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RESEARCH ARTICLE

Sediment transport under increasing anthropogenic stress: Regime shifts within the Yellow River, China

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Abstract Ecosystems respond to climatic and anthropogenic forcings with regime shifts and reorganizations of their system structures. In river basins, changes in sediment transport can have cascading effects that cause ecosystem regime shifts. The Yellow River, once the world's most sediment-rich river, has experienced dramatic regime shifts. Although recent intervention has returned sediment discharge in the Yellow River to pristine levels, our understanding of previous regime shifts remains inadequate, particularly for the regime shift to a sediment rich period during early historical time. We reanalyzed previous datasets to clarify the first historical sediment transport regime shift in the Yellow River. Our results show that while historical climatic changes (e.g., the Medieval Warm Period, about 900–1100 AD) caused changes in sediment transport, a regime shift occurred only under increased forcing from anthropogenic stresses (started from about 1350 AD, reached the tipping point after 1900 AD). This unique behavior of the Yellow River under increasing anthropogenic forces may provide perspective for sustainable river basin management.

Keywords Anthropogenic stresses · Climate change · Regime shift · Sediment transport · Yellow River

INTRODUCTION

Regime shifts are reorganizations of a system's structure and function; they can be caused endogenously by gradual or cumulative changes within an ecosystem, or be triggered exogenously by anthropogenic or natural disturbances (Collie et al. 2004; Rocha et al. 2018). Due to the complex feedbacks between climate, human activities and sediment transport processes in large river basin systems, changes in sediment discharge often initiate cascading regime shifts (Hughes et al. 2013; Best 2019). Therefore, by understanding the drivers of changes in sediment transport and their impacts on regime shift development, we can develop strategies to bolster the resilience of river basin systems.

The Yellow River, China, is one of the most sediment-rich rivers in the world and has experienced two large-scale regime shifts as a result of changes in sediment transport, generating attentions from around the world (Fig. 1) (Wang et al. 2007; Wei et al. 2016; Lappalainen et al. 2018). Around 2000 years ago, China entered a more unified period of human history that saw more extensive use of the Yellow River Basin. Increasing anthropogenic stresses throughout the historical period caused the sediment discharge of the Yellow River to increase from pristine levels to a sediment-rich regime by the mid-20th century (Ren and Zhu 1994). However, human intervention in the Yellow River Basin has made structural changes and led to a dramatic decrease of the sediment discharge during the past 60 years (Yu et al. 2013; Wang et al. 2016). Therefore, it is generally believed that the annual sediment discharge of the Yellow River has returned to pristine levels, marking the most recent regime shift (Chen et al. 2015).

Although the sediment discharge of the Yellow River reduced, the ecosystem remains fragile, and we must maintain the balance between ecosystem services in middle and lower reaches of the Yellow River (Fu et al. 2017). To best manage river basins, it is critical to understand the drivers and impacts of regime shifts. Numerous studies have analyzed various aspects of the drivers, processes, and outcomes of the most recent regime shift of the Yellow River (e.g., Yu et al. 2013; Wang et al. 2016; Ji et al. 2018). The results showed that comprehensive reason, including less runoff, more withdrawing and vegetation restoration, led the changes in sediment transport, while human's

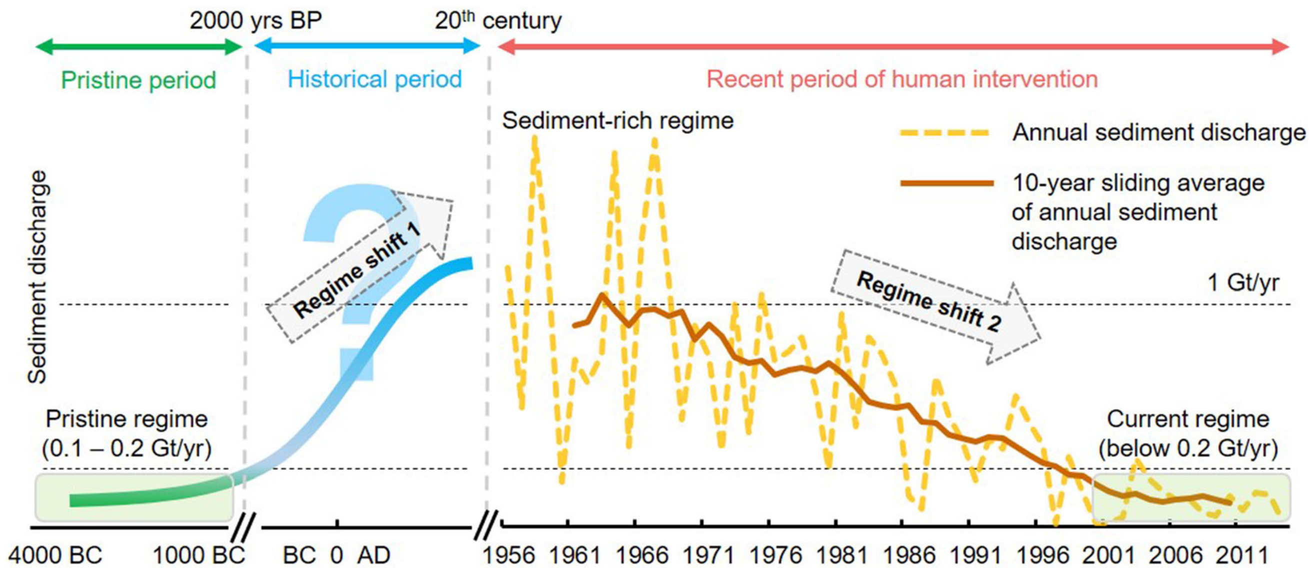

Fig. 1 Historical sediment transport regime shifts of the Yellow River (adapted from (Wang et al. 2007). According to sediment discharge of the Yellow River, two regime shifts can divide the timeline into three periods (green: pristine period, blue: historical period, and red: the recent period of human intervention). There is still a knowledge gap that how sediment discharge changed from the pristine regime to the sediment-rich regime during the historical period

