

Identifying regime transitions for water governance: Take the Yellow River Basin in China as case

Shuang Song¹, Shuai Wang¹, Xutong Wu¹, yongping Wei², Graeme S.
Cumming³, Yue Qin⁴, Xilin Wu⁵, Bojie Fu^{1,5}

¹ State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University,
Beijing, 100875, Beijing, China.

² School of Earth and Environmental Sciences, The University of Queensland, Brisbane, 4067, QLD,
Australia.

³ ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, 4811, QLD,
Australia.

⁴ College of Environmental Sciences and Engineering, Peking University, Beijing, 100875, Beijing, China.

⁵ State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences,
Chinese Academy of Sciences, Beijing, 100875, Beijing, China.

Key Points:

- We developed an Integrated Water Governance Index (IWGI) to detect regime shifts in water governance.
- We interpret how water governance shifts within a rapidly-changing large river basin.
- We developed an approach to analyzing intertwines of water governance, hydrosocial transition, and human-water relationships.

Corresponding author: Shuai Wang, shuaiwang@bnu.edu.cn

Abstract

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

Plain Language Summary

Missing governance means missing sustainability. However, the lack of a comprehensive but straightforward approach to identifying the changes in water governance presents a challenge for efforts to underpin it. Therefore, we choose indicators for the corresponding aspects (water stress, water services purpose, and water allocation) and combine them into an integrated water governance index (IWGI) to analyze long-term changes in a large river basin.

1 Introduction

Water, being “at the centre of the planetary drama of the Anthropocene”, is essential not only for earth system processes but also in supporting development and human wellbeing (Gleeson, Wang-Erlandsson, et al., 2020; Gleeson, Wang-Erlandsson, et al., 2020). As an integral part of earth system governance, successful water governance requires a deep understanding of changes in the complex relationships between humans and water (Ahlström et al., 2021; Biermann et al., 2012; Steffen et al., 2020). Human activities stemming from our reliance on water have profoundly modified the natural water cycle, resulting in rivers that are dominated by a hybrid of social and natural drivers (Sivapalan et al., 2012; D. Qin et al., 2014; Abbott et al., 2019). Facing transitions from natural to human-dominated regimes, many big river basins worldwide (which are hot spots of civilization and economic growth) are urgently in need of more effective water governance (Best, 2019; Di Baldassarre et al., 2019).

Water governance refers to the political, social, economic, and administrative systems that influence the use and management of water (OECD, 2018; J. Wang et al., 2017), essentially about “who gets water, when and how”(Lasswell, 2018). Therefore, the United Nations Development Programme (UNDP) has suggested that three core aspects of water use decided by water governance correspondingly: “When and what water to use?” (stress), “How does water provide different services for human well-being?” (purpose), and “Who can use water equally and efficiently?” (allocation) (UNDP Water Governance Facility, 2016). Responding the questions for better water governance practices, previous studies can divide into two categories of comprehensive indicators by focusing on water systems or governance systems. From the governance side, an integrated index can explicitly denote what practices are effecting water governance. However, a comprehensive and detailed list of the key components for assessment of water governance is rare, hence quantitative studies usually propose indexes by using proxy dataset of human activities as a simpler way (Varis et al., 2019). A qualitative approach to the assessment of water governance can list more elements regarding to water governance, where OECD’s index and assessment dataset are the most widely used. From the water side, intuitive indexes can provide an embodiment

of governance outcomes. Water stress is the most widely concerned aspect, which has been far developed in comprehensive index when incorporating human's regulation step by step. As instances, traditional water stress index only demands and supply, water scarcity index by involving accessibility, and SFV-index further integrated flexibility. These easy-to-use indexes of water stress, however, seem to have difficulty in providing a comprehensive characterization of the above water governance aspects without concerning its social usage (i.e., water use purpose and water allocation). Standing from water side for comprehensively quantify governance outcomes, here we aim to develop an integrated water governance index to identify its changes by involving apportionments of water uses between regions and sectors.

An important reason for developing this new index is practices of water governance changes throughout development under a hybrid of social and natural drivers. First, besides climate change impacts embedded in current water yield concerns, water stress is also tightly related to an increasingly insatiable demands from economic activities, while developing water storage to release the stress (Y. Qin et al., 2019; Wada et al., 2014; Huang et al., 2021). Second, the purpose of how water services human well-being is tilting the trade-offs between provisioning uses (e.g., drinking and food production) and non-provisioning uses (e.g., energy production) (J. Liu et al., 2017; Flörke et al., 2018; Jaeger et al., 2019). Third, the allocation of water across the whole basin is not only decided by regionally socio-economic and environmental context but also influenced by growing systematic regulations (Schmandt & Kibaroglu, 2021; Speed & Asian Development Bank, 2013). Since the transition to a human-dominated regime induced substantive changes in the three interwind aspects (stress, purpose, and allocation), considering them separately can lead to systematic failure in water governance.

