Supplementary Information for

Identifying regime transitions for water governance at the Yellow River Basin, China

Shuang Song[1], Shuai Wang[1], Xutong Wu[1], yongping Wei[2], Graeme S. Cumming[3], Yue Qin[4], Xilin Wu[5], Bojie Fu[1,5]

[1] State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing, 100875, Beijing, China.

[2] School of Earth and Environmental Sciences, The University of Queensland, Brisbane, 4067, QLD, Australia.

[3] ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, 4811, QLD, Australia.

[4] College of Environmental Sciences and Engineering, Peking University, Beijing, 100875, Beijing, China.

[5] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, 100875, Beijing, China.

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Introduction Section 1 provides a brief introduction to four regions (Source Region, Upper Region, Middle Region, and Lower Region -SR, UR, MR, and LR) of the YRB. Section S2 detailed explains the changing trend of three indicators. Section S5 describes the correlations between the three indicators and Section S1 provides some sensitivity analysis for testing robustness.

YRB Regions When calculating the indicators of IS and IA in this study (the SFV-index and the allocation entropy metric), we need consider data at a regional scale. The YRB can be divided into four regions to calculate the indicators considering both socio-economic and natural conditions. The division aligns with the customary schema from publications and the YRCC (Yellow River Water Conservancy Commission, 2010; Wang et al., 2019), hydrological characteristics are described in Figure S2.

- **Source Region (SR):** Over 50% of natural runoff originates from this region. The most ecological function here is water yield, as sparsely populated and less economically developed.

- **Upper Region (UR):** With the highest per capita irrigated land area, there are numbers of large irrigation lands in this region. However, irrigation efficiency is relatively much lower than its lower reaches.

- **Middle Region (MR):** Crossing Loess Plateau, a famous rich-sand area, Yellow River loads most of its sediments here with the highest soil erosion risk. The "grain for the green" project changed the water utilization here strikingly to reverse this situation (Wu et al., 2020).

- **Lower Region (LR):** With a dense population and the traditional agricultural trajectory, the lower region used to be the largest water use region. However, as the industrial transformation going, the proportion of agriculture keeps decreasing, but LR is still the largest water use region in each aspect.

Based on the above vary characteristics, we applied the division of the YRB: source region (SR), upper region (UR), middle region (MR), and lower region (LR). Four important hydrological stations can distinguish the regions (see Figure S1).

Trend of Indicators

The index of stress (SFV indicator, IS) in the study period (including three different periods) showed a change trend of first decreasing, then rapidly increasing, and finally slightly decreasing again (Figure S5 A), indicating that water resource pressure first decreased, then rapidly increased, and then stabilized. Among the four different regions (Figure S5 B), the source region (SR) has almost no contribution to IS changes in the three periods, and the downstream region (DR) only has a weak negative contribution in the governance transforming regime and the adaptation oriented regime. The upper and middle reaches (UR and MR) had the greatest impact on the IS changes. Wherein, the upper region (UR) made the greatest contribution during the massive supply regime and governance transforming regime, while the middle reaches made the greatest contribution in adaptation oriented regime.

In terms of water use purpose indicator, IP remained basically unchanged in a massive supply regime, but showed a rapid decline in the period of governance transformation and adaptation oriented regime (Figure S3 A). Throughout the three periods, the change of irrigation water dominated the change of the IP, while urban and rural water for human settlements and rural livestock had almost no influence on the change of IP (Figure S4 B).

The water allocation (IA) showed an obvious "V-shaped" trend, indicating that water resources in the different regions within the YRB first gradually moved away from uniform distribution, and then gradually tended to uniform distribution since 2000 (Figure S4).

Correlation of Indicators

By analyzing the correlation of the integrated management index (IWGI) and its three sub-indexes: stress (IS), purpose (IP) and allocation (IA) in three different periods, namely, the massive supply regime (P1: 1965 $\sim$ 1978), governance transforming regime (P2: 1979 $\sim$ 2001) and adaptation oriented regime (P3: 2002 $\sim$ 2013), the following results are obtained.

When we focus on the correlation from P1 to P3, the results show significant negative correlation between IS and IP (correlation coefficient is $r = -0.75$, $p < 0.01$), indicating that there is a strong negative relationship between IS and IP. On the other hand, there is a significant positive correlation between IA and IWGI (correlation coefficients are $r = 0.75$, $p < 0.01$), indicating a positive relationship between IA and IWGI. However, the correlations of other combinations are not statistically significant overall.

