Supplementary Information for

Identifying regime transitions for water governance: Take the Yellow River Basin in China as case

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Introduction When calculating the indicators (especially the SFV water stress index and the allocation entropy metric), we should use data at a lower (regional scale in this study) spatial scale. Therefore, we divide the YRB into four regions: source region (SR), upper region (UR), middle region (MR), and lower region (LR), according to characteristics and customary practices in the 1. The formulation in detail for applying the SFV-index is available in the S1. We used multiple sources of datasets in this study, textitSupporting Information S7 introduces where they came from and how we harmonies them for analysis.

YRB Regions We divide the YRB 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 (?, ?; Wang et al., 2019; ?, ?), so four important hydrological stations can distinguish the regions (see Figure S1).

- **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.

SFV-index By taking water flexibility and variability into account, the scarcity-flexibility-variability (SFV) index focus more on dynamic responses to water resources in a developing perspective, which is a valid metric of temporal changes in water stresses (Qin et al., 2019). To apply this method, we need to combine three metrics following:

First, for scarcity, $A_{i,j}$ is the total water consumption as a proportion of regional multi-year average runoff volume in year j and region i (in this study, four regions in the YRB, textitSupporting Information 1):

$$A_{i,j} = \frac{WU_{i,j}}{R_{i,avg}} \tag{1}$$

Second, for flexibility, $B_{i,j}$ is the inflexible water use $WU_{inflexible}$ (i.e. for thermal power plants or humans and livestock) as a proportion of average multi-year runoff, in year i and region j:

$$B_{i,j} = \frac{WU_{i,j,inflexible}}{R_{i,avg}} \tag{2}$$

Finally for variability, the capacity of the reservoir and the positive effects of storage on natural runoff fluctuations are also considered.

$$C_i = C1_i * (1 - C2_i) \tag{3}$$

$$C1_{i,j} = \frac{R_{i,std}}{R_{i,avg}} \tag{4}$$

$$C2_i = \frac{RC_i}{R_{i,avg}},\ ifRC < R_{i,avg} \tag{5}$$

$$C2_i = 1,\ ifRC >= R_{i,avg} \tag{6}$$

In all the equations above, $R_{i,avg}$ is the average runoff in region i, RC_i is the total storage capacities of reservoirs in the region i, $R_{i,std}$ is the standard deviation of runoff in the region i.

Finally, assuming three metrics (scarcity, flexibility and variability) have the same weights, we can calculate the SFV index after normalizing them:

$$V = \frac{A_{normalize} + B_{normalize} + C_{normalize}}{3} \tag{7}$$

$$a = \frac{1}{V_{max} - V_{min}}; \tag{8}$$

$$b = \frac{1}{V_{min} - V_{max}} * V_{min} \tag{9}$$

$$SFV = a * V + b \tag{10}$$

The index of scarcity (SFV index) in the study period (including three different periods) showed A change trend of first decreasing, then rapidly increasing, and finally slightly decreasing again (Figure S6 A), indicating that water resource pressure first decreased, then rapidly increased, and then stabilized. In the four different regions (Figure S6 B), the source region has almost no contribution to SFV index changes in the three periods, and the downstream region only has a weak negative contribution in the governance transition period and the adaptation enhancement period. The upper and middle reaches of the Yellow River had the greatest impact on the scarcity. The upper reaches made the greatest contribution to SFV change in the period of centralized water supply and governance change, while the middle reaches made the greatest contribution in the period of adaptation enhancement.

In terms of water use purpose, the proportion of supply water remained basically unchanged in the period of centralized water supply, but showed A rapid decline in the period of governance transformation and adaptation enhancement (Figure S4 A). In the three periods, the change of irrigation water dominated the change of the proportion, while urban and rural water for human settlements and rural livestock had almost no influence on the change of the proportion (Figure S5 B).

The index change of distribution mode showed an obvious "V-shaped" trend, indicating that water resources in the source region, upper, middle and lower reaches of the Yellow River first gradually moved away from uniform distribution, and then gradually tended to average distribution after 2000 (Figure S5).

By analyzing the correlation of the integrated management index (IWGI) and its three sub-indexes: stress (IS), priority (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 $r = -0.86$, $p < 0.01$).

Datasets

Descriptions

This study used multiple types of data (see Table S1): statistical datasets, hydrological datasets, and political datasets.

