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Research Article

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Posted Date: November 13th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11357439/v1

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Additional Declarations: No competing interests reported.

Alleviated Water-sediment Imbalance in the Middle Yellow River evaluated by hysteresis patterns

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Abstract

Purpose This study investigates the imbalance between water flow and sediment in the Middle Yellow River. The main research questions are: (1) A better method to evaluate the temporal synchrony between the hydrology and erosion processes, and (2) the change of water-sediment relationship in the Middle Yellow River.

Methods Data from experimental plots and hydrology stations of the Middle Yellow River has been collected. Flood event data of more than 780 experimental plots were collected to evaluate the availability of different hypothesis index to find a better method to evaluate the process-based sediment transport. Month scale data of more than 70 hydrology stations in the Middle Yellow River were collected to evaluate the change of water-sediment relation in the whole Middle Yellow River. Methods of Lawer and Aich were selected to evaluate the process-based hysteretic of the Sediment-discharge relationship in experimental plots.

Results Analysis showed that hypothesis index evaluated by Aich method is much more stable, and can be used to compare different flood events and between different watersheds. Besides, the discharge interval of 25% is enough for evaluating the process-based sediment transport. Data of hydrology station shows that, with the average hypothesis index value decreased from 0.15 to 0.11, while the dominance of sediment transport during the high-flow period over the low-flow period has decreased by 27%.

Conclusions Ecological remediation has alleviated the water-sediment imbalance in the Middle Yellow River. However, the alleviation varies in different watersheds.

Keywords: hysteresis index; sediment-discharge relationship; ecological remediation; Middle Yellow River

1 Introduction

Sediment related issues in the middle of the Yellow River have persisted for a long time. Following large-scale ecological remediation efforts, significant changes have occurred in both the total sediment load and sediment transport processes (Chia et al., 2025; Wang et al., 2016). The total sediment load decreased significantly (Chia et al., 2025), and the sediment transport processes have also changed (Liu et al., 2024; Zhao et al., 2025). However, the imbalance between water flow and sediment transport remains. Nevertheless, the specific changes to this imbalance following ecological remediation remain unclear. This necessitates the identification of suitable parameters for quantitative assessment.

The hysteretic characteristics of the discharge-sediment (Q-S) relationship illustrates the temporal synchrony between the hydrology and erosion processes, and can be used to explain process-based sediment transport and dynamic response of the suspended sediment to changes in the discharge (Nadal-Romero et al., 2008). When water flow and sediment transport are coordinated, high flow rates correspond to high sediment concentrations, and the Q-S relationship lies on a single straight line. This indicates that an increase in discharge results in high sediment transport (Fang et al., 2011). However, the complexity of sediment transport means that S-Q relationships are not usually represented by simple linear or univariate associations (Zhang et al., 2016; Hamshaw et al., 2018; Misset et al., 2019). When suspended sediment concentration peaks occur earlier than discharge peaks, the suspended sediment hysteresis type is clockwise (Williams, 1989; Rovira and Batalla, 2006). For clockwise loops, a positive peak indicates limited sediment sources within the channel or even sediment depletion. There is sufficient energy for materials to be removed from the channel or its close proximity (Keesstra et al., 2019). When sediment concentration peaks occur later than discharge peaks, it is a counterclockwise loop (Klein, 1984). An anticlockwise hysteresis loop indicates a remote source of sediment. An 8-shaped hysteresis loop is a combination of clockwise and counterclockwise hysteresis (Seeger et al., 2004). Some hypothesis loop can be grouped as complex or no hysteresis (Malutta et al., 2020). No hysteretic occurs in areas with substantial and easily transported sediment, and it is less frequent (Zhu et al., 2023). The functional hysteresis type of the dynamic response of the sediment to changes in discharge could be elucidated by different parameters. Measuring water-sediment coordination can utilise the peak phase difference (PK method) (Haddadchi and Hicks, 2021). However, the PK method only provides the phase difference between flood and sediment peaks, failing to assess sediment transport during both the rising and falling phases between flood and sediment. Additionally, comparisons across basins of differing areas present challenges. Another approach considers the shaded areas corresponding to the rising and falling phases within the Q-S relationship curve. This method is less suitable for inter-basin comparisons. Another method involves using the HI index. The calculation of HI also varies in several aspects, including the formula used for HI calculation, whether the sediment content data in the

flow is dimensionless, the method for dimensionless conversion, and the flow rate selected for HI calculation. Researches pointed out that, the calculation of the index using only the mid-point (50 %) in discharge can be problematic (Lloyd et al., 2015, 2016). The other pointed out that the beginning and end of the loops may lead noisy to hysteresis index (Lawer et al., 2006). Then, some analysis used different discharge intervals, i.e., Zhu et al. (2023) adopted 10% discharge intervals. Lloyd et al. (2015) compared the effects of discharge intervals on HI value. There are different ways of data adopted, raw data and normalized data ($Q_{i_norm} = \frac{Q_i - Q_{min}}{Q_{max} - Q_{min}}$ and $Q_{i_norm} = \frac{1}{Q_{max}} Q_i$).

In the Yellow River basin, sediment load varies significantly between different sub-basins. Even within a single sub-basin, sediment load fluctuates considerably over time and can undergo abrupt changes in the short term. Multiple factors compromise the applicability of many existing formulas. To assess changes in the Q-S relationship following vegetation restoration in the middle area of the Yellow River, this study first selects appropriate HI parameters to ensure comparability of HI values across different basins while accommodating basins with highly variable sediment loads. Monthly dataset from hydrology stations throughout the middle drainage area are then used to evaluate shifts in the Q-S relationship and changes of the mismatch within the middle Yellow River basin.

2 Materials and Methods

2.1 Materials and Data

Measured data of 784 storm events across 19 experimental plots were collected. These experimental plots located in tributaries of the Middle Yellow River, including Kuye River (Mengjiagou, Yangyagou), Weihe River (Yaojiagou, Dicungou, Sigou, Anmingou, Nangou), Yanhe River (Dabiangou, Xiaobiangou), and Wuding River (Jiuyuangou, Peijiamaogou, Xiangtagou, Tuanyuangou, Wangmaozhuanggou, Lijiazhaigou, Qingcaogou, Wangjiagou, Tiaogou, Lijiagou). For instance, Jiuyuangou is located in Suide County, which is located in the tributary of the middle Yellow River, namely Wuding River, while Mengjiagou is situated in Shenmu County near to the Wenjiachuan Hydrology station, which is an important hydrology station of Kuye River. All these flood measurements were primarily conducted between 1954 and 1976. For the Q-S relationship, the most important factors are climate, vegetation and human activities (Shi et al., 2014; Wang et al., 2016). Besides, characteristics of watersheds (soil properties, topography, geomorphology, erodible area and size)also influences the hypothesis (Klein, 1984; Wei et al., 2007). Some researchers also pointed out that the magnitude of peak discharge, sediment particle sizes are primary factors for storm event scales (Marttila and Kløve, 2010; Lenzi and Marchi, 2000). The flood

characteristics of these collected flood events varies, including discharge, suspended sediment concentration, precipitation intensity, and duration time of precipitation, duration of flood events.