The correlations between time periods are very different with the overall trend above. There is no significant correlation between any indicator combinations in the massive supply regime (P1). In the governance transforming regime (P2), there is a significant negative correlation between IS and IP (correlation coefficient $r = -0.90$, $p < 0.01$), a significant negative correlation between IS and IA (correlation coefficient $r = -0.87$, $p < 0.01$), and a significant positive correlation between IP and IA (correlation coefficient $r = 0.77$, $p < 0.01$). The correlations between IS and IP, IS and IA, and IS and IWGI were not statistically significant in the adaptation oriented regime (P3). However, there is a significant negative correlation between IP and IA (correlation coefficients are $r = -0.86$, $p < 0.01$).

Robustness In order to enhance the robustness of this study, we tested the identification results of mutation points at different significance levels. Our results that only two mutation points (1978 and 2001) could be identified at the confidence level of 0.0005 to 0.05 (Figure S7).

We have also employed a series of popular breakpoint detection methods to validate the results obtained through the Pettitt test. The names of these methods, their respective results, and the references to the pertinent literature can be found in the accompanying table S2. A consensus was observed among all methods regarding the identification of the second breakpoint, which consistently emerged around the year 2000. There was a minor variation of three years in the identification of the first breakpoint, pinpointed either in 1975 or 1978.

After a thorough evaluation, we opted for the Pettitt method, which identified 1977 as the first breakpoint. This decision was influenced by our intent to ensure a balanced distribution of the number of years across each identified period. The consistency in the identification of breakpoints, especially the second one, across different methods underscores the robustness of our findings, attesting to their insensitivity to the choice of the breakpoint detection algorithm. This robustness reinforces the credibility and reliability of our analyses and conclusions, reflecting the methodological rigor embedded in our study.

In addition, we analyzed the changes of reservoir flow that are not reflected in the IWGI. Among all the reservoirs (Figure S6), we focused on 9 major reservoirs built successively and find that the reservoirs began to enhance their variability after the governance transforming regime, suggesting a higher level of regulating (Figure S8).

Last, we tried our best to strengthen the period of this study despite the limitations of time span of the multiple-source dataset. We calculated the IWGI from 2003 to 2017 by using data from Yellow River Water Resources Bulletin to extend the study period. Since our results suggest no significant regime change (Figure S9), we think it is robust that the YRB experienced two significant water governance regime changes in 1978 and 2001, without further changing since 21th century.

References

Bai, J. (1997, June). Estimating Multiple Breaks One at a Time. *Econometric Theory*, *13*(3), 315–352. doi: 10.1017/S0266466600005831

Keogh, E., Chu, S., Hart, D., & Pazzani, M. (2001, November). An online algorithm for segmenting time series. In *Proceedings 2001 IEEE International Conference on Data Mining* (pp. 289–296). doi: 10.1109/ICDM.2001.989531

Killick, R., Fearnhead, P., & Eckley, I. A. (2012, December). Optimal detection of changepoints with a linear computational cost. *Journal of the American Statistical Association*, *107*(500), 1590–1598. doi: 10.1080/01621459.2012.737745

Matteson, D. S., & James, N. A. (2014, January). A Nonparametric Approach for Multiple Change Point Analysis of Multivariate Data. *Journal of the American Statistical Association*, *109*(505), 334–345. doi: 10.1080/01621459.2013.849605

Pettitt, A. N. (1979). A Non-Parametric Approach to the Change-Point Problem. *Journal of the Royal Statistical Society. Series C (Applied Statistics)*, *28*(2), 126–135. doi: 10.2307/2346729

Wang, S., Fu, B., Bodin, O., Liu, J., Zhang, M., & Li, X. (2019, September). Alignment of social and ecological structures increased the ability of river management. *Science Bulletin*, *64*(18), 1318–1324. doi: 10.1016/j.scib.2019.07.016

Wu, X., Wei, Y., Fu, B., Wang, S., Zhao, Y., & Moran, E. F. (2020, October). Evolution and effects of the social-ecological system over a millennium in China's Loess Plateau. *Science Advances*, *6*(41), eabc0276. doi: 10.1126/sciadv.abc0276

Yellow River Water Conservancy Commission. (2010). *Yellow River Basin Comprehensive Plan.* Zhengzhou, Henan: Yellow River Water Conservancy Press.

