Article Title

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Abstract

The abstract serves both as a general introduction to the topic and as a brief, non-technical summary of the main results and their implications. Authors are advised to check the author instructions for the journal they are submitting to for word limits and if structural elements like subheadings, citations, or equations are permitted.

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1 Introduction

Water has been described as being "at the centre of the planetary drama of the Anthropocene" [20]. It is essential not only for earth system processes but also in supporting the economic development and continued well-being of human societies. Human activities stemming from our reliance on the water have profoundly modified the natural water cycle, moving rivers dominated by a hybrid of social and natural tendencies [1, 20, 31, 41, 46]. Facing this major transformation, many big river basins worldwide (which are hot spots of civilization and economic growth) are urgently in need of successful water governance for sustainability [7, 17, 18]. 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 [9, 17, 49].

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. [50]. 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?" (supply), "How water provides different services to well-beings?" (purpose), and "Who can use water equally and efficiently?" (allocation) [27, 37, 50]. As a locally stable state of a system, function, and dominant controls, habitual relationships between humans and water maintain regimes of water governance [11]. 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 [22, 43]. Therefore, as both signals and consequences of substantive changes in human-water systems, regime shifts can trigger changes in the three key dimensions of water governance (supply, purpose, and allocation), with new challenges to sustainability [27, 37, 50]. First, the supply of water 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 [23, 42, 52]. 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) [19, 28, 36]. 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 [44, 47]. 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). With drastically anthropogenic intervention, the YRB experienced the most intense water challenges in China, leading to long-standing sustainability barriers. From about 550BC until half a century ago, flooding and the huge sediment loads of the Yellow River brought frequent human disasters, and the constant shifts of channels made it difficult for its governance [32, 53]. Since the 1960s, the implementation of conservation measures, regulation reservoirs, and levee constructions have contained the issues caused by high-sediment loads [53, 58]. However, water over-use has led to depletions of the over-burdened river, creating new governance challenges that have been addressed through a range of related policies (e.g., regulating water use and limiting water withdrawals) [59]. Today, it is still impossible to completely cover water demands, balance trade-offs between ecosystem services, and lead to equities in different regions; -who gets water, when and how is still an open question for sustainable water governance [55, 56]. The YRB has been among the most rapidly-changing large river basins worldwide, with myriad responses to the endless governance challenges induced by environmental, economic, social and political factors. 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 first use the three key dimensions (supply, purpose and allocation) 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 scheme as 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 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, the remarkable downward trend correlates significantly to the decreasing allocation and stress indicators (Figure 2B). In the second period (P2, 1979-2001), the increasing stress indicator significantly 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 significant share in contributions,

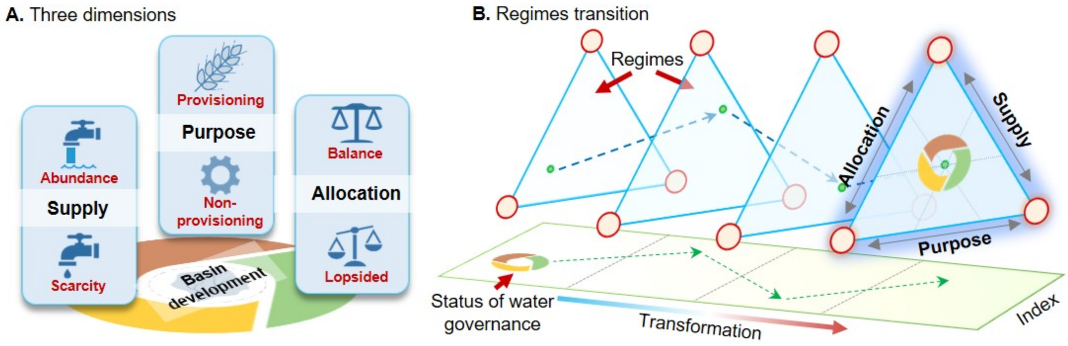

Fig. 1 A framework for understanding the relationship between water governance regimes and transitions of a hydrosocial cycle. We aim to detect regime shifts using a simple and comprehensive index. **A:** there are three key dimensions (supply, purpose and allocation) of water governance (see **Methods** for details). Each dimension has two poles (denoted in red) which indicate the two potential directions of changes along that axis: (1) "supply" shifts between scarcity and abundance. (2) "purpose" is weighted between consumptive services or non-consumptive uses. (3) "allocation" changes between balanced or lopsided. **B:** along a trajectory of hydrosocial water cycle, governance changes are related to the combination of trends across the three dimensions. When abrupt change occurs, it may indicate a regime shift in water governance [1, 31, 48].