interventions played the principal role in regime shift. However, a systematic understanding of the first historical regime shift, from pristine to sediment-rich discharge levels, has not been developed. This is particularly important under the current regime, as the sediment discharge of the Yellow River, although presently at pristine levels, could potentially become a sediment-rich regime and lead to cascading regime shifts. Thus, understanding increases in sediment discharge are essential not only for the Yellow River but also more broadly for precautionary and sustainable river basin management. The leap of sediment discharge in the Yellow River, which had been widely detected in Holocene research, occurred in historical period (Fig. 1), with relevant methods including sedimentology, pollen, and isotopes (Milliman et al. 1987; Saito et al. 2001, p. 201; Shi et al. 2002; Liu et al. 2004). However, previous studies tended to collect natural evidence with no cross-analysis in terms of regime shifts and neglected potential impacts on a coupled human and natural system. Therefore, we analyze related human or natural datasets in terms of data content and credibility to obtain a more general understanding of the first regime shift.

Here, by reanalyzing datasets from past researches, we reconsider the dynamics of climatic and anthropogenic drivers during different historical periods and assess their impacts to sediment transport of the Yellow River. Then, by detecting when key impact factors were no longer resilient to changes of previous drivers, we established a coherent understanding of the first historical regime shift within the Yellow River.

MATERIALS AND METHODS

Study area

The Yellow River, lying in arid and semi-arid areas of North China, cuts through the Sanmen Valley and flows into the Bohai Sea (Fig. 2). The sediment discharge of the Yellow River during its pristine regime (~ 0.1–0.2 Gt/year, according to Ren and Zhu 1994) had been the highest in the world which still increased by roughly an order of magnitude during the historical period (Fig. 1). Furthermore, due to unbalanced water and sediment supplies to the middle and lower reaches of the Yellow River, frequent flooding, levee breaching, and river diversions have challenged Chinese dynasties.

The middle section of the Yellow River crosses the Loess Plateau, the world's biggest and deepest loess deposition, which is a fertile and easily workable land that has supported Chinese civilizations for generations (Fu et al. 2017). The sand-rich area of the Loess Plateau contributes 77.2% of the coarse sand carried by the Yellow River where reclamation can intensify sediment loads of the Yellow River and cause heavy siltation downstream (Xu et al. 2006). From a historical perspective, the Yellow River Basin had been a primary zone of agricultural development in northern China. Limited productivity in