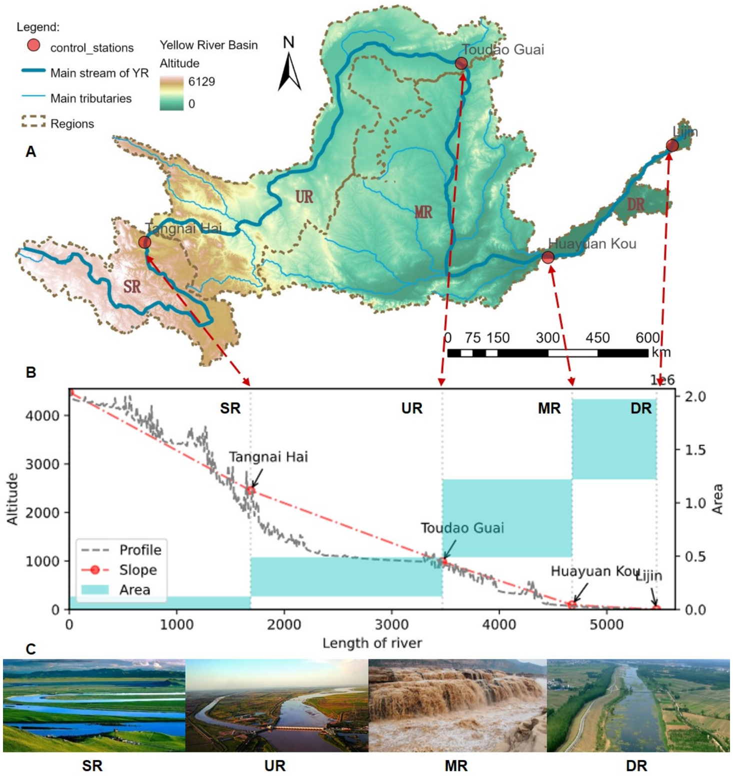

Figure S1. The study area. **A.** Diagram of the YRB and the subdivision of the basin (SR: Source Region, UR: Upper Region, MR: Middle Region, DR: Downstream region). **B.** Profile of the main channel of the Yellow River. The hydrological stations control the SR, UR, MR and DR. **C.** Typical landscapes in different regions in the YRB.

