Identifying regime transitions for water governance at a basin scale

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Abstract

In many large river basins, transition of water governance regimes from natural to social-ecological or 'hydrosocial' situations profoundly changes who gets water, when, and how. Identifying changes of governance regimes is therefore critical to understanding the transition and guiding the efficient and sustainable use of water. We combined three main dimensions of water governance (supply, purpose and allocation) to develop a quantitative Integrated Water Governance Index (IWGI) that can detect regime shifts in water governance at a basin scale. Applying the index to a rapidly-changing large river basin (the Yellow River Basin, China), it describes how water governance shifts between three regimes over half a century (massive supply regime; governance transformation regime; and adaptation oriented regime, respectively). Our application of the IWGI offers a comprehensive and straightforward way to link the shifts of water governance to environmental, economic social and political factors. As a potentially widespread transition schema for water governance regimes, the different governance challenges that occurred at different phases of the transition of the Yellow River also suggest potentially useful guidelines on the coordinated governance of big river basins in general.

Keywords: Regime shifts, Water governance, Transformation, Sustainability

1 Introduction

Water, being "at the centre of the planetary drama of the Anthropocene" [16], is essential not only for earth system processes but also in supporting the economic development and human well-being. 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 [1, 16, 26, 34, 39]. 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 [4, 13, 14]. As an integral part of a proposed earth system governance framework, water governance requires a deep understanding of changes in the complex relationships between humans and water [6, 13, 42].

Governance is essentially about "who gets what, when and how". Specifically, water governance refers to the political, social, economic, and administrative systems that influence the use and management of water For water resources in populated areas, missing governance means missing sustainability, and a first important step in understanding transitions toward successful water governance is identifying the different regimes. [43]. Corresponding to "who gets what, when and how", the United Nations Development Programme (UNDP) suggests three key dimensions of water use are decided by the water governance directly: "When and what water to use?" (stress), "How water provides different services to well-beings?" (purpose), and "Who can use water equally and efficiently?" (allocation) [23, 30, 43].

As a temporary stable state in structure, function, and dominant controls, a specific regime of water governance maintains by concreted intertwines within human-water systems (such as management, institutions, and exploitations) [8]. However, large and persistent changes in key properties may lead to a loss of systematical stability, potentially resulting in a regime shift with impacts on system outcomes and widespread cascading effects [18, 36]. Therefore, as both signals and consequences of substantive changes in human-water systems, regime shifts align with changing three key dimensions of water governance (stress, purpose, and allocation), sometimes leading to new challenges in sustainability [23, 30, 43]. 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 [19, 35, 45]. 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) [15, 24, 29]. Third, the allocation of water across the whole basin is influenced not only by regionally socio-economic and environmental context but also by systematically regulating resources [37, 40]. 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 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).

As an informative example, we focus on the Yellow River Basin (YRB, see *Appendix* Methods S1 and Figure S1 for details), the fifth-largest river in the world. With drastically anthropogenic intervention, the YRB experienced the most intense water governance challenges in China, leading to long-standing sustainability barriers. Since the 1960s, the implementation of conservation measures, regulation reservoirs, and levee constructions have contained the issues caused by high-sediment loads [46, 51]. However, water over-use has led to depletions of the over-burdened river, creating new challenges and new governance practices, including water use regulation and water transfer across basins [52]. 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 still an open question for sustainable water governance [48, 49]. However, 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 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 regimes of water governance and their leading causes in a comprehensive but straightforward way. 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.

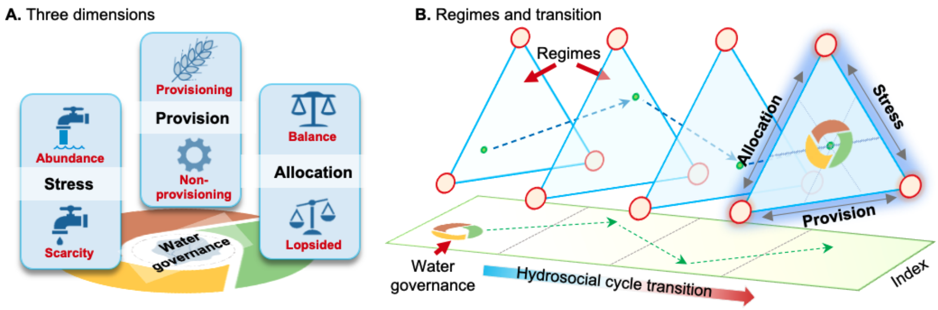

Fig. 1 A framework for identifying the water governance regimes and transitions of a hydrosocial cycle. **A:** water governance has three key dimensions (stress, purpose and allocation), each of which has two potential directions (denoted in red) when changing: (1) "stress" of water shifts between scarcity and abundance; (2) "purpose" of water is weighted between consumptive services or non-consumptive uses; (3) "allocation" changes between balanced or lopsided. **B:** along a transition of hydrosocial water cycle, water governance shifts in line with the three dimensions. By combining corresponding indicators, an abrupt change of the IWGI thus indicates a regime shift in water governance.