A first critical step in understanding the successes and failures of water governance is to identify the different regimes that underpin it (Kjellén et al., 2015; Grafton et al., 2013). Regimes of water governance arise within linked human-water systems (based on management, institutions, and exploitation) to create local equilibria in social-ecological structures and functions (Falkenmark & Wang-Erlandsson, 2021; Bressers & Kuks, 2013; Loch et al., 2020). For example, under a human-dominated regime, reservoirs make water stress easier to be alleviated because of flexibility; growing energy and industrial demands make water services purposes lopsided to non-provisioning sectors; conveyance systems make water allocation more planned (Figure 1 A). However, the lack of a comprehensive but straightforward approach to identifying changes in water governance regimes represents a challenge for efforts to enhance the sustainability of water resource use. Filling this gap, which is the aim of this paper, is essential for the appropriate alignment of human and water systems.

The Yellow River Basin (YRB), which contains the fifth-largest and most sediment-rich river in the world, needs integrated water governance because of geological and human history (Mostern & Horne, 2021; Best, 2019). Since the 1960s, governance practices such as reservoirs, levees, and conservation measures have contained the issues troubled by thousands of years of high sediment loads (Zhang et al., 2019). However, new challenges such as decreased streamflows and water depletions occurred in more recent times, leading to water use regulation and water transfer across basins -different focused water governance tactic (S. Wang et al., 2019). Today, it is still impossible to completely solve water stress, trade-offs between ecosystem services, or lopsided development in different regions in the YRB to the satisfaction of all actors (Zhang et al., 2019). Governance challenges induced by environmental, economic, social, and political factors have resulted in YRB being among the most intensively-governed large river basins worldwide (Nickum & Shaofeng, 2021). Identifying regime shifts in water governance within the YRB can thus provide crucial insights into rapidly-changing big river basins and how governance may respond to meeting challenges to their sustainability.

Here, we depict three aspects of water governance -stress, purpose and allocation with corresponding indicators (see methods) and thus develop an Integrated Water Governance Index (IWGI) by equally weighting them, to indicate results from water governance (see

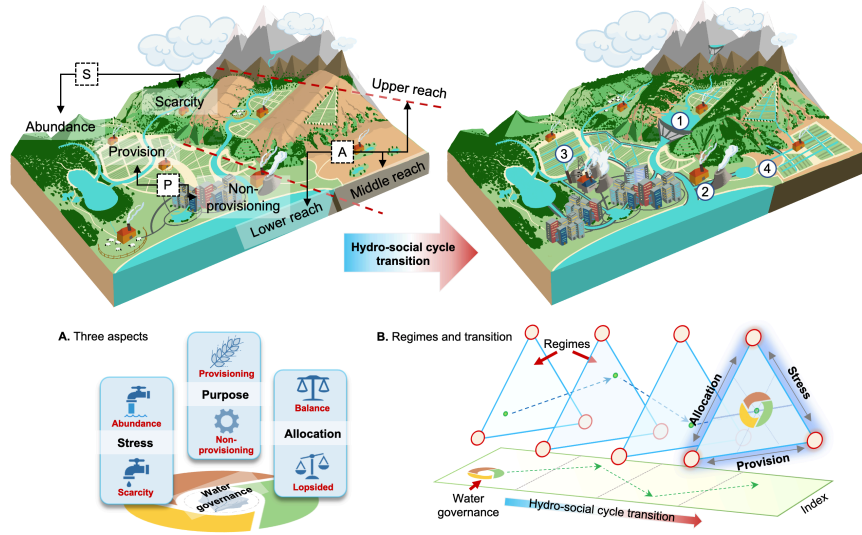


Figure 1. Identifying the water governance regimes in transitions of a hydrosocial cycle with an integrated water governance index (IWGI). Water stress (S), purposes of water services (P), and water allocation (A) are three aspects to be considered (A.). Along with hydrosocial-cycle transitions, a human-dominated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

Figure 1 B). Then, by applying the index to a typical rapid-changing big river basin (the YRB), we show how IWGI helps detect and describe complicated water governance regimes comprehensively but straightforwardly. Following synthetic analyses of the changes in water demand, supply, economic outcomes, and institutions, we interpret the leading causes of the regime shifts. Finally, we propose a general regime transition schema that offers a practical guideline for a coordinated approach to exploring the challenges faced by big river basin governance.

2 Materials and Methods

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

2.1 Integrated Water Governance Index (IWGI)

As shown in the framework Figure 1, the IWGI combines the three aspects (Stress, Purpose, and Allocation) of water governance:

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

We selected an indicator (I_x , $x = S$, P , or A , corresponding to stress, purpose, and allocation, respectively) to quantify the aspects effectively. Then, the above equation was

transformed into a natural logarithm to facilitate calculation:

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

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

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

where:

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

Since the IWGI essentially comprises by three aspects' indicator with same weights, its prerequisite is to keep the same data source for each indicator throughout time, to ensure time series continuity. However, vary data sources can be used when estimating the specific indicator or cross different indicators, which makes IWGI a flexible framework for substituted indicators.

