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Institutional shifts and sustainable water use of the Yellow River Basin

Shuang Song[1,2], Huiyu Wen[3], *Shuai Wang[1,2], Xutong Wu[1,2], Graeme S. Cumming[4] and Bojie Fu[1,2,5]

[1]State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, P.R. China;
[2]Institute of Land Surface System and Sustainability, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, P.R. China;