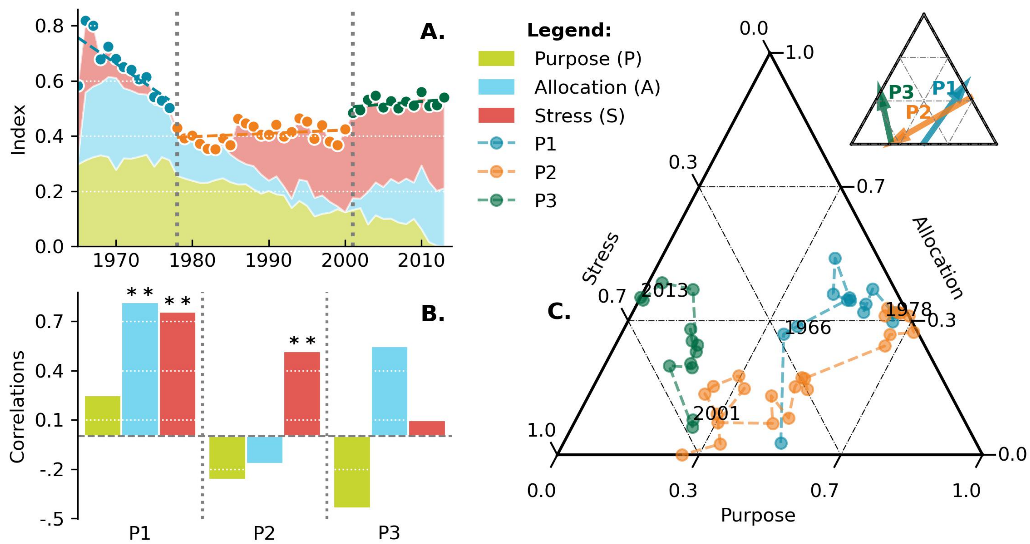

Fig. 2 Changes in the IWGI index and corresponding water governance regimes: P1: 1965-1978, P2: 1979-2001, and P3: 2002-2013. **A,** detecting change points of IWGI and contributions from each indicator. Two significant change points ($p < 0.01$) occurred in 1978 and 2001. **B,** correlation of trends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

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, spectively), 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 biggest share in contributions (57.11% on average), the increased allocation indicator and decreased purpose indicator changed the regime of IWGI.

The ternary shows overall features of the three dimensions in different periods, where each regime shift is relative to a directional change in the combination of three dimensions (Figure 2C). Throughout P1, the IWGI shifts paralleled the left axis because the Purpose indicator barely changed, and the other two changed in similar trends. Analogously, as the stress indicator is unchanged during the P3, the IWGI shifts paralleled with the right side of the axis while the other two changed in opposite trends. The regime then experienced a long-distance shift during the P2, as three indicators simultaneously changed their contribution ratios to IWGI. The three different periods corresponded to 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

Underlying causes of changes in the IWGI associates to various factors, but different in dominates of the two regime shifts. The expansion of irrigated areas and the economic growth of industry and services were critical to the change in purpose between P1 and P2. 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), and irrigation water was the dominant water use (81.56% of the total water use in 1965, and 83.17% in 1978 *SI Appendix* Fig. S3). Entering the transformation governance regime (P2), however, the expansion of irrigated area slowed down, and industry and services gradually took off, with more water demands (Figure3 A 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) (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* 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 P3 (*SI Appendix* Fig. S3).

Finally, 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 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 (e.g., the "87 Water Allocation Scheme") (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 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

3.1 Challenges along with the transition

Our results show that there have been three distinct but sequential governance regimes within the YRB: a massive supply regime (P1: 1965-1978), a governance transforming regime (P2: 1979-2001) and an adaptation oriented regime (P3: 2002-2013). Furthermore, shifts between these regimes were caused by different environmental, economic, social or political drivers, deciding who gets water, when and how. The process echoes how social systems can change water governance regimes by enhancing their adaptive capacity. However, the IWGI quantitatively identifies and reveals that

