream bank caving contributed large amounts of bedload to the reach with an ~40% suspended load of sand (Kesel, 1989; Kesel et al., 1992). As a result, the normalized super-elevation may have increased over this period, favouring large breach outflow ratios. However, after 1963, sediment delivered to the lower Mississippi River was reduced to ~0.155 Gt yr⁻¹ with the construction of dams in the basin and concrete revetments on the lower river, as well as a series of channel cutoffs (Kesel, 1988; Kesel, 2003). These engineered modifications were unfavourable for increasing the normalized super-elevation.

Hence, to rebuild floodplains behind levees, a diversion should preferentially be placed in an area with a high normalized super-elevation. To construct a diversion that is self-sustainable in the long run, an increasing normalized super-elevation is required to offset bed erosion upstream from the diversion. The offset can be promoted through the removal of dams and revetments upstream, through the restriction of sand mining, and through maintenance of natural meanders. In addition, a diversion should be designed with a small initial lip height to facilitate a large initial breach outflow ratio and establish a positive feedback that favours self-sustainability. A modelling study using the process-based Delit3D model has already suggested that channel aggradation downstream from a diversion structure may develop along the lower Mississippi River (Meselhe et al., 2016).

Conclusions

We estimated the amount of sediment storage in the floodplains outside levees along the lower Yellow River for AD 1580–1849 using a multi-exponential regression model for the probability of levee breaches. We compiled historical accounts to obtain quantified information on the magnitudes of >100 breaches during this period for accurate calibrations and a realistic uncertainty estimation for the breach outflow ratio. We constructed the preliminary sediment budgets for the lower Yellow River for four historical periods and summarized how floodplain sedimentation was affected by human activities over the past two millennia.

For AD 1580–1849, sediment inputs to the lower Yellow River totalled 270–350 Gt, of which 21.2–27.5% was stored in the channel belt and floodplains within its levees, 18.8–30.1% was stored in the floodplains outside the levees, and 42.4–60.0% was delivered to the delta. The uncommonly high delivery ratio to the floodplains outside the levees was due to a remarkable human-induced increase in sediment delivery to the lower Yellow River. A condition favouring breach outflows was created as sediment deposition within levees generated significant super-elevation relative to the mean main channel depth. The latter should hence be considered when managing self-sustainable diversion for floodplain restoration.

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References


Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

**Table S1:** The conditions of the lower Yellow River during AD 1546 and AD 1855 when its course was along the Old Yellow River. The data are based on records of *The Chronicle of the Yellow River* [Shen et al., 1935]. Ancient Chinese documented the details of many major breaches, such as dates of breach initiations, breach durations, outflow ratios. Dates of breach initiations are according to the Chinese calendar, is about 40 days behind the Gregorian calendar.

**Table S2:** The performances of regression models for all the cases in the uncertainty analyses. Numbers in red are the calibration values for the outflow ratio in breach years.