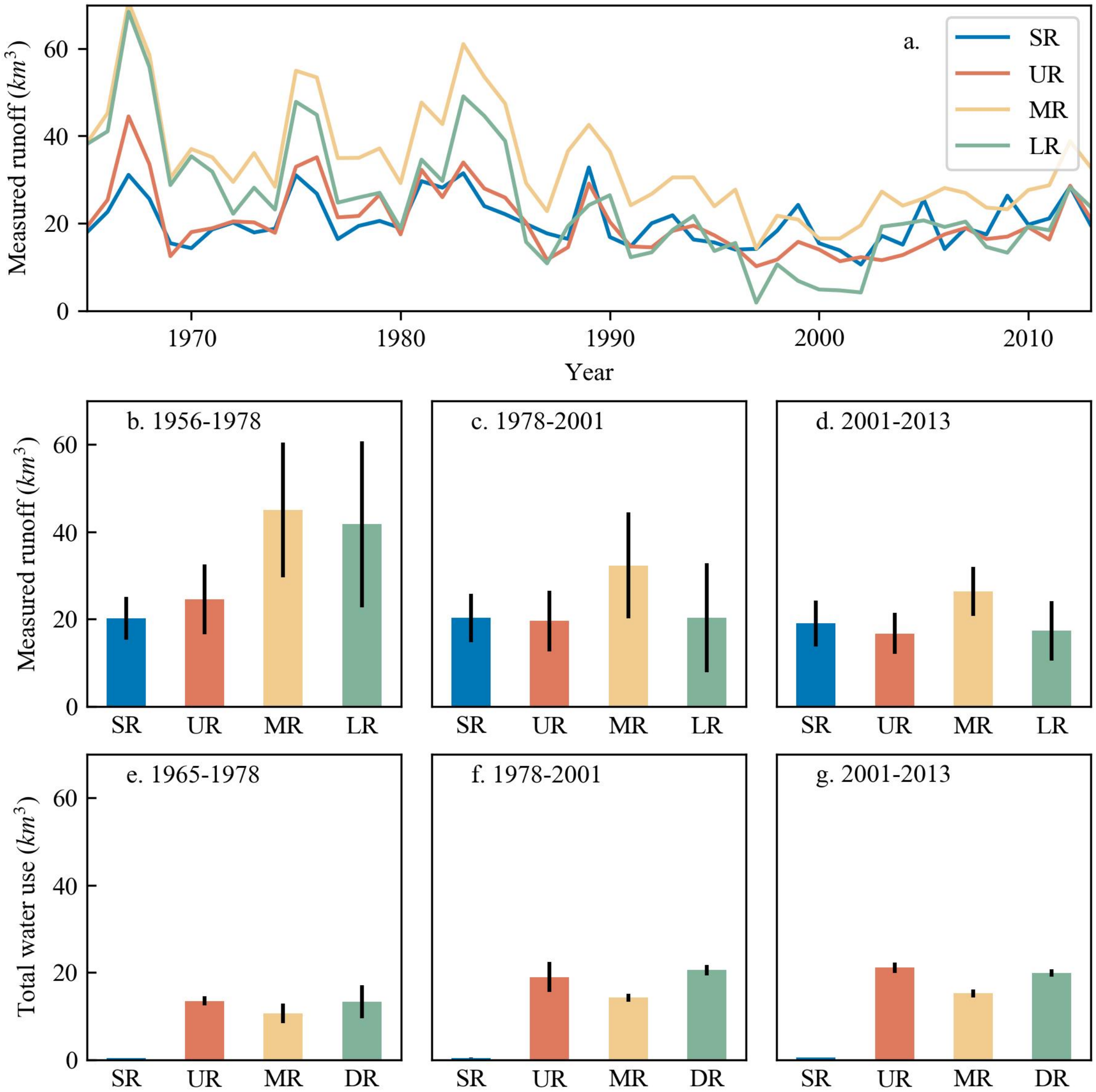

Figure S2. **a.** Measured runoff of different regions in the Yellow River Basin from 1965 to 2013. **b.** Measured runoff of different regions under different water governance regimes. **c.** Natural river runoff of different regions under different water governance regimes.

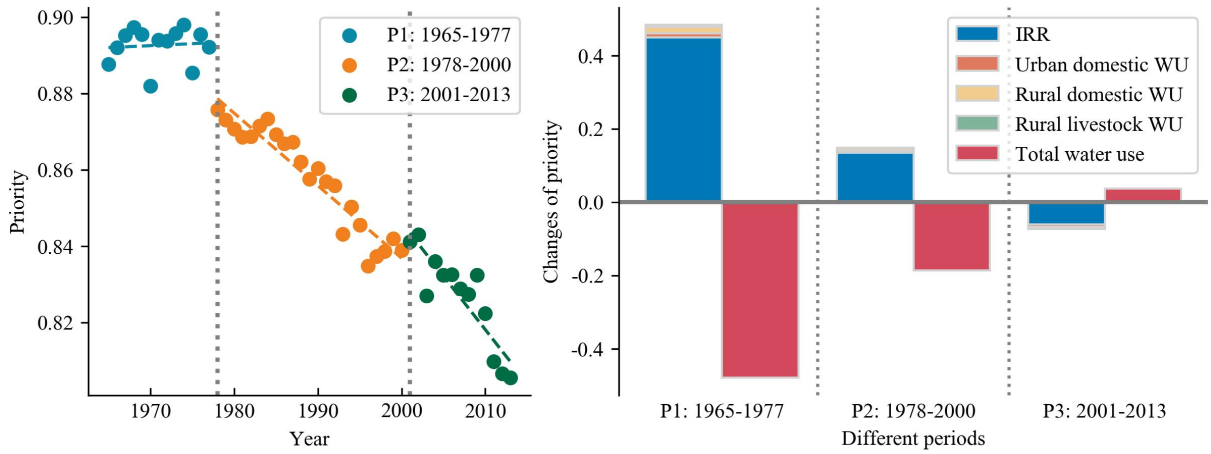

Figure S3. **left** Changing trend of the indicator of purpose (IP) **right** contributions of different water use sectors to the IS's changes.

