Identifying regime transitions for water governance at a basin scale

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Abstract

In many large river basins, water governance regimes from natural to social-ecological or 'hydrosocial' situations profoundly change who gets water, when, and how. Therefore, identifying regime changes is critical to understanding the transition and guiding sustainability in water governance. We combined three main dimensions -stress, purpose and allocation- to develop a quantitative Integrated Water Governance Index (IWGI) to detect water governance regimes at a basin scale. Applying the IWGI to a rapidly-changing basin (the Yellow River Basin, China) describes how water governance shifts between massive supply, transformation governance, and adaptation-oriented regimes. In the YRB, the regime shifts' underlying causes were increasing water supply and demand before the governance transformation and re-allocation and regulation after the transformation. The IWGI offers a comprehensive and straightforward approach to linking the water governance regimes to the following challenges in sustainability, along with the hydrosocial transition.

Keywords: Regime shifts, Water governance, Transformation, Social-hydrology, Sustainability

1 Introduction

Water, being "at the centre of the planetary drama of the Anthropocene", is essential not only for earth system processes but also in supporting the development and human well-being [1, 2]. As an integral part of earth system governance, water governance requires a deep understanding of changes in the complex relationships between humans and water [3–5]. Human activities stemming from our reliance on the water have profoundly modified the natural water cycle, resulting in rivers dominated by a hybrid of social and natural tendencies [6–8]. Facing this transition, many big river basins worldwide (which are hot spots of civilization and economic growth) are urgently in need of successful water governance for sustainability [9, 10].

Water governance refers to the political, social, economic, and administrative systems that influence the use and management of water [11, 12]. For populated large river basins, missing governance means missing sustainability, and a first important step in understanding the transitions with successful water governance is identifying the different regimes [13, 14]. Regimes of water governance maintained by concreted intertwine within human-water systems (such as management, institutions, and exploitations), as a stable state in structures and functions [15–17]. Therefore, regime shifts sometimes lead to new water governance challenges as both signals and consequences of substantive changes in human-water systems. The lack of a comprehensive but straightforward approach to identifying changes in water governance regimes challenges sustainability, and filling this gap can well align human and water systems (Figure 1).

Governance is essentially about "who gets what, when and how"[18]. The United Nations Development Programme (UNDP) thus suggested that three key dimensions of water use are decided by the water governance directly: "When and what water to use?" (stress), "How does water provides different services to well-beings?" (purpose), and "Who can use water equally and efficiently?" (allocation) [19]. First, water stress depends not only on climate (with increasing scarcity and uncertainty in many regions) but also on the increasingly insatiable demands from economic activities such as irrigation and industry; water storage can resolve some but not all of these issues [20–22]. Second, the purpose of how water services human well-being is to consider trade-offs between consumptive uses (e.g., drinking and food production) and non-consumptive uses (e.g., energy production) [23–25]. Third, the allocation of water across the whole basin is not only decided by regionally socio-economic and environmental context but also influenced by systematically regulating [26, 27]. Despite regime shifts in water governance related to substantive changes in any of the three dimensions, separately considering their intertwines within human-water systems can lead to holistic failure in governing water.

The Yellow River Basin (YRB), the fifth-largest river in the world, was most in need of integrated water governance because drastically anthropogenic intervention led to intense governance challenges in sustainability [28]. Since the 1960s, the implementation of conservation measures, regulation reservoirs, and levee constructions have contained the governance issues troubled by thousands of years of high sediment loads [29, 30]. However, decreased streamflows and water over-use then led to depletions of the over-burdened river, creating new challenges and new governance practices, including water use regulation and water transfer across basins [31]. Today, it is still impossible to completely solve water stress, trade-offs between ecosystem services, or lopsided development in different regions in the YRB; - "who gets water, when and how" is always an open question for sustainable development [32]. Confronting governance challenges induced by environmental, economic, social, and political factors, numerous governance practices have led the YRB to be among the most drastically-governing large river basins worldwide [33]. Identifying regime shifts in water governance within the YRB can thus provide crucial insights into rapidly-changing big river basins and how governance may respond to meeting challenges to their sustainability.

Here, we use the three core dimensions (stress, purpose and allocation) and corresponding indicators of water governance to develop an Integrated Water Governance Index (IWGI) that can detect and describe changes in water governance at a basin-scale (see Figure 1 and methods). Then, by applying the index to a typical rapid-changing big river basin (the YRB), we show how to analyze the complicated water governance regimes in a comprehensive but straightforward way. Following synthetic analyses of the changes in water demand, supply, economic outcomes, and institutions, we interpret the leading causes of the regime shifts. Finally, we propose a general regime transition schema as a practical guideline for a coordinated approach to exploring the challenges faced by big river basin governance.

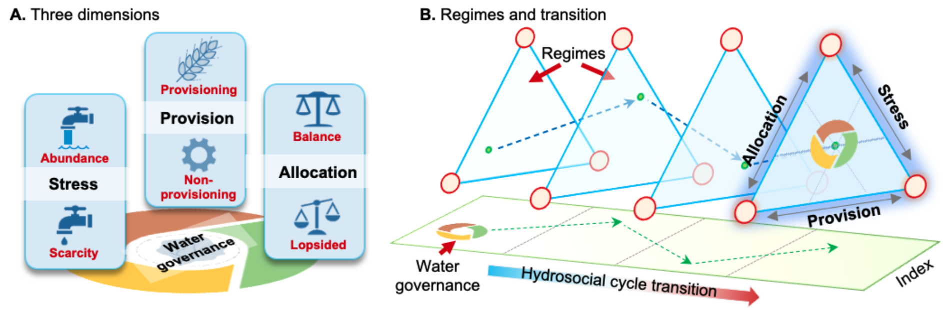

Fig. 1 Identifying the water governance regimes in transitions of a hydrosocial cycle. **A.** Water governance has three key dimensions (stress, purpose and allocation), each of which has two potential directions (denoted in red) when changing. (1) “stress” of water shifts between scarcity and abundance; (2) weighting “purpose” of water between consumptive services or non-consumptive uses; (3) “allocation” changes between balanced or lopsided. **B.** Along with a transition in hydrosocial water cycle, water governance shifts in line with the three dimensions. Combining corresponding indicators, an abrupt change of the IWGI thus indicates a regime shift in water governance.