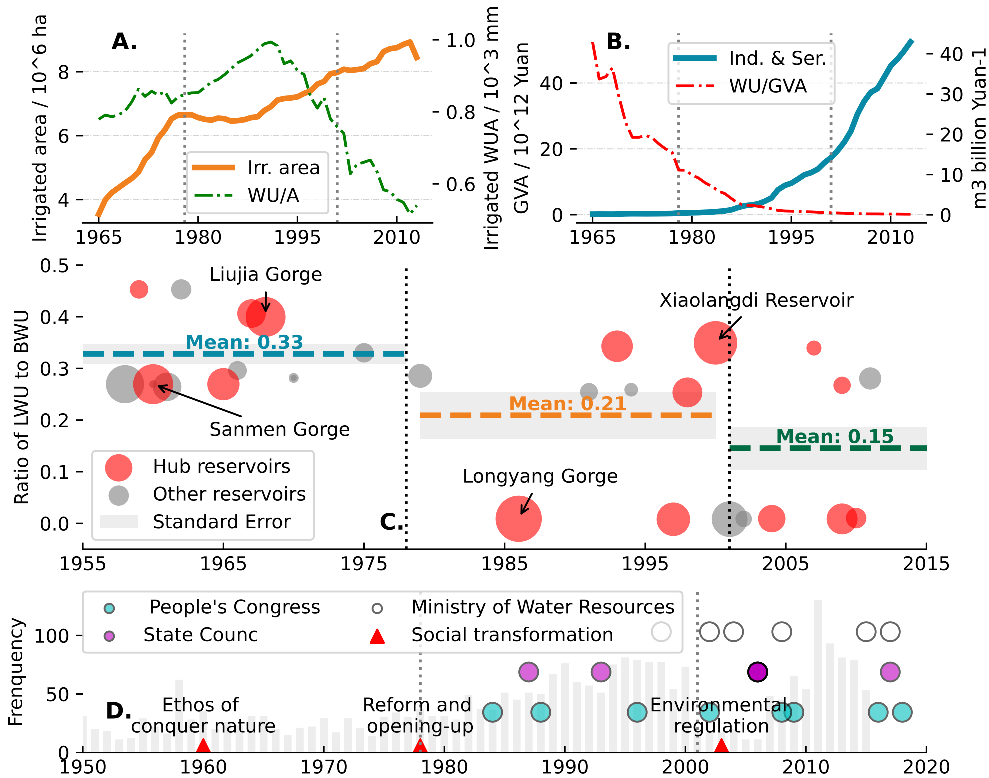

Fig. 3 Causes of water governance regime shifts in the YRB: environmental change, economic growth and efficiency changes, social transformation, and governance policies. **A.** Changes in the total irrigated area (orange line) and water use intensity (WU/A, water use divided by the area, the green dot 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 were constructed mainly for managing floodwater discharge and water regulation. These named reservoirs are significant for the whole basin rather than for local development. **D.** Social transformations (red triangles) and national-level governance policies (the circles, different colors denote signed by different state institution, see *SI Appendix* Table S2). The lightgray bars year-by-year show frequency of official documents related to the YRB at a basinal scale (see *SI Appendix* Table S3).

abstract pattern, thus characterizing the transition of water governance in detail for the first time. It is important to note that each indicator or cause changes gradually, but emerging regime shifts move water governance along with the hydrosocial water cycle at a basin scale. As a result, the water governance challenges were primarily economic and environmental at the beginning of the trajectory and social and policy-related towards the end (Figure 4 C and D).

