Identifying regime transitions for water governance at a basin scale

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

[1*]State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University,, Xinjiekouwai Street, 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.

*Corresponding author(s). E-mail(s): bfu@rcees.ac.cn;
Contributing authors: songshgeo@mail.bnu.edu.cn; shuaiwang@bnu.edu.cn; wuxutong@bnu.edu.cn; yongping.wei@uq.edu.au; graeme.cumming@jcu.edu.au; qinyue@pku.edu.cn; wuxilin20@mails.ucas.ac.cn;

Abstract

Water governance determine “who gets water, when, and how” in most large river basins. Shifts in water governance regimes from natural to social-ecological or “hydrosocial” carry profound implications for human wellbeing; identifying regime changes in water governance is critical to navigating social-ecological transitions and guiding sustainability. We characterized water governance along with the three main aspects - stress, purpose, and allocation - to develop a quantitative Integrated Water Governance Index (IWGI) at a basin scale. Applying the IWGI to the rapidly-changing Yellow River Basin (YRB) in China clarifies shifts in water governance between massive supply, transformation governance, and adaptation-oriented regimes. In the YRB, the underlying causes of regime shifts were increasing water supply and demand before the governance transformation and re-allocation and regulation after the change. The IWGI offers a comprehensive and straightforward approach to linking water governance regimes to sustainability, providing valuable insights into hydrosocial transitions.

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 development and human well-being [1, 2]. As an integral part of earth system governance, successful 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 water have profoundly modified the natural water cycle, resulting in rivers that are dominated by a hybrid of social and natural drivers [6–8]. Facing transitions from natural to human-dominated regimes, many big river basins worldwide (which are hot spots of civilization and economic growth) are urgently in need of more effective water governance [9, 10].

Water governance refers to the political, social, economic, and administrative systems that influence the use and management of water [11, 12], essentially about "who gets water, when and how"[13]. Therefore, the United Nations Development Programme (UNDP) has suggested that three core aspects of water use decided by water governance correspondingly: "When and what water to use?" (stress), "How does water provide different services for human well-being?" (purpose), and "Who can use water equally and efficiently?" (allocation) [14]. 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 [15–17]. 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) [18–20]. Third, the allocation of water across the whole basin is not only decided by regionally socio-economic and environmental context but also influenced by systematic regulation [21, 22]. Since the transition to a human-dominated regime induced substantive changes in the three interwind aspects (stress, purpose, and allocation), considering them seperately can lead to systematic failure in water governance.

A first critical step in understanding the successes and failures of water governance is to identify the different regimes that underpin it [23, 24]. Regimes of water governance arise within linked human-water systems (based on management, institutions, and exploitation) to create local equilibria in social-ecological structures and functions [25–27]. For example, under a human-dominated regime, reservoirs make water stress easier to be alleviated because of flexibility; growing energy and industrial demands make water services purposes lopsided to non-provisioning sectors; conveyance systems make water allocation more planned (Figure 1 A) However, the lack of a comprehensive but straightforward approach to identifying changes in water governance regimes represents a challenge for efforts to enhance the sustainability of water resource use. Filling this gap, which is the aim of this paper, is essential for the appropriate alignment of human and water systems.

The Yellow River Basin (YRB), which contains the fifth-largest and most sediment-rich river in the world, needs integrated water governance because of geological and human history [9, 28]. Since the 1960s, governance practices such as reservoirs, levees, and conservation measures have contained the issues troubled by thousands of years of high sediment loads [29, 30]. However, new challenges such as decreased streamflows and water depletions occurred in more recent times, leading to water use regulation and water transfer across basins -different focused water governance tactic [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 to the satisfaction of all actors [32]. Governance challenges induced by environmental, economic, social, and political factors have resulted in YRB being among the most intensively-governed 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 depict the three aspects of water governance (stress, purpose and allocation) with corresponding indicators (see methods) and thus develop an Integrated Water Governance Index (IWGI) by equally weighting them, to indicate results from water governance (see Figure 1 B). Then, by applying the index to a typical rapid-changing big river basin (the YRB), we show how IWGI helps detect and describe complicated water governance regimes comprehensively but straightforwardly. 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 that offers a practical guideline for a coordinated approach to exploring the challenges faced by big river basin 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 aspects (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. Taken together,