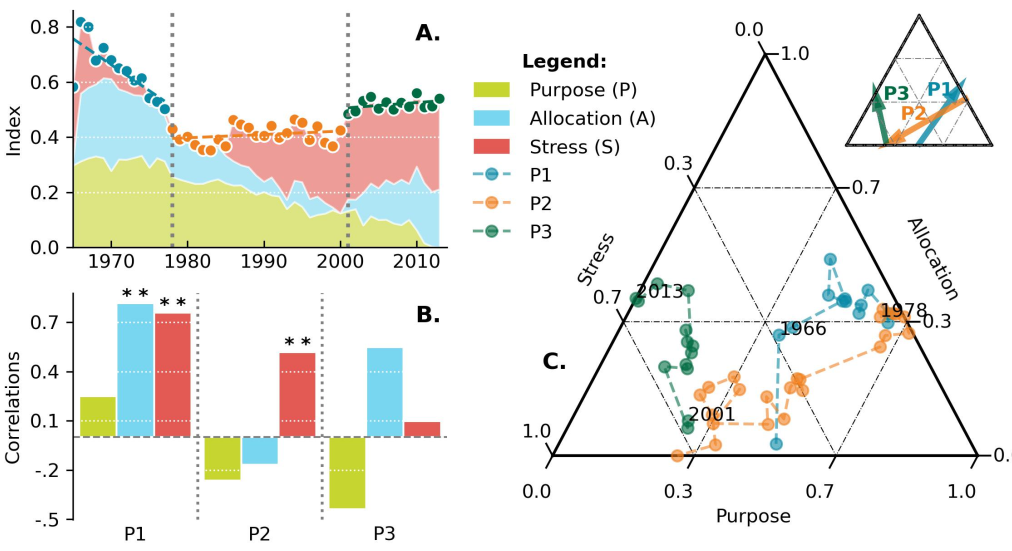

Fig. 2 Changes in the IWGI index. **A,** Change points detection. With significant change points in 1978 and 1994, the IWGI has three different periods. **B,** Contributions of each dimension to the changes of IWGI within each of the three periods. Supply, purpose and allocation were the main positive contributors to P1, P2 and P3. **C,** Combination of contributions across three dimensions in different periods (S: supply; P: purpose; A: allocation). The closer a point is to an angle of the outside triangle, the greater the proportion of the contribution of this dimension. The red indicator line in this plot denotes a 1:1 contributions between purpose (P) and allocation (A). When the points are below this line, the contribution ratio of allocation is lower than that of function, and *vice versa*.

the increased allocation indicator and decreased purpose indicator changed the regime of IWGI.

Overall features of the three dimensions in different periods are shown in Ternary, where each regime shift associates to a directional change in the combination of three dimensions (Figure 2C). Throughout P1, the IWGI shifts paralleled with the left axis because the Purpose indicator was barely changed and others two changed in similar trends. Analogously, as the stress indicator unchanged during the P3, the IWGI shifts paralleled with the right axis while others two changed in opposite trends. The regime then experienced a long distance shift during the P2, as three indicators simultaneously changed their ratios of contribution to IWGI. The three different periods corresponded to three distinct water governance regimes: a massive supply regime (P1: 1965-1978), governance transforming regime (P2: 1979-2001), and a demand regulating regime (P3: 2002-2013).

2.2 Causes of water governance regime shifts

Digging more deeply into the underlying causes of changes in the IWGI, the expansion of irrigated area and the economic growth of industry and services were key to the change in purpose between P1 and P2. During P1, the area of irrigated agriculture in the Yellow River Basin 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 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 a 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 area kept its slowly expansion in P3 (Figure3A), industry and urban services also assumed stronger 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 unit irrigated area or unit production (Figure 3A and Figure 3B). As a result, the differences between sectors of water use were 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 P1 (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 P2, the number of new reservoirs decreased significantly and allocation of water was rigorously controlled by significantly increased basinal policies (e.g., the "87 Water Allocation Scheme") (Figure 3D, p¡0.01 and *SI Appendix* Fig. S6). Entering P3, more national-level water governance policies were proposed under the guide of national strategy "environmental regulation" (Figure 3D). Taken together, the regime shift from P1 to P2 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 transition of water governance regimes

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 a demand regulating regime (P3: 2002-2013). Furthermore, shifts between these regimes were caused by different environmental, economic, social or political drivers, then decide 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 conceptual pattern, thus characterizing the transition of water governance in detail for the first time. It is important to note that each indicator or cause changed gradually, but emerging regime shifts moves water governance along with the hydrosocial water cycle at a basin scale. As a result, the challenges were primarily economic and environmental at the beginning of the YRB's water governance trajectory and social and policy-related towards the end (Figure 4).