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

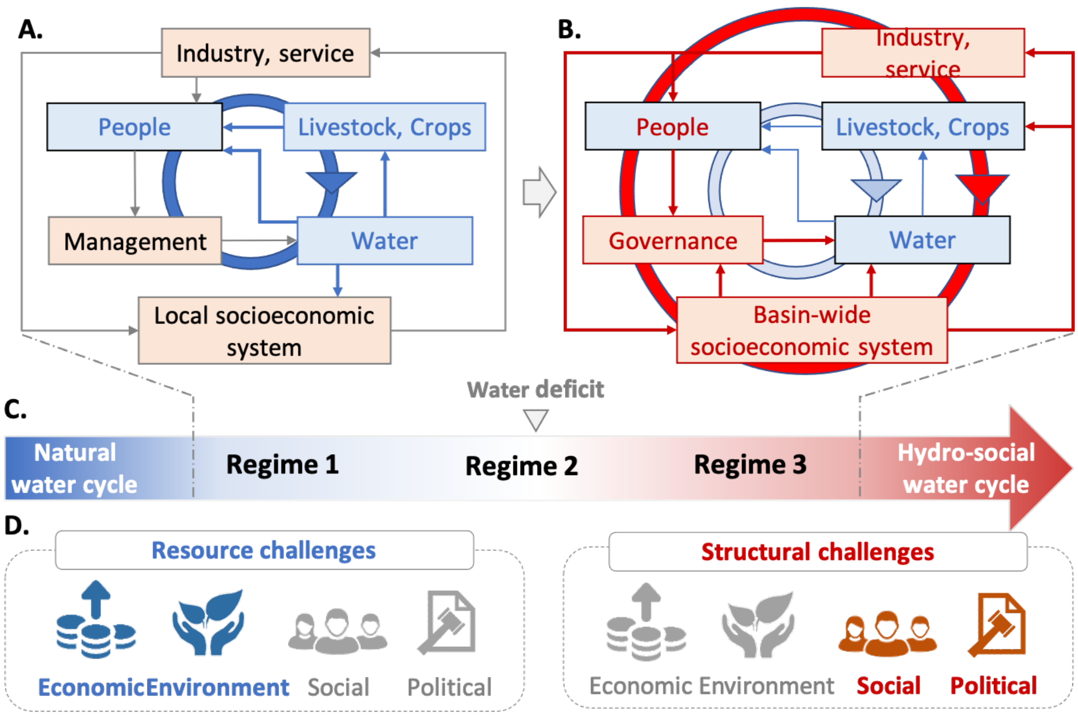

Fig. 4 Transition schema in hydrosocial cycle and water governance regimes. The natural water cycle dominates blue pathways while socio-economic feedback dominate red pathways. **A. Early phase.** As socio-economic systems developing, non-provisioning water demand increases; simultaneously, increased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

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. [54]. 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 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. 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 [50].

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 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 [47]. 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.

Finally, it came into an adaptation-oriented regime (P3: 2002-2013), when drastically shifting in societies occurred with stable 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 [11]. 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. 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 [25].

In general, the shift between the governance regimes advances in parallel with the trajectory of the hydrosocial cycle (Figure 4A, B and C). The transition from biophysical control to social and institutional control of ecosystem dynamics may become increasingly widespread in social-ecological systems as increasing anthropogenic impacts gradually change the world [5, 9, 10]. With intensive anthropogenic intervention, the YRB may be the most prominent example in this general transition of water governance - “improving supply, transforming governance, and enhancing adaptation” The transition regimes identified here also echo the two kinds of major water governance challenges globally (resource challenges and structural challenges, Figure 4 and *SI Appendix* Fig. S9) [33, 38]. Our analysis suggests that the early phase of transition often leads to resource-focused challenges that result from economic and environmental change, while structural challenges dominate the later phases of governance in social and political aspects. Resource challenges, represented as water shortage and water supplying difficulties, are mainly faced by undeveloped and developing basins [2, 15, 27]. Alternatively, highly-controlled and developed basins (especially for transboundary rivers) must mainly resolve structural challenges, such as water disputes or lack of equity, and maybe in urgent need of novel flexible, efficient sociopolitical governance structures [22, 22, 37, 44]. Typically, resource and structural challenges occur sequentially during the transition of water governance within the YRB. From the perspective of the core dimensions emphasized by the UNDP for water governance, our proposed schema connects governance challenges and the transformation of large river basins toward a hydrosocial water cycle.

3.2 Implications, limitations, and future directions

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. As the ubiquitous tele-coupling 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. Within the growing hydro-social cycle, the IWGI index depicts the increase of the adaptive capacity and sketches the transitional water governance regimes in a relatively straightforward but comprehensive way. It is important for scientists and decision-makers to recognize the changing governance challenges because models, institutions, engineering, and approaches developed under one regime are not necessarily useful under a different regime In the case of the YRB, an essential institution of water quota in the governance transforming regime became rigid during the enhanced adaptation phase. On the contrary, additional water from the ambitious cross-basins water diversion project, which originated in the phase of massive supply, can play an even more crucial role in today’s enhancing adaptation phase. Overall, applications of IWGI can induce a straightforward understanding of the water governance in the transition of the hydrosocial cycle, as descriptions from some previous conceptual frameworks suggested for all large-scale basins worldwide.

One of the main limitations of applying IWGI is abundant data availability for a long-term period. For example, we used the stress-flexibility-variability (SFV index) here, one of the most comprehensive indexes, as an indicator of the water stress dimension. With other indicators, therefore, we obtained various datasets in the YRB: water use in different regions and sectors, streamflows in different reaches, reservoir capacity and completion time, with furthermore information in social, economic, and institutional for interpretation. It 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. 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.