2 Results

2.1 Water governance regimes

Two significant breakpoints divide the changes in the IWGI into three periods, with different contributions from three dimensions (Figure 2A). In the first period (P1, 1965-1978), the IWGI decreased rapidly. While the indicator of purpose and allocation contributed more to the IWGI (49.45% and 34.95% on average, respectively), the remarkable downward trend correlates significantly ($p < 0.01$) to the decreasing allocation and stress indicators (Figure 2B). In the second period (P2, 1979-2001), the increasing stress indicator significantly ($p < 0.01$) contributed to the upward IWGI, while the allocation and purpose indicators played negative roles in changing the IWGI. During the third period (P3, 1995-2013), while the stress indicator kept its most prominent share in contributions (57.11% on average), the increased allocation indicator and decreased purpose indicator changed the regime of IWGI. Taken together, the overall features of the three dimensions in different periods are relative to a directional change in the combination of three dimensions (Figure 2C). The results suggest three distinct water governance regimes: a massive supply regime (P1: 1965-1978), a governance transforming regime (P2: 1979-2001), and an adaptation oriented regime (P3: 2002-2013).

2.2 Causes of the regime shifts

The underlying causes of changes in the IWGI are associated with various factors but are different in the two regime shifts. Changing water demands and supply were critical to the shift between P1 and P2. As the dominant water demand during the massive supply regime (P1), the area of irrigated agriculture in the YRB expanded rapidly at a rate of $0.25 * 10^6 ha/yr$ (Figure3 A), simultaneously supported by increasing supply through the construction of reservoirs (*SI Appendix* Figure B4). Entering the transformation governance regime (P2), however, the expansion of irrigated areas slowed down, and industry and services gradually took off (Figure3 A and B). Then, the efficiency of water use changed obviously from P2 to P3. Not only irrigated areas keep their slow expansion in the adaptation oriented regime (P3) (Figure3A), but industry and urban services also assumed a more vital economic role (represented by Gross Added Values, GVA) (Figure 3B). However, because of more efficient technology and better water conservation practices (*SI Appendix* Figure B3), both experienced significant declines in water use for a unit irrigated area or unit production (Figure 3A and Figure 3B). As a result, the differences between sectors and regions in water use reduced while the total water stress steadily remained high during the adaptation oriented regime (Figure 2A).

Environmental context, social transformation and policies played roles in all three regimes. We calculated the ratios of regional and basinal water use for each reservoir (R/B ratio) (Figure 3C), with a higher ratio representing a potential role in water supply rather than basinal

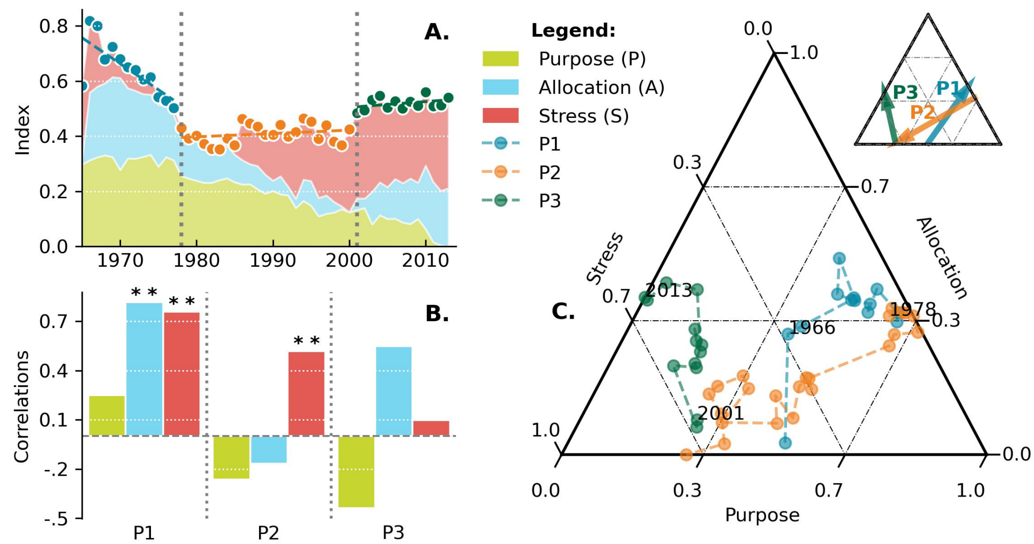

Fig. 2 Changes in the IWGI index and corresponding water governance regimes: P1: 1965-1978, P2: 1979-2001, and P3: 2002-2013. **A,** detecting change points of IWGI and contributions from each indicator. Two significant change points ($p < 0.01$) occurred in 1978 and 2001. **B,** correlation of trends between the IWGI and the indicators. **C,** across three indicators, changing components of the IWGI, whose directions shifts between different regimes.

regulations. Under the guiding ethos of "conquering nature", most of the reservoirs were built in regions with high water demands during the massive supply regime (R/B ratios were significantly higher, $p < 0.01$, see Figure 3C), when natural water resources were also relatively abundant (*SI Appendix* Figure A2). Since the transformation governance regime (P2), the number of new reservoirs decreased significantly and significantly increased basinal policies rigorously controlled the allocation of water (Figure 3D, $p < 0.01$ and *SI Appendix* Figure B4). In the adaptation oriented regime, authorities proposed more national-level water governance policies under the guidance of the national strategy "environmental regulation" (Figure 3D). Taken together, the regime shift from P1 to P2 is in line with the increasing water supply and demands; while driven by regulatory policies and efficiency enhancement under stable water stress from P2 to P3.