Statistical datasets

The water resources use dataset was published by Zhou et al. (Zhou et al., 2020), which records water utilization in different sectors along with social-economic situations at the Prefectures level. 2nd National Water Resources Assessment Program mainly extracted this dataset launched in 2002, led by the National Development and Reform Commission and the Ministry of Water Resources (see ref (1) and `http://www.mwr.gov.cn/english/publs/` for more details). Since then, the statistics from the survey using the same criteria have been supplemented and harmonized with the 2013 administrative divisions.

The data covers a total of subcategories of water use under four broad categories: agriculture (IRR), industry (IND), urban (URB) and rural (RUR) water use (see Zhou et al., for details (Zhou et al., 2020)).

Hydrological datasets

The reservoir dataset was collected by Wang et al. (Wang et al., 2019), which introduced includes the significant new reservoirs built in the YRB since 1949 (Figure S2). YRCC labelled the regulation-oriented reservoirs among them, see `http://www.yrcc.gov.cn/`

hhyl/sngc/). In addition, annual runoff data derived from hydrological station measurements are the same as the datasets used in (Wang et al., 2019) and (?, ?).

Political datasets

The policy dataset collects laws and policies listed in the book (?, ?), which are related to the Yellow River basin promulgated and implemented by departments at (such as YRCC) and above (such as national institutions) at the Basin's level (Table S2). In addition, some are difficult to categorize; not a landmark, but numerous water governance practices in the YRB had been recorded in "Yellow River Events" by the YRCC; we collected them from http://www.yrcc.gov.cn/hhyl/hhjs/.

Methods S3. Harmonization

Due to the wide sources of our data set and the different spatial scales, we need to harmonize them into a practical scale.

- 1. Datasets at watersheds scales: We directly divided the annual hydrological data and measured runoff data according to their watersheds' corresponding hydrological stations (see Figure S1 A and B).

- 2. Prefecture: We calculate the area of each prefecture to determine whether they belong to a region, with the threshold of 95%:

$$S_{ij} = MAX(S_ij/S_i) \tag{11}$$

Where i refers to a specific prefecture and j refers to a region within YRB, i.e. SR, UR, MR, or DR. S_i refers to the area of perfect i, and S_{ij} refers intersecting area between perfect i and region j. We define perfecture i belongs to region j if their intersecting area S_{ij} over 95% of S_i, i.e.:

$$MAX(S_{ij}) > 0.95 * S_i \tag{12}$$

- 3. Province: According to the major provinces contained in different regions, we determine which region the data of that province is merged into by referring to the traditional division practice:
  - SR: Qinghai Gansu and Sichuan,
  - UR: Ningxia and Inner Mongolia,
  - MR: Shanxi and Shaanxi,
  - DR: Shandong, Hebei and Henan.

Finally, when we process the location data (i.e., the location data of the reservoirs), we judge the province it belongs to according to its location and then fit it to the regional scale.

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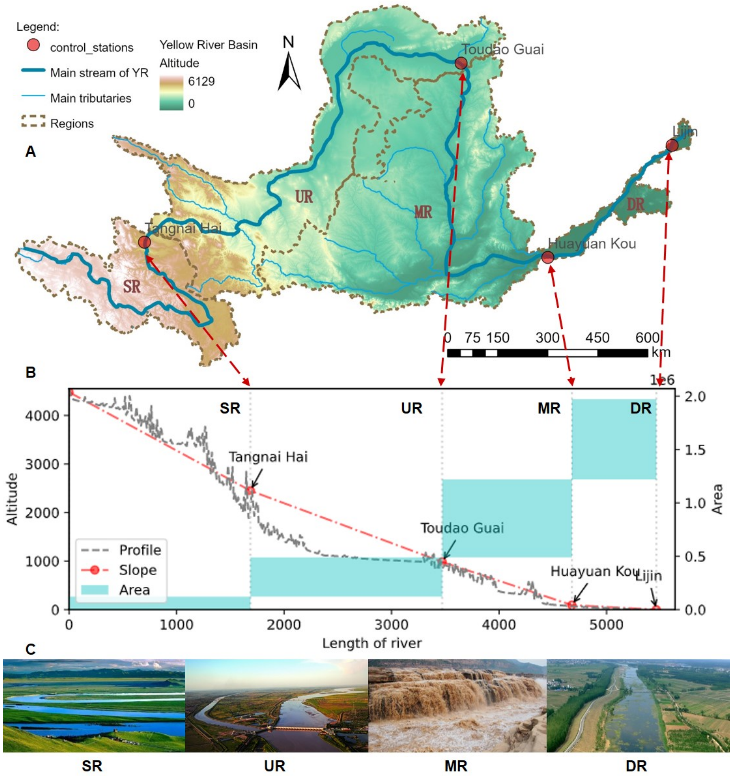