During the massive supply regime (1965-1978 in the YRB), practices of water governance thus tended to boost water supply for agriculture (e.g. by construction of reservoirs and channels). Due to the limited effects of socio-economic feedbacks on this regime, water governance had few protective policies, assumed an unlimited water supply, and took little consideration of the impacts of water use on social equity and the environment

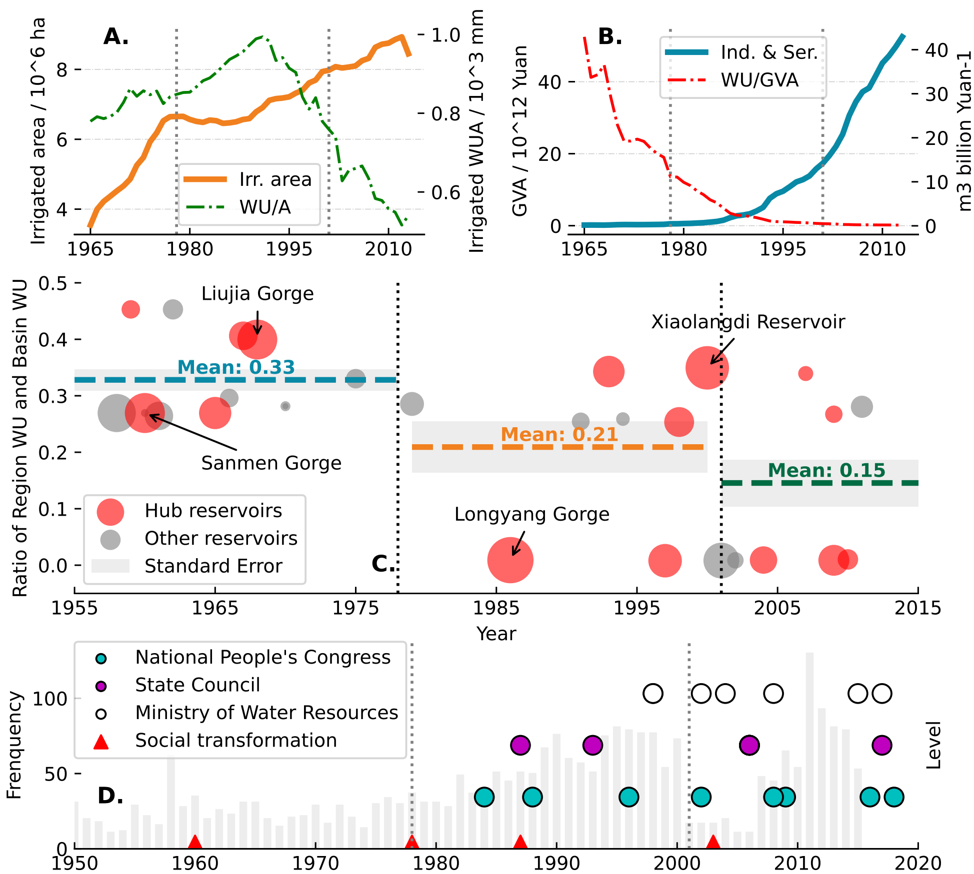

Fig. 3 Causes of water governance regime shifts in the Yellow River Basin: environmental change, economic growth and efficiency changes, social transformation, and water governance policies. **A.** Changes in total irrigated area (orange line), and in water use intensity (WU/A, water use divided by the area, the green dot line), see *SI Appendix* Methods S2). **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) (*SI Appendix* Methods S2). **C.** Completed time of each new reservoir and their located region's (source, upper, middle, or lower reaches) water use percentages as a proportion of the basin's total water use (WU) 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 important 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 flood water discharge and water supply. The named reservoirs are significant for the entire basin, not only for regional development. **D.** Social transformations and national-level policies related to water governance (see *SI Appendix* Methods S1 and Table S2). In order, the four transformations are "ethos of conquer nature (since 1958)", "reform and opening-up (since 1978)", "the 87 Water Allocation Scheme (since 1987)", "environmental regulation (since 2003)" in order (see *SI Appendix* Methods S1).