Indicator of stress

We used the scarcity-flexibility-variability (SFV) water stress index proposed by Y. Qin et al. (2019) to evaluate water stress. This indicator integrates the share of runoff being consumed, the share of consumption in these inflexible categories and the historical variability of runoff weighted by storage capacity (Y. Qin et al., 2019), where impacts from both management measures and climate changes are included. The SFV-index, which has many applications, is the most comprehensive index of water stress we know.

Based on the hydrological and economic context of YRB, four second-level regions are divided (Source Region, Upper Region, Middle Region, and Lower Region, see *Supporting Information S1*). For the whole YRB, the indicator of water stress I_S is the average of all regions' SFV-index:

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

Where SFV_i is the SFV-index for region i , and the detailed calculation of SFV_i can be found in the *Supporting Information S2*.

Indicator of purpose

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

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

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

Indicator of allocations

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

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

where p_i is the water proportion of region i to the whole basin (here, $N = 4$ considering divided regions in the YRB, see *Supporting Information S1*).

2.2 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 (Pettitt, 1979). 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, meaning that the probability of a statistically significant change-point judgment being valid was more than 99.9%. We divided the series into two at that point and analyzed each series separately until all significant change points were detected. Though two break points in the main text with $\alpha = 0.001$, the threshold from 0.0005 to 0.05 does not affect our results, and the breakpoints we identified are robust (see *Supporting Information Figure S3*).

2.3 Datasets

In order to calculate IWGI in the YRB, all the datasets we need are listed in the *SI Appendix* Table S1 with a detailed description in *Supporting Information S3*.

3 Results

3.1 Water governance regimes

Two significant breakpoints divide the changes in the IWGI into three periods, with different contributions from three aspects (Figure 2A). In the first period (P1, 1965 ~ 1978),

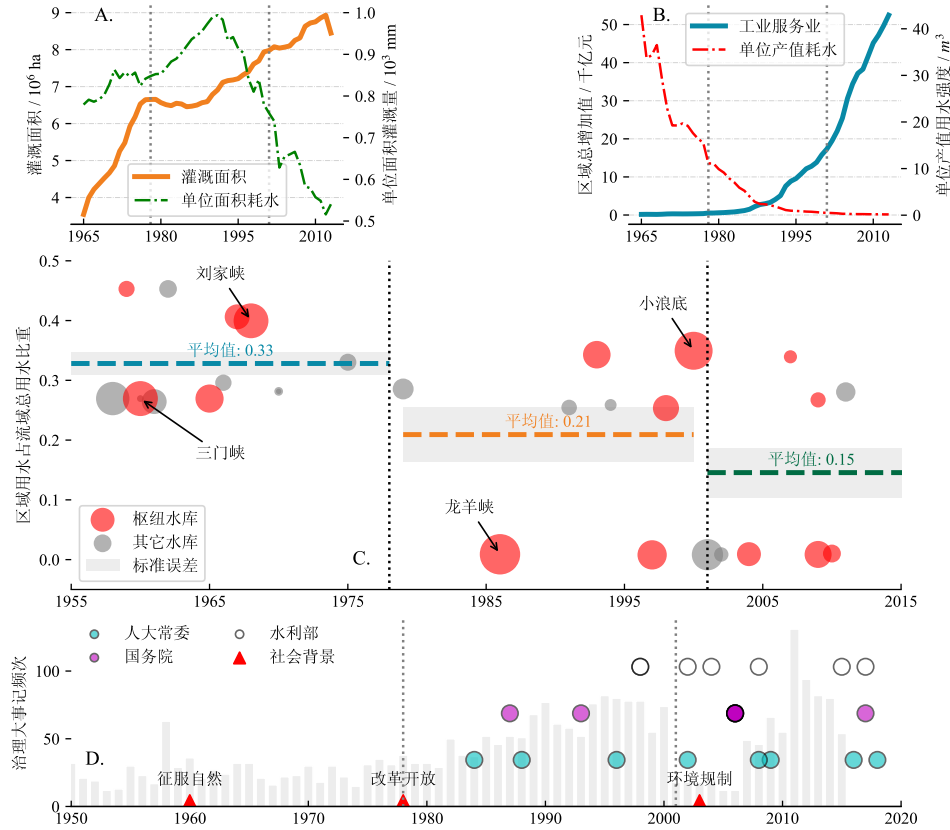


Figure 3. Causes of water governance regime shifts in the YRB. **A.** Changes in the total irrigated area (orange line) and water use intensity (WU/A , water use divided by the irrigated area, the green dot line). **B.** Changes in gross values added (GVA) of industry and services (blue line) and their water use intensities (WU/GVA , WU divided by the GVA, the red dot line). **C.** Completed time of each new reservoir and their located region's water use (LWU) percentages as a proportion of the total basinal water use (BWU) at that time. Red circles denote the reservoirs mainly for managing and regulating the whole basin. The size of each circle indicates the magnitude of its water storage capacity. **D.** Social transformations (red triangles) and national-level governance policies (the circles, different colours denote signed by different state institutions, see *Supporting Information Table S2*). The light grey bars count official documents related to the YRB on a basinal scale (the Yellow River Events).