3 Discussion

Water governance gradually becomes a national or international concern from a primarily local concern because large river basins are critical sources of ecosystem services, economic development, and human well-being [9, 34]. As the ubiquitous telecoupling is rising additional water governance challenges in the tighter connected world, the transition of hydrosocial cycle and regime shifts align with different human-water relationships [35]. The process echoes how societies can change governance practices by enhancing their adaptive capacity in the hydrosocial cycle, and the IWGI quantitatively identifies this transition [17, 36]. It is vital for scientists and decision-makers to recognize the changing governance challenges because models, institutions, engineering, and approaches developed under one regime are not necessarily applicable under a different regime [37].

In the case of the YRB, our results show that there have been three distinct but sequential governance regimes: a massive supply regime (P1: 1965-1978), a governance transforming regime (P2: 1979-2001) and an adaptation oriented regime (P3: 2002-2013) (Figure 2). During the massive supply regime with lower water stress (1965-1978 in the YRB), water governance thus tended to boost water supply for services (mainly provisioning purposes then -livestock and crops) by constructing reservoirs and channels. As the popular slogan "man will conquer nature" suggested, however, the enhancement of water supply

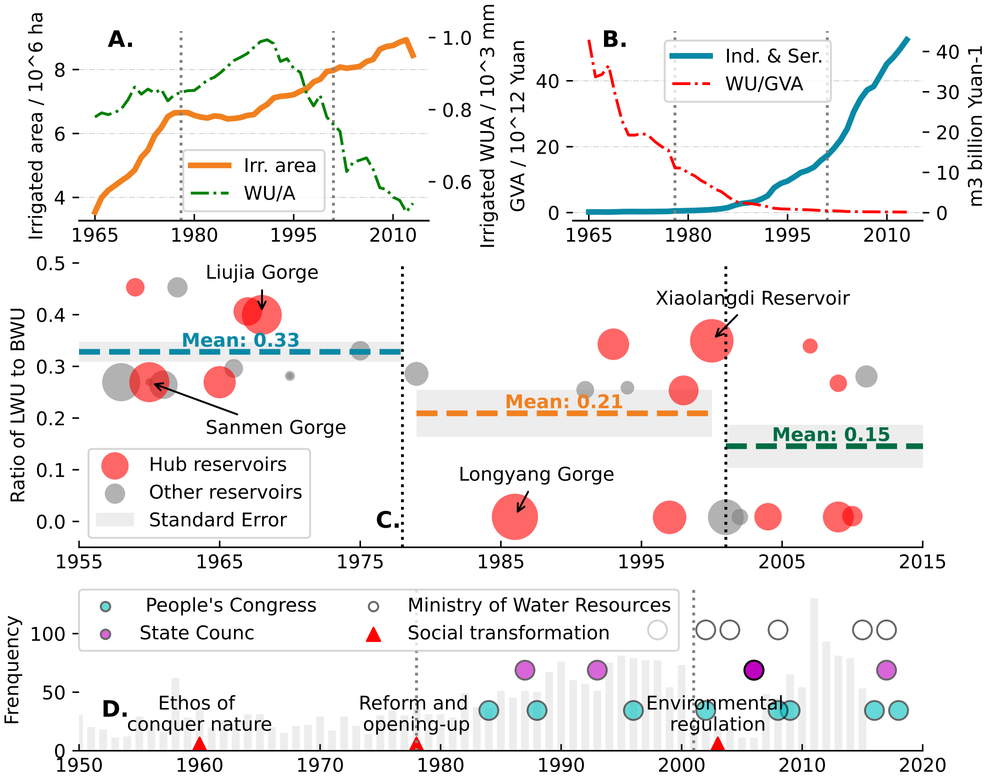

Fig. 3 Causes of water governance regime shifts in the YRB: environmental change, economic growth and efficiency changes, social transformation, and governance policies. **A.** Changes in the total irrigated area (orange line) and water use intensity (WU/A, water use divided by the area, the green dot line). **B.** Changes in gross values added (GVA) of industry and services (blue line) and their water use intensities (WU/GVA WU divided by the GVA, the red dot line). **C.** Completed time of each new reservoir and their located region's water use (LWU) percentages as a proportion of the total basinal water use (BWU) at that time. Red circles denote the reservoirs mainly for managing and regulating the whole basin. The size of each circle indicates the magnitude of its water storage capacity. Some crucial reservoirs include (1) Xiaolangdi reservoir and Sanmen Reservoir, which were constructed mainly for managing sediments; and (2) Impoundments at Liujia Gorge, Longyang Gorge, which was constructed mainly for managing floodwater discharge and water regulation. These named reservoirs are significant for the whole basin rather than local development. **D.** Social transformations (red triangles) and national-level governance policies (the circles, different colours denote signed by different state institutions, see *SI Appendix* Table S2). The light grey bars year-by-year show the frequency of official documents related to the YRB at a basinal scale (see *SI Appendix* Table S3).

aligned with little consideration of the irreversible changes in the human-water relationship, thus drastically increasing water demand with little consideration in basinal conservation [38]. The rapid expansion of irrigated farmland and water diversion facilities in that decade brought the overburdened YRB close to the critical point, where keeping increasing supply to meet the unlimited demand is unpractical [17]. As a result, the over 80% surface water use then led to river depletions frequently since 1972, with ecological issues, such as wetlands shrinkage and declines in biodiversity [31]. In addition, as the water stress also limited the industrial economy in the ascendant, the existing modes of water governance led to a social-ecological crisis and challenged sustainability rigorously [32].