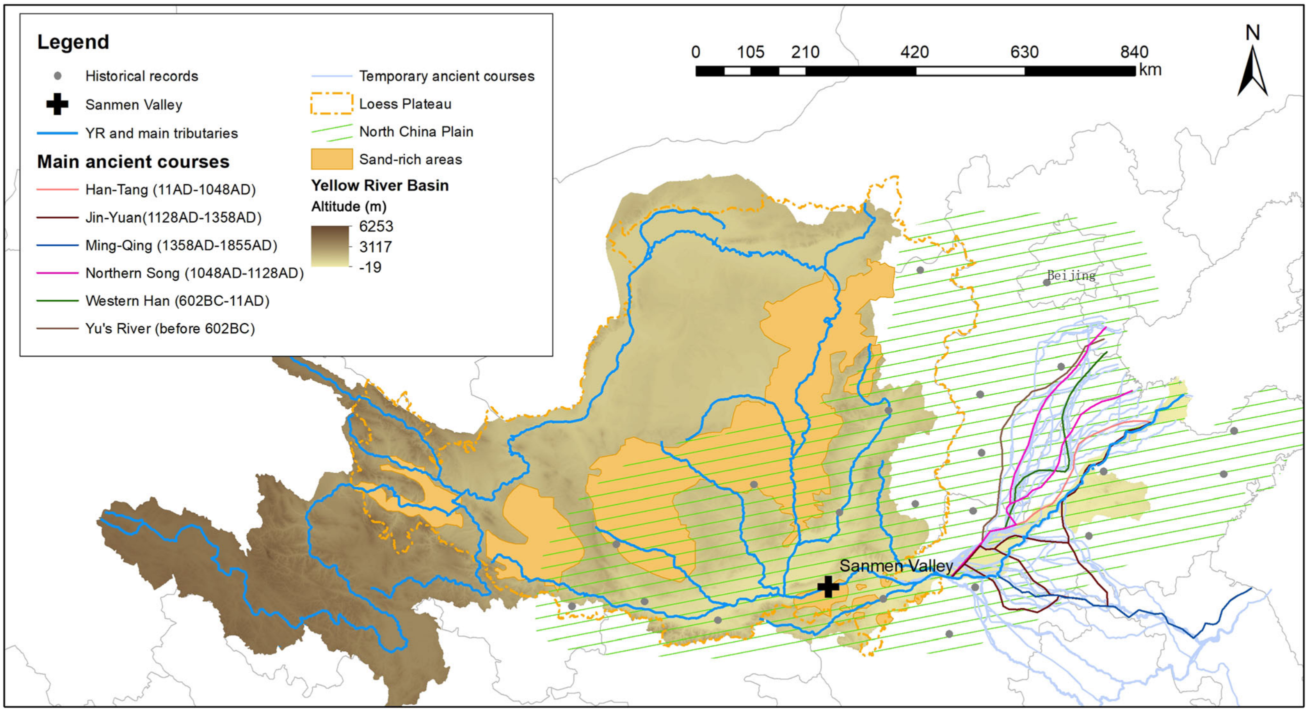

Fig. 2 The Yellow River (YR) Basin and ancient downstream river courses. The Yellow River cuts through the Sanmen Valley and across sand-rich areas of the Loess Plateau. Downstream courses of the Yellow River have changed frequently during historical times (according to Chen et al. 2012). The climate datasets used in this paper were reconstructed from historical deposits distributed across the North China Plain and well represent the historical climates in sand-rich and downstream areas

these areas and high demands from the increasing population have led to the extensive clearing of vegetation for farming land, the primary cause of soil erosion during historical periods.

As erosion developed, increased sediment loads accumulating in overhanging channels, downstream of the Yellow River. These silted channels experienced increased frequencies of flooding and levee breaching during historical periods, leading to a series of dramatic river diversions between six main ancient courses and a myriad of temporary ones (Chen et al. 2012). Typically, the Sanmen Valley was once a barrier of navigation, crossing here was vital for a dynasty to deliver food regularly. With severe siltation, the Sanmen Valley can become extremely un-navigable due to numerous elusive shoals. However, a humid climate period with a deeper water level can facilitate voyage.

Interpreting regime shifts

The first historical regime shift of the Yellow River can be characterized by a rise of sediment discharge which no longer resilient to generic climate fluctuations. Here, we consider the effects of environmental (i.e., periodic climate changes; driver 1, Fig. 3) and anthropogenic forcings (mainly food production; driver 2, Fig. 3) on sediment transport and focus on the shift of the sediment transport regime, as indicated by changes of related impact factors (deposition, navigation, and flood breaches, Fig. 3). However, sediment discharge and water discharge, related to drivers, are principal features in sediment transport, which may affect the impact factor at the same time. Therefore, we detect regime shifts by a coherent interpretation of two connected parts: drivers and the combination of impacts.

As two main drivers, climate change and food production played critical roles in regime shifts: (1) During a wetting climate period, soil erosion and runoff are increased by more abundant precipitation. It potentially leads to a regime shift because of increased water discharge carrying more sediments. (2) Similarly, reclamation caused by food production usually decreases the coverage of vegetation which leads to more floods and intensifies soil erosion, increasing sediment transportation.

On the other hand, main impacts include downstream deposition rates, deterioration of navigation routes, and more frequent levee breaches or floods. (1) Deposition (Fig. 4A–C): Changes of sediment deposition rate in riverbed and delta, two main deposition places, are a potential sign of regime shift. However, due to varying of the Yellow River's channel, different conditions of relict deltaic systems (fluvial, tidal, sea level, and wave regime) made them difficult to be compared. Therefore, we apply

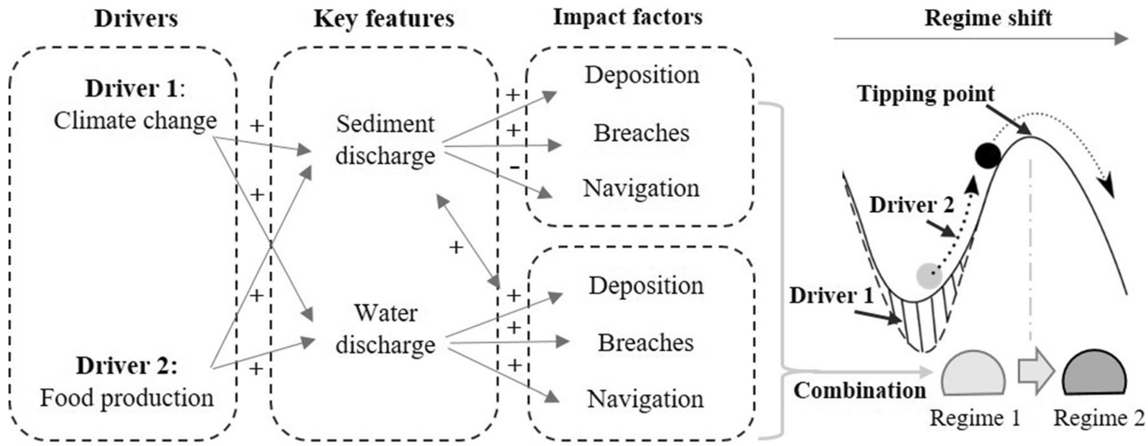

Fig. 3 A diagram of regime shifts within the Yellow River Basin. The gray arrows with symbol indicate positive or negative correlations between drivers, key features, and impact factors. After the change of drivers reaches a tipping point, the alter of impact factors' combination will be an indication of a regime shift