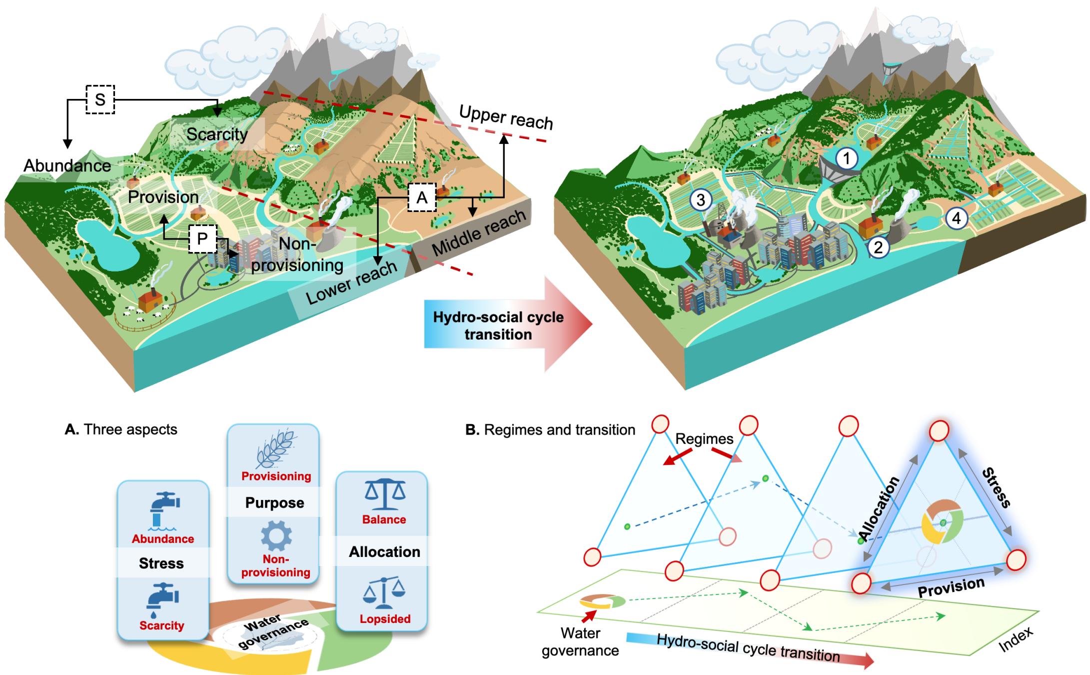

Fig. 1 Identifying the water governance regimes in transitions of a hydrosocial cycle with an integrated water governance index (IWGI). Water stress (S), purposes of water services (P), and water allocation (A) are three aspects to be considered (**A.**). Along with hydrosocial-cycle transitions, a human-dominated regime influences these aspects of water governance. For example, the construction of reservoirs (1) aims to alleviate water stress; growth of energy and industry (2); water-lead intensive agriculture (3); conveyance system (4) controls water allocation. Therefore, the methodology is to combine three aspects' corresponding indicators, and then an abrupt change of the IWGI can indicate a regime shift in water governance (**B.**).

the overall features of the three aspects in different periods are relative to a directional change in the combination of three aspects (Figure 2C).

2.2 Causes of the regime shifts

The underlying causes of changes in the IWGI 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 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 (*Appendix* Figure B2). Ensuing the 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 did irrigated areas continue to expand slowly

