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Assessing effects of dam operation on flow regimes in the lower Yellow River

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Abstract

River flow regimes are considered to be primary drivers of riverine ecosystems, while substantially altered by human activities such as damming and reservoir construction. A number of hydrologic indices were recognized to be ecological relevant and used to describe the different characters of flow regimes. At the same time several sets of indicators were developed to assess flow regime alterations, among which Indicators of Hydrologic Alteration (IHA) character the magnitude, duration, timing, frequency and rate of change. The Histogram Matching Approach (HMA) uses the degree of histogram dissimilarity employing the quadratic-form distance between the frequency vectors of the pre- and post- histograms based on the IHA. In this study, Mann-Kendall method (MK) were applied to investigate the temporal abrupt in the lower Yellow River, and then critical influential factors were explored for flow regimes in the lower Yellow River using HMA. Pre- and post- by the year 1984 was separated based on the analysis on daily streamflow records from 1958 to 2006 at the Lijin gauge station. Results revealed that after the separating year, the frequency of low flow is much higher during all twelve months, especially for April. no middle or high flow was recorded, and the calculated distance between pre- and post- equals to 1.0704. The 1-day, 3-day, 7-day, 30-day and 90-day minimum and maximum flow magnitude are shrinking, with the average distances are 0.337 and 0.417, respectively. Duration of low pulse has extended and high pulse has shortened. It can be concluded that the flow magnitude of YR (the Yellow River) is much smaller; the high flows are cut as well as postponed temporally. April should be taken as the critical periods for water resources management because of high frequency of low flow, and important water demands for most vegetation's germination in downstream of the Yellow River Basin

Key word: Yellow River, flow regime, hydrologic alteration, Mann-Kendall, Range of Variation Approach

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1. Introduction

River flow regime is considered to be the most driven force to sustain the ecological health of a river [1]. As a widespread way of controlling water resources the construction of dams and reservoirs facilitate agriculture irrigation, flood control, power generating and reliable water resource. Meanwhile, regulation of dams for human activities substantially change the river flow regime, such as reducing peak flows during the flooding season and releasing during the dry season [2]. In recent years, abilities of the dams to change natural hydrologic processes have increased in many river basins. In order to understand and predict the biological impact of altered flow regimes on riverine biota, recently, many researchers have identified different ecologically relevant hydrological indicators to assess or describe the alterations of natural river flow regime [3], which comprise of magnitude of flows; timing of extreme flows; the frequency, predictability and duration of floods, droughts, and intermittent flows; daily, seasonal and annual flow variability; and rate of change [4]. As one set of proposed hydrologic indices, the Indicators of Hydrologic Alteration (IHA) was commonly used worldwide [5-9]. Indicators of Hydrologic Alteration (IHA) considered a full range of natural flow variability, including magnitude, frequency, timing, duration and rate of change[10]. 32 IHA parameters were categorized into these five groups of hydrologic features. In order to determine the flow regime target using IHA, Range of Variability Approach (RVA) was established [11]. RVA incorporated natural flow regime to optimizing water release strategies, it presumes the natural (or pre-impact) flow series be the ideal condition, and when environmental flow schemes attain the target ranges as the natural flow series at a 50% frequency (the interval between 25% and 75%), the ecological health would be expected. Usually, the pre- and post-impact years are divided by a separating year. The year can be selected as the separating year when the river flow regimes were disturbed significantly after huge dams were built or reservoirs began to operate [6-8, 12]. When using RVA target, the variations of parameter value without the target range are not taken into account [13]. To conquer this weakness, Shiau [13] revised the RVA and employed a Histogram Matching Approach (HMA). The HMA uses the degree of histogram dissimilarity employing the quadratic-form distance between the frequency vectors of the pre- and post- histograms based on the IHA and prescribe the whole variance of the hydrologic alterations. And for different types of rivers, a certain similarity function was used.