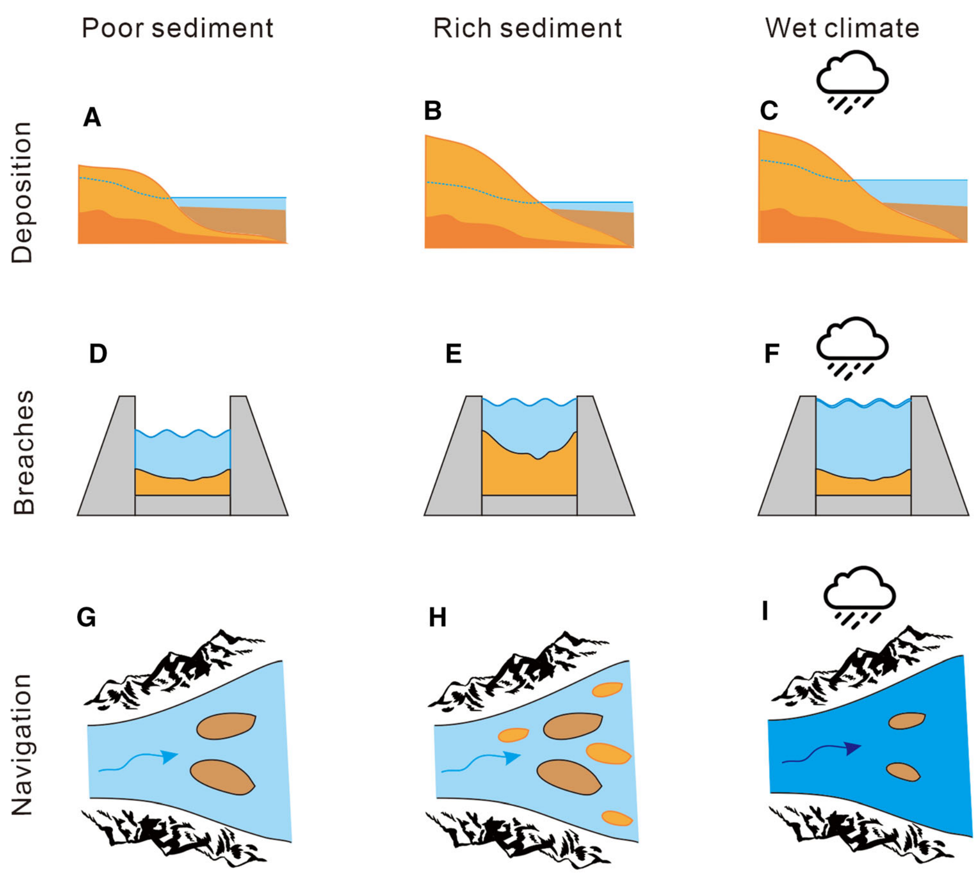

Fig. 4 Schematic diagram of impact factors (Deposition: A–C; Breaches: D–F; Navigation: G–I) related to key features (sediment discharge and water discharge) under different categories: (1) For deposition data, higher sediment discharge (from A to B) or water discharge (from A to C) both lead to an increased downstream deposition rate. (2) For breaches data, raised channel bed by sediments (from D to E) can increase the frequency of flooding breaches, or a wetter climate (from D to F) does so, too. (3) For navigation data, increased shoals will block navigation under more abundant sediment loads (from G to H), while wet climate (from G to I) can make it easier

deposition rates of relict riverbeds as a variable, which are relatively comparable, throughout. (2) Breaches (Fig. 4D–F): With sediments continually raising the channel bed and decaying levees, breaches or floods can be another potential sign of a regime shift. However, a wet climate also affects the likelihood of breaches and should be considered as well. (3) Navigation (Fig. 4G–I): Under a rich-sediment regime, changeable shoals make Sanmen Valley worse for navigating, while a wet climate may assist navigating.

Due to the difficulty of achieving reliable data, it is essential to interpret datasets with their credibility. Based on the above framework, we can detect and comprehensively explain the shift of regimes within the Yellow River.

Data and processing

Focusing on the drivers and impacts of the first historical regime shift, we liberally draw from the wealth of published research and historical data on the Yellow River Basin's history (Table 1).

While selected driver datasets do not require further processing, we unified the impact datasets and divided each dataset into three levels (Table 2). For comparison, we rescaled the credibility of each dataset according to min–max normalization. (1) For deposition rate, since each data is an average estimation from samples of a relict riverbed, credibility decreases when each sample represented longer years. (2) For levee breaches' data, whose credibility is highly related to the confidence of official historical materials, we refer to previous evaluations. (3) For Navigation data, we counted the number of records in each period, for indicating credibility because abundant records of the situation can reduce uncertainty.

Analysis and indicators

Based on our interpretive framework, we analyzed different time intervals dominated by different drivers and compared whether the combined impact factors represent a credible change before, during, and after those intervals.

Because dry and wet periods in China tend to occur over cycles of 80–100 years (Ge 2011), we set 100 years as the minimum threshold to detect climate-driven periods (CDPs). As the humidity index and flooding frequency reflect wetter environments and extreme precipitation, we considered both to be indicators of CDPs. That is, we interpreted intervals longer than 100 years that were characterized by an increased frequency of flooding relative to drought events and by increasing cumulative humidity index anomalies to be CDPs.