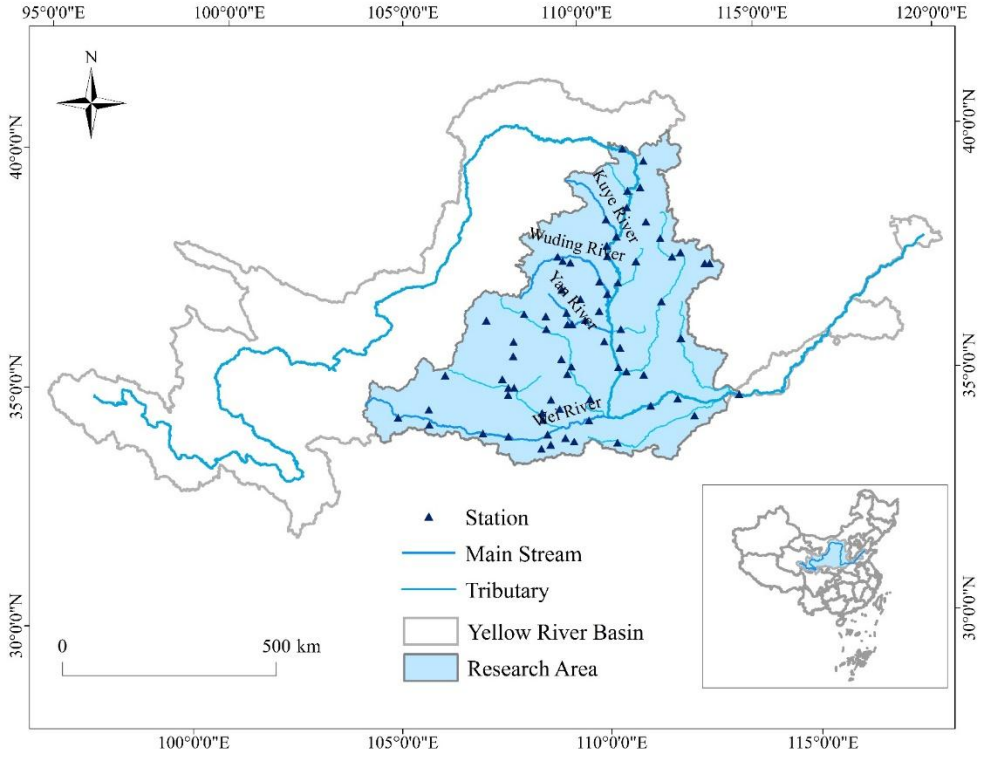


Figure 1 The Middle Yellow River, the four tributaries where experimental plots locate, and hydrology stations

Table 1 Summary of flood characteristics of flood events

Items	784		502	
	Range	Average	Range	Average
Maximum Discharge (m^3/s)	(0.001, 431.000)	7.170	(0.007, 196.000)	2.450
Average Discharge (m^3/s)	(0.001, 18.900)	0.560	(0.001, 3.620)	3.620
Maximum Sediment Concentration (kg/m^3)	(0.140, 1160.000)	313.460	(0.250, 1130.000)	260.490
Average Sediment Concentration (kg/m^3)	(0.005, 1020.000)	204.020	(0.005, 1060.000)	167.500

Erosion modulus (m^3/km^2)	(0.010, 29630.000)	695.960	(0.010, 29630.000)	649.910
Duration Time of Floods (h)	(0.356, 355.000)	20.250	(0.5000, 355.000)	21.040
Duration Time of Precipitation (h)	(0.150, 127.850)	10.250	(0.183, 120.970)	11.300
Rainfall (mm)	(0.100, 152.700)	27.720	(0.100, 151.800)	30.110
Rainfall Intensity (mm/h)	(0.300, 85.000)	6.910	(0.300, 85.00)	7.230

For measured flood event data at hydrology stations, the measurements are conducted in flood season every year, and no comparable experiments would be conducted. For each pair of comparable experimental plots, one plot is designed to remain unchanged, and the comparable one would be regulated by land cover or silt dam. Each pair of experimental plots are adjacent to each other. Thus, measured flood events in these pairs of comparable experimental plots are important supplementary data besides daily data and event data of hydrology stations. For data in each pair of comparable plots, soil properties, watershed size and sediment sources, and topography are comparable and constant in short-term. Human activities (including silt dam and vegetation change) will change vegetation extent, the connectivity of sediment transport, and the dynamic process of discharge and sediment transportation. Climate factors (rainfall intensity, duration time) are comparable in each pair of experimental plots as the adjacent location. Thus, all the storm events in pairs of comparable experiment plots are measured under comparable precipitation and also the occurring time. A total of 502 flood events were selected from 14 pairs of experimental plots, with significant varied watershed size. The watershed sizes of these experimental plots vary from 0.45 km^2 to 70.1 km^2. The topography of these 14 plots includes semi-arid sandy areas, loess hilly gully regions, soil-rock zones, and terraced areas of the Loess Plateau. Thus, these 14 pairs of plots are paired in the water conservation design, representing managed and unmanaged watershed areas. Gully density also showed considerable variation, spanning from 0.91 km/km^2 to 8.04 km/km^2, slopes ranged from 1.22% to 12.3%.

Table 2 Characteristics of flow and suspended sediment collected in these 19 experimental plots

Num.	Experimental Plot		Area (km^2)	Density (km/km^2)	Slop (%)	Watershed (conservation Y/N)
1	Tiaogou	Yulin	0.745	8.04	2	Y

2	Lijiagou	Yulin	0.693	5.84	6.7	N
3	Xiangtagou	Suide	0.454	-	-	Y
4	Tuanyuangou	Suide	0.491	-	-	N
5	Mengjiagou	Shenmu	2.03	2.15	3.8	Y
6	Yangyagou	Shenmu	1.88	-	-	N
7	Wangmaozhuanggou	Suide	5.967	5.63	2.7	Y
8	Lijiazhaigou	Suide	4.92	3.02	3.1	N
9	Yaojiagou	Xian	7.815	2.1	12.3	Y
10	Dicungou	Xian	4.4	0.91	8.7	N
11	Dabiangou	Yanan	3.70	2.6	3.38	Y
12	Xiaobiangou	Yanan	4.05	3.84	3.5	N
13	Jiuyuangou	Suide	70.1	5.34	-	Y
14	Peijiamaogou	Suide	41.2	2.69	1.22	N

*'-' indicate data are unavailable.