Environmental context, social transformation, and policies played roles in all three periods. We calculated the ratios of regional and basinal water use for each reservoir (R/B ratio) (Figure 3C), with a higher ratio representing a potential role in water supply rather than basinal regulations. Under the banner of “conquering nature” most of the reservoirs were built in regions with high water demands during the P1 (R/B ratios were significantly higher ($p < 0.01$, see Figure 3C)). Ensuing the P2, the number of new reservoirs decreased but boosted their role in water regulating and management (more red circles in Figure 3C, and larger water conveyance variability in Supplementary Materials Figure S7). Basin policies significantly increased, rigorously controlled the allocation of water (Figure 3D, $p < 0.01$ and *Supporting Information Figure S2*). During the P3, authorities proposed more national-level water governance policies under the guidance of the national strategy “environmental regulation” (Figure 3D). The regime shift from P1 to P2 is in line with the increasing water

supply and demands; while driven by regulatory policies and efficiency enhancement under stable water stress from P2 to P3.

4 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 (Best, 2019; Best & Darby, 2020). As tele-coupling raises additional water governance challenges in an increasingly tightly-connected world, regime shifts in water governance align with different human-water relationships (Díaz et al., 2019). The process echoes how societies have been proposed to change governance practices by enhancing their adaptive capacity in the hydrosocial cycle, and the IWGI quantitatively identifies this transition (Loch et al., 2020; Turton, 1999). 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 (Reyers et al., 2018).

In the case of the YRB, our results show that there have been three distinct governance regimes; we named them: a massive supply regime (P1: 1965 ~ 1978), a governance transforming regime (P2: 1979 ~ 2001), and an adaptation oriented regime (P3: 2002 ~ 2013) (Figure 2). During the massive supply regime with lower water stress (1965 ~ 1978 in the YRB), water governance thus tended to boost water supply for services (mainly provisioning purposes then -livestock and crops) by constructing reservoirs and channels. As the Chinese slogan “man will conquer nature” suggested then, however, the enhancement of water supply did not align with irreversible changes in the human-water relationship; it drastically increased water demand with little consideration for ecological conservation (Zhou et al., 2020). The rapid expansion of irrigated farmland and water diversion facilities in the same decade brought the overburdened YRB close to a critical point, where increasing supply to meet demand was impractical (Loch et al., 2020). Use of over 80% of the surface water since 1972 has led to frequent river depletion, causing additional ecological issues such as wetland shrinkage and declines in biodiversity (S. Wang et al., 2019). In addition, since water stress also limited the growing industrial economy, the existing modes of water governance led to a social-ecological crisis (Wohlfart et al., 2016).

The start of the governance transforming regime (P2: 1979 ~ 2001) coincided with rising competition for water use after the “reform and opening-up”. The results from the YRB mirror those of the theoretical analysis: continuous increases in water demand when the basin’s total supply is stable can follow substantial changes in governance regime and a rapid enhancement in overall social adaptive capacity (Loch et al., 2020). As a pioneer in shifting governing institutions, the YRB triggered institutional changes during this regime. These include, for example, slowing the growth of irrigated acreage; leading water-saving infrastructure; creation of China’s first water quota scheme, and the creation of a preliminary cross-boundary water transfer plan (Z. Wang & Zheng, 2019; Long et al., 2020; Nickum & Shaofeng, 2021). Consequently, although water stress remained and increased (due to reducing streamflow and flexibility), the last depletion of the Yellow River in 1999 led to a climax in this transformation in water governance (Z. Wang & Zheng, 2019).

The ensuing adaptation-oriented regime (P3: 2002 ~ 2013) involved a significant societal shift in adapting to stable high water stress. Partially because of changed climate (Han et al., 2023; Y. Liu et al., 2020), the runoff of the YRB was significantly lower than before when the overall water uses remained stable, which was an important reason for the rise of water stress in this stage (Figure ?? and Figure ??). Socio-economic trade-offs between water-dependent regions and sectors, however, played a more important role in this regime, so water governance had to achieve efficient water allocation while balancing different demands in the face of limited water supply (Dalin et al., 2015; Song et al., 2022). Widespread reconstruction of resources in different industries and regions led to calls for adaptation in

water governance, using the urgent requirements of adjusting rigid quota shares from the previous regime as an example (Z. Wang & Zheng, 2019). Many national-level governance practices were proposed under the regime because the absence of such policies to support high-quality development became new a structural challenge for water governance (Konar et al., 2019).