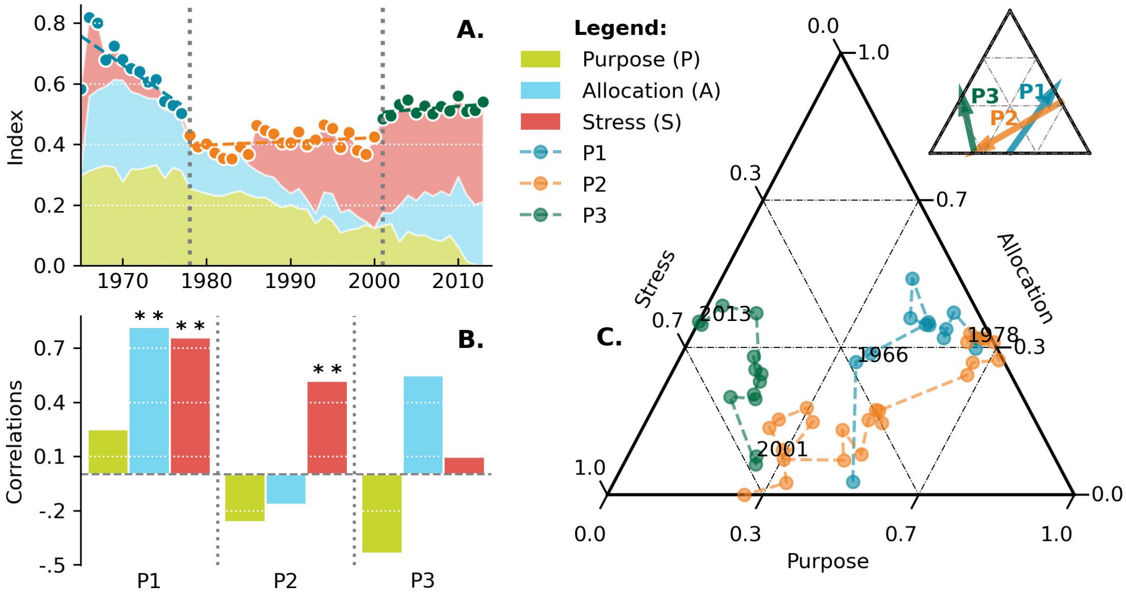

Fig. 2 Changes in the IWGI index and corresponding water governance regimes: P1: 1965-1978, P2: 1979-2001, and P3: 2002-2013. **A,** detecting change points of IWGI and contributions from each indicator. Two significant change points ($p < 0.01$) occurred in 1978 and 2001. **B,** correlation of trends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

during the P3 (Figure3 A), but industry and urban services also assumed a more vital economic role (represented by Gross Added Values, GVA) (Figure 3 B). Because of increased efficiency, however, they both experienced significant declines in water use for a unit irrigated area or unit production (Figure 3 A and Figure 3 B). As a result, the differences between sectors and regions in water use reduced while the total water stress steadily remained high during the P3 (Figure 2A).

Environmental context, social transformation, and policies played roles in all three periods. 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 regulations. Under the banner of "conquering nature" most of the reservoirs were built in regions with high water demands during the P1 (R/B ratios were significantly higher ($p < 0.01$, see Figure 3C)). Ensuing the P2, the number of new reservoirs decreased significantly and significantly increased basin policies rigorously controlled the allocation of water (Figure 3D, $p < 0.01$ and *SI Appendix* Figure B2). During the P3, authorities proposed more national-level water governance policies under the guidance of the national strategy "environmental regulation" (Figure 3D). The regime shift from P1 to P2 is in