For hydrology station, sediment data are measured at flood scale and daily scale, all the data are published as yearly book. To assess variation of water-sediment mismatch in the middle area of the Yellow River before and after ecological governance, monthly data are adopted. Monthly data from 72 hydrology stations in the middle reaches were collected and compiled for the period 1959–2015. Data for 1991–1999 were severely incomplete. Approximately 2,300 sets of monthly data were compiled, with pre-ecological governance data accounting for about 77.3% of the total.

2.2 Method

Two methods (Lawer and Aich) are adopted to evaluate the "thickness" of the hysteresis loop by HI-values.

Lawer et al. (2006) method for HI value is estimated as

$$\mathrm{HI}_{Lawer} = \frac{1}{n}\sum_{i=1,n}\mathrm{HI}_{L_i} \quad (1)$$

$$\mathrm{HI}_{\mathrm{L_i}} = \begin{cases} \left({}^{TU_{RL_i}}\!/_{TU_{FL_i}}\right) - 1 \;\; if\ \left(TU_{RL_i} > TU_{FL_i}\right) \\ -\left({}^{TU_{RL_i}}\!/_{TU_{FL_i}}\right) - 1\ if\ \left(TU_{RL_i} < TU_{FL_i}\right) \end{cases} \quad (2)$$

$$Q_{i_norm} = \frac{Q_i - Q_{min}}{Q_{max} - Q_{min}},\ S_{i_norm} = \frac{S_i - S_{min}}{S_{max} - S_{min}} \quad (3)$$

In which, TU_{RL_i} and TU_{FL_i} are the sediment concentration at Q_i on the rising and the falling phase, respectively. Q_{i_norm} and S_{i_norm} are normalized discharge and concentration. It can be adopted to describe the hysteresisby direction and strength between the rising phase and falling phase. However, the HI value will be influenced by the absolute values of concentration when raw data is used, and high concentrations lead to lower values of HI. The comparing between different catchments or different events with different concentration in the same catchment may lead to errors. After

normalization, the HI value is more comparable. However, if the normalized S_{i_norm} in the rising and the falling phases have different magnitudes, the HI value varies.

The method of Lawer was improved by different researchers. The Lawer method estimate the HI value at the mid-point in discharge (50%). Lloyd et al. (2015) improved the Lawer method. According to Lloyd et al. (2015), the HI value is estimated as $\mathrm{HI}_{Lloyd} = TU_{RL} - TU_{FL}$, and the definition of TU_{RL} and TU_{FL} are the same as Lawer method. However, it estimates HI values by the average value at every 25, 10, 5, and 1% of the discharge Thus, Lloyd method will not be adopted to make comparison.

Aich et al. (2014) method for HI value is

$$\mathrm{HI}_{Aich} = D_{rise} + D_{fall} \quad (4)$$

$$Q_{i_norm} = \frac{1}{Q_{max}} Q_i,\ S_{i_norm} = \frac{1}{S_{max}} S_i \quad (5)$$

The Aich method identifies the rising and the falling phases differently from the Lawer method. A line could be draw by connecting the point with maximum discharge and the point of the last sample. The whole hysteresis loop could be divided as the rising and falling phase by this line. Then, D_{rise} and D_{fall} are the maximum distances to this line of the rising and the falling phases , respectively. In this paper, Aich method is improved to calculate the HI value at different discharge intervals.

In the method of Langlois et al., (2005), it is no adopted as the comparable of different magnitude of suspended sediment concentration.

In the method of Zhu et al. (2023), it incorporates coefficient K to indicate the concentrations magnitudes. This coefficient K ($\mathrm{K} = \cdots, 0.001, 0.01, 0.1, 1, 10, \cdots$) will vary at the rising and falling phase in floods with large concentration. Thus, method of Zhu et al. (2023) is not compared in this analysis.

Firstly, the HI value was calculated using different intervals of discharge (50, 25, 10, 5 and 1%). For each discharge interval, the average HI value is the adopted to compare and analyze. Subsequently, the selected method was employed to quantitatively assess variation in water-sediment mismatch in the middle area of the Yellow River after ecological measures. All month scale dataset were divided into pre- and post-ecological management periods, specifically before 1989 and after 1990.

3 Results

3.1 HI values in experimental plots

HI values were estimated using different methods for 784 flood events at the 50% flow point were compared. As shown in the figure, significant differences exist between the HI values calculated by the two methods, with the Lawer method yielding more fluctuating results. HI values calculated by the Aich method ranged from (-1.01) to (1.05), while those from the Lawer method fluctuated between (-102.05, 10.96). Furthermore, some HI values from the Lawer method exceeded the 25%-75% range. This is attributed to severe sediment erosion in the watershed, causing substantial

variations in suspended sediment concentration in both the rising and the falling phases. For example, during the flood event at Jiuyuangou on September 1, 1954, the sediment concentrations at the 50% flow rate during the rising and the falling phases are 31.43 kg/m³ and 2.63 kg/m³, respectively. The corresponding dimensionless values are 0.61 and 0.05, respectively.