However, this method is not suitable for assessing the combined impact of the dams in the upper river. The Mann-Kendall (M-K) method, which is widely employed to detect the temporal and spatial trend of hydrologic time series, can identify the abrupt point, thus to identify the separating year [14-15]. The lower Yellow River basin is characterized by cascade dams and thus increasingly intensified human regulations, which further altered the river flow regime to the coastal ocean over the past 50 years[16]. Exploring the extent to which human intervention affected the hydrologic regimes of the lower Yellow River can better understand the trend of flow alteration in lower Yellow River and aid the basin management. The objectives of this paper were: 1) to identify and evaluate the most influential factors on the hydrologic regimes of lower Yellow River; and 2) to explore the impacts of dams operation for these variations between two periods.

2. Study area

The study reach in the lower Yellow River Basin lies in the area from 118°E to 119°24′E and from 37°20′N to 38°N, and belongs to the warm temperate monsoon region. The annual average air temperature is 12.1℃, annual average rainfall 551.6 mm, and the number of frostless days is 196 [17]. We selected the Lijin gauge (Figure 1) as the control node to study the influence of its upstream dams on the hydrologic regime. Zero-flow events occurred recent 50 years owing to the dam operation above this gauge. The Lijin gauge is the last gauge station, located in the Yellow River Delta. The reach below the Lijin gauge is one of the most active reach of land-ocean interaction worldwide. A huge load of sediment were supplied to the Bohai Sea through the China North Plain, forming a delta complex at the Bohai Sea coast [18]. Large number of dams and reservoirs were built in the middle and lower basin between 1950 and 2001 aiming to control floods and to reduce sediment deposition downstream [6]. Up to now, there are 24 reservoirs scattering widely in the river basin with storage capacities exceeding 0.10×10^9 m^3, among which four major reservoirs along the mainstream of the Yellow River are most influential: the Sanmenxia, Liujiaxia, Longyangxia, and Xiaolangdi reservoirs [2]. The disturbances have accumulation effects on hydrological processes in the downstream and estuary in the Yellow River. Correspondingly, sediment load carried by river discharges reduced due to the flow regime alteration.