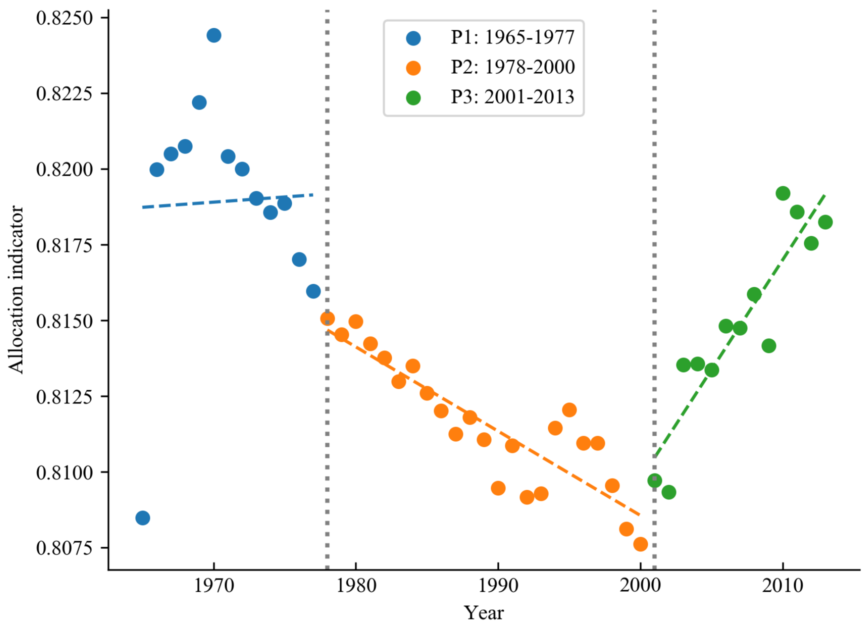

Figure S4. Changing trend of the indicator of allocation (IA)

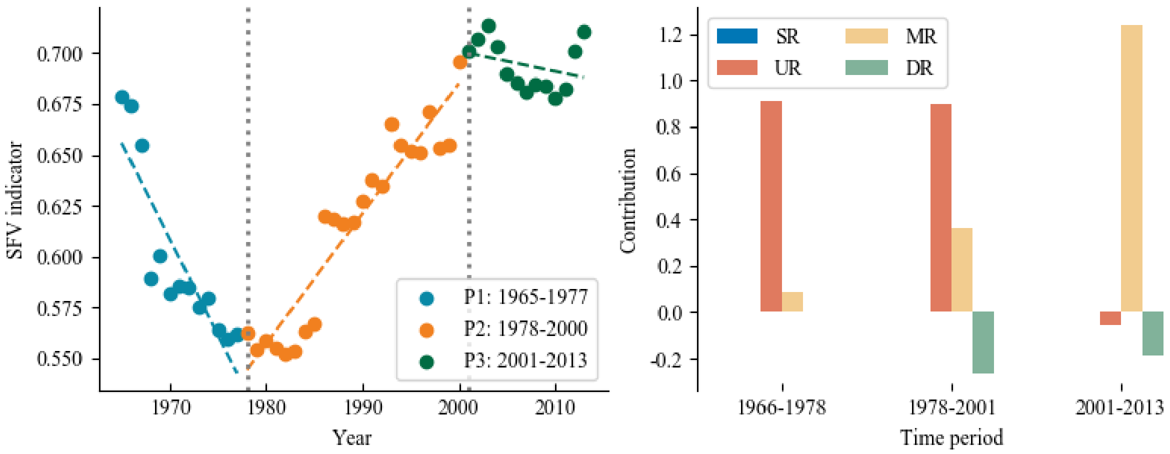

Figure S5. **Left** Changing trend of the indicator of stress (IS). **Right** contributions of different region to the IS's changes.

Table S1. The correlation of the Integrated Governance Index (IWGI) and its three sub-indicators (IS, IP, IA)

Period	IS vs IP	IS vs IA	IP vs IA	IP vs IWGI	IA vs IWGI	IS vs IWGI
P1 to P3	-0.75 *	-0.29	0.36	0.37	0.75 *	0.14
P1	-0.08	-0.31	0.06	0.14	0.51	0.65
P2	-0.90 *	-0.87 *	0.77 *	-0.18	-0.13	0.5
P3	0	-0.38	-0.86 *	-0.33	0.61	0

Method	Breakpoints	Parameters*	Reference
Generalized ESD Test	1975, 1978, 2001	No	(Matteson & James, 2014)
Pettitt Method	1977, 2000	No	(Pettitt, 1979)
Pelt	1975, 2000	$pen = 0.05$	(Killick et al., 2012)
Binary Segmentation	1975, 2000	$bkp = 2$	(Bai, 1997)
Bottom-Up Segmentation	1975, 2000	$bkp = 2$	(Keogh et al., 2001)

pen: Penalty coefficient; *bkp*: Number of breakpoints. *No*: Non-parametric test.