One of the main elements of anthropogenic forcing is population growth in the middle reaches of the Yellow River, which is related to agricultural expansion. Although precise population figures in the middle reaches of the

Table 1 Sources and credibility of indicator datasets used in this study

Dataset	Type	Description	Original material	Credibility
Drought and flood frequency (Ge 2011)	Driver	Number of years characterized by droughts and floods within 50-year periods between 150 BC and 2000 AD in the North China Plain	Official and local records spanning over 2000 years	Credibility is inconsistent between different time periods
Cumulative humidity anomaly (Zheng et al. 2006)	Driver	Calculated from various climate records and assessments of humidity levels	Official and local records spanning over 2000 years	Credibility is inconsistent between different time periods
Population in middle reaches of the Yellow River (Chen et al. 2012)	Driver	Mid-stream population estimated from historical records	Household registration information	Populations are conservatively estimated, but reflect the overall trend
Northern limit of the agricultural zone (Tan 1982; Xu 2003)	Driver	Index based on average distance from the boundary between agriculture and animal husbandry (latitude of Tongguan Station)	*Chinese historical atlas*	Temporal coverage is poor, but data are reliable relatively
Navigation in Sanmen Valley (Yu and Wu 1996)	Impact	Navigation records in Sanmen Valley based on four levels in primitive data: 1, free navigation; 2, navigable with traction; 3, navigation often failed; 4, completely un-navigable	Official and local historical records spanning over 2000 years	Data are from reliable historical descriptions but it may have missing. Records from the past 100 years are scarce but highly credible as modern evidence is conclusive
Breaches in lower reaches of the Yellow River (Chen et al. 2012)	Impact	Number of levee breaches (including floods and natural breaches) in the lower reaches of the Yellow River	Official and local historical records spanning over 2000 years	Credibility is the same as flood frequency because they are both derived from historical records of flooding
Deposition rate in ancient channels (Xu 2003)	Impact	Combined comparison of historical maps and average sediment thicknesses of ancient channels	Dating data from borehole sediment samples	Samples that span fewer years are more accurate

Table 2 Data divisions and credibility of impact factors

Data	Redefinition of credibility[a]	Level 1	Level 2	Level 3
Deposition rate	$1/\frac{1}{n}\sum_{i=1}^{n} T_i$	0–2 cm/year	2–4 cm/year	>4 cm/year
Levee breaches	$\prod_{i=1}^{n} C_i$	Occasional (< 10 records per 20 years)	Regular (10–20 records per 20 years)	Frequent (> 20 records per 20 years)
Navigation	N_i	Freely navigable	Navigable with human intervention	Un-navigable

[a]Within a specific period, "n" is the number of data records. (1) T_i is the length of years denoted by each data. (2) C_i indicates the credibility level, determined by original materials, of each number. (3) N_i counts the number of records during each period

Yellow River are unavailable, several periods of significant population growth are widely recognized and consistent with changes in China's historical population (Ge 2000; Chen et al. 2012). Furthermore, the extent of the farming region (i.e., the average latitudinal distance from Tongguan Station, near the lower boundary of the Yellow River Basin, to the northern limit of the agricultural zone; see Table 1) serves as an auxiliary indicator of population growth. Therefore, we consider the simultaneous occurrence of population growth and a northward expansion of agriculture, or significant rapid population growth alone, to be characteristic of human-driven periods (HDPs) because these indicators represent potential increases in the area and density of cultivated land.

After classifying each period as climate- or human-driven, we used the combined impact factors as a compound indicator of regime shifts. We recognized changes in the sediment transport regime of the Yellow River only when the impact factors are consistent with the dominant driving forces and when irreversible changes emerged.

RESULTS

Drivers

Before 400 AD, the credibility of the raw data is weak, and we will not discuss drivers before that time (Fig. 4A). During the past 2000 years, the climate in the North China Plain was generally dry, with 223 drought years and 182 flooding years. Among flooding-dominant multiyear, the increased variance of the cumulative humidity anomaly indicates there were three potential CDPs, though only two are considered credible, i.e., later than 400 AD (CDP1 and CDP2, Fig. 4B). There are no visible indications of anthropogenic forcings before 900 AD (Fig. 4C). Agricultural zones expanded northward during ~ 900–1000 AD and ~ 1350–1650 AD; the second expansion coincided with a marked population increase, and we, therefore, identified it as a HDP (HDP1, Fig. 4C). We identified a second HDP when the population quadrupled during the 20th century (HDP2, Fig. 4C). Thus, we subdivided the historical period relative to these two CDPs and two HDPs, as summarized in Table 3.

Impacts

Based on the above subdivisions, the level of levee breaches transformed from occasional to frequent during the CDP1, while navigating through the Sanmen Valley became easier (Fig. 5, CDP1). At the same period, it shows that the downstream deposition rate exceeded 4 cm/year for the first time, in the two samples. However, during the after CDP1 period, fewer flooding breaches and worse navigation situation returned, again, after that humid period, though there are no deposition samples estimating

Table 3 Subdivisions of the historical period and their characteristics

Time span	Subdivision	Characteristics
200 BC–400 AD	Low credibility period	No reliable dominant forcing
400–900 AD	Before CDP1	No dominant forcing
900–1100 AD	CDP1	Climatic forcing under the influence of relatively primitive human activities
1100–1350 AD	After CDP1	No dominant forcing
1350–1700 AD	Before CDP2	An extension of HDP1 (1350–1650 AD), with a northward expansion of agricultural zones, population growth
1700–1900 AD	CDP2	Climatic forcing under enhanced human activities
1900–2000 AD	HDP2	Rapid population increase

sediment discharge directly (Fig. 5, after CDP1). Finally, as the HDP1 period enters, more samples exhibit a distinct upward trend in the deposition rate (Fig. 5, HDP1 to HDP2). What's more, the most frequent flooding breaches and the worst navigating levels had been throughout this period.