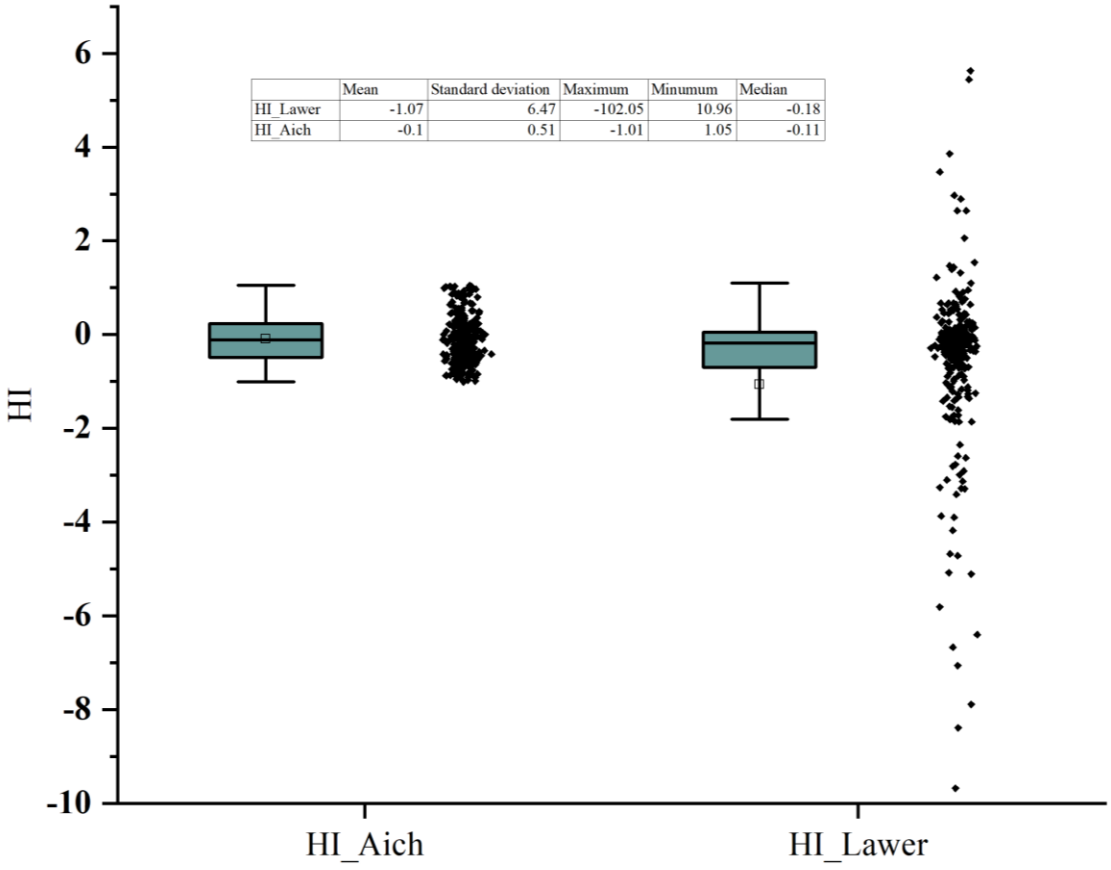
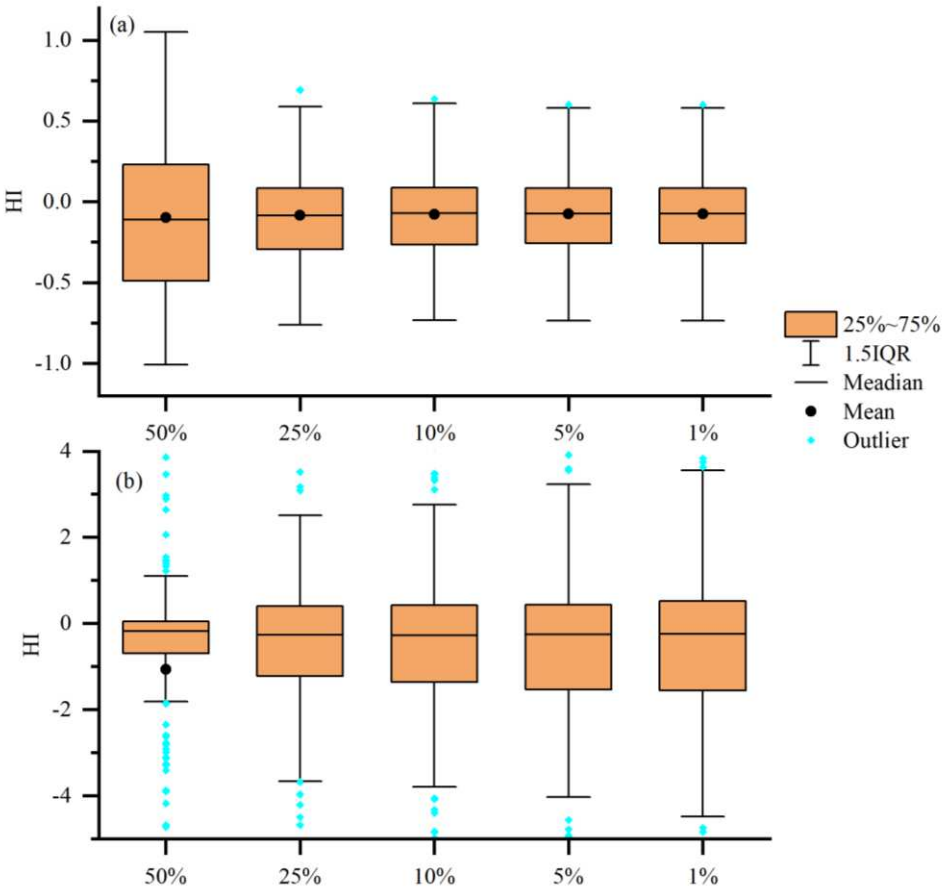


Figure 2 Comparison of HI values by method of Lawer and Aich at mid-point in discharge

Further analysis using different discharge intervals reveals that to accurately assess the HI value of a sediment transport process, a sufficient number of sediment concentration data points are required. Results from varying discharge intervals indicate that a 25% discharge interval is adequate to characterize the flood characteristics of most flood events.



222

223 **Figure 3 HI values of Aich (a) and Lawer (b) method at different discharge**

224 **intervals, 50%, 25%, 10%, 5% and 1%.**

225 For the 502 comparable catchment data sets, we grouped the data to investigate its
226 influence further to HI values, including three groups by sizes of experimental plots
227 (<1km^2, 1-10 km^2, 10-100 km^2) and the comparative plot areas with or without
228 vegetation management. Besides, the hypothesis type of all the 502 hypothesis loop
229 were distinguished manually. HI values for different catchments were calculated using
230 25% discharge intervals. As shown in the figure, HI values calculated by the Lawer
231 method and the Aich method exhibit similar trends. Moreover, in floods within small-
232 to-medium-sized watersheds (<10 km^2), a negative peak indicates sufficient sediment
233 sources. Simultaneously, with low runoff, the energy is insufficient for removing
234 materials from the channel or its vicinity (Keesstra et al., 2019). Flood HI values in
235 large-area runoff sub-basins tend toward positive values, meaning sediment
236 concentration peaks occur earlier than discharge peaks (Williams, 1989; Rovira and
237 Batalla, 2006). For floods in large-scale watershed areas (10 km², 100 km²), HI values
238 are positive. However, values calculated by the Aich method are closer to zero.
239 Simultaneously, sediment transport gradually transitions from the falling phase to the
240 rising phase as basin area increases. Following ecological restoration of the basin,
241 sediment transport becomes more concentrated during the falling flow phase. The

primary reason is that small-to-medium-sized flood events account for 57% of occurrences, and in these smaller catchments, sediment transport is primarily concentrated during the falling phase (HI values < 0).