Figure S1. The study area. **A.** Diagram of the YRB and the subdivision of the basin (SR: Source Region, UR: Upper Region, MR: Middle Region, DR: Downstream region). **B.** Profile of the main channel of the Yellow River. The hydrological stations control the SR, UR, MR and DR. **C.** Typical landscapes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

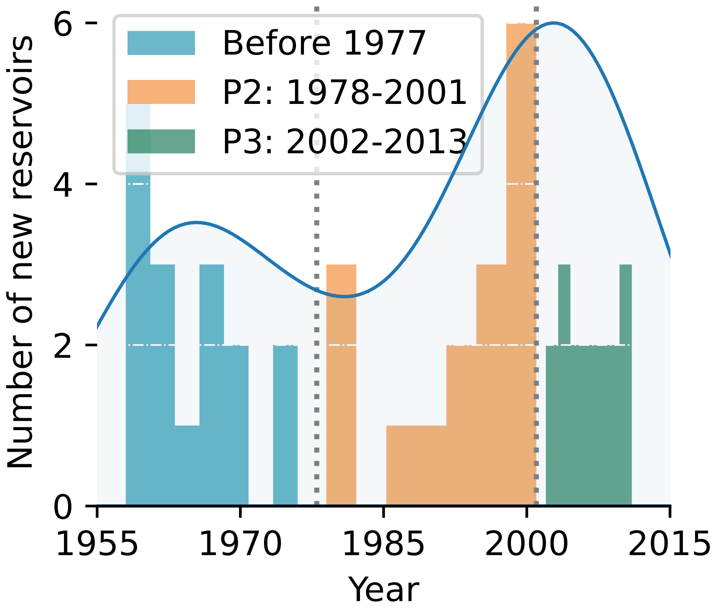

Figure S2. Numbers of new reservoirs in each year.

