

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. 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 the massive supply regime, governance transformation regime, and adaptation oriented regime. 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

052 natural tendencies [6–8]. Facing this transition,
 053 many big river basins worldwide (which are hot
 054 spots of civilization and economic growth) are
 055 urgently in need of successful water governance for
 056 sustainability [9, 10].

057 Water governance refers to the political, social,
 058 economic, and administrative systems that influ-
 059 ence the use and management of water [11, 12].
 060 For populated large river basins, missing gover-
 061 nance means missing sustainability, and a first
 062 important step in understanding the transitions
 063 with successful water governance is identifying
 064 the different regimes [13, 14]. Regimes of water
 065 governance maintained by concreted intertwine
 066 within human-water systems (such as manage-
 067 ment, institutions, and exploitations), as a stable
 068 state in structures and functions [15–17]. There-
 069 fore, regime shifts sometimes lead to new water
 070 governance challenges as both signals and conse-
 071 quences of substantive changes in human-water
 072 systems. The lack of a comprehensive but straight-
 073 forward approach to identifying changes in water
 074 governance regimes challenges sustainability, and
 075 filling this gap can well align human and water
 076 systems (Figure 1).

077 Governance is essentially about “who gets
 078 what, when and how” [18]. The United Nations
 079 Development Programme (UNDP) thus suggested
 080 that three key dimensions of water use are decided
 081 by the water governance directly: “When and
 082 what water to use?” (stress), “How does water
 083 provides different services to well-beings?” (pur-
 084 pose), and “Who can use water equally and
 085 efficiently?” (allocation) [19]. First, water stress
 086 depends not only on climate (with increasing
 087 scarcity and uncertainty in many regions) but also
 088 on the increasingly insatiable demands from eco-
 089 nomic activities such as irrigation and industry;
 090 water storage can resolve some but not all of these
 091 issues [20–22]. Second, the purpose of how water
 092 services human well-being is to consider trade-
 093 offs between consumptive uses (e.g., drinking and
 094 food production) and non-consumptive uses (e.g.,
 095 energy production) [23–25]. Third, the allocation
 096 of water across the whole basin is not only decided
 097 by regionally socio-economic and environmental
 098 context but also influenced by systematically reg-
 099 ulating [26, 27]. Despite regime shifts in water
 100 governance related to substantive changes in any
 101 of the three dimensions, separately considering
 102

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 gov-
 ernance challenges in sustainability [28]. Since
 the 1960s, the implementation of conservation
 measures, regulation reservoirs, and levee con-
 structions 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 regula-
 tion 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]. Con-
 fronting governance challenges induced by envi-
 ronmental, 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 indica-
 tors 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 ana-
 lyze the complicated water governance regimes
 in a comprehensive but straightforward way. Fol-
 lowing synthetic analyses of the changes in water
 demand, supply, economic outcomes, and insti-
 tutions, 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.

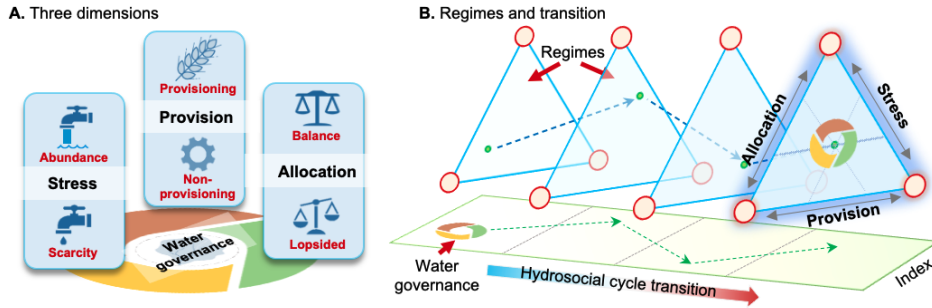


Fig. 1 Identifying the water governance regimes in transitions of a hydrosocial cycle. **A.** Water governance has three key dimensions (stress, purpose and allocation), each of which has two potential directions (denoted in red) when changing. (1) “stress” of water shifts between scarcity and abundance; (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 $0.25 \times 10^6 \text{ ha/yr}$ (Figure 3A), simultaneously supported by increasing supply through the construction of reservoirs (SI Appendix Fig. S3). Entering the transformation governance regime (P2), however, the expansion of irrigated areas slowed down, and industry and services gradually took off, with more water demands (Figure 3A and B), leading to an 8% reduction in the proportion of irrigation water use (SI Appendix S3).

From P2 to P3, the efficiency of water use changed obviously. Not only irrigated areas keep their slow expansion in the adaptation oriented regime (P3) (Figure 3A), 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 Fig. S4), 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 of water use reduced while the total water stress remained stable during the adaptation oriented regime (SI Appendix Fig. S3).