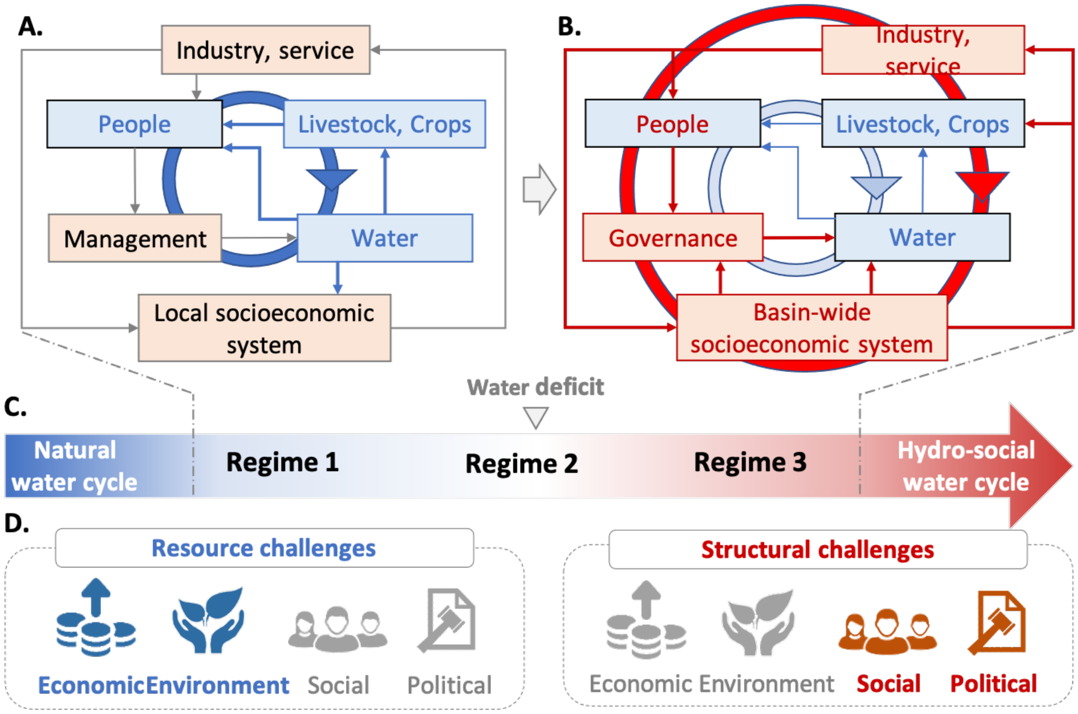

Fig. 4 Transition schema in hydrosocial cycle and water governance regimes. The natural water cycle dominates blue pathways, while socio-economic feedback dominates red pathways. **A.** As socio-economic systems develop, non-provisioning water demand increases; simultaneously, increased adaptive capacity by engineering allows people to manage water resources to alleviate the water stress. **B.** With further human interventions, trade-offs between provisioning-purpose and non-provisioning water use become prominent; a basin-wide socio-economic system requires more organized water governance. Thus, **C. the hydrosocial water cycle transition** correlates with the water governance regime shifts (in the YRB, they are massive supply regime, transformation governance regime, and adaptation oriented regime). The transformation governance regime shift occurs following the water deficit, with the rapid growth of adaptive capacity. **D. Water governance challenges** Through the transitional regimes, water governance faces primarily economic and environmental challenges but social and policy challenges later.

The start of the governance transforming regime (P2: 1979-2001) coincided with the rising competition for water use after the "reform and opening-up". The results in the YRB keep in line with the suggestions from the theoretical analysis: continuous increases in water demand when the basinal total supply is stable can follow substantial changes in governance regime and the rapid enhancement in overall social adaptive capacity [17]. Being a pioneer in shifting governing institutions, the YRB triggered a series of changes in "who gets water, when and how" during this regime: slowing growth of irrigated acreage; leading water-saving infrastructure; China's first water quota scheme; The preliminary cross-boundaries water transfer plan and so on [33, 39, 40]. Consequently, though water stress remained and increased (mainly led by reducing streamflow and flexibility), the last depletion of the Yellow River in 1999 added a footnote to the climax of this transformation in water governance [39].

When it came to an adaptation-oriented regime (P3: 2002-2013), drastically shifting in societies adapted to the stable high water stress. Socio-economic trade-offs between water-dependent regions and sectors played a more important role in this regime, so water governance had to achieve efficient water allocation while balancing different purposes in the face of limited water supply [41, 42]. Reconstruction of resources widespread in different industries and regions was calling for adaptation in water governance, where the urgent requirements of adjusting the rigid quota shares from the previous regime can be an example [39]. Like this, many national-level governing practices were proposed under the regime because the absence of such policies with the social dilemma of high-quality development became new structural challenges for water governance [43].

In general, water governance of the YRB is among the most prominent example in the general transition of hydrosocial cycle - "improving supply, transforming governance, and enhancing adaptation". With each dimension changing gradually, the emergence of regime shifts drives the water governance challenges at a basin-scale: primarily economic and environmental before the transformation but social and policy-related towards the end (Figure 4) [44, 45]. In the analogy at a global scale, the resource challenges, represented as water shortage and water supplying difficulties, are mainly faced by undeveloped and developing basins [27, 46, 47]. Alternatively, highly-controlled and developed basins (especially for transboundary rivers) must mainly resolve structural challenges, such as water disputes or lack of equity, and may be in urgent need of novel flexible, efficient sociopolitical governance structures [48, 49]. Linking regime shifts to the governance challenges, the implementation of IWGI thus offers a comprehensive and straightforward way to interpret the intertwines between water governance and the hydrosocial transition.