In general, water governance of the YRB is among the most prominent example in the widespread transition to a hydrosocial cycle -“improving supply, transforming governance, and enhancing adaptation”. With each dimension changing gradually, the emergence of different regimes drives water governance challenges at a basin-scale: these were primarily economic and environmental before the transformation, but social and policy-related towards the end (Figure 4) (Singh et al., 2019; Porcher & SAUSSIÉ, 2019). In an analogy at a global scale, the resource challenges, represented by water shortage and water supplying difficulties, are mainly faced by undeveloped and developing basins (Allan et al., 2019; Speed & Asian Development Bank, 2013; J. Liu & Yang, 2012). 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 (UNEP-DHI et al., 2016; Mirumachi, 2015). 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.

Future’s tightly intertwined socio-hydro interactions can lead water governance challenges even more complex and comprehensive, combining resources issues and structural barriers (Huggins et al., 2022). For example, climate change may alter water scarcity levels and make it more difficult to effectively use water due to extreme climate events, strengthening water stress and threatening infrastructures (J. Liu et al., 2017; Di Baldassarre et al., 2019). Additionally, adapting to climate change could lead to transformations (Sachs et al., 2019; Barnes et al., 2020), prompting a reevaluation of governance strategies of social water usage (priority and allocation) which is being increasingly altered by current regime transitions. It may be difficult to exhaust what is considered in a good watershed governance strategy, but the IWGI at least gives us a sense of where the a river basin is heading and how challenged.

One of the main limitations in the approach is the lack of multi-sources data in long-term period worldwide, which means there is still a gap between comprehensively identifying and applying the IWGI widely. We propose that all water governance issues, however, can change “who gets water, when and how” so monitoring such an integrated index is essential, even use simpler indicators. We suggest that choices of indicators for different aspects can be adapted according to available datasets -e.g., replace the SFV-index (IA) with simpler scarcity index or proportion-based priority indicator (IP) by complicated one. Another limitation is the lack of latest datasets which is coherent with the historical datasets, so our analysis had to discontinued in 2013 despite potential shifts existing. As a supplement, we examined IWGI framework with fewer datasets from different source in recent decades where showing no significant regime changes (supplementary Figure 4). Therefore, we suggest IWGI framework can be applied with adaptive indicators and flexible time series according to accessible datasets in future studies.

In today’s world, regime shifts from biophysical to hydrosocial control of water dynamics seem likely to become increasingly widespread; comprehensive strategies to address governance challenges will have to become the core of complex human-water systems (Cumming & von Cramon-Taubadel, 2018; Cumming et al., 2014; Jaeger et al., 2019). Although river basins have shown improvements in water management technologies and water use efficiency, many are still approaching local, regional, and planetary boundaries where human-water systems may collapse (Gleeson, Cuthbert, et al., 2020; Wang-Erlandsson et al., 2022). 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

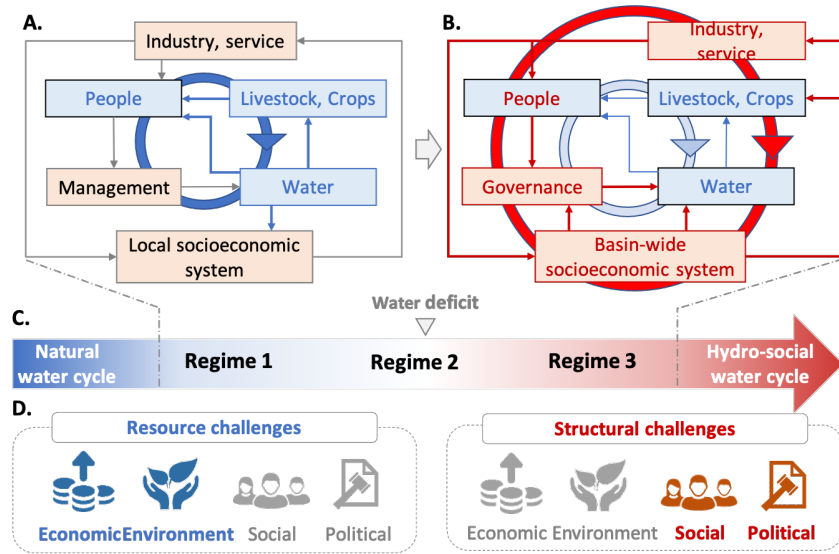


Figure 4. Transition schema in hydrosocial cycle and water governance regimes. The natural water cycle dominates blue pathways, while socio-economic feedback dominates red. **A.** As socio-economic systems develop, non-provisioning water demand increases; simultaneously, increased adaptive capacity by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

of the basin’s social-ecological system and improving its sustainability (Falkenmark et al., 2019).

5 Conclusion

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

Open Research Section

All the used datasets and access source are listed in the *SI Appendix* Table S1 with a detailed description in *Supporting Information S3*.

Acknowledgments

Funding was provided by the National Natural Science Foundation of China (CN) (Grant Nos. NSFC 42041007).