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

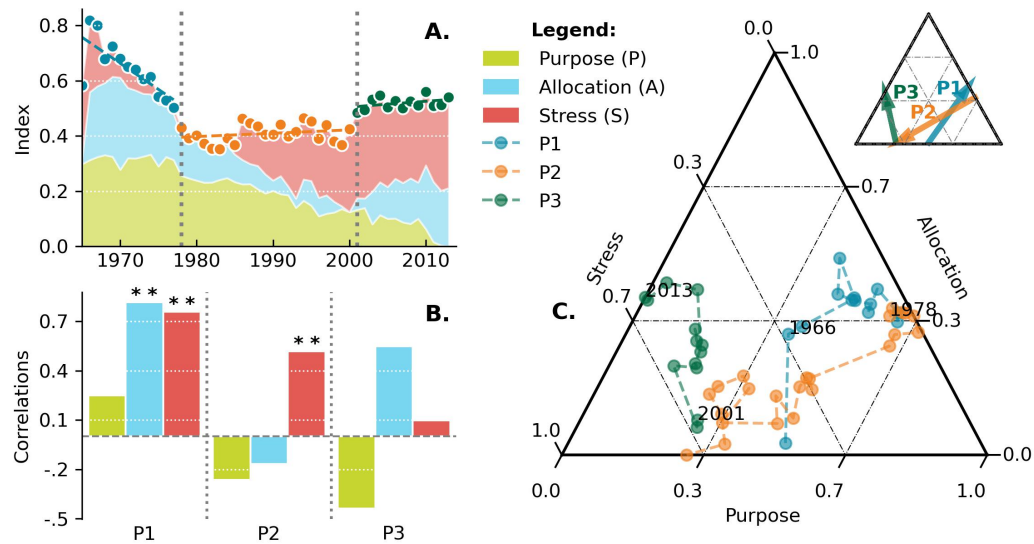


Fig. 2 Changes in the IWGI index and corresponding water governance regimes: P1: 1965–1978, P2: 1979–2001, and P3: 2002–2013. **A**, detecting change points of IWGI and contributions from each indicator. Two significant change points ($p < 0.01$) occurred in 1978 and 2001. **B**, correlation of trends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

potential role in water supply rather than basinal 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, see Figure 3C, $p < 0.01$), when natural water resources were also relatively abundant (SI Appendix Fig. S5). 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 Fig. S6). In the adaptation oriented regime, 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 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). 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,

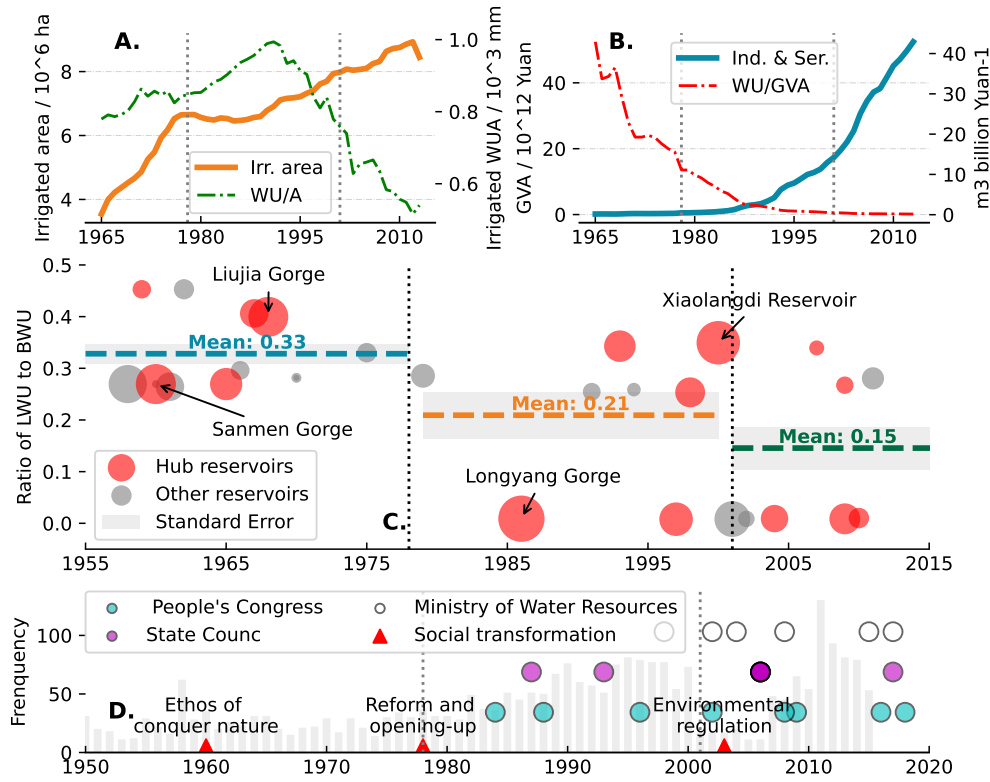


Fig. 3 Causes of water governance regime shifts in the YRB: environmental change, economic growth and efficiency changes, social transformation, and governance policies. **A.** Changes in the total irrigated area (orange line) and water use intensity (WU/A , water use divided by the area, the green dot 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).

however, the enhancement of water supply 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].