One of the main limitations in the approach is the few data worldwide with a long-term period, which means still a gap between the comprehensively identifying and widespread application of IWGI. However, we assumed that all water governance issues are relative to "who gets water, when and how", so water stress, purposes of water services, and water allocation patterns matter. Therefore, we suggest that choices of the indicators for the dimensions can be adapted according to available datasets as the intertwines between the underlying components are much more crucial in understanding the transition of governance regimes holistically. In today's world, the regime shifts from biophysical to hydrosocial control of dynamics may become increasingly widespread, so the comprehensive strategies to address governance challenges have become the core of complex human-water systems [25, 50, 51]. Although river basins have shown improvements in water management technologies and water use efficiency, many of them are still approaching planetary boundaries where human-water systems may collapse [52, 53]. A deeper understanding of governance that incorporates ideas of non-linear regime shifts and transformations should help shift the focus of governance towards maintaining the resilience of the basin's social-ecological system and improving its sustainability [54].

4 Conclusion

Three dimensions of water governance change along with the hydrosocial cycle transition: water stress, services purpose, and water allocation, affecting "who gets water, when and how". We developed an Integrated Water Governance Index (IWGI) to detect regime shifts in water governance by integrating them. Applying the index to a rapidly-changing large river basin (the Yellow River Basin, China) describes how water governance shifts between three regimes over half a century (massive supply regime; governance transformation regime; and adaptation oriented regime, respectively). Our approach quantitatively identifies the general schema for water governance regimes in the YRB, in line with previous theoretical analysis with a representative transition process. Linking regime shifts to the underlying causes, the implementation of IWGI offers a comprehensive and straightforward way to interpret changes in intertwines of water governance, hydrosocial transition, and human-water relationships.

5 Methods

To develop a comprehensive and straightforward approach to identifying water governance regimes. First, we constructed the Integrated Water Governance Index (IWGI) based on three dimensions (Stress, Purpose, and Allocation, see Figure 1). Then, we analyzed the changes in the IWGI from 1965 to 2013 using change point detection methods. The normalized Indicator for each dimension affects the IWGI by changing trends and contributions.

5.1 Integrated Water Governance Index (IWGI)

As shown in the framework Figure 1, the IWGI combines the three core dimensions (Stress, Purpose, and Allocation) of water governance. Each dimension keeps two directions, and we assumed the hydrosocial cycle aligns with one of them, respectively:

$$Transformation \propto S * P * A \quad (1)$$

We selected an indicator (I_x, $x = S$, P or A, corresponding to stress, purpose, and allocation, respectively) to quantify the dimensions effectively. Then, the above equation was transformed into a natural logarithm to facilitate calculation:

$$Transformation \propto ln(I_S) + ln(I_P) + ln(I_A) \quad (2)$$

Then, the Integrated Water Governance Index (IWGI) is the average of the normalized indicators I'_x:

$$IWGI = I'_S + I'_P - I'_A \quad (3)$$

where:

$$I'_x = (I_x - I_{x,min})/(I_{x,max} - I_{x,min}) \quad (4)$$

Indicator of stress

We used the scarcity-flexibility-variability (SFV) water stress index proposed in Qin et al., 2019 to evaluate water stress [20]. This metric takes into account management measures (such as the construction of reservoirs) and the impact of changes in the structure of water use on the evaluation of water scarcity. Based on the hydrological and economic context of YRB, four main regions are divided (Source Region, Upper Region, Middle Region, and Lower Region, see *A*). For the whole YRB, the indicator of water stress I_S is the average of all regions' SFV-index:

$$I_S = \frac{1}{4} * \sum_{i=1}^{4} SFV_i \quad (5)$$

Where SFV_i is the SFV-index for region i, and the detailed calculation of SFV_i can be found in the **??**.

Indicator of purpose

To quantify purpose I_P, we used Non-Provisioning purpose Shares (NPS) of water use as an indicator. While provisioning purpose water use (WU_{pro}) includes domestic, irrigated, and livestock water uses, non-provisioning purpose water use ($WU_{non-pro}$) includes industrial and urban services water uses. We calculated the NPS as:

$$NPS = \frac{WU_{pro}}{WU_{pro} + WU_{non-pro}} \quad (6)$$

In this study, we consider water for livestock, rural or urban domestic and water for agriculture as provisioning water. Others are non-provisioning water uses, such as energy water use.

Indicator of allocations

To describe allocations I_A, we designed an indicator based on entropy, called Allocation Entropy Metric (AEM), which measures the degree of evenness in water allocation:

$$I_A = CEM = \sum_{i=1}^{N} -log(p_i) * p_i \quad (7)$$

where p_i is the water proportion of region i to the whole basin ($N = 4$ regions in sum). Based on the hydrological and economic context of YRB, four main regions are divided (Source Region, Upper Region, Middle Region, and Lower Region, see *A*).

5.2 Change points detection

With no assumptions about the distribution of the data, we applied the Pettitt (1979) approach of change-point detection to detect a single change-point in hydrological time series with continuous data [55]. It tests $H0$: The variables follow one or more distributions with the exact location parameter (no change) against the alternative: a change point exists. Mathematically, when a sequence of random variables is divided into two segments represented by $\mathrm{x}_1, \mathrm{x}_1, \ldots, x_{t_0} \mathrm{and} x_{t_0+1}, x_{t_0+2}, \ldots, x_T$, if each segment has a common distribution function, i.e., $F_1(x)$, $F_2(x)$ and $F_1(x) \neq F_2(x)$, then the change point is identified at t_0. To achieve the identification of change point, a statistical index $U_{t,T}$ is defined as follows:

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} sgn(X_i - X_j), 1 \leqq t < T \quad (8)$$

where:

$$\operatorname{sgn}(\theta) = \begin{cases} 1 & \text{if } \theta > 0 \\ 0 & \text{if } \theta = 0 \\ -1 & \text{if } \theta < 0 \end{cases} \tag{9}$$

The most probable change point τ is found where its value satisfies $K_\tau = max$U_−t, T″ and the significance probability associated with value K_τ is approximately evaluated as:

$$p = 2\exp\left(\frac{-6K_\tau^2}{T^2 + T^3}\right) \tag{10}$$

Given a certain significance level α, if $p < \alpha$, we reject the null hypothesis and conclude that x_τ is a significant change point at level α.