References

- Abbott, B. W., Bishop, K., Zarnetske, J. P., Hannah, D. M., Frei, R. J., Minaudo, C., ... Pinay, G. (2019, November). A water cycle for the Anthropocene. *Hydrological Processes*, 33(23), 3046–3052. doi: 10.1002/hyp.13544
- Ahlström, H., Hileman, J., Wang-Erlandsson, L., García, M. M., Moore, M.-L., Jonas, K., ... Svedin, U. (2021, December). An Earth system law perspective on governing social-hydrological systems in the Anthropocene. *Earth System Governance*, 10, 100120. doi: 10.1016/j.esg.2021.100120
- Allan, J. R., Levin, N., Jones, K. R., Abdullah, S., Hongoh, J., Hermoso, V., & Kark, S. (2019, April). Navigating the complexities of coordinated conservation along the river Nile. *Science Advances*, 5(4), eaau7668. doi: 10.1126/sciadv.aau7668
- Barnes, M. L., Wang, P., Cinner, J. E., Graham, N. A. J., Guerrero, A. M., Jasny, L., ... Zamborain-Mason, J. (2020, August). Social determinants of adaptive and transformative responses to climate change. *Nature Climate Change*, 1–6. doi: 10.1038/s41558-020-0871-4
- Best, J. (2019, January). Anthropogenic stresses on the world’s big rivers. *Nature Geoscience*, 12(1), 7–21. doi: 10.1038/s41561-018-0262-x
- Best, J., & Darby, S. E. (2020, June). The Pace of Human-Induced Change in Large Rivers: Stresses, Resilience, and Vulnerability to Extreme Events. *One Earth*, 2(6), 510–514. doi: 10.1016/j.oneear.2020.05.021
- Biermann, F., Abbott, K., Andresen, S., Bäckstrand, K., Bernstein, S., Betsill, M. M., ... Zondervan, R. (2012, March). Navigating the Anthropocene: Improving Earth System Governance. *Science*, 335(6074), 1306–1307. doi: 10.1126/science.1217255
- Bressers, H., & Kuks, S. (2013, January). Water governance regimes: Dimensions and dynamics. *International Journal of Water Governance*, 1(1), 133–156. doi: 10.7564/12-IJWG1

- Cumming, G. S., Buerkert, A., Hoffmann, E. M., Schlecht, E., von Cramon-Taubadel, S., & Tscharnkte, T. (2014, November). Implications of agricultural transitions and urbanization for ecosystem services. *Nature*, *515*(7525), 50–57. doi: 10.1038/nature13945
- Cumming, G. S., & von Cramon-Taubadel, S. (2018, September). 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. doi: 10.1073/pnas.1807026115
- Dalin, C., Qiu, H., Hanasaki, N., Mauzerall, D. L., & Rodriguez-Iturbe, I. (2015, April). Balancing water resource conservation and food security in China. *Proceedings of the National Academy of Sciences*, *112*(15), 4588–4593. doi: 10.1073/pnas.1504345112
- Díaz, S., Settele, J., Brondízio, E. S., Ngo, H. T., Agard, J., Arneth, A., ... Zayas, C. N. (2019, December). Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science*, *366*(6471). doi: 10.1126/science.aax3100
- Di Baldassarre, G., Sivapalan, M., Rusca, M., Cudennec, C., Garcia, M., Kreibich, H., ... Blöschl, G. (2019, August). Sociohydrology: Scientific Challenges in Addressing the Sustainable Development Goals. *Water Resources Research*, *55*(8), 6327–6355. doi: 10.1029/2018WR023901
- Falkenmark, M., & Wang-Erlandsson, L. (2021, February). A water-function-based framework for understanding and governing water resilience in the Anthropocene. *One Earth*, *4*(2), 213–225. doi: 10.1016/j.oneear.2021.01.009
- Falkenmark, M., Wang-Erlandsson, L., & Rockström, J. (2019, January). Understanding of water resilience in the Anthropocene. *Journal of Hydrology X*, *2*, 100009. doi: 10.1016/j.hydroa.2018.100009
- Flörke, M., Schneider, C., & McDonald, R. I. (2018, January). Water competition between cities and agriculture driven by climate change and urban growth. *Nature Sustainability*, *1*(1), 51–58. doi: 10.1038/s41893-017-0006-8
- Gleeson, T., Cuthbert, M., Ferguson, G., & Perrone, D. (2020). Global Groundwater Sustainability, Resources, and Systems in the Anthropocene. *Annual Review of Earth and Planetary Sciences*, *33*.
- Gleeson, T., Wang-Erlandsson, L., Zipper, S. C., Porkka, M., Jaramillo, F., Gerten, D., ... Famiglietti, J. S. (2020, March). The Water Planetary Boundary: Interrogation and Revision. *One Earth*, *2*(3), 223–234. doi: 10.1016/j.oneear.2020.02.009
- Gleeson, T., Wang-Erlandsson, L., Porkka, M., Zipper, S. C., Jaramillo, F., Gerten, D., ... Famiglietti, J. S. (2020, April). Illuminating water cycle modifications and Earth system resilience in the Anthropocene. *Water Resources Research*, *56*(4). doi: 10.1029/2019WR024957
- Grafton, R. Q., Pittock, J., Davis, R., Williams, J., Fu, G., Warburton, M., ... Quiggin, J. (2013, April). Global insights into water resources, climate change and governance. *Nature Climate Change*, *3*(4), 315–321. doi: 10.1038/nclimate1746
- Han, Z., Zuo, Q., Wang, C., & Gan, R. (2023, January). Impacts of Climate Change on Natural Runoff in the Yellow River Basin of China during 1961–2020. *Water*, *15*(5), 929. doi: 10.3390/w15050929
- Huang, Z., Yuan, X., & Liu, X. (2021, October). The key drivers for the changes in global water scarcity: Water withdrawal versus water availability. *Journal of Hydrology*, *601*, 126658. doi: 10.1016/j.jhydrol.2021.126658
- Huggins, X., Gleeson, T., Kummer, M., Zipper, S. C., Wada, Y., Troy, T. J., & Famiglietti, J. S. (2022, December). Hotspots for social and ecological impacts from freshwater stress and storage loss. *Nature Communications*, *13*(1), 439. doi: 10.1038/s41467-022-28029-w
- Jaeger, W. K., Amos, A., Conklin, D. R., Langpap, C., Moore, K., & Plantinga, A. J. (2019, August). Scope and limitations of drought management within complex human-natural systems. *Nature Sustainability*, *2*(8), 710–717. doi: 10.1038/s41893-019-0326-y
- Kjellén, D. M., Tropp, D. H., & Jiménez, D. A. (2015). *Water governance in perspective: Water Governance Facility 10 years 2005-2015* (Tech. Rep.). Water Governance Facility.