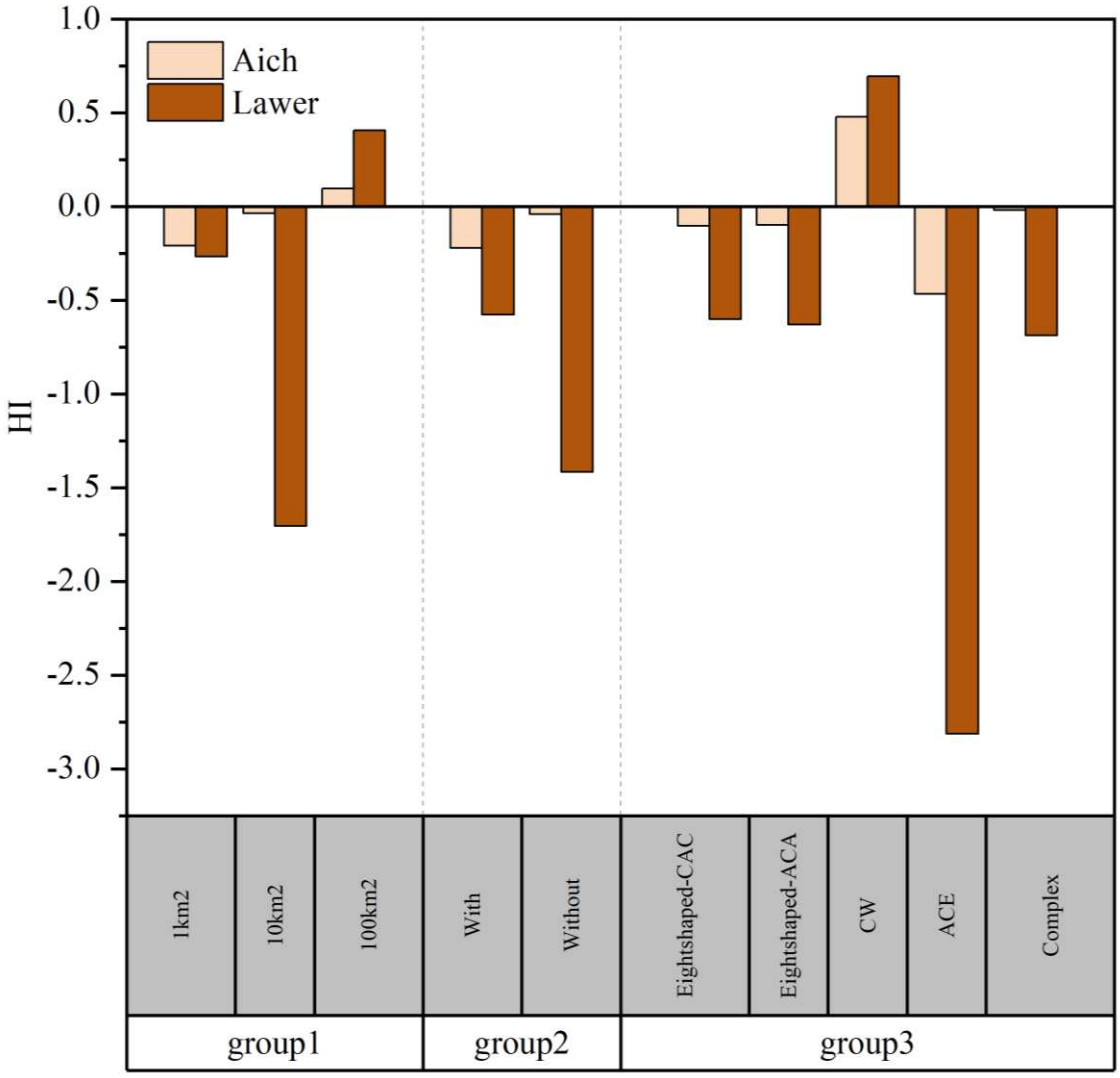


Figure 4 Comparison of HI values by method Lawer and Aich at mid-point in discharge. Group 1 is grouped as the watershed area of experimental plots. Group 2 is grouped according to with ecological remediation efforts or without ecological remediation efforts. Group 3 is grouped according to the manual identification of Q-S relationship.

3.2 Changes of HI in Middle Yellow River

The Aich method was employed to quantify the monthly sediment-runoff relationship at stations along the middle reaches of Yellow River. Following large-scale ecological remediation efforts, the proportion of monthly concentration with HI>0 (where sediment transport is more dominant during rising flow periods) decreased from 75% to 58%. Concurrently, the average HI value (indicating the degree to which sediment transport is more dominant during rising flow periods compared to falling periods) decreased from 0.15 to 0.11 (Figure 5). This indicates that while improved vegetation in the basin did not fundamentally alter the water-sediment mismatch in the middle reaches, it mitigated the severity of this imbalance. Monthly water-sediment relationships became more coordinated, with approximately 33% of stations exhibiting improved coordination (as evidenced by a basin-average HI value closer to 0 post-management). Consequently, the sediment "storage-release" pattern within the basin underwent transformation.

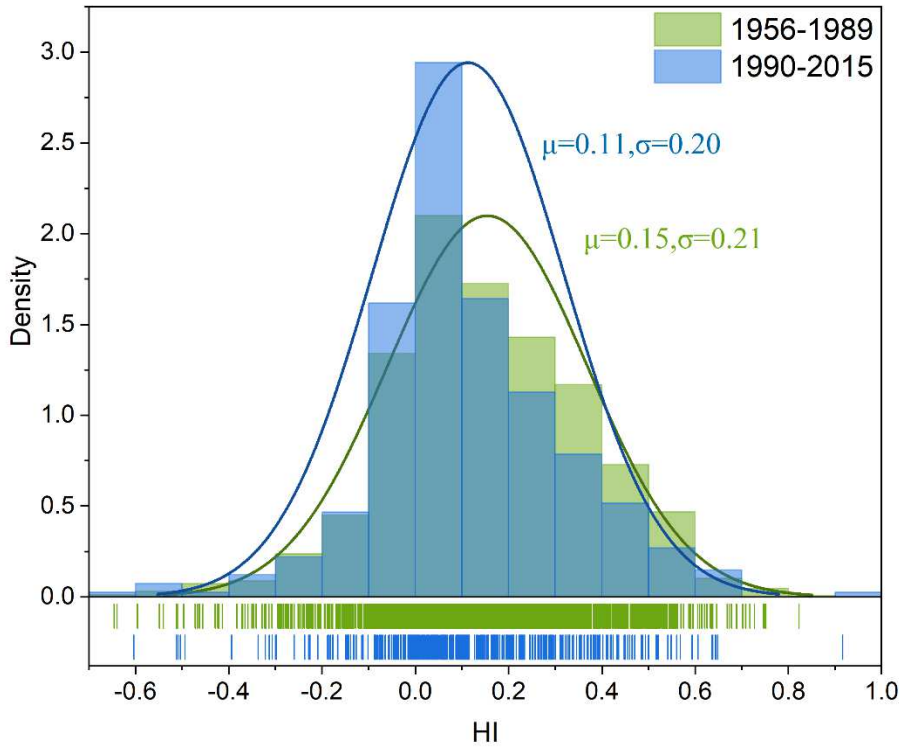


Figure 5 Changes of HI values by Aich method at middle Yellow River

4 Discussion

4.1 HI value of Typical Flood Events

Comparative plots of computational results for typical floods were generated. It can be observed that both the Lawer method and the Aich method accurately calculate corresponding HI values for runoff processes characterized by steeply increasing sediment content.