We used $\alpha = 0.001$ as the threshold level of the p-value, meaning that the probability of a statistically significant change-point judgment being valid was more than 99.9%. We divided the series into two at that point and analyzed each series separately until all significant change points were detected. Though two breakpoints were detected in the main text with $\alpha = 0.001$, in fact the threshold from 0.0005 to 0.05 does not affect our results, and the breakpoints we identified are fairly robust (see *SI Appendix* Figure B5).

5.3 Datasets

In order to calculate IWGI from 1965 to 2013, we need to calculate multiple indicators and sub-indicators. All the datasets used are listed in the *SI Appendix* table S1. A detailed description of the data is provided in the supplementary materials *SI Appendix* Methods S2.

Supplementary information. If your article has accompanying supplementary file/s please state so here.

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- Conflict of interest/Competing interests (check journal-specific guidelines for which heading to use)
- Ethics approval
- Consent to participate
- Consent for publication
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Appendix A YRB Regions

Since the socio-economic and natural conditions were both considered in this study, we integrated the two schemes above and divided the Yellow River Basin into four regions, which can be distinguished by three important hydrological control stations (see Figure A1). Previous studies have also shown that such a division is valid when both social water use and the natural conditions of the basin are considered, as the regions exhibit strong heterogeneity among themselves (see Fig. S1-C) [31]:

- **Source Region (SR):** Over 50% of natural runoff was produced in this region. The most ecology 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, the efficiency of irrigation are used to be very low.
- **Middle Region (MR):** Crossing Loess Plateau, famous rich-sand area, Yellow River loads most of its sediments here with the highest soil erosion risk. To reverse this situation, the grain for green project changed the water utilization here strikingly.
- **Lower Region (LR):** With dense population and the traditional agricultural trajectory, lower region used to be the largest water use region. However, as the industrial transformation going, proportion of agriculture keeps decreasing, but LR is still the largest water use region in each aspect.

In general, there are obvious inter-regional differences in the economic layout, distribution of water resources, distribution of water consumption, and population distribution of the Yellow River Basin (Figure A2). On the basis of these fundamental differences, social development and watershed management continue to influence and reshape their changes, making the Yellow River Basin the world's most intimately connected and dramatically changing large river basin.

Appendix B SFV-index

By taking changes of water flexibility and variability into account, the scarcity-flexibility-variability (SFV) index focus more on dynamic responses to water resources in developing perspective, which considered a valid metric of temporal changes in water stresses [20].

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:

$$A_{i,j} = \frac{WU_{i,j}}{R_{i,avg}} \tag{B1}$$

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:

$$B_{i,j} = \frac{WU_{i,j,inflexible}}{R_{i,avg}} \tag{B2}$$

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

$$C_i = C1_i * (1 - C2_i) \tag{B3}$$

$$C1_{i,j} = \frac{R_{i,std}}{R_{i,avg}} \tag{B4}$$

$$C2_i = \frac{RC_i}{R_{i,avg}},\ if RC < R_{i,avg} \tag{B5}$$

$$C2_i = 1,\ if RC >= R_{i,avg} \tag{B6}$$

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 SFV index after normalizing them:

$$V = \frac{A_{normalize} + B_{normalize} + C_{normalize}}{3} \tag{B7}$$

$$a = \frac{1}{V_{max} - V_{min}}; \tag{B8}$$

$$b = \frac{1}{V_{min} - V_{max}} * V_{min} \tag{B9}$$

$$SFV = a * V + b \tag{B10}$$

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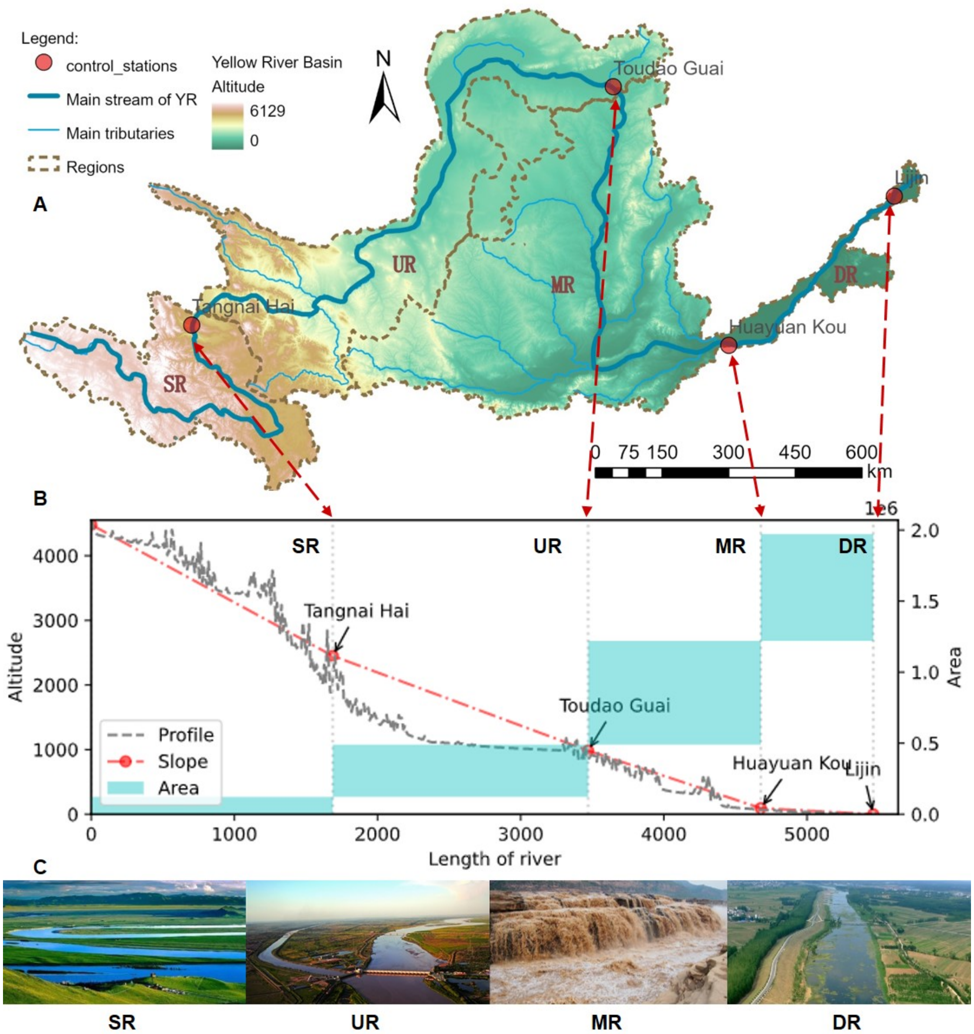