- Konar, M., Garcia, M., Sanderson, M. R., Yu, D. J., & Sivapalan, M. (2019, February). Expanding the Scope and Foundation of Sociohydrology as the Science of Coupled Human-Water Systems. *Water Resources Research*, 55(2), 874–887. doi: 10.1029/2018WR024088
- Lasswell, H. D. (2018). *Politics: Who Gets What, When, How*. Pickle Partners Publishing.
- Liu, J., Yang, H., Gosling, S. N., Kumm, M., Flörke, M., Pfister, S., ... Oki, T. (2017). Water scarcity assessments in the past, present, and future. *Earth's Future*, 5(6), 545–559. doi: 10.1002/2016EF000518
- Liu, J., & Yang, W. (2012, August). Water Sustainability for China and Beyond. *Science*, 337(6095), 649–650. doi: 10.1126/science.1219471
- Liu, Y., Song, H., An, Z., Sun, C., Trouet, V., Cai, Q., ... Zeng, X. (2020, August). Recent anthropogenic curtailing of Yellow River runoff and sediment load is unprecedented over the past 500 y. *Proceedings of the National Academy of Sciences*, 117(31), 18251–18257. doi: 10.1073/pnas.1922349117
- Loch, A., Adamson, D., & Dumbrell, N. P. (2020). The Fifth Stage in Water Management: Policy Lessons for Water Governance. *Water Resources Research*, 56(5), e2019WR026714. doi: 10.1029/2019WR026714
- Long, D., Yang, W., Scanlon, B. R., Zhao, J., Liu, D., Burek, P., ... Wada, Y. (2020, December). South-to-North Water Diversion stabilizing Beijing's groundwater levels. *Nature Communications*, 11(1), 3665. doi: 10.1038/s41467-020-17428-6
- Mirumachi, N. (2015). *Transboundary Water Politics in the Developing World*.
- Mostern, R., & Horne, R. M. (2021). *The Yellow River: A natural and unnatural history*. New Haven: Yale University Press.
- Nickum, J. E., & Shaofeng, J. (2021). The Yellow River Basin. In A. Kibaroglu & J. Schmandt (Eds.), *Sustainability of Engineered Rivers In Arid Lands: Challenge and Response* (pp. 107–120). Cambridge: Cambridge University Press. doi: 10.1017/9781108261142.009
- OECD. (2018, March). OECD Water Governance Indicator Framework. In *Implementing the OECD Principles on Water Governance* (pp. 49–105). Author. doi: 10.1787/9789264292659-5-en
- Pettitt, A. N. (1979). A Non-Parametric Approach to the Change-Point Problem. *Journal of the Royal Statistical Society. Series C (Applied Statistics)*, 28(2), 126–135. doi: 10.2307/2346729
- Porcher, S., & SAUSSIER, S. (Eds.). (2019). *Facing the Challenges of Water Governance*. Palgrave Macmillan.
- Qin, D., Lu, C., Liu, J., Wang, H., Wang, J., Li, H., ... Chen, G. (2014, March). Theoretical framework of dualistic nature–social water cycle. *Chinese Science Bulletin*, 59(8), 810–820. doi: 10.1007/s11434-013-0096-2
- Qin, Y., Mueller, N. D., Siebert, S., Jackson, R. B., AghaKouchak, A., Zimmerman, J. B., ... Davis, S. J. (2019, June). Flexibility and intensity of global water use. *Nature Sustainability*, 2(6), 515–523. doi: 10.1038/s41893-019-0294-2
- Reyers, B., Folke, C., Moore, M.-L., Biggs, R., & Galaz, V. (2018, October). Social-Ecological Systems Insights for Navigating the Dynamics of the Anthropocene. *Annual Review of Environment and Resources*, 43(1), 267–289. doi: 10.1146/annurev-enviro-110615-085349
- Sachs, J. D., Schmidt-Traub, G., Mazzucato, M., Messner, D., Nakicenovic, N., & Rockstroem, J. (2019, September). Six Transformations to achieve the Sustainable Development Goals. *Nature Sustainability*, 2(9), 805–814. doi: 10.1038/s41893-019-0352-9
- Schmandt, J., & Kibaroglu, A. (2021). Better Basin Management with Stakeholder Participation. In A. Kibaroglu & J. Schmandt (Eds.), *Sustainability of Engineered Rivers In Arid Lands: Challenge and Response* (pp. 260–270). Cambridge: Cambridge University Press. doi: 10.1017/9781108261142.018
- Singh, A., Saha, D., & Tyagi, A. C. (Eds.). (2019). *Water Governance: Challenges and Prospects*. Springer Singapore.
- Sivapalan, M., Savenije, H. H. G., & Blöschl, G. (2012, April). Socio-hydrology: A new