In most flood events, the HI values calculated by the Lawer method and the Aich method are comparable. The Lawer method and Aich method can both accurately the corresponding HI values for flood processes with steeply increasing sediment concentration. For instance, during the flood falling phase when sediment concentration decreases slowly, both methods yield negative HI values. During the flood rising phase, the HI values calculated by the Aich method are smaller than those from the Lawer method. The unexpected value of HI by Lawer method for discharge interval of 1% is the point where discharge is almost zero (flow discharge is 0.01 m3/s) while sediment concentration is still much larger (corresponding sediment concentration is 275 kg/m^3). The calculated HI value by Lawer method results in unreasonable high HI value (Normalized Q_i=0.01, Turl and TU_{FL} are 0.35 and 0.91, HI=-1.59).

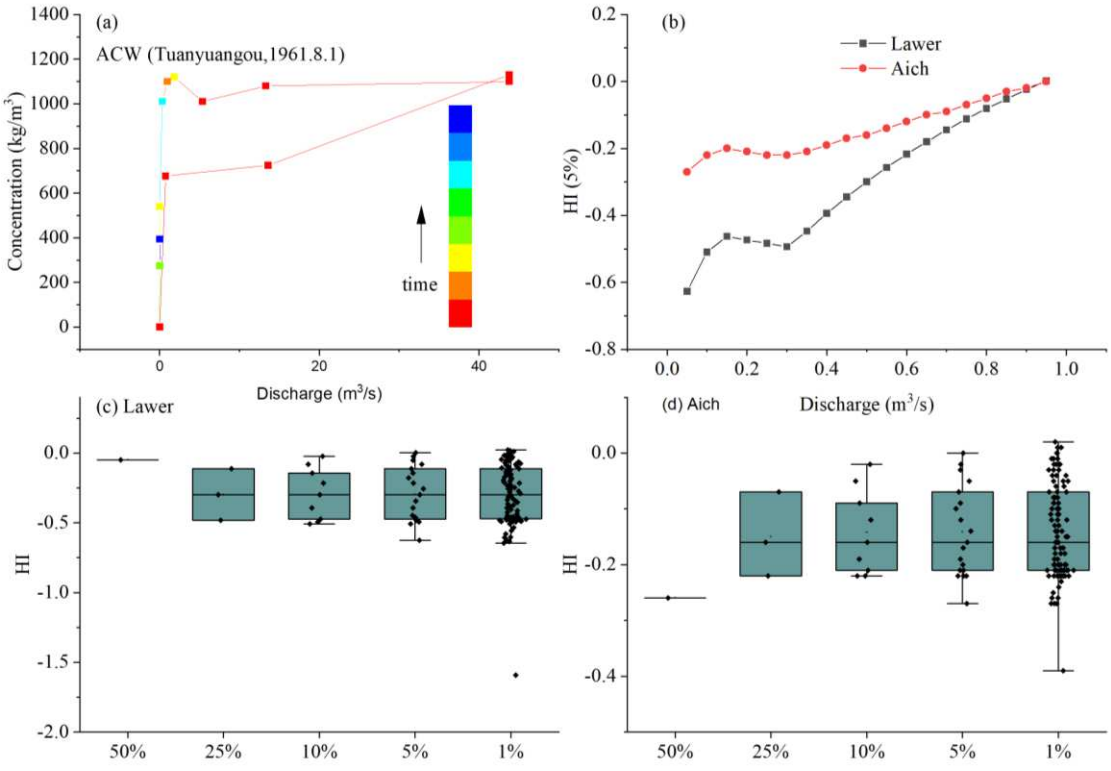


Figure 6 Typical storm event (Tuanyuangou, 1st August 1961) (a), HI values with discharge interval of 5% by Lawer and Aich methods (b), variation of average HI values by methods of Lawer (c) and Aich (d)

Similarly, when flow discharge is relatively high compared to flood peak but sediment concentration is zero, the Lawer method may yield unreasonable values. As shown in Figure ?, the dimensionless flow discharge is 0.106 and sediment concentration dropped to zero (flow discharge is 0.022 m3/s and sediment concentration is zero). And calculated HI value by Lawer method results in unreasonable high HI value (Normalized Qi=0.25, Turl and TUfl are 0.41 and 0.004, HI=99.05).