[62]. Since nearly 80% of surface water was used (mainly for provisioning purposes), the Yellow River dried up during the second half of the regime (*SI Appendix* Figure S7). Ecological issues, such as wetlands shrinkage and declines in biodiversity, emerged as the drying up became more and more serious, leading a huge social-ecological crisis and

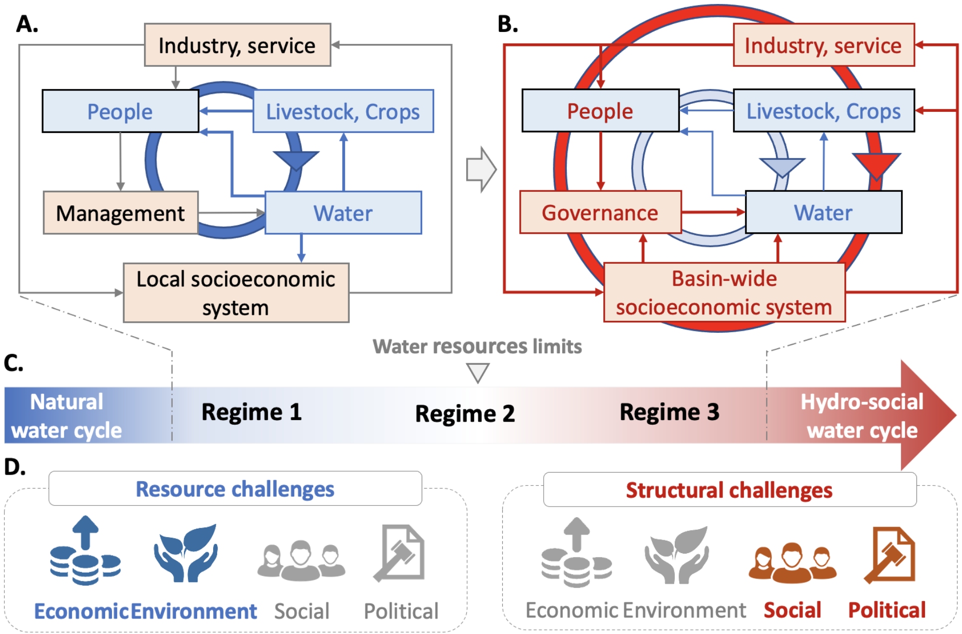

Fig. 4 Transition schema of water governance during transformation towards a hydrosocial water cycle. The natural water cycle dominates blue pathways while socio-economic feedbacks dominate red pathways. Finally, there is a transformation towards the hydrosocial water cycle where red loop increases. **A. Early phase.** As socio-economic systems develop, industry and services gradually demand increasing amounts of water; at the same time, increasing social organization and technological capacity allow people to manage water resources more intensively, including intensive intervention in the natural water cycle. **B. Late phase** With further developed and economically efficient industries and services, trade-offs between provisioning-purpose and non-provisioning water use become prominent. Rather than being determined by local socio-economic systems, water withdraws and management are scaled up to the entire basin. Thus, **C. Transformation from a natural water cycle towards the hydro-social water cycle** occurs in paralleled with a transformation towards a hydrosocial water cycle. This is generally distinguished when water resource limits are reached. The three water governance regimes seen in the YRB are identified along this transition (Regime 1: massive supply regime, Regime 2: purpose-focused regime, Regime 3: many-sided governance regime). **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.

a significant challenge to existing modes of water governance rigorously [57].

The start of the purpose-focused regime (1978) coincided with Chinese "reform and opening-up". This huge social transformation led to the emergence of industry and services, broke the dominance of agriculture, and resulted in higher competition for water use (Figure 3 and *SI Appendix* Fig. S8). In the face of ongoing environmental challenges and new economic challenges, the Yellow River Conservancy Commission (*SI Appendix* Methods S1) underwent a reorganization and received instructions from the Ministry of Water Resources (then called the Ministry of Water Resources and Electric Power) to resume and strengthen work on hydrology and basin management in the YRB [4]. As a result, new policies and regulations (e.g., "the 87 Water Allocation Scheme") were introduced in the YRB ahead of the rest of the country to allocate water for stopping the expansion of water consumption [54].

The next shift, to the many-sided governance regime, did not occur until a significant increase in water use efficiency in about 1993, overcame some resource limits [34]. Since socio-economic trade-offs between water-dependent regions and sectors played a more important role at this regime, water governance had to achieve efficient water allocation while balancing different purposes in the face of limited water supply [15]. For example, the water rights conversion project that has been popularized during this regime may even save regional agricultural water for industrial developments in other regions, and water transfer has been another huge project to meet water demands within the YRB [6, 61]. On the other hand, the old water policy (e.g., "the 87 Water Allocation Scheme"), which once helped the YRB resolve its environmental crisis, limited social equity and coordinated allocation under the new regime because of path dependence [54]. Many national-level water policies were proposed or adjusted under this regime, as the absence of such policies and social injustice in water use became new structural challenges for governance [29].