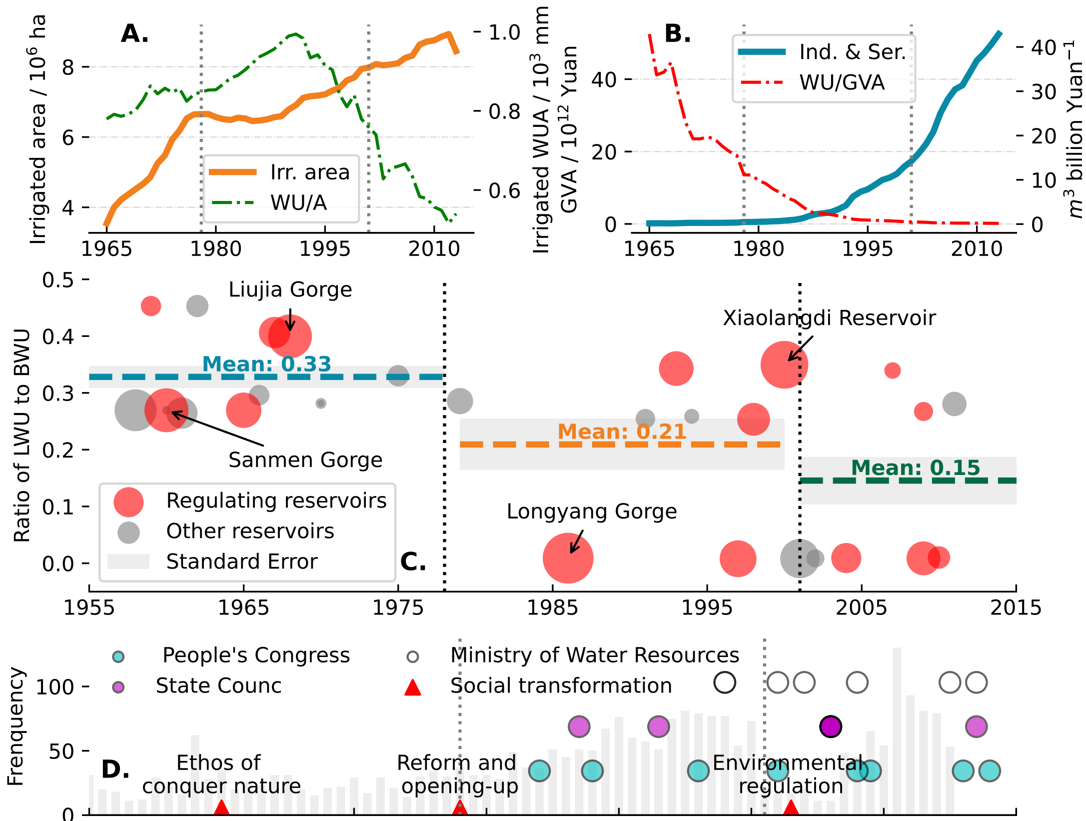

Fig. 3 Causes of water governance regime shifts in the YRB. **A.** Changes in the total irrigated area (orange line) and water use intensity (WU/A, water use divided by the irrigated area, the green dot line). **B.** Changes in gross values added (GVA) of industry and services (blue line) and their water 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. **D.** Social transformations (red triangles) and national-level governance policies (the circles, different colours denote signed by different state institutions, see *Appendix* Table C2). The light grey bars count official documents related to the YRB on a basinal scale (the Yellow River Events).

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

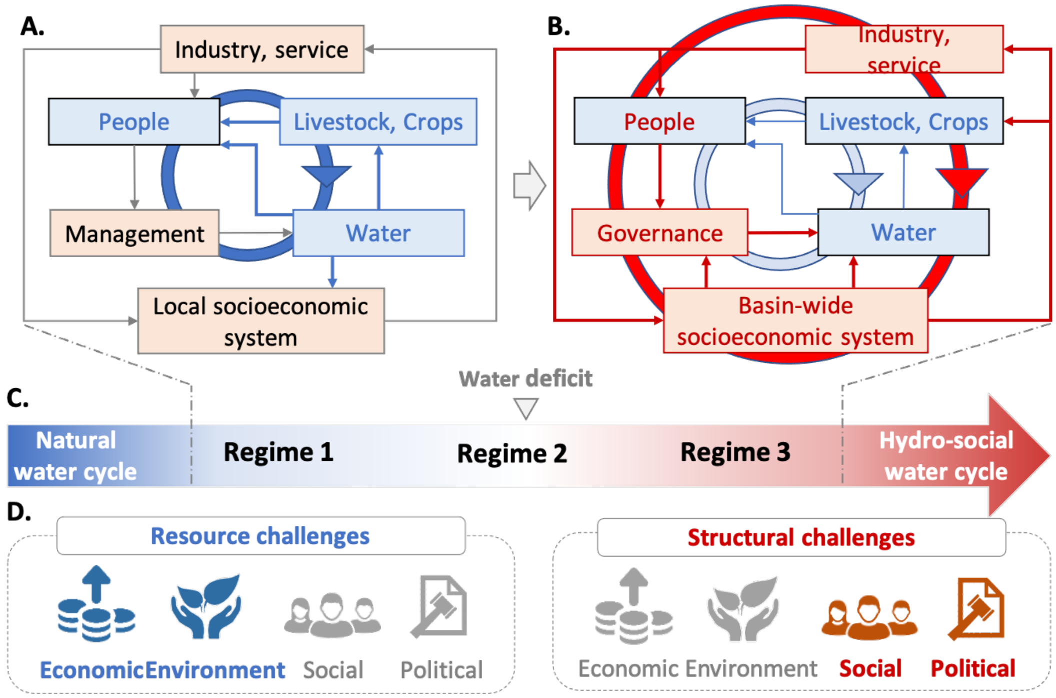

Fig. 4 Transition schema in hydrosocial cycle and water governance regimes. The natural water cycle dominates blue pathways, while socio-economic feedback dominates red. **A.** As socio-economic systems develop, non-provisioning water demand increases; simultaneously, increased adaptive capacity by engineering allows people to manage water resources to alleviate 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. 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.