- science of people and water: INVITED COMMENTARY. *Hydrological Processes*, 26(8), 1270–1276. doi: 10.1002/hyp.8426
- Song, C., Fan, C., Zhu, J., Wang, J., Sheng, Y., Liu, K., ... Ke, L. (2022, September). A comprehensive geospatial database of nearly 100 000 reservoirs in China. *Earth System Science Data*, 14(9), 4017–4034. doi: 10.5194/essd-14-4017-2022
- Speed, R., & Asian Development Bank. (2013). *Basin water allocation planning: Principles, procedures, and approaches for basin allocation planning*. Metro Manila, Philippines: Asian Development Bank, GIWP, UNESCO, and WWF-UK.
- Steffen, W., Richardson, K., Rockström, J., Schellnhuber, H. J., Dube, O. P., Dutreuil, S., ... Lubchenco, J. (2020, January). The emergence and evolution of Earth System Science. *Nature Reviews Earth & Environment*, 1(1), 54–63. doi: 10.1038/s43017-019-0005-6
- Turton, A. (1999). *Water Scarcity and Social Adaptive Capacity: Towards an Understanding of the Social Dynamics of Water Demand Management in Developing Countries*. SOAS.
- UNDP Water Governance Facility. (2016, August). *Issue sheet: Water governance* (Tech. Rep.). Stockholm.
- UNEP-DHI, UNEP, & UNEP. (2016). *Transboundary River Basins: Status and Trends*.
- Varis, O., Taka, M., & Kummu, M. (2019, October). The Planet’s Stressed River Basins: Too Much Pressure or Too Little Adaptive Capacity? *Earth’s Future*, 7(10), 1118–1135. doi: 10.1029/2019EF001239
- Wada, Y., Gleeson, T., & Esnault, L. (2014, September). Wedge approach to water stress. *Nature Geoscience*, 7(9), 615–617. doi: 10.1038/ngeo2241
- Wang, J., Wei, Y., Jiang, S., Zhao, Y., Zhou, Y., & Xiao, W. (2017, February). Understanding the Human-Water Relationship in China during 722 B.C.-1911 A.D. from a Contradiction and Co-Evolutionary Perspective. *Water Resources Management*, 31(3), 929–943. doi: 10.1007/s11269-016-1555-8
- Wang, S., Fu, B., Bodin, O., Liu, J., Zhang, M., & Li, X. (2019, September). Alignment of social and ecological structures increased the ability of river management. *Science Bulletin*, 64(18), 1318–1324. doi: 10.1016/j.scib.2019.07.016
- Wang, Z., & Zheng, Z. (2019). Things and Current Significance of the Yellow River Water Allocation Scheme in 1987. *Yellow River*, 41(10), 109–127. doi: 10.3969/j.issn.1000-1379.2019.10.019
- Wang-Erlandsson, L., Tobian, A., van der Ent, R. J., Fetzer, I., te Wierik, S., Porkka, M., ... Rockström, J. (2022, April). A planetary boundary for green water. *Nature Reviews Earth & Environment*, 1–13. doi: 10.1038/s43017-022-00287-8
- Wohlfart, C., Kuenzer, C., Chen, C., & Liu, G. (2016, July). Social-ecological challenges in the Yellow River basin (China): A review. *Environmental Earth Sciences*, 75(13), 1066. doi: 10.1007/s12665-016-5864-2
- Zhou, F., Bo, Y., Ciais, P., Dumas, P., Tang, Q., Wang, X., ... Wada, Y. (2020, March). Deceleration of China’s human water use and its key drivers. *Proceedings of the National Academy of Sciences*, 117(14), 7702–7711. doi: 10.1073/pnas.1909902117