For today's world, water-related challenges remain one of the major gaps in our progress towards sustainability, while development-first strategies are still a dominant guideline in many places and maybe in opposition to improving governance [19, 28, 53]. Although most large river basins have shown improvements in water management technologies and water use efficiency along with development, freshwater use is still approaching planetary boundaries where human-water systems may collapse [3, 12, 21]. [17]. In the future, without successful governance, complicated governance structures dominated by hydrosocial water cycles may result in less flexible water use and undermine the resilience of social-ecological systems at a basin-scale [20, 26, 35]. From these perspectives, we need more flexible and comprehensive strategies to address governance challenges because the core problems are dynamic and complex [6, 7, 31, 42]. A deeper understanding of governance that incorporates ideas of non-linear change, regimes, and transitions should help to shift the focus of governance towards maintaining the resilience of the basin's social-ecological system and improving its sustainability.

4 Conclusion

5 Methods

This analysis aimed to develop a transparent and easily replicable approach to identifying water governance regimes and regime shifts; thus, it is not intended to provide a comprehensive model of social-ecological water dynamics. First, we constructed the Integrated Water Governance Index (IWGI) based on three dimensions (Supply, Purpose, and Allocation, see Figure 1). Then, we identify the changes in the index's periods over time using change point detection. An independent indicator reflects each dimension after normalization, and water governance regimes were characterized by the combination of impacts along each dimension at different periods. Finally, we decomposed the contribution of each indicator to changes in the IWGI at each regime.

5.1 Integrated Water Governance Index (IWGI)

Our Integrated Water Governance Index offers an accessible and operational way of measuring regime changes based on the transparent underlying assumptions that water resources governance system is closely related to a transformation towards a hydrosocial water cycle in the three dimensions below (see Figure 1 and SI 322 Appendix Methods S4 for details) [1, 26, 41].

- **Stress** (S): Socio-economic dominance may lead to further demands on the water supply because of increasing water withdrawals. However, since effective water governance may boost supply capacities to meet water demands through technical solutions in the process of development:

$$Transformation \propto S^{-1} \tag{1}$$

- **Purpose**(P): Transformation is usually accompanied by a change of purpose in water governance towards socio-economic services (usually towards non-provisioning purposes), because of higher returns:

$$Transformation \propto P \tag{2}$$

- **Allocation**(A): Transformation usually leads to more complicated structures in water allocation, as a result of division and cooperation between regions and sectors because of environmental context and economic comparative advantages:

$$Transformation \propto A \tag{3}$$

We combined these three dimensions into a single integrated index, keeping their positive or negative relationship with the transformation towards a hydrosocial water cycle:

$$Transformation \propto S * P * A \tag{4}$$

To effectively represent the three dimensions, we selected an appropriate indicator (I_x, $x = S$, P or A corresponding to stress, purpose, and allocation respectively) for each dimension. Then, the above equation was transformed into a natural logarithm to facilitate calculation:

$$Transformation \propto ln(I_S) + ln(I_P) + ln(I_A) \tag{5}$$

Assuming they have equal weights, the Integrated Water Governance Index (IWGI) is:

$$IWGI = I'_S + I'_P - I'_A \tag{6}$$

where I'_x is a normalization of log-transformed indicator I_x for a certain dimension:

$$I'_x = normalize(ln(I_x)) \tag{7}$$

Normalization

We tested different normalization methods, and they made no difference in change points detection (see *SI Appendix* Methods S5. Sensitivity analysis). We performed min-max normalization using the formulation below:

$$normalize(X) = (X - X_{min})/(X_{max} - X_{min}) \tag{8}$$

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 [35]. 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:

$$I_S = \frac{1}{4} * \sum_{i=1}^{4} SFV_i \tag{9}$$

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:

$$NPS_i = \frac{WU_{non-pro,i}}{WU_{pro,i} + WU_{non-pro,i}} \tag{10}$$

Where i refers a certain region, or the whole basin, i.e:

$$I_P = NPS_{basin} \tag{11}$$

Indicator of allocations

To describe allocations I_A, we designed an indicator based on information entropy, called Allocation Entropy Metric (AEM), AEM measures the degree of evenness of water allocation (see *SI Appendix* Methods S4). Our indicator I_A was intended to reflect the idea that with the development of society, water resources allocation becomes more balanced among regions and generally meets the needs of different sectors, but different regions have a trend of division of labour among various sectors (with larger gaps):

$$I_A = \frac{AEM_r * AEM_s}{AEM_{rs}} \tag{12}$$

where AEM_r and AEM_s are Allocation Entropy Metric in different regions and different sectors. AEM_{rs} describes differences between sectors in a certain region relative to the whole basin (see *SI Appendix* Methods S4).