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 tele-coupling raises additional water governance challenges in an increasingly tightly-connected world, regime shifts in water governance align with different human-water relationships [35]. The process echoes how societies have been proposed to change governance practices by enhancing their adaptive capacity in the hydrosocial cycle, and the IWGI quantitatively identifies this transition [27, 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 governance regimes; we named them: a massive supply regime (P1: 1965-1978), a governance transforming command (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 Chinese slogan "man will conquer nature" suggested then, however, the enhancement of water supply did not align with irreversible changes in the human-water relationship; it drastically increased water demand with little consideration for ecological conservation [38]. The rapid expansion of irrigated farmland and water diversion facilities in the same decade brought the overburdened YRB close to a critical point, where increasing supply to meet demand was impractical [27]. Use of over 80% of the surface water since 1972 has led to frequent river depletion, causing additional ecological issues such as wetland shrinkage and declines in biodiversity [31]. In addition, since water stress also limited the growing industrial economy, the existing modes of water governance led to a social-ecological crisis [32].

The start of the governance transforming regime (P2: 1979-2001) coincided with rising competition for water use after the "reform and opening-up". The results from the YRB mirror those of the theoretical analysis: continuous increases in water demand when the basin's total supply is stable can follow substantial changes in governance regime and a rapid enhancement in overall social adaptive capacity [27]. As a pioneer in shifting governing institutions, the YRB triggered institutional changes during this regime. These include, for example, slowing the growth of irrigated acreage; leading water-saving infrastructure; creation of China's first water quota scheme, and the creation of a preliminary cross-boundary water transfer plan [33, 39, 40]. Consequently, although water stress remained and increased (due to reducing streamflow and flexibility), the last depletion of the Yellow River in 1999 led to a climax in this transformation in water governance [39].

The ensuing adaptation-oriented regime (P3: 2002-2013) involved a significant societal shift in adapting to 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 demands in the face of limited water supply [41, 42]. Widespread reconstruction of resources in different industries and regions led to calls for adaptation in water governance, using the urgent requirements of adjusting rigid quota shares from the previous regime as an example [39]. Many national-level governance practices were proposed under the regime because the absence of such policies to support high-quality development became new a structural challenge for water governance [43].

In general, water governance of the YRB is among the most prominent example in the widespread transition to a hydrosocial cycle - "improving supply, transforming governance, and enhancing adaptation". With each dimension changing gradually, the emergence of different regimes drives water governance challenges at a basin-scale: these were primarily economic and environmental before the transformation, but social and policy-related towards the end (Figure 4) [44, 45]. In an analogy at a global scale, the resource challenges, represented by water shortage and water supplying difficulties, are mainly faced by undeveloped and developing basins [22, 46, 47]. 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 lack of long-term data worldwide, which means there is still a gap between comprehensively identifying and applying the IWGI more widely. However, we propose that all water governance issues result in changing "who gets water, when and how", so monitoring water stress, purposes of water services, and water allocation patterns do help. Choices of indicators for different aspects can be adapted according to available datasets; the connections between underlying components remain crucial in holistically understanding transitions in governance regimes. In today's world, regime shifts from biophysical to hydrosocial control of water dynamics seem likely to become increasingly widespread; comprehensive strategies to address governance challenges will have to become the core of complex human-water systems [20, 50, 51]. Although river basins have shown improvements in water management technologies and water use efficiency, many are still approaching local, regional, and 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