To further explore the above-mentioned visible changes of impacts, we combined three factors with their credibility for each period (Fig. 6). There are some notable differences between the processes of change before and after the period of increased sand transport mentioned above (Fig. 6, A to C with D to F). Firstly, as the most direct indicator of sediment discharge, the deposition rates, whose credibility remained weak from HDP1, had a credible increment after the ending of HDP2 (Fig. 6E to F). Secondly, although the two humid CDPs (Fig. 6, A to B and D to E) both promoted flooding breaches, no facilitation of navigating during HDP2 (Fig. 6D, E), with a beforehand change had occurred during the HDP1 (Fig. 6C, D). These indicate that the two change processes (Figs. 5 and 6, CDP1 and HDP1 to HDP2) are different, anyhow.

DISCUSSION

Regime shift identification

The periods of forcings that we detected (two CDPs and two HDPs, Fig. 7) are consistent with existing research, respectively. (1) CDP1 was a typical humid period from 900 to 1100 AD which often referred to as the "Medieval Warm Period" (Zhang 1994; Ge et al. 2003). During this warm and humid period, a general northward shift of climatic zones and agricultural areas occurred (Tan 1982; Ge 2011). However, a previous data reconstruction showed that cultivated land accounted for only 20% of the Loess Plateau during this period and that human activities were finite (He et al. 2012). Our interpretation that CDP1 was a typical CDP rather than a HDP is therefore reasonable. (2) CDP2 encompasses almost the entire Qing Dynasty of ancient China, and various datasets show that it was a typical wet period (Ge et al. 2008; Ge 2011). (3) During HDP1, the population in the Loess Plateau reached 11.5 million by 1491 AD, a year with credible historical records, and land reclamation had accelerated (Wang et al. 2006). (4) The rapidly increasing population during HDP2 is also well documented by frequent land disputes due to increasingly intense land use (Ge 2000).

The impact factors show changes in climate-driven periods, as potential references for identifying regime shifts. Increased flooding and precipitation during humid CDPs promoted soil erosion and sediment transport, causing the increased frequency of levee breaches during the two CDPs (Fig. 6, A to B and D to E), consisted with a previous study (Chen et al. 2012). Furthermore, humid years are conducive to navigation in the Sanmen Valley, as shown in the navigation levels data (Fig. 5, CDP1). This corresponding to a historical fact that food usually transported along waterways of the Yellow River during the North Song Dynasty (dominating during CDP1) (Yu and Wu 1996). Finally, several studies on the historical and modern Yellow River have shown a strong correlation between humid years and increased sediment transport (Wang 1991; Yu et al. 2013).

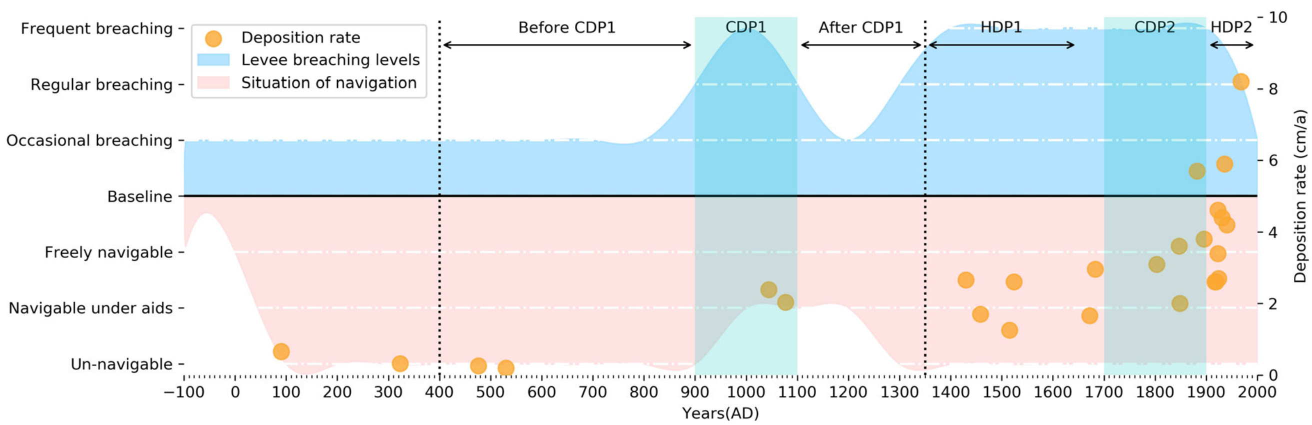

Fig. 5 Historical variations of regime shift impacts. Blue and red filled areas exhibit levels of flooding breaches and navigation, respectively (boundaries smoothed for aesthetic). Scatter plot exhibit downstream deposition rates, with each point indicating a sample from relict riverbeds