5.2 Change points detection

With no assumptions about the distribution of the data, the Pettitt (1979) approach of change-point detection is commonly applied to detect a single change-point in hydrological time series with continuous data [32]. It tests $H0$: The variables follow one or more distributions that have the same location parameter (no change), against the alternative: a change point exists. The non-parametric statistic is defined as:

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:

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} sgn(X_i - X_j), 1 \leqq t < T \quad (13)$$

where:

$$\mathrm{sgn}(\theta) = \begin{cases} 1 & \text{if } \theta > 0 \\ 0 & \text{if } \theta = 0 \\ -1 & \text{if } \theta < 0 \end{cases} \quad (14)$$

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:

$$p = 2 \exp\left(\frac{-6K_\tau^2}{T^2 + T^3}\right) \quad (15)$$

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 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 seach series separately, until all significant change points were detected.

5.3 Contribution decomposition

We decomposed the amount of variation in each index at different periods to quantify each influence's contribution to the index. Using the Integrated Water Governance Index (IWGI) as an example, its value is influenced by normalized indicators in three dimensions: stress (I'_S), purpose (I'_P) and allocation (I'_A). We can calculate their differences between two certain years (y_2 and y_1, $y_2 > y_1$) by:

$$\Delta IWGI = (I'_{P_{y_2}} + I'_{A_{y_2}} - I'_{S_{y_2}}) - (I'_{P_{y_1}} + I'_{A_{y_1}} - I'_{S_{y_1}}) \quad (16)$$

$$= (I'_{P_{y_2}} - I'_{P_{y_1}}) + (I'_{A_{y_2}} - I'_{C_{y_1}}) + (I'_{S_{y_1}} - I'_{S_{y_2}}) \quad (17)$$

$$= \Delta I'_P + \Delta I'_A + (-\Delta I'_S) \quad (18)$$

Then, the contribution of dimension x to IWGI's changes can be referred to as:

$$Contribution_x = \frac{\Delta I'_x}{|\Delta IWGI|} \quad (19)$$

5.4 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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- Consent to participate
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Appendix A Section title of first appendix

References

[1] Abbott BW, Bishop K, Zarnetske JP, et al (2019) A water cycle for the Anthropocene. Hydrological Processes 33(23):3046–3052. https://doi.org/10.1002/hyp.13544

[2] Allan JR, Levin N, Jones KR, et al (2019) Navigating the complexities of coordinated conservation along the river Nile. Science Advances 5(4):eaau7668. https://doi.org/10.1126/sciadv.aau7668

[3] An W, Li Z, Wang S, et al (2017) Exploring the effects of the "Grain for Green" program on the differences in soil water in the semi-arid Loess Plateau of China. Ecological Engineering 107:144–151. https://doi.org/10.1016/j.ecoleng.2017.07.017

[4] Best J (2019) Anthropogenic stresses on the world's big rivers. Nature Geoscience 12(1):7–21. https://doi.org/10.1038/s41561-018-0262-x

[5] Best J, Darby SE (2020) The Pace of Human-Induced Change in Large Rivers: Stresses, Resilience, and Vulnerability to Extreme Events. One Earth 2(6):510–514. https://doi.org/10.1016/j.oneear.2020.05.021

[6] Biermann F, Abbott K, Andresen S, et al (2012) Navigating the Anthropocene: Improving Earth System Governance. Science 335(6074):1306–1307. https://doi.org/10.1126/science.1217255

[7] Bodin Ö (2017) Collaborative environmental governance: Achieving collective action in social-ecological systems. Science 357(6352):eaan1114. https://doi.org/10.1126/science.aan1114

[8] Carpenter SR, Cole JJ, Pace ML, et al (2011) Early Warnings of Regime Shifts: A Whole-Ecosystem Experiment. Science 332(6033):1079–1082. https://doi.org/10.1126/science.1203672

[9] Cumming GS, von Cramon-Taubadel S (2018) Linking economic growth pathways and environmental sustainability by understanding development as alternate social–ecological regimes. Proceedings of the National Academy of Sciences 115(38):9533–9538. https://doi.org/10.1073/pnas.1807026115

[10] Cumming GS, Buerkert A, Hoffmann EM, et al (2014) Implications of agricultural transitions and urbanization for ecosystem services. Nature 515(7525):50–57. https://doi.org/10.1038/nature13945

[11] Dalin C, Qiu H, Hanasaki N, et al (2015) Balancing water resource conservation and food security in China. Proceedings of the National Academy of Sciences 112(15):4588–4593. https://doi.org/10.1073/pnas.1504345112