Focusing on "who gets water, when and how", three aspects of water governance change along with the hydrosocial cycle transition: water stress, water services purpose, and water allocation. We developed an Integrated Water Governance Index (IWGI) to detect regime shifts in water governance by integrating them. Applying the IWGI to a rapidly-changing large river basin (the Yellow River Basin, China), we interpret how water governance shifts between three regimes over half a century. 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 aspects (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 aspects (Stress, Purpose, and Allocation) of water governance. Each dimension keeps two directions, and we assumed the hydrosocial cycle aligns with one of them, respectively:

$$Transformation \propto S * P * A \tag{1}$$

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

$$Transformation \propto ln(I_S) + ln(I_P) + ln(I_A) \tag{2}$$

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

$$IWGI = (I'_S + I'_P + I'_A)/3 \tag{3}$$

where:

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

Indicator of stress

We used the scarcity-flexibility-variability (SFV) water stress index proposed in Qin et al., (2019) to evaluate water stress [15]. This metric considers management measures (such as the construction of reservoirs) and the impact of changes in water use structure on the evaluation of water scarcity. Based on the hydrological and economic context of YRB, four second-level regions are divided (Source Region, Upper Region, Middle Region, and Lower Region, see *Appendix*A). For the whole YRB, the indicator of water stress I_S is the average of all regions' SFV-index:

$$I_S = \frac{1}{4} * \sum_{i=1}^{4} SFV_i \tag{5}$$

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

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:

$$NPS = \frac{WU_{pro}}{WU_{pro} + WU_{non-pro}} \tag{6}$$

In this study, we consider livestock water use, rural and urban domestic water use, and agricultural water use as provisioning water because they directly service for survival. Others are non-provisioning: services and industrial water use because they mainly service the economy.

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:

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

where p_i is the water proportion of region i to the whole basin (here, $N = 4$ considering divided regions in the YRB, see *Appendix*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 $\mathrm{x}_1, \mathrm{x}_1, \ldots, x_{t_0}$ 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:

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

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 break points in the main text with $\alpha = 0.001$, the threshold from 0.0005 to 0.05 does not affect our results, and the breakpoints we identified are robust (see *Appendix* Figure B3).

5.3 Datasets

In order to calculate IWGI in the YRB, all the datasets we need are listed in the *SI Appendix* Table C1 with a detailed description in C.

Supplementary information. 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 A. The formulation in detail for applying the SFV-index is available in the B. We used multiple sources of datasets in this study, *Appendix* C introduces where they came from and how we harmonise them for analysis.

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Declarations

- Funding
- Conflict of interest/Competing interests (check journal-specific guidelines for which heading to use)
- Ethics approval
- Consent to participate
- Consent for publication
- Availability of data and materials
- Code availability
- Authors' contributions

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Appendix A 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 [29, 31, 56], so four important hydrological stations can distinguish the regions (see Figure A1).

- **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 [57].
- **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.