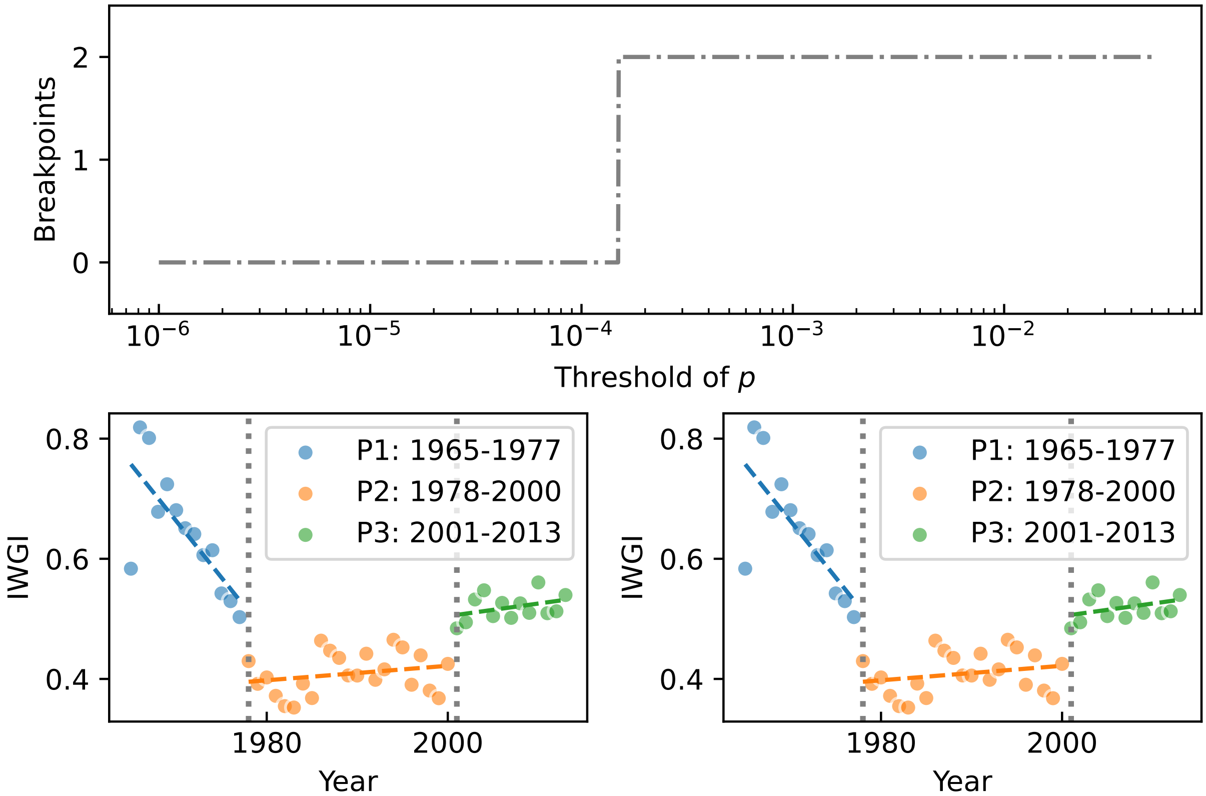

Figure S3. Sensitivity analysis of the threshold of p-values. **A.** number of breakpoints in different p-values, the scheme with two-breakpoints are the dominant situation. **B.** Threshold of p-values $\alpha = 0.0005$. **C.** Threshold of p-values $\alpha = 0.05$.