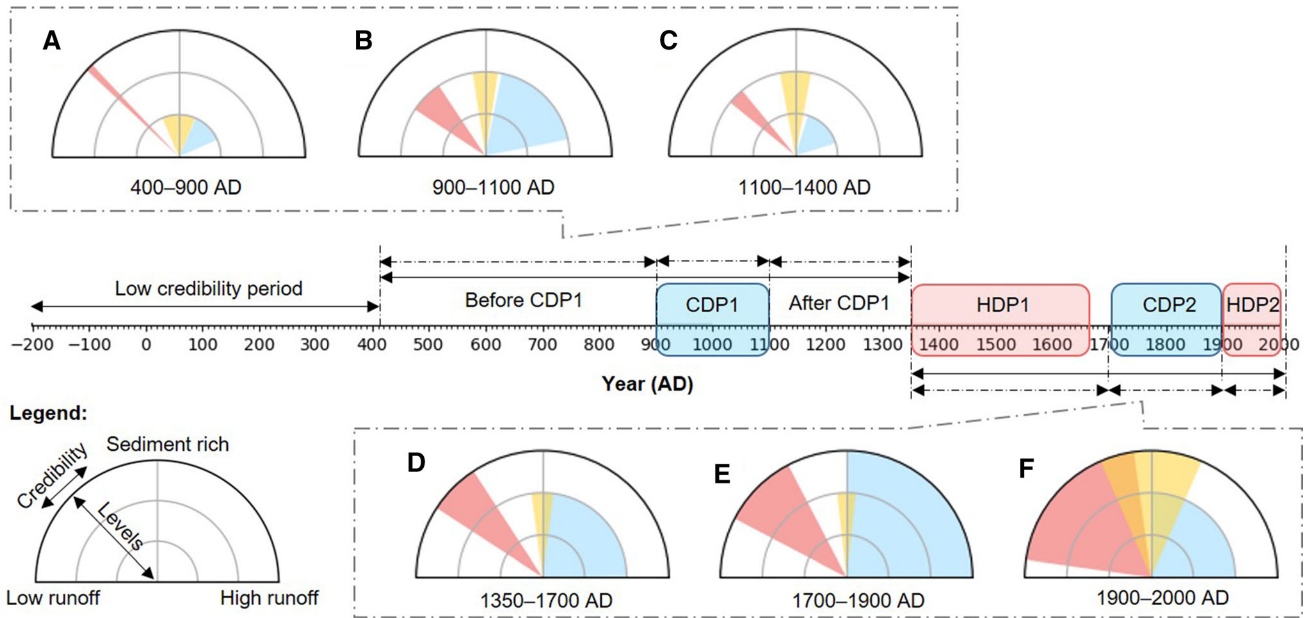

Fig. 6 Combined impact factors of each period with their credibility. In each semicircular diagram, long edges of bar plots (fan-shaped radius) under polar coordinates denoting the levels of data, whose credibility expressed in arc length (see 2.3 Data and processing). Different colors show different impact factors: red, yellow, and blue, denoting deterioration of navigation, downstream deposition rate, and levee flooding breaches, respectively. Since the correlations with runoff discharge are opposite between flooding breaches and navigation, we set them in different quadrants, with upward standing high sediment discharge. In a word, a larger colored ratio indicates a higher possibility of the sediment-rich regime during a specific period: **A** 400–900 AD; **B** 900–1100 AD; **C** 1100–1350 AD; **D** 1350–1700 AD; **E** 1700–1900 AD; and **F** 1900–2000 AD

Based on the above general knowledge, we identify regime shifts by considering the drivers and impacts holistically. The changes that occurred during CDP1, i.e., increased deposition rate, improved navigation, and more frequent flooding, are expected during humid periods. Following CDP1, though the deposition rate remained relatively unchanged (with weak credibility) due to finite agricultural expansion, the ease of navigation and flooding returned to previous levels. Thus, during CDP1, humid climate affected sediment discharge with human activities exacerbating these effects, but a tipping point for regime shift was not reached (Fig. 8A). Then, accumulated anthropogenic stresses during HDP1 had made some differences (Fig. 6C to D), and the humid climate during CDP2 only affected the frequency of flooding but not the deposition rate and navigation. Following CDP2 and into HDP2, sediment transport remained increasing, instead of declining to prior levels (Fig. 6: E to F). Thus, all indications suggest that the regime shift emerged in the above processes, dominated by anthropogenic stresses, causing sediment transport to no longer be resilient to climate drivers (Fig. 8B).

Effects of regime shift

We have focused on a historical span of more than 2000 years, a period of drastic climatic variations (e.g., the Medieval Warm Period) and increasing anthropogenic stresses. Climatic or anthropogenic forcings, exceeding a critical limit, are widely suggested as the main factor in triggering regime shifts. Our above discussion demonstrates that, although the sediment discharge of the Yellow River once increased under climatic forcings, a rapid regime shift did not emerge until anthropogenic stresses drove sediment transport to a critical tipping point. In the Yellow River Basin, the anthropogenic force that reached the tipping point was food production, similar to most other regime shifts reported globally (Rocha et al. 2018).

In the context of the Anthropocene, food production needs to increase rapidly with a population such that tipping points are much easier to exceed under anthropogenic forcings. Indeed, recent controls on land reclamation in the middle reaches of the Yellow River Basin imposed by the "Grain for Green" project have reduced the elevated sediment discharge of the Yellow River, which resulted from hundreds to thousands of years of climatic and anthropogenic forcings, to pristine levels in just 60 years (Wang et al. 2016; Ji et al. 2018). Nonetheless, to avoid future potential regime shifts, care must be taken to not exceed such tipping points by limiting or reducing anthropogenic stress.