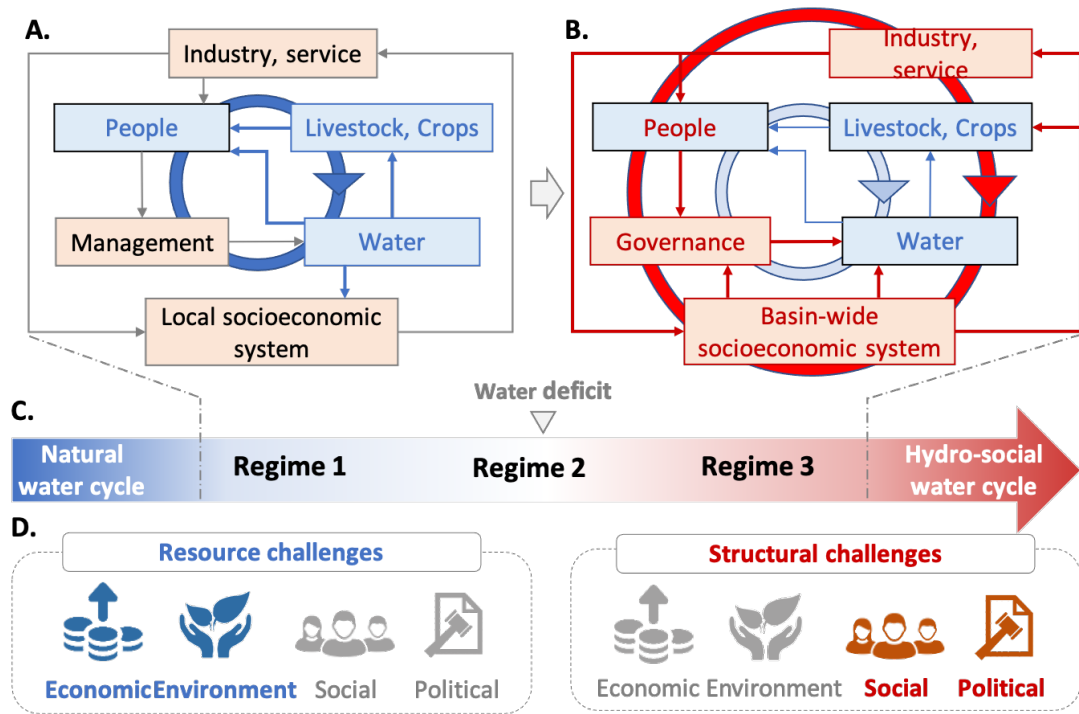


Fig. 4 Transition schema in hydrosocial cycle and water governance regimes. The natural water cycle dominates blue pathways, while socio-economic feedback dominates red pathways. **A.** As socio-economic systems develop, non-provisioning water demand increases; simultaneously, increased adaptive capacity 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 (SFV_i) as the Indicator in a particular region i [20]. This metric takes into account management measures (such as the construction of reservoirs) and the impact of changes in the industrial structure of water use on the evaluation of water scarcity (see *SI Appendix Methods S4* for details). 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 $i = 1$ to 4 refers SR, UR, MR, and DR (see *SI Appendix Methods S1 Definition of study area*).

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:

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

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 regions in sum). The YRB is divided into 4 regions (i.e., $N = 4$) according to the natural and socio-economic backgrounds (see *SI Appendix XX*).

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 H_0 : 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 x_1, x_1, \dots, x_{t_0} and $x_{t_0+1}, x_{t_0+2}, \dots, x_T$, 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:

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

where:

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

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:

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

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 (see *SI Appendix* Methods S5 for Sensitivity analysis), meaning that the probability of a statistically significant change-point judgment being valid was more than 99.9%. Since this method can only return one significant change point, we divided the series into two at that point and analyzed each series separately until all significant change points were detected.

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.

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Acknowledgments. Acknowledgments are not compulsory. Where included they should be brief. Grant or contribution numbers may be acknowledged.

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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 Section title of first appendix

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