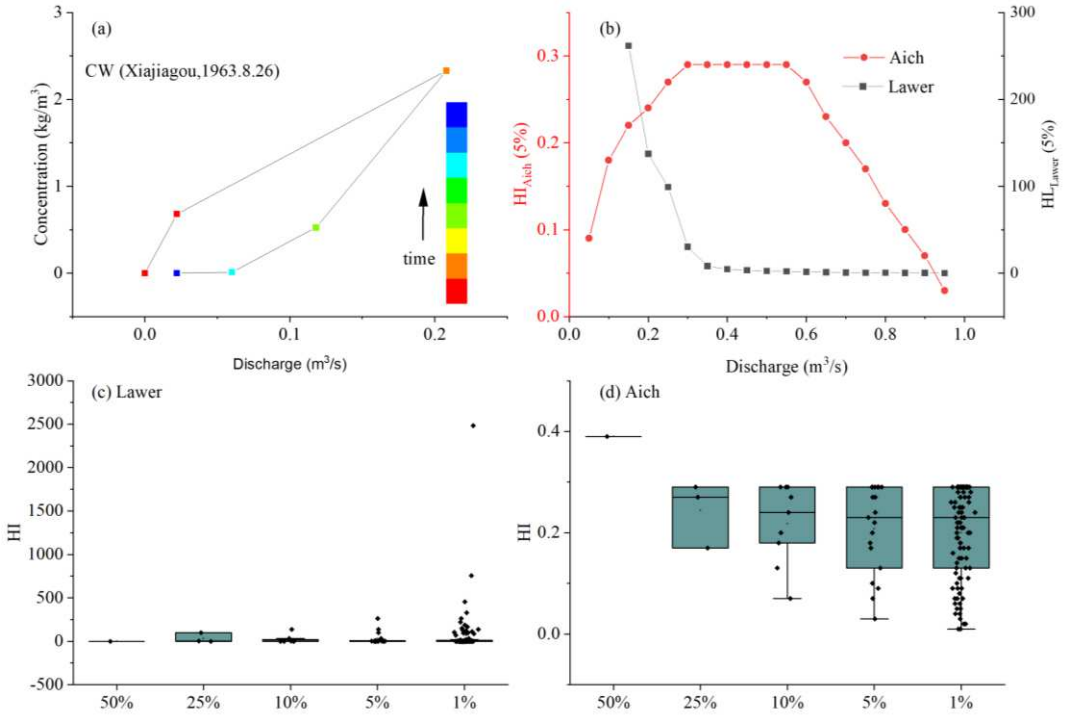


Figure 7 Typical storm event (Xiajiagou, 26th August 1963) (a), HI values with discharge interval of 5% by Lawer and Aich methods (b), variation of average HI values by methods of Lawer (c) and Aich (d)

The Lawer method is susceptible to significant variations in sediment concentration during the rising and falling phase, leading to unstable HI values. As shown in Fig. 8, when normalized discharge is 0.1, the corresponding TU values for the rising and falling phase are 0.36 and 0.09, respectively, and the corresponding HI value is 2.87.

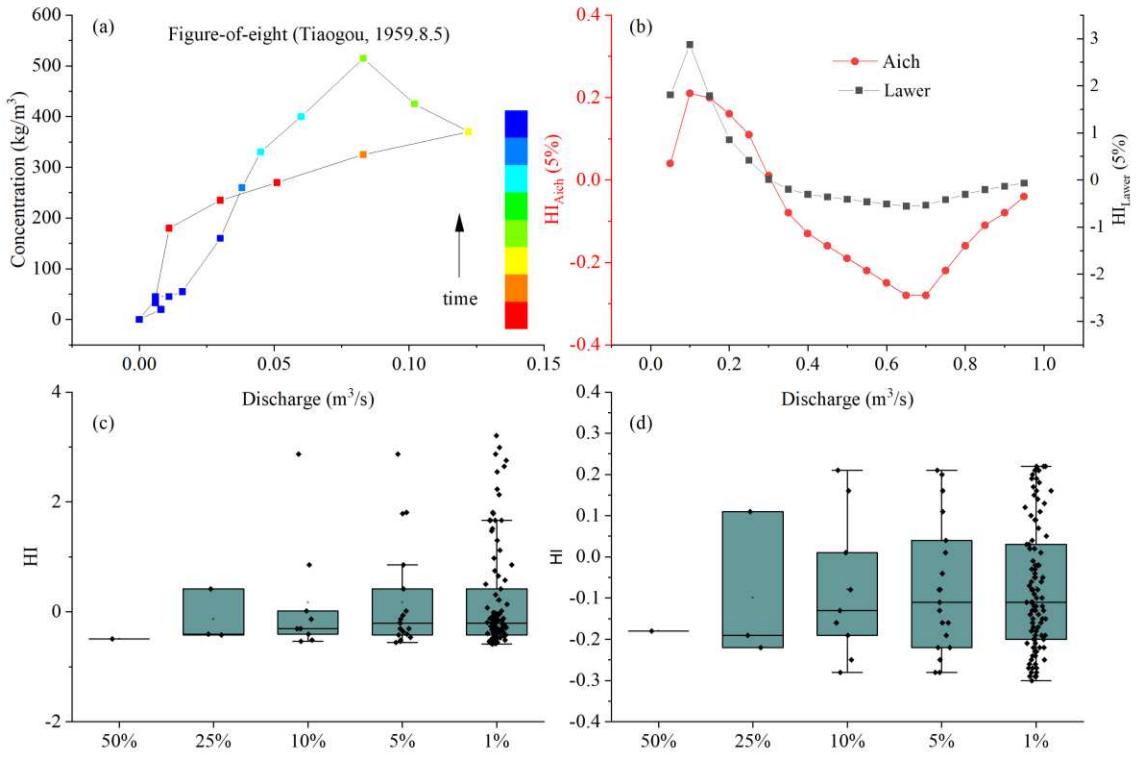


Figure 8 Typical storm event (Tuanyuangou, 1st August 1961) (a), HI values with discharge interval of 5% by Lawer and Aich methods (b), variation of average HI values by methods of Lawer (c) and Aich (d)

4.2 Spatial Heterogeneity of change of HI

For the whole Middle Yellow River, the monthly water-sediment relationships became more coordinated. However, the water-sediment relationship in different tributary watershed varies, and the changes of HI before and after large-scale ecological remediation efforts show spatial heterogeneity. For instance, monthly hydrology data in Zhangjiashan Hydrology station indicates an increase of HI value of the Jinghe River (0.23 versus 0.28) (Figure. 9), while the HI values in the Gaojiachuan Hydrology Station decrease from 0.03 to -0.02 (Figure 10). In the Jinghe River, suspended sediment is still mainly transported before flood season. However, in the Tuweihe River, suspended sediment concentration is mainly transported after flood season. Besides, it indicates limited sediment sources within the channel or even sediment depletion after the large-scale ecological remediation efforts in Tuweihe River.

For monthly hypothesis loop, sediment source area (Hudson, 2003), climate and vegetation were the most important factors (Zhu et al., 2023). Vegetation extent has complex effects on the hypothesis relationship, and it can directly affect discharge and sediment (Pruski and Nearing, 2002; Li et al., 2012; Nearing et al., 2005). Precipitation

(changes in the long-term pattern or interannual variability) has directly and indirect effects on discharge and sediment (Nearing et al., 2005; Pruski and Nearing, 2002; Seeger et al., 2004; Ran et al., 2013; Correll et al., 1999; Yang et al., 2015) lead to significant changes in the sediment. However, the quantifying the hysteresis pattern can help the understanding of the water-sediment relationship, the overall sustainability in a watershed, sustainable development of watershed ecology, and macro decision making on sediment regulation (Yeshaneh et al., 2014; Brandt et al., 2018).

The hysteresis patterns elucidate the interrogation of in-stream physical and chemical responses to storm events, which have been shown to be important periods for the transport of nutrients and sediment within catchments (Burt et al., 2015; Evans and Johnes, 2004).