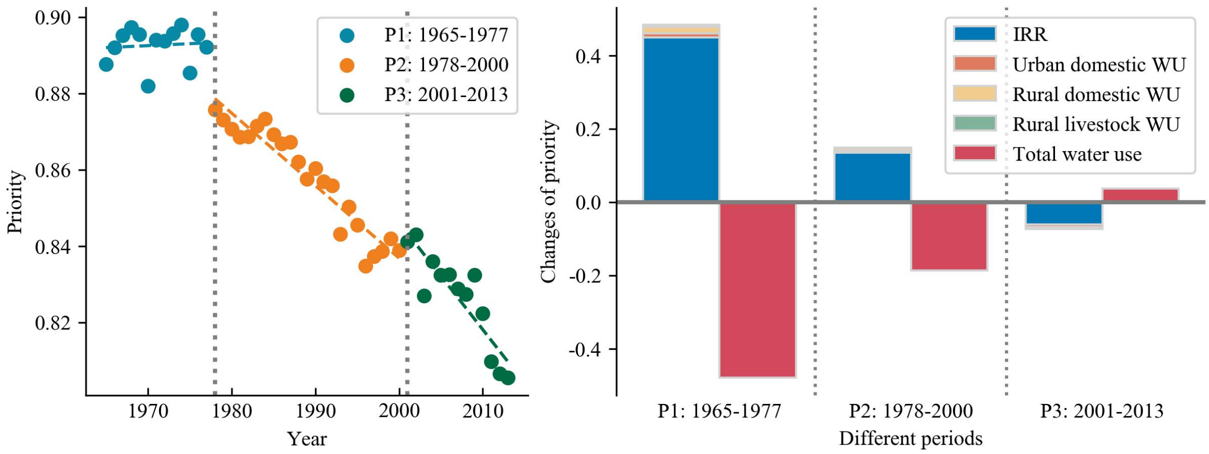

Figure S4. Changing trend of the indicator of priority

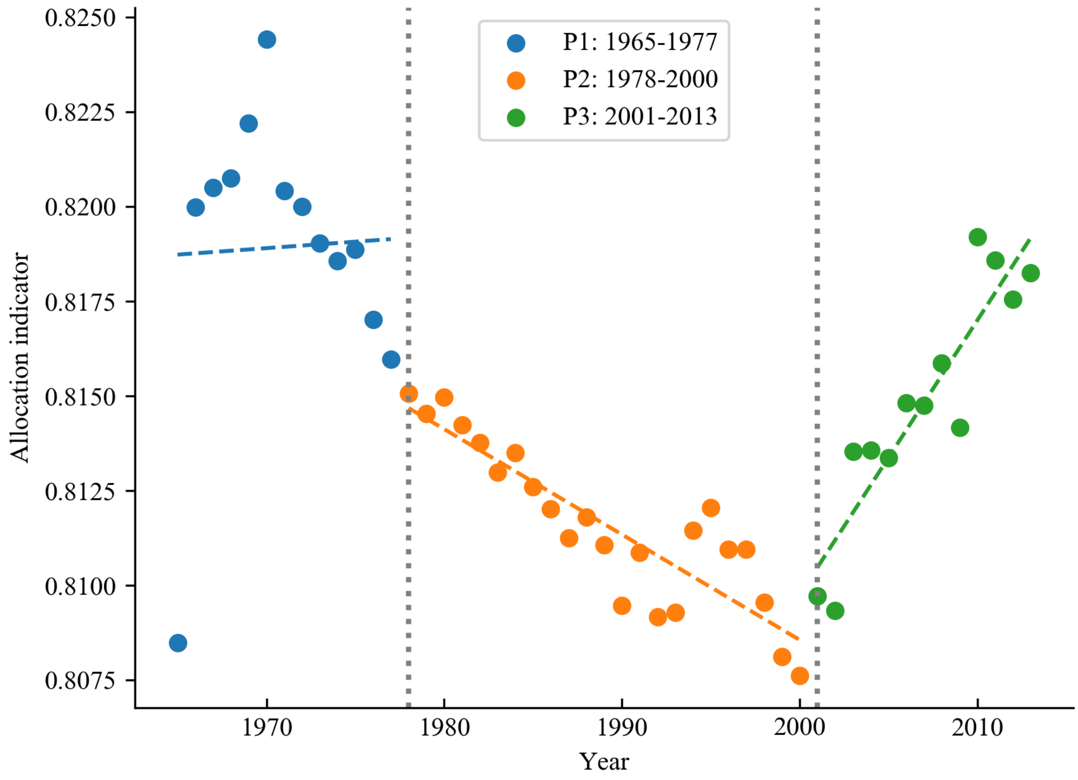

Figure S5. Changing trend of the indicator of allocation

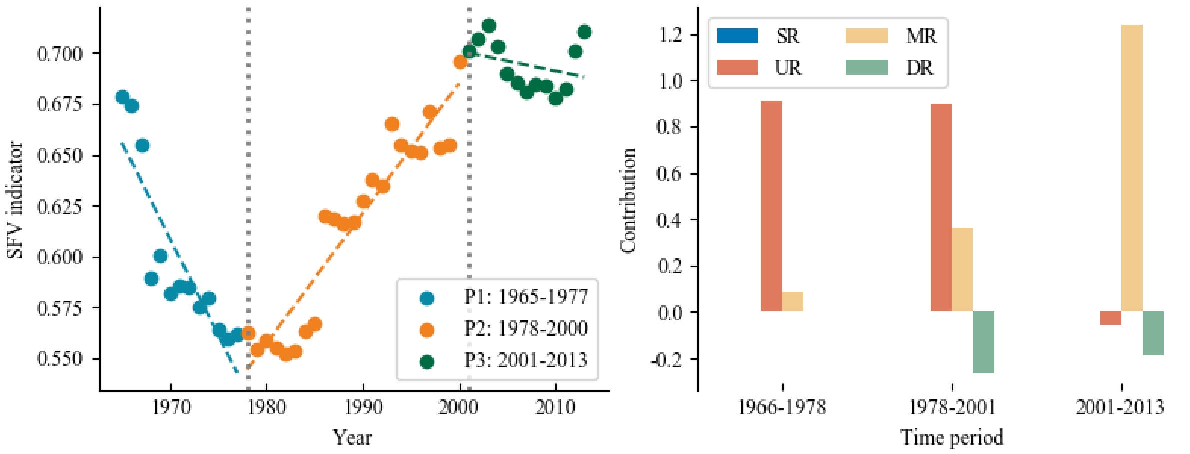

Figure S6. Changing trend of the indicator of stress

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

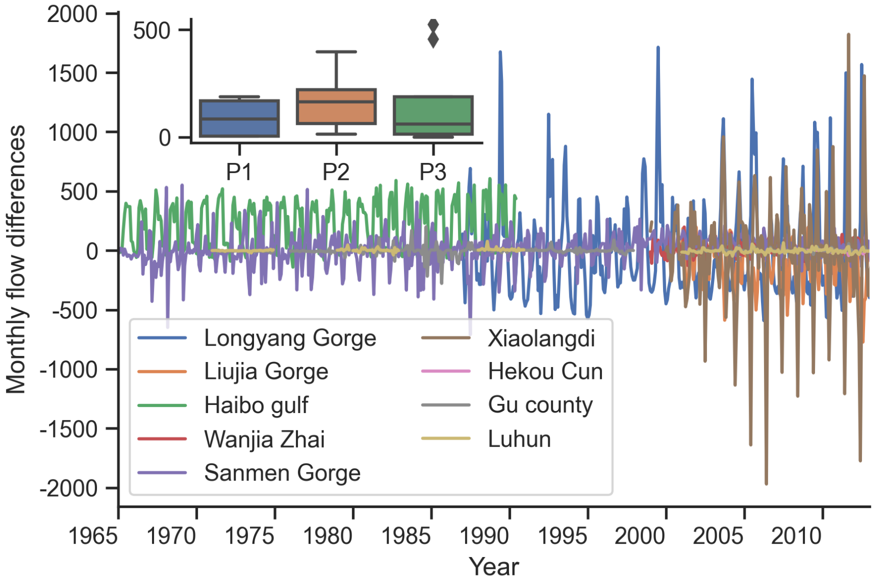

Figure S7. Monthly conveyance flow differences of the reservoirs mainly for managing and regulating the whole basin and their variability

Table S1. Used datasets and their sources.

Dataset	Type	Spatial scale	Time scale	Source
1. Administrative water use	Statistical	Prefectures	1965-2013	2nd National Water Resources Assessment Program (Zhou et al., 2020)
2. GDP	Statistical	Province	1949-2019	Wind database
3. Streamflow withdrawals	Statistical	Watershed	2003-2019	Yearbooks `http://www.yrcc.gov.cn/other/hhgb/`
4. Reservoirs	Hydrological	Location	1949-2015	Publication (Wang et al., 2019)
5. Measured runoff	Hydrological	Location	1949-2019	Measured data (Wang et al., 2019; ?, ?)
6. Laws	Political	Documents	1949-2013	YRCC (?, ?)
7. History of YRCC	Political	Documents	1949-2002	YRCC (Archives, 2004)
8. YRB Events	Political	Documents	1949-2015	YRCC: `http://www.yrcc.gov.cn/hhyl/hhjs/`

Table S2. Policies and regulations above YRB level which affected the whole basin in water utilization

Name	Year	Agency
1. Water Law of PRC	1988	National People's Congress of the PRC
2. Water Law of PRC -revised 1	2009	National People's Congress of the PRC
3. Water Law of PRC -revised 2	2016	National People's Congress of the PRC
4. Regulations on the Administration of Water Drawing Licences and The Collection of water resource fees	2006	State Council of the PRC