The case of sediment transport in the Yellow River is useful for understanding regime shifts because such abrupt and massive changes have occurred throughout Earth's

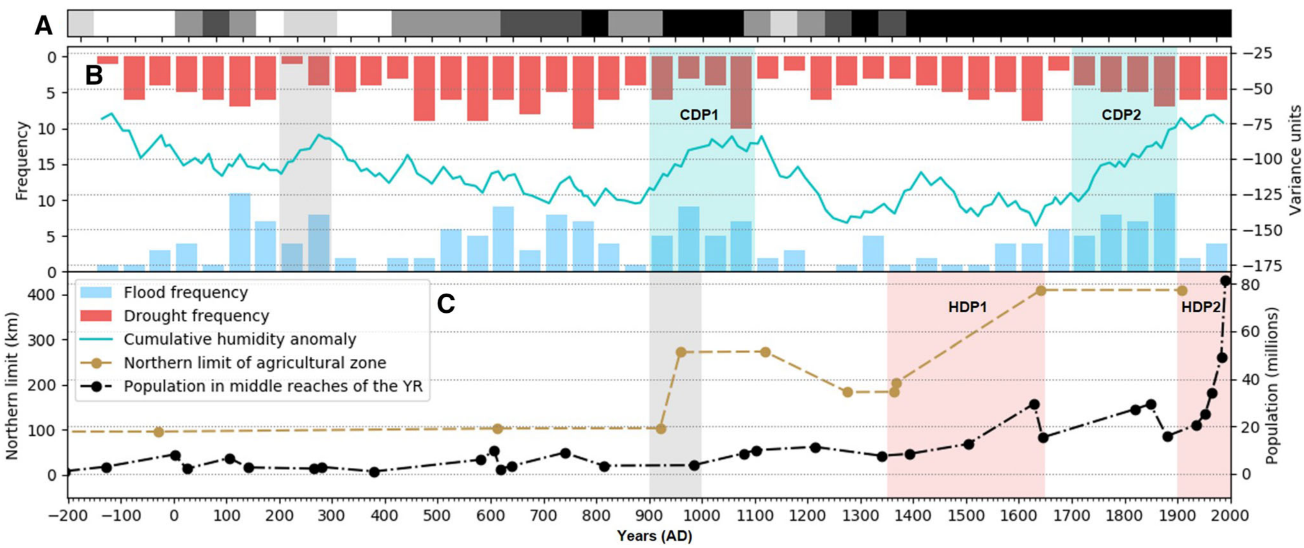

Fig. 7 Historical variations of regime shift drivers. **A** Combined credibility of the raw data, ranging from noncredible (white) to highly credible (black). **B** Climate drivers: Two CDPs (shaded in light blue) were identified based on the frequency of extreme weather (drought or flood) and the cumulative humidity anomaly. Although an earlier CDP may have occurred during ~ 200–300 AD (shaded in gray), whose credibility of the raw data during this period is too low. **C** Human drivers: Two HDPs (shaded in red) were identified based on population growth in the middle reaches of the Yellow River and the northern expansion of agricultural lands. Although agricultural lands expanded northward during ~ 900–1000 AD (shaded in gray), the lack of population growth during that time makes it unclear whether this change was due to anthropogenic stresses

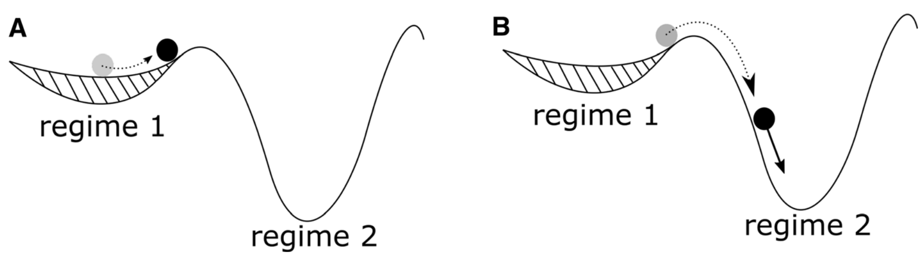

Fig. 8 Interpretive diagram of changes and regime shifts of sediment transport within the Yellow River. Regime 1 and regime 2 denoting the pristine and sediment-rich regime, respectively. Gray circles with dotted arrows denote the state of the river basin system under climatic forcings. Black circles with solid arrows denote additional anthropogenic stresses. **A** Changes from 400 to 1350 AD (corresponding to Fig. 6 A to C). **B** Changes from 1350 to 2000 AD (corresponding to Fig. 6 D to F)

history in aquatic, terrestrial, and interfacial ecosystems (Hughes et al. 2013; Rocha et al. 2018). Our results highlight that the complicated relationship between society and river basin systems can lead to cascading effects at various scales (Best 2019). By furthering our understanding of the relationship between forcings and their impacts, we can better gauge system resilience and regime shifts to develop sustainable management strategies (Scheffer and Carpenter 2003).

CONCLUSION

We investigated historical shifts of the sediment transport regime of the Yellow River to demonstrate the dynamics of the fundamental process of a regime shift. By focusing on the two main drivers of sediment transport in the Yellow River Basin, climate change and food production, we subdivided the entire historical period based on the dominant drivers. Then, we focused on the emergence of a regime shift in sediment transport by comparing impact factors between the different periods. Our results show that historical climatic changes (e.g., the Medieval Warm Period) led to changes in sediment transport. However, a regime shift, dominated by anthropogenic stresses, occurred only when the tipping point was reached, causing sediment transport to no longer be resilient to climate drivers. Since similar drivers of these abrupt and massive changes dominate globally, the case in the Yellow River is useful for understanding cascading effects within various social-ecological systems. It is, therefore, crucial to understand the relationship between regime shifts and their drivers/impacts when developing resilience management strategies within river basin systems.

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