[12] de Graaf IEM, Gleeson T, (Rens) van Beek LPH, et al (2019) Environmental flow limits to global groundwater pumping. Nature 574(7776):90–94. https://doi.org/10.1038/s41586-019-1594-4

[13] Di Baldassarre G, Sivapalan M, Rusca M, et al (2019) Sociohydrology: Scientific Challenges in Addressing the Sustainable Development Goals. Water Resources Research 55(8):6327–6355. https://doi.org/10.1029/2018WR023901

[14] Falkenmark M, Wang-Erlandsson L, Rockström J (2019) Understanding of water resilience in the Anthropocene. Journal of Hydrology X 2:100,009. https://doi.org/10.1016/j.hydroa.2018.100009

[15] Flörke M, Schneider C, McDonald RI (2018) Water competition between cities and agriculture driven by climate change and urban growth. Nature Sustainability 1(1):51–58. https://doi.org/10.1038/s41893-017-0006-8

[16] Gleeson T, Wang-Erlandsson L, Porkka M, et al (2020) Illuminating water cycle modifications and Earth system resilience in the Anthropocene. Water Resources Research 56(4). https://doi.org/10.1029/2019WR024957

[17] Grafton RQ, Williams J, Perry CJ, et al (2018) The paradox of irrigation efficiency. Science 361(6404):748–750. https://doi.org/10.1126/science.aat9314

[18] Gregr EJ, Christensen V, Nichol L, et al (2020) Cascading social-ecological costs and benefits triggered by a recovering keystone predator. Science https://doi.org/10.1126/science.aay5342

[19] Greve P, Kahil T, Mochizuki J, et al (2018) Global assessment of water challenges under uncertainty in water scarcity projections. Nature Sustainability 1(9):486–494. https://doi.org/10.1038/s41893-018-0134-9

[20] Grill G, Lehner B, Thieme M, et al (2019) Mapping the world's free-flowing rivers. Nature 569(7755):215–221. https://doi.org/10.1038/s41586-019-1111-9

[21] Huggins X, Gleeson T, Kummu M, et al (2020) The social-ecological dimensions of changing global freshwater availability. Preprint, EarthArXiv

[22] Kitroeff N (2020) 'This Is a War': Cross-Border Fight Over Water Erupts in Mexico. The New York Times

[23] Kjellén DM, Tropp DH, Jiménez DA (2015) Water governance in perspective: Water Governance Facility 10 years 2005-2015. Tech. rep., Water Governance Facility

[24] Kleemann J, Schröter M, Bagstad KJ, et al (2020) Quantifying interregional flows of multiple ecosystem services – A case study for Germany. Global Environmental Change 61:102,051. https://doi.org/10.1016/j.gloenvcha.2020.102051

[25] Konar M, Garcia M, Sanderson MR, et al (2019) Expanding the Scope and Foundation of Sociohydrology as the Science of Coupled Human-Water Systems. Water Resources Research 55(2):874–887. https://doi.org/10.1029/2018WR024088

[26] Levia DF, Creed IF, Hannah DM, et al (2020) Homogenization of the terrestrial water cycle. Nature Geoscience 13(10):656–658. https://doi.org/10.1038/s41561-020-0641-y

[27] Liu J, Yang W (2012) Water Sustainability for China and Beyond. Science 337(6095):649–650. https://doi.org/10.1126/science.1219471

[28] Liu J, Rhland KM, Chen J, et al (2017) Aerosol-weakened summer monsoons decrease lake fertilization on the Chinese Loess Plateau. Nature Climate Change 7(3):190–+. https://doi.org/10.1038/NCLIMATE3220

[29] Liu J, Yang H, Gosling SN, et al (2017) Water scarcity assessments in the past, present, and future. Earth's Future 5(6):545–559. https://doi.org/10.1002/2016EF000518

[30] Maria Jacobson, Fiona Meyer, Ingvild Oia, et al (2013) User's Guide on Assessing Water Governance. United Nations Development Programme

[31] Muneepeerakul R, Anderies JM (2020) The emergence and resilience of self-organized

governance in coupled infrastructure systems. Proceedings of the National Academy of Sciences 117(9):4617–4622. https://doi.org/10.1073/pnas.1916169117

[32] Pettitt AN (1979) A Non-Parametric Approach to the Change-Point Problem. Journal of the Royal Statistical Society Series C (Applied Statistics) 28(2):126–135. https://doi.org/10.2307/2346729

[33] Porcher S, SAUSSIER S (eds) (2019) Facing the Challenges of Water Governance. Palgrave Studies in Water Governance: Policy and Practice, Palgrave Macmillan