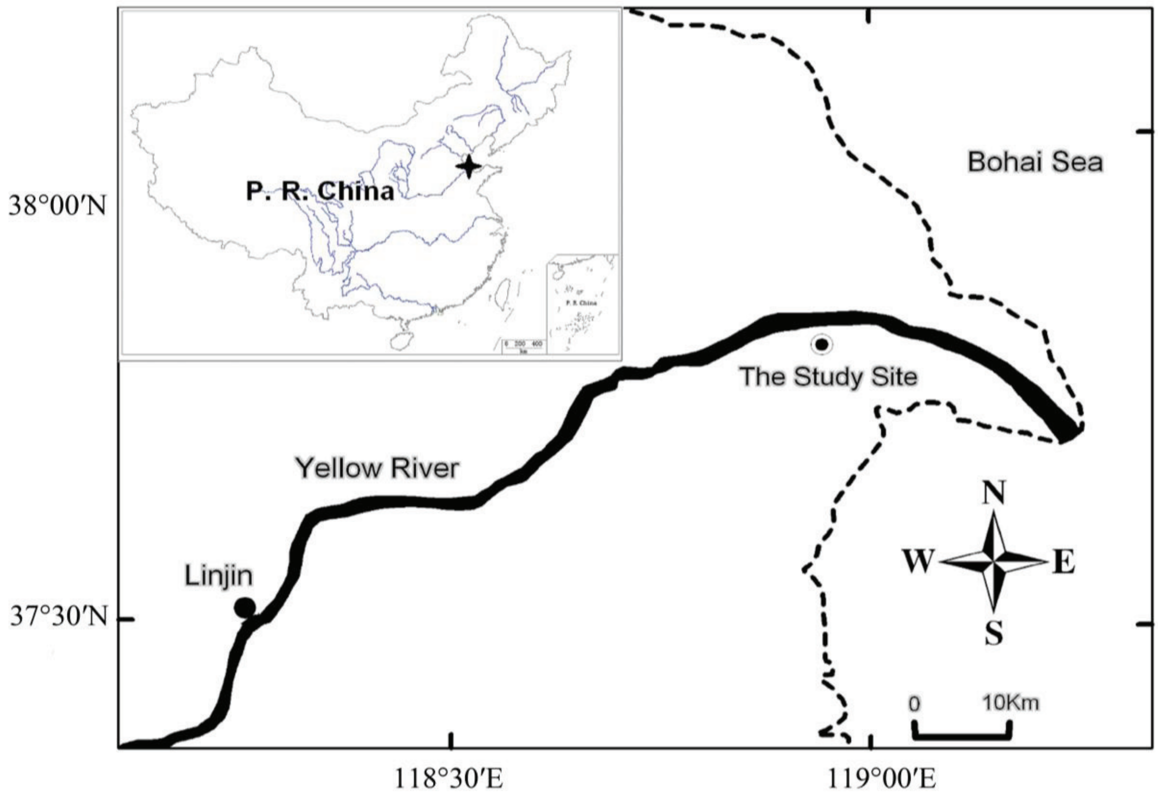

Fig. 1. Location of the study reach—below the Lijin gauge [19]

3. Methods

3.1. The Mann-Kendall (MK) method

The non-parametric Mann-Kendall (MK) method was used to detect the abrupt point during the study period, which has been widely used as an effective method to identify the statistically significant trend in hydrological time series [14-15, 20-21]. In this paper, the year in which the abrupt occurred is considered to be the separating year for the IHA calculation.

3.2. The IHA method

IHA were employed to evaluate the hydrologic alteration after the separating year. In Table 1, 33 parameters were categorized into five groups including the magnitude, timing, frequency, duration, and rate of change. While, 7-day-minimum-divided, number of zero-flow days and employ number of flow reversals was included in the calculation instead of number of rises and falls[10]. The 7-day minimum value was divided by the annual mean flow, and number of flow reversals equal to the sum of rise count and fall count.

In this study, 2 steps were implemented to calculate the IHA,

Step 1. Define the data series (e.g., stream gauge or well records) for pre- and post-impact periods in the ecosystem of interests.

Step 2. Calculate values of hydrologic attributes.

We calculated Values for each of 32 ecologically relevant hydrologic attributes for each year in each data series, i.e., one set of values for the pre-impact data series and one for the post-impact data series.

3.3. The HMA method

In order to assess the flow alteration of the post-impact series from the natural flow regimes, we employed the HMA to evaluate the trend of river flow below Lijin gauge after the separating year based on the quadratic-form distance between the frequency vectors of the pre- and post-impact histograms weighted by a specified similarity matrix [13].

4. Results

4.1. Trend analysis

The M-K method with a nominal rejection rate of 5% was applied to reveal the temporal trends for more accurate results for annual runoff. The results were presented in Figure 2. There is a cross point of C1 and C2 in 1984, which indicates that there was an obvious abrupt change in 1984 at 95% confidence level. The year 1984 can be selected as the separating year for IHA alteration and HMA calculation. We divided the Lijin gauge mean daily flow data from 1958 to 2006 into pre- and post- impact data series.

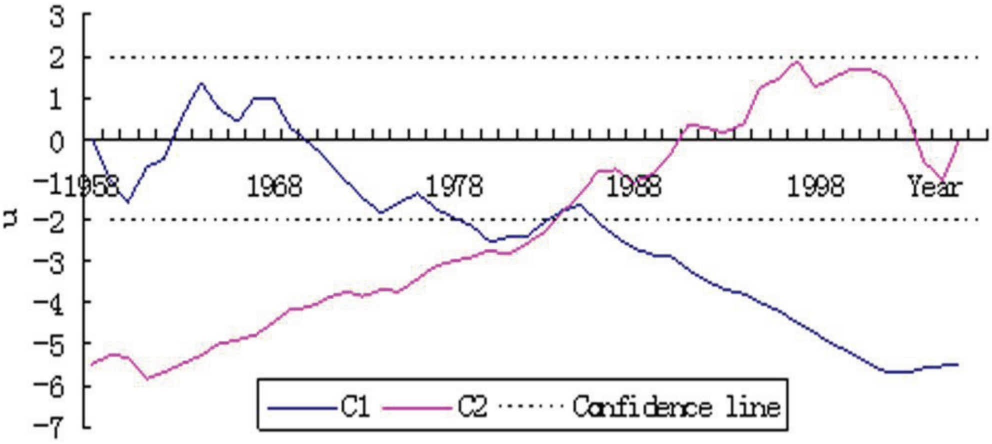

Fig. 2. The abrupt change tested by the Mann-Kendall method for annual flow series in Lijin station from 1958 to 2006.