5. Regulations on the Administration of Water Drawing Licences and The Collection of water resource fees -revised 1	2017	State Council of the PRC
6. Regulations on the Allocation of Water in the Yellow River	2006	State Council of the PRC
7. Yellow River water supply distribution scheme	1987	State Council of the PRC
8. Measures for the Administration of Water Drawing Permits	2008	Ministry of Water Resources of the PRC
9. Measures for the Administration of Water Drawing Permits -revised 1	2015	Ministry of Water Resources of the PRC
10. Measures for the Administration of Water Drawing Permits -revised 2	2017	Ministry of Water Resources of the PRC
11. Regulations on the Allocation of Water in the Yellow River	2006	State Council of the PRC
12. Annual distribution of available water supply of the Yellow River and mainstream water dispatching scheme	1998	Ministry of Water Resources of the PRC
13. The Yellow River water dispatching management measures	1998	Ministry of Water Resources
14. Measures for the Implementation of the Yellow River Water Rights Conversion Management	2004	Ministry of Water Resources
15. Regulations on the Administration of Water Drawing Licences and The Collection of water resource fees	2006	State Council of the PRC
16. Measures for the implementation of the water drawing Permit system	1993	
State Council of the PRC		
17. Measures for the demonstration and management of water resources in construction projects	2002	Ministry of Water Resources of the PRC
18. Implementation Opinions on the Reform of Water Conservancy Project Management System	2006	State Council of the PRC

[1] If a policy was proposed by multiple legacies, we only show the highest one.