Fig. A1 The study area. **A.** Diagram of the YRB and the subdivision of the basin (SR: Source Region, UR: Upper Region, MR: Middle Region, DR: Downstream region). **B.** Profile of main channel of the Yellow River. SR, UR, MR and DR are divided by main hydrological stations. **C.** Typical landscapes in different regions in the YRB.

Table B1 Used datasets and their sources.

Dataset	Type	Spatial scale	Time limit	Source
1. Water use	Statistical	Prefectures	1965-2013	2nd National Water Resources Assessment Program
2. GDP	Statistical	Province	1949-2019	Wind database
3. Groundwater and surface water use	Statistical	Watershed	2003-2019	Yearbooks of YRB by the YRCC.
4. Reservoirs	Hydrological	Location	1949-2015	Wang et al. [31]
5. Measured runoff	Hydrological	Location	1949-2019	Measured data from YRCC
6. Laws	Political	Documents	1949-2013	YRCC [56]
7. History of YRCC	Political	Documents	1949-2002	YRCC [57]

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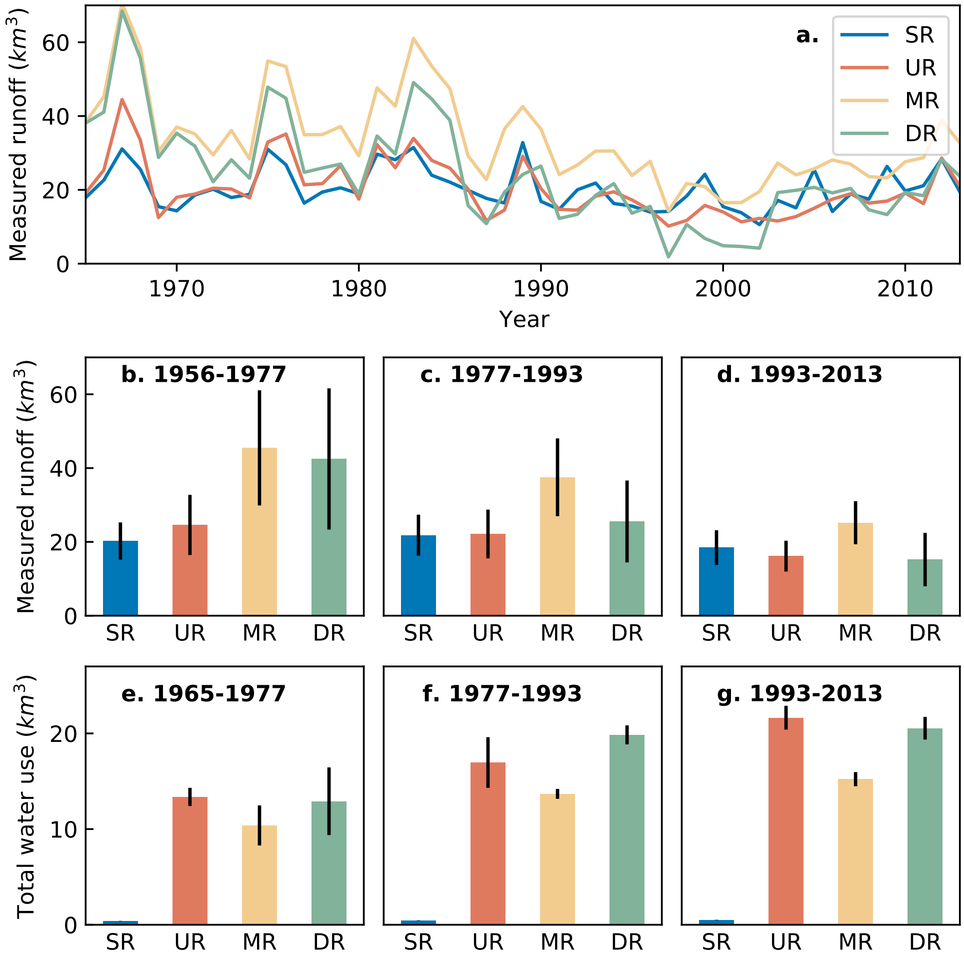

Fig. A2 Water resources in different regions. **A,** changing trend of measured runoff, **B, C and D** average measured runoff within different periods. **E, F and G** average total water consumptions within different periods.