Table S2. Comparison of different breakpoints detection methods

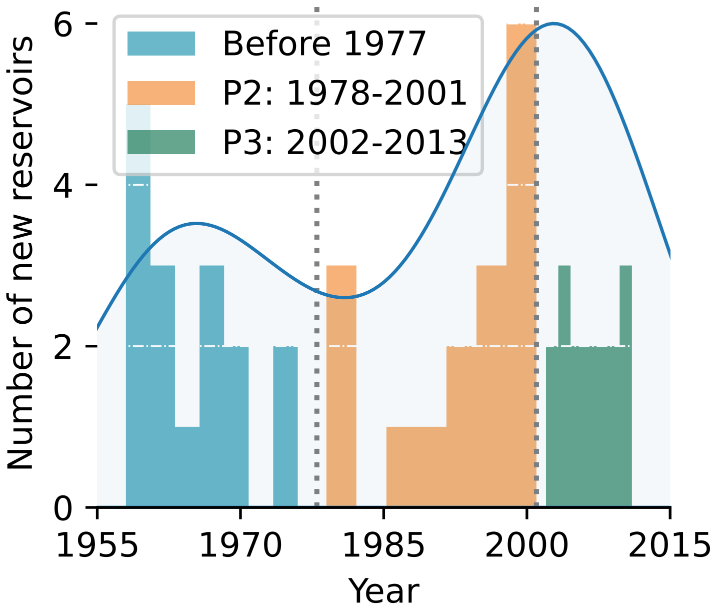

Figure S6. Numbers of new reservoirs in each year.