4.2. Changes in the magnitude of flows

First, we calculated the IHA values of 33 parameters for each year, and then calculated the means and coefficient of variations for the pre- and post-impact, respectively. Further more, the degree of variation by RVA and distances (d_Q) between pre- and post- impact HMA algorithm were calculated (Table 1). Means of monthly flow throughout the post-impact period showes a decreasing trend compared with that in the pre-impact period. The dispersions of variation were higher than those for the pre-impact period, indicating a higher monthly fluctuation in the post-impact period. The reason for this phenomenon may be that the monthly mean flows were lower in the post-impact period.

The greatest effect of impoundment at monthly scales was concentrated in two months: March and April. The distances for March and April were 65.7% and 96.6%, respectively. Associated with the diversion the overall degrees of flow regime alteration in these two months were relatively high (see Fig. 3). For March, the frequency of flows lower than 500m^3/s was 0.83 and occurrence between 500 m^3/s to 1000 m^3/s was 0.17, while for data pre-impact the frequency were 0.32 and 0.26, respectively. In contrast, the occurrence of flow above 1000 m^3/s was not observed for post- impact period. The above trend also applied to April, in which the frequency of daily flow below 800 m^3/s was close to 100%, while flow above 800 m^3/s was not observed during the past- diversion period.

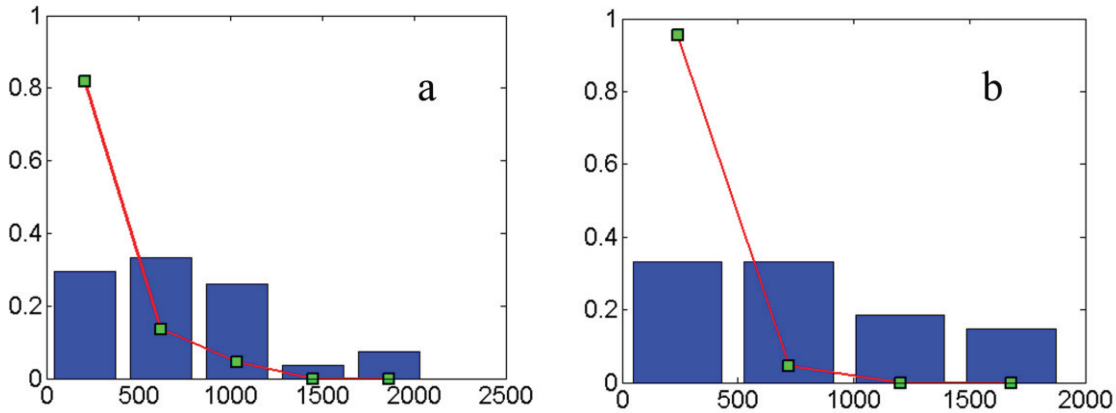

Fig. 3. (a) Frequency histograms of pre- and post- diversion series of monthly flows in March; (b) Frequency histograms of pre- and post-diversion series of monthly flows in April