[34] Qin D, Lu C, Liu J, et al (2014) Theoretical framework of dualistic nature–social water cycle. Chinese Science Bulletin 59(8):810–820. https://doi.org/10.1007/s11434-013-0096-2

[35] Qin Y, Mueller ND, Siebert S, et al (2019) Flexibility and intensity of global water use. Nature Sustainability 2(6):515–523. https://doi.org/10.1038/s41893-019-0294-2

[36] Rocha JC, Peterson G, Bodin Ö, et al (2018) Cascading regime shifts within and across scales. Science p 6

[37] Roobavannan M, Kandasamy J, Pande S, et al (2017) Role of Sectoral Transformation in the Evolution of Water Management Norms in Agricultural Catchments: A Sociohydrologic Modeling Analysis: ECONOMIC DIVERSIFICATION IN WATER USEAGE. Water Resources Research 53(10):8344–8365. https://doi.org/10.1002/2017WR020671

[38] Singh A, Saha D, Tyagi AC (eds) (2019) Water Governance: Challenges and Prospects. Springer Water, Springer Singapore

[39] Sivapalan M, Savenije HHG, Blöschl G (2012) Socio-hydrology: A new science of people and water: INVITED COMMENTARY. Hydrological Processes 26(8):1270–1276. https://doi.org/10.1002/hyp.8426

[40] Speed R, Asian Development Bank (2013) Basin Water Allocation Planning: Principles, Procedures, and Approaches for Basin Allocation Planning. Asian Development Bank, GIWP, UNESCO, and WWF-UK, Metro Manila, Philippines

[41] Steffen W, Rockstrom J, Richardson K, et al (2018) Trajectories of the Earth System in the Anthropocene. Proceedings of the National Academy of Sciences of the United States of America 115(33):8252–8259. https://doi.org/10.1073/pnas.1810141115

[42] Steffen W, Richardson K, Rockström J, et al (2020) The emergence and evolution of Earth System Science. Nature Reviews Earth & Environment 1(1):54–63. https://doi.org/10.1038/s43017-019-0005-6

[43] UNDP Water Governance Facility (????) Water Governance: Issue Sheet. Tech. rep.

[44] UNEP-DHI, UNEP, UNEP (2016) Transboundary River Basins: Status and Trends

[45] Wada Y, Bierkens MFP, Konar M, et al (2017) Human–water interface in hydrological modelling: Current status and future directions. Hydrol Earth Syst Sci p 26

[46] Wang S, Fu B, Piao S, et al (2016) Reduced sediment transport in the Yellow River due to anthropogenic changes. Nature Geoscience 9(1):38–41. https://doi.org/10.1038/ngeo2602

[47] Wang Y, Peng S, Jiang G, et al (2018) Thirty Years of the Yellow River Water Allocation Scheme and future Prospect. MATEC Web of Conferences 246:01,083. https://doi.org/10.1051/matecconf/201824601083

[48] Wang Y, Zhao W, Wang S, et al (2019) Yellow River water rebalanced by human regulation. Scientific Reports 9(1):9707. https://doi.org/10.1038/s41598-019-46063-5

[49] Wohlfart C, Kuenzer C, Chen C, et al (2016) Social-ecological challenges in the Yellow River basin (China): A review. Environmental Earth Sciences 75(13):1066. https://doi.

org/10.1007/s12665-016-5864-2

[50] Wohlfart C, Liu G, Huang C, et al (2016) A River Basin over the Course of Time: Multi-Temporal Analyses of Land Surface Dynamics in the Yellow River Basin (China) Based on Medium Resolution Remote Sensing Data. Remote Sensing 8(3):186. https://doi.org/10.3390/rs8030186

[51] Wu X, Wei Y, Fu B, et al (2020) Evolution and effects of the social-ecological system over a millennium in China's Loess Plateau. Science Advances 6(41):eabc0276. https://doi.org/10.1126/sciadv.abc0276

[52] Xia C, Pahl-Wostl C (2012) The Development of Water Allocation Management in The Yellow River Basin. Water Resources Management 26(12):3395–3414. https://doi.org/10.1007/s11269-012-0078-1

[53] Xu Z, Chau SN, Chen X, et al (2020) Assessing progress towards sustainable development over space and time. Nature 577(7788):74–78. https://doi.org/10.1038/s41586-019-1846-3

[54] Zhou F, Bo Y, Ciais P, et al (2020) Deceleration of China's human water use and its key drivers. Proceedings of the National Academy of Sciences p 201909902. https://doi.org/10.1073/pnas.1909902117