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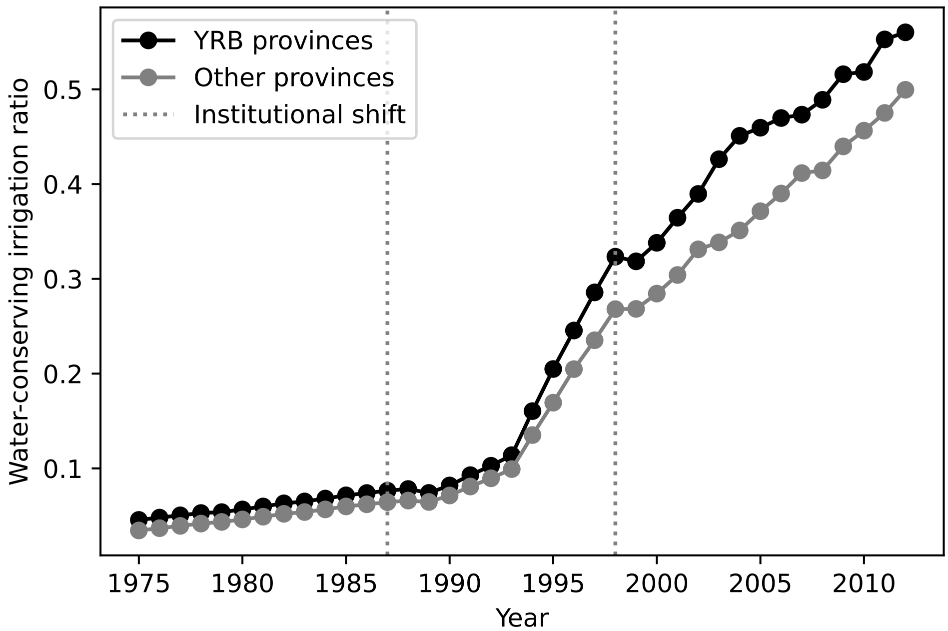

Fig. B3 Ratio of irrigated areas with water-saving equipments.

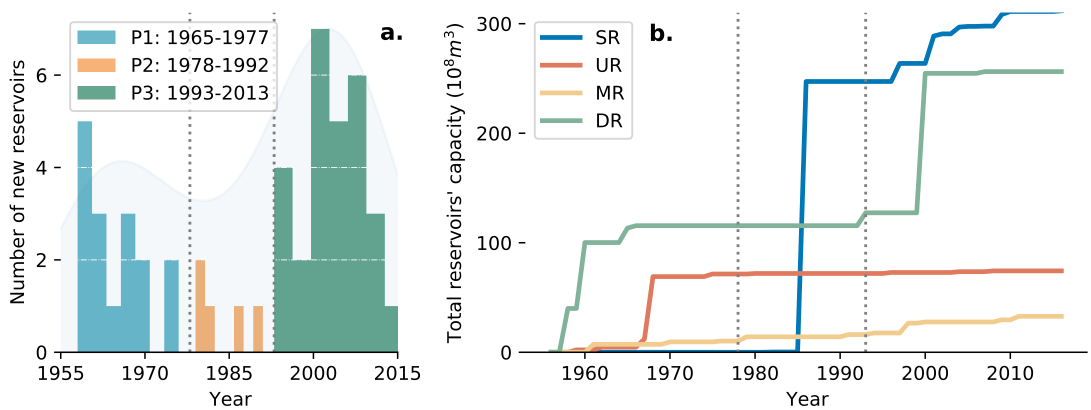

Fig. B4 Reservoirs.

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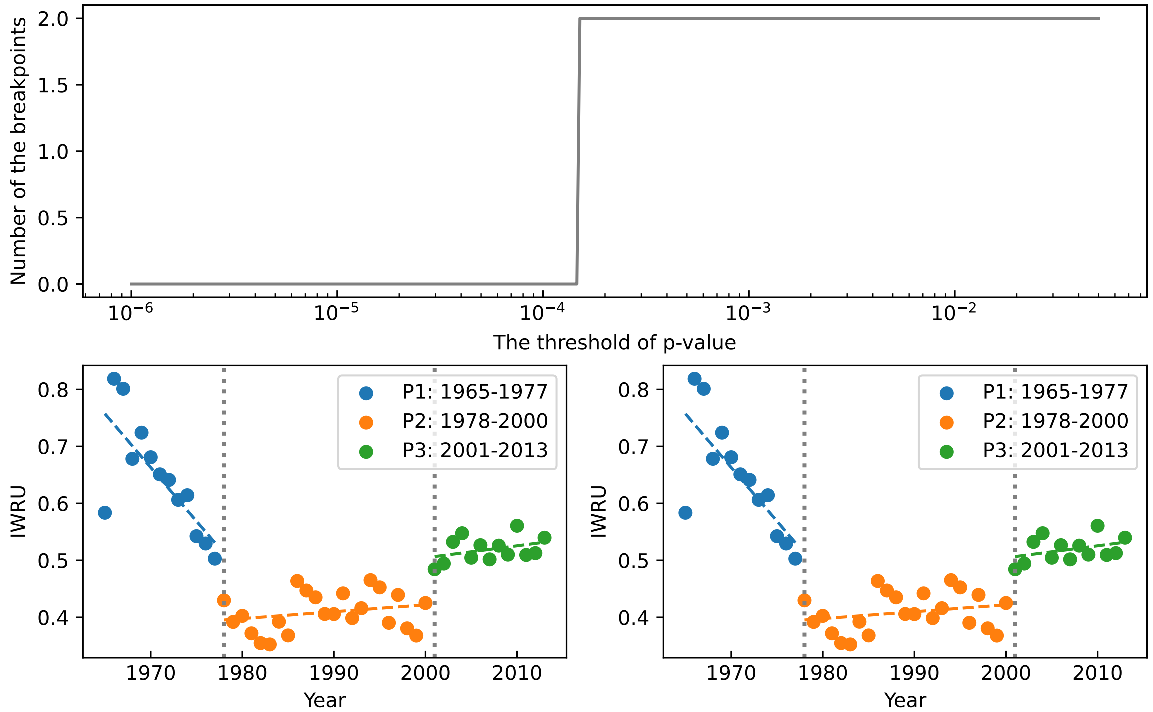

Fig. B5 Sensitivity analysis of the threshold of p-values. **A.** number of breakpoints in different p-values, the scheme with two-breakpoints are the dominant situation. **B.** A typical result of two breakpoints. **C.** A typical result of three breakpoints.

Table B2 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 main stream 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

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