Table 1 IHA alteration and HMA distance for Lijin gauge

Hydrologic parameter	Pre-impact period:1958-1984 (27 years)		Post-impact period:1985-2006, (22 years)		HMA: dQ (%)	RVA: %
	Means	Coeff. Of Variation	Means	Coeff. Of Variation		
IHA Group 1						
January	516	0.47	387	0.45	41.0	9.1
February	435	0.58	314	0.62	22.7	-81.8
March	854	0.62	317	0.80	65.7	-45.5
April	916	0.57	211	0.91	96.6	-45.5
May	861	0.80	264	1.09	45.8	-18.2
June	640	1.14	497	1.17	16.5	-63.6
July	1647	0.68	1053	0.65	35.7	0.0
August	2684	0.56	1346	0.87	54.7	-36.4
September	2861	0.62	1581	0.88	38.2	-9.1
October	2572	0.59	1540	0.88	29.1	-72.7
November	1645	0.54	800	0.84	52.2	-63.6
December	800	0.64	491	0.66	38.2	-27.3
IHA Group 2						
1-day minimum	68	1.27	30	1.53	19.7	81.8
1-day maximum	5756	0.33	7574	1.41	62.2	-63.6
3-day minimum	74	1.24	34	1.38	21.6	81.8
3-day maximum	5443	0.35	4540	0.86	46.6	-72.7
7-day minimum	86	1.19	39	1.29	21.6	90.9
7-day maximum	4935	0.36	3551	0.64	36.9	-63.6
30-day minimum	199	0.76	86	1.00	44.3	-9.1
30-day maximum	3849	0.43	2449	0.61	37.4	-54.5
90-day minimum	454	0.63	183	0.85	57.3	-45.5
90-day maximum	2904	0.50	1734	0.63	38.0	-63.6
7-day minimum divided	0	1.26	0	1.13	19.1	36.4
Zero-flow days	10.05	3.20	4.11	1.88	--	0.0
IHA Group 3						
Julian date of annual minimum	133	0.70	113	0.40	37.1	-9.1
Julian date of annual maximum	237	0.32	224	0.19	46.9	-18.2
IHA Group 4						
Number of high pulses	5	0.59	7	0.45	39.8	9.1
Number of low pulses	7	0.47	6	0.44	48.1	-9.1
Duration of high pulses	110	0.91	41	0.59	75.0	-36.4
Duration of low pulses	43	0.66	92	1.14	55.7	-63.6
IHA Group 5						
Rise rate	162	0.23	137	0.83	63.8	-72.7
Fall rate	121	0.22	108	0.80	33.4	-63.6
number of reversals	108	0.17	134	0.19	67.9	-45.5

4.3. Changes of the extremes and timing of flows

There were significant differences in the annual minima 1-, 3-, 7-, 30- and 90-day means between the two periods, and the post- impact values were all smaller than the pre- impact values. On average, these 5 indicators for flows have declined at least 50% (Table 1). However, due to the human regulation, the zero flow days has declined, the average days for pre- and post-impact are 10.05 and 4.11, respectively.

Duration of high pulses has dropped from 110 to 41 days, and the hydrologic alteration factors for HMA and RVA are 75% and -36.4% (minus means decline). And on the other hand, the duration of low pulses has rise significantly, from 43 to 92 days. The hydrologic alteration factors were 55.7% and -63.6%, respectively.

5. Discussions

The current research has shed light on the impacts of dams on hydrological regimes. For the Yellow River, in particular, operation of dams and reservoirs are the most important human activities affecting the river hydrological cycle [2]. Review of the monthly average water discharge from 1950 to 2000 shows that the discharge decreasing were undoubtedly caused by the operations of the Sanmenxia, Liujiaxia, Longyangxia and Xiaolangdi reservoirs. Yang et al. [6] using RVA and mapping technique investigate the spatial variability of hydrologic alteration (HA) due to dam construction along the middle and lower Yellow River over the past five decades. The HA results indicated that the Xiaolangdi reservoir has significantly changed the hydrologic alteration, impacts of reservoirs on hydrological processes downstream of the dams are closely associated with the regulating activities.

In this paper, Lijin gauge records were used for RVA calculation, and the RVA factors are -36.4 and the distance from the pre-impact period are 75.0. Both the results show that the duration of high flow has shrunk. Almost at the same period, using records at Huayuankou gauge, located at the end of the middle reaches, Wang et al. [2] found that the measured water discharge in flood seasons accounted for more than 60% of the annual water discharge in the 1950s, but decreased to 43% in the 1990s, and the number of days of high pulse was reduced sharply in response to the operation of dams and reservoirs.

6. Conclusion

Construction and operation of dams, in order to increase the reliability of water resource, inevitably induced high hydrologic alteration. The annual distribution pattern of water discharge has bee changed during the period of 1958 to 2006. It can be concluded that:

1） The duration of high pulse has reduced, the flow magnitude of YR is much smaller and the high flows are cut as well as postponed temporally.

2） The magnitude and timing of the hydrologic events have been changed significantly. April should be taken as the critical periods for water resources management because of high frequency of low flow, and important water demands for most vegetation's germination in downstream of the Yellow River Basin. These alterations have severe impacts of the natural balance of eco-flow regimes.

3) The alteration of flow regime can bring substantial threats to wild species and consequently result in undesirable ecological effects. Therefore, it is necessary to further investigate the responses to hydrological regimes alteration resulting from dam construction.

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