In general, shifts between the three governance regimes occurred sequentially during a transformation towards the hydrosocial cycle. Transition from biophysical control to social and political control of ecosystem dynamics may become increasingly widespread in social-ecological systems as increasing anthropogenic impacts gradually change the world [8, 12, 14]. Some implications of this kind of change, when accompanied by engineering solutions, have been explored in the Millennium Assessment's 'Technogarden' scenario [5]. The transition regimes identified here echo the two kinds of major water governance challenges globally (resource challenges and structural challenges, Figure 4 and *SI Appendix* Fig. S9) [40, 45]. Resource challenges, represented as water shortage and water supplying difficulties, are mainly faced by undeveloped and developing basins and are highly related to economic and environmental changes [2, 19, 33]. 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 [26, 26, 44, 51]. It is typical that resource challenges and structural challenges have occurred sequentially during the transition of water governance within the YRB. Our analysis thus suggests that the initial phase of transition often leads to resource-focused challenges that result from economic, demographic and environmental change; while later phases are dominated by structural challenges relating to social and political aspects of governance. 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 towards a hydrosocial water cycle.

Additional challenges are raised by the process of upscaling that occurs as river basins transition between regimes. Under the influence of economic forces, water use gradually changes from being a primarily local concern to becoming a national or international concern, with large river basins being critical sources of ecosystem services, economic development, and human wellbeing. For example, the requirement in the ecological system management of water and sediment diversion in the Xiaolangdi Dam of the Yellow River leads to rapid cutting of the downstream river, which makes it impossible for farmers to get irrigation water resources for a long time [30]. Successful navigation of water regime transitions through an upscaling process requires a corresponding upscaling in the governance regime and the creation of higher-level institutions that can regulate and manage cross-scale effects [13].

3.2 Implications and future directions

The IWGI index captures the transitional regimes of water governance in a relatively simple but comprehensive way. It is important for scientists and decision makers to recognize the changing governance challenges, because development is not a panacea for all basin issues regarding sustainability. Models and approaches developed under one regime are not necessarily useful under a different regime. For today's world, water-related challenges remains one of the major gaps in our progress towards sustainability, while development-first strategies are still a dominant guideline in many places and may be in opposition to improving governance [23, 35, 60]. Although most large river basins have shown improvements in water management technologies and water use efficiency along with development, freshwater use is still considered to be approaching planetary boundaries where human-water systems may collapse [3, 16, 25]. Overall, there are probably two main reasons for this apparent failure of governance. First, significant improvement in agricultural irrigation efficiency is usually accompanied by a re-expansion of irrigated area, resulting in an unabated trend of water resources stress (the paradox of efficiency) [21]. Second, 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 [24, 31, 42]. From these perspectives, we need better and more comprehensive strategies to address governance challenges because the core problems are complex and difficult to manage [9, 10, 38, 49]. A deeper understanding of governance that incorporates ideas of non-liner 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, 31, 48].

- **Supply(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 by technical solutions in the process of development:
$$Transformation \propto S^{-1} \quad (1)$$
- **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:
$$Transformation \propto P \quad (2)$$
- **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:
$$Transformation \propto A \quad (3)$$

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

$$Transformation \propto S * P * A \quad (4)$$

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

$$Transformation \propto ln(I_S) + ln(I_P) + ln(I_A) \quad (5)$$

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

$$IWGI = I'_S + I'_P - I'_A \quad (6)$$

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

$$I'_x = normalize(ln(I_x)) \quad (7)$$

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 supply

We used the scarcity-flexibility-variability (SFV) water stress index proposed in Qin et al., 2019 to evaluate water supply capacities (SFV_i) as the indicator in a certain region i [42]. 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 supply capacity 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 [39]. 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 $\mathrm{x}_1, \mathrm{x}_1, \ldots, x_{t_0} \text{and} x_{t_0+1}, x_{t_0+2}, \ldots, x_T$, 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:

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

where:

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

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:

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

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:

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

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

$$= \Delta I'_P + \Delta I'_A + (-\Delta I'_S) \tag{18}$$

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

$$Contribution_x = \frac{\Delta I'_x}{|\Delta IWGI|} \tag{19}$$

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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Declarations

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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
- Availability of data and materials
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Appendix A Section title of first appendix

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