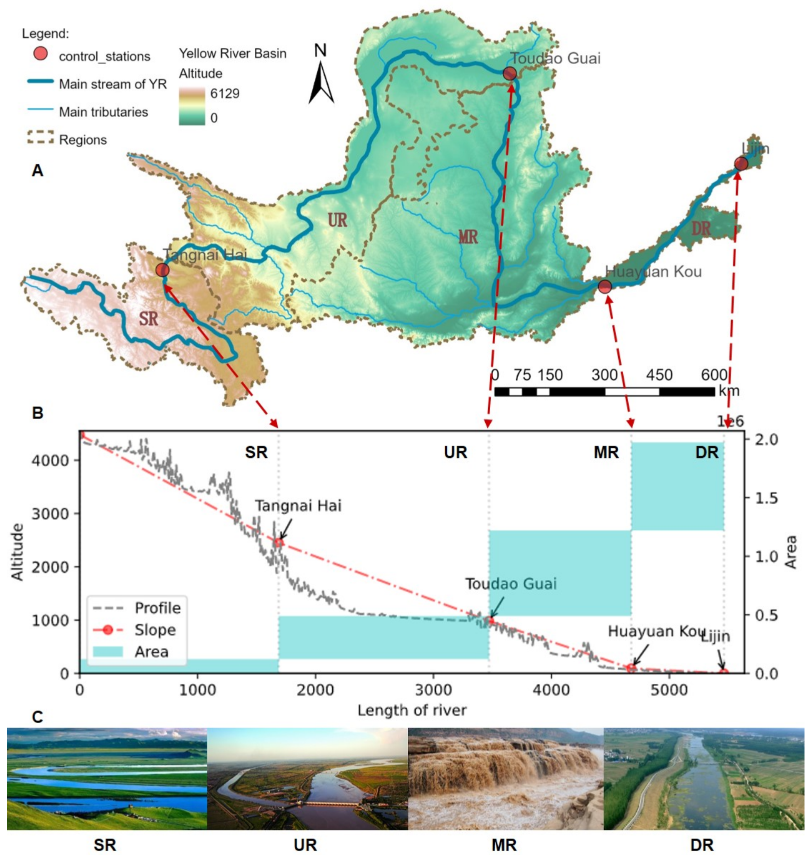

Fig. A1 The study area. **A.** Diagram of the YRB and the subdivision of the basin (SR: Source Region, UR: Upper Region, MR: Middle Region, DR: Downstream region). **B.** Profile of the main channel of the Yellow River. The hydrological stations control the SR, UR, MR and DR. **C.** Typical landscapes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

Appendix B 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 [15]. 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, *Appendix* A):

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

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.

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

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

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

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

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 the SFV index after normalizing them:

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

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

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

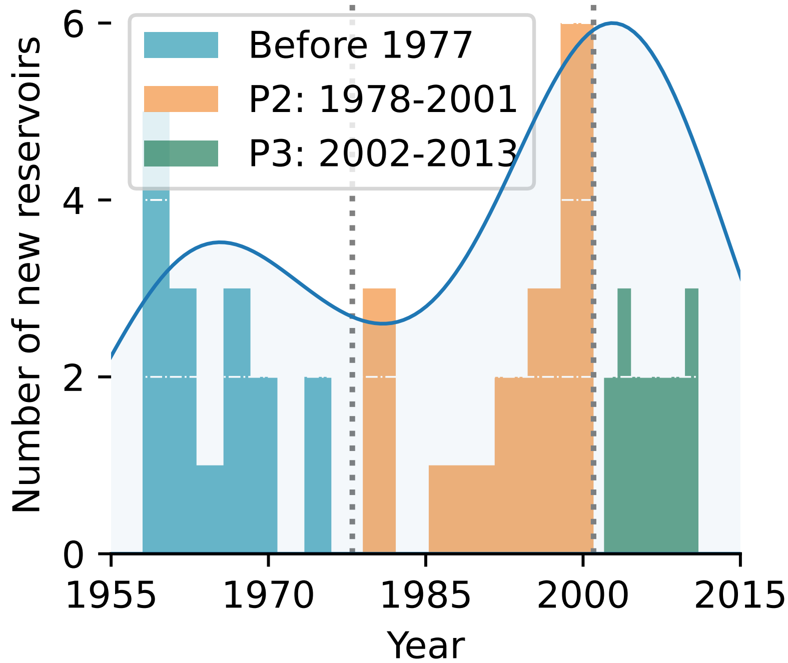

Fig. B2 Numbers of new reservoirs in each year.

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

Appendix C Datasets

Descriptions

This study used multiple types of data (see Table C1): statistical datasets, hydrological datasets, and political datasets.

Statistical datasets

The water resources use dataset was published by Zhou et al. [38], 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