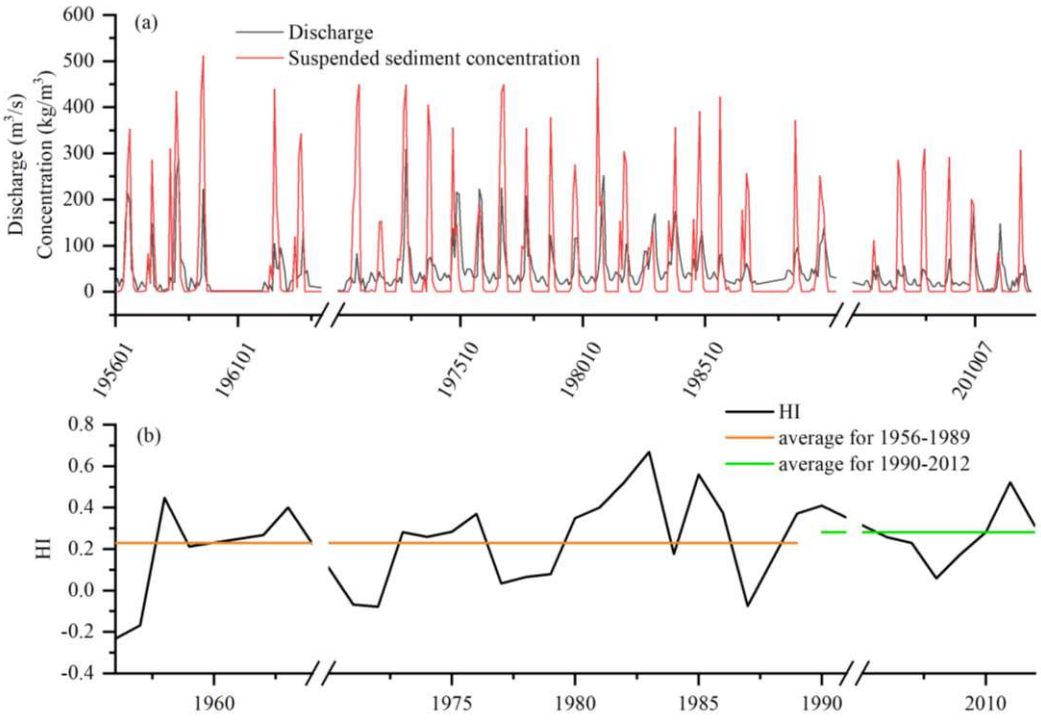


Figure 9 Monthly discharge and suspended sediment concentration and the corresponding HI values in Zhangjiashan hydrology station, Jinghe River, the Middle Yellow River

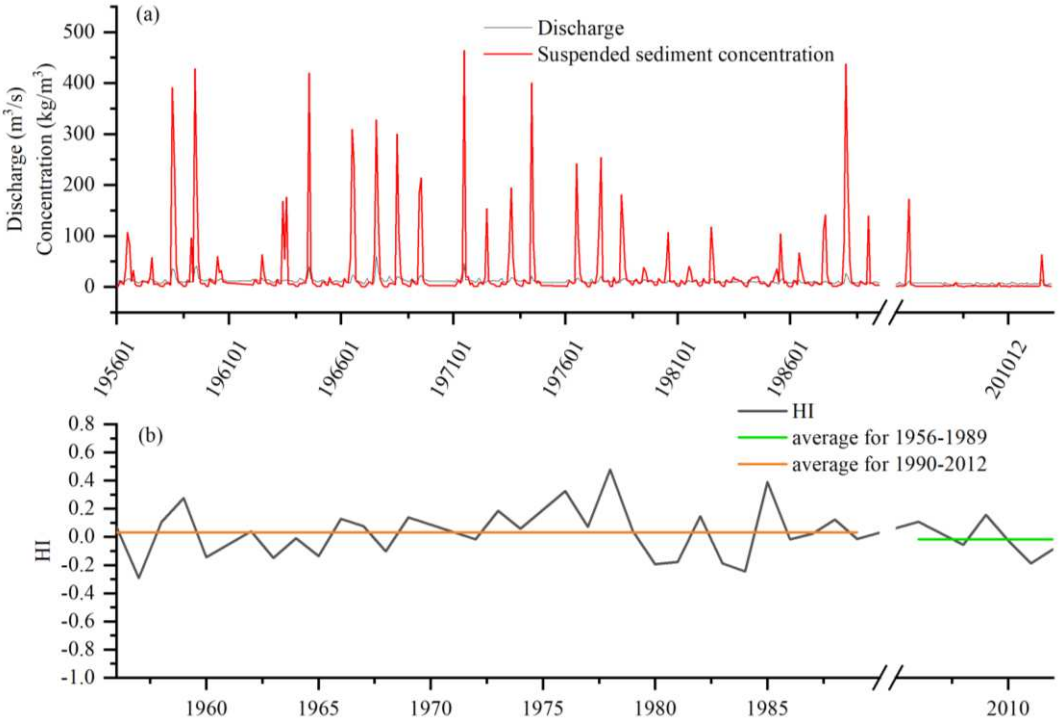


Figure 10 Monthly discharge and suspended sediment concentration and the corresponding HI values in Ggaojiachuan hydrology station, Tuweihe River, the Middle Yellow River

5 Conclusion

Based on flood data from experimental plots and monthly sediment-water data from hydrological stations in the middle Yellow River, the method for evaluate the hypothesis loop was evaluated and confirmed as the advantages of the Aich method. Subsequently, the Aich method was employed to assess changes in sediment-water coordination in the middle Yellow River following the implementation of ecological measures.

HI values by Aich method is much more stable, and can be used to compare different flood events and between different watersheds. HI values evaluated by Lawer

method fluctuates as it has certain drawbacks. For instance, the HI value by Lawer method is influenced by different magnitude concentration in the rising phase and falling phase, small discharge with large corresponding concentration, and large discharge with small corresponding concentration. Besides, the discharge interval of 25% is enough for evaluating the hypothesis loop. As the advantages of Aich method, it could be used to make comparison between different watersheds.

Both flood data from runoff sub-basins and long-term monthly data from hydrological stations indicate that ecological remediation has alleviated the water-sediment imbalance. In the middle reaches of the Yellow River, the dominance of sediment transport during the high-flow period over the low-flow period has decreased by 27%. In total, quantification hysteresis reveals understanding of catchment function.

Author contributions:

Data curation, writing—original draft preparation, P. Shen; writing—review and editing, P. Shen and H. Li; project administration, L. He; funding acquisition, L. He.

Funding This study was supported by the National Nature Science Foundation of China (U2243226 and 51979264).

Declarations

Conflicts of Interest: The authors declare that the research was conducted without commercial or financial relationships that could be construed as potential conflicts of interest.

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