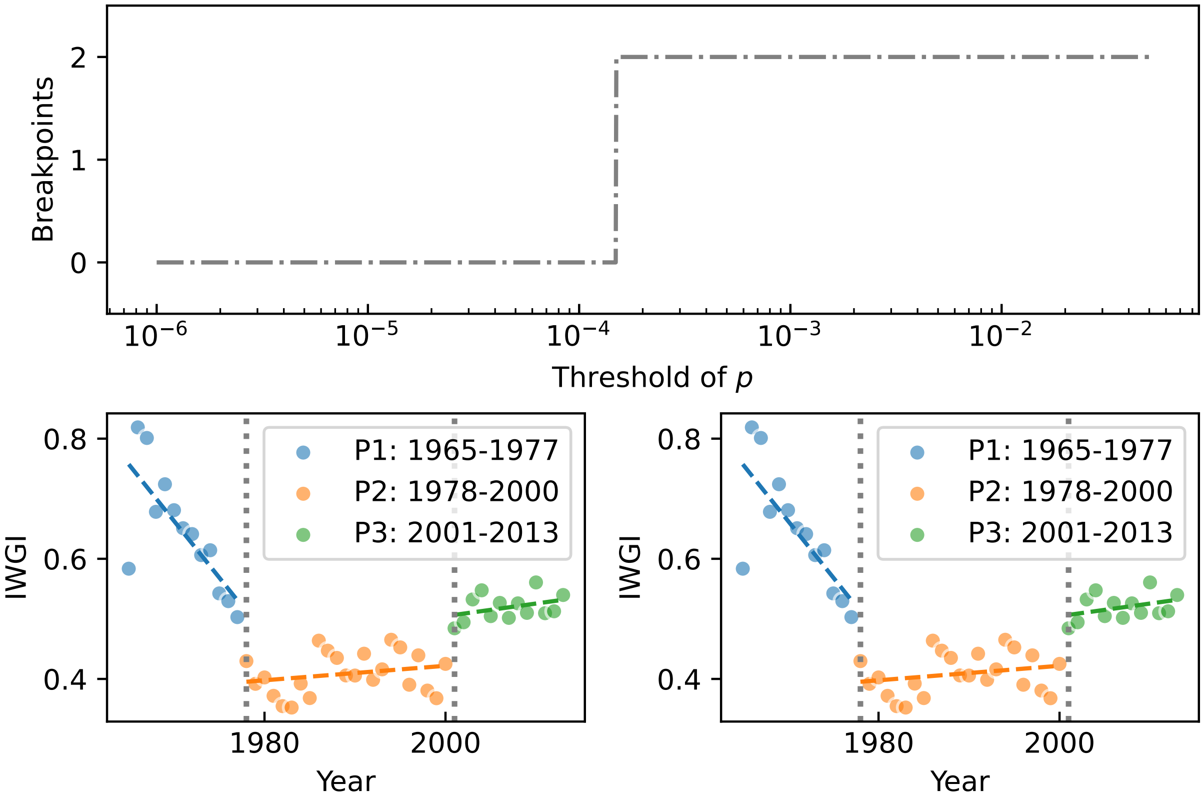

Figure S7. Sensitivity analysis of the threshold of p-values. **A.** number of breakpoints in different p-values, the scheme with two-breakpoints are the dominant situation. **B.** Threshold of p-values $\alpha = 0.0005$. **C.** Threshold of p-values $\alpha = 0.05$.

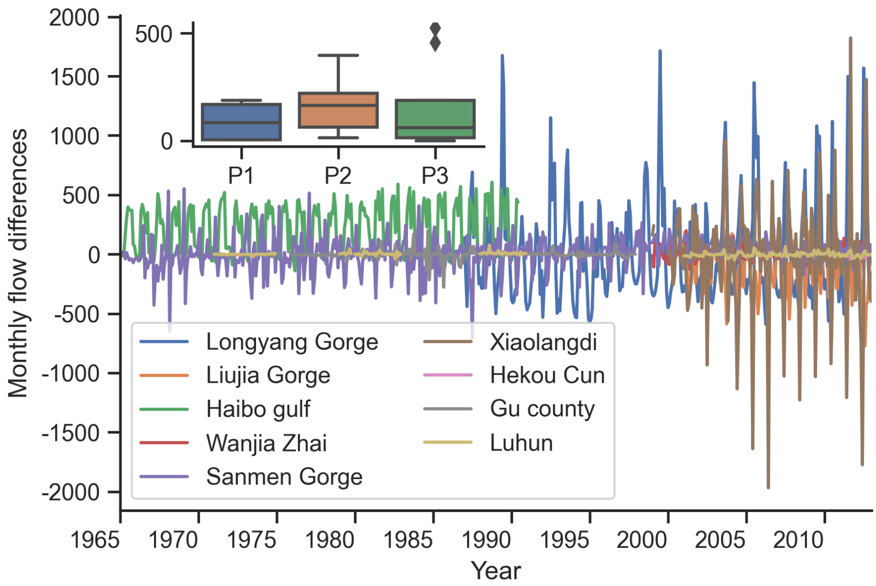

Figure S8. Monthly conveyance flow differences of the reservoirs mainly for managing and regulating the whole basin and their variability

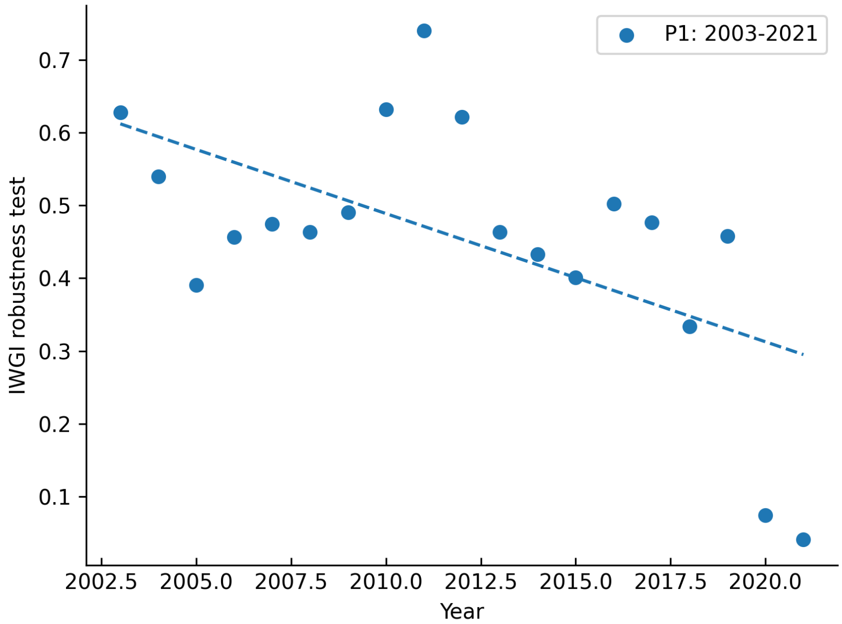

Figure S9. Recent years' IWGI changes calculated by data from Yellow River Water Resources Bulletin. No significant changing point exists