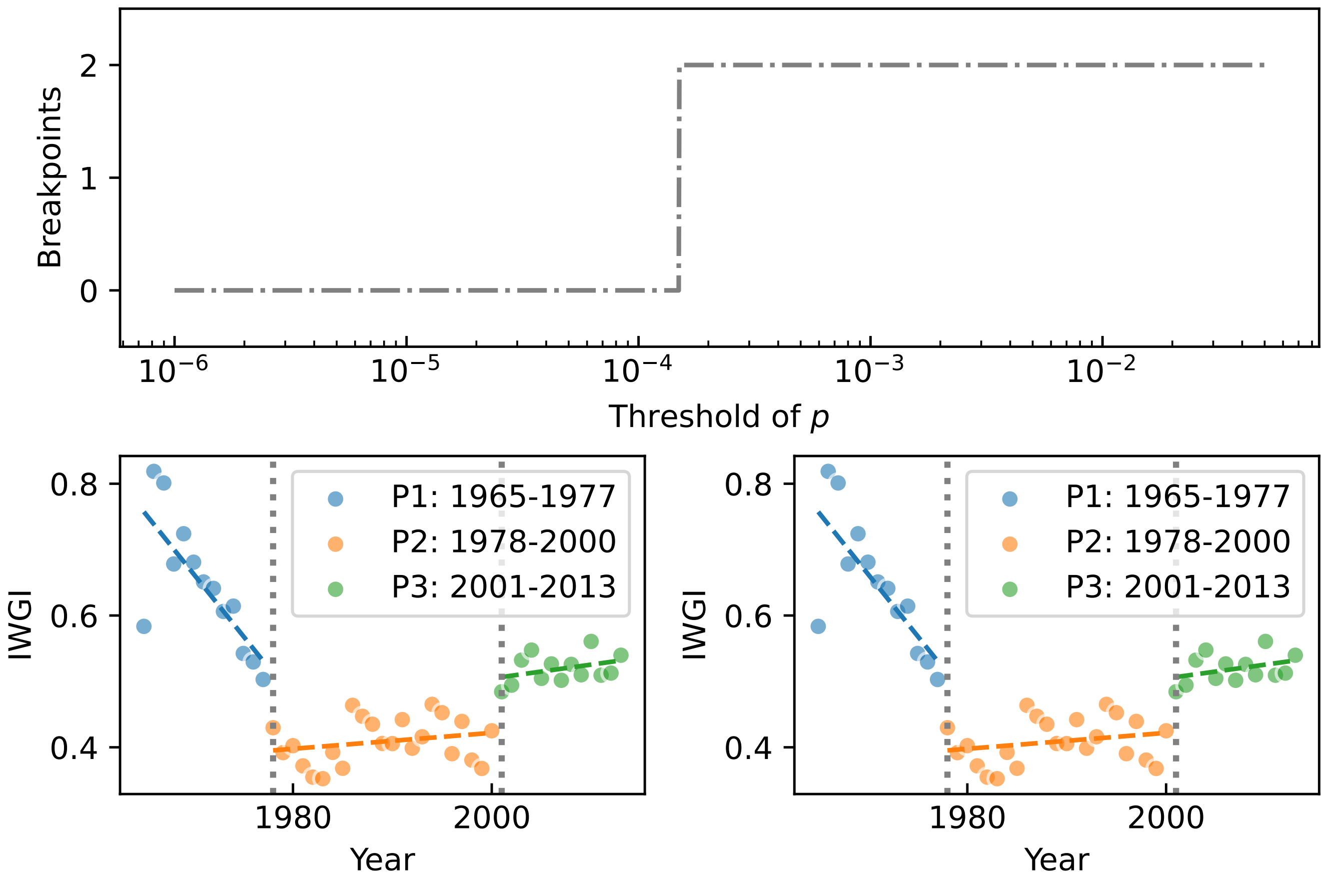

Fig. B3 Sensitivity analysis of the threshold of p-values. **A.** number of breakpoints in different p-values, the scheme with two-breakpoints are the dominant situation. **B.** Threshold of p-values $\alpha = 0.0005$. **C.** Threshold of p-values $\alpha = 0.05$.

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 [38]).

Hydrological datasets

The reservoir dataset was collected by Wang et al. [31], which introduced includes the significant new reservoirs built in the YRB since 1949 (Figure B2). 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 [31] and [29].

Political datasets

The policy dataset collects laws and policies listed in the book [56], 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 C2). 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 A1 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%:

$$S_{ij} = MAX(S_i j/S_i) \tag{C11}$$

  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.:

$$MAX(S_{ij}) > 0.95 * S_i \tag{C12}$$

- 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.

Table C1 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 [38]
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 [31]
5. Measured runoff	Hydrological	Location	1949-2019	Measured data [29, 31]
6. Laws	Political	Documents	1949-2013	YRCC [56]
7. History of YRCC	Political	Documents	1949-2002	YRCC [58]
8. YRB Events	Political	Documents	1949-2015	YRCC: http://www.yrcc.gov.cn/hhyl/hhjs/

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Table C2 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 State Council of the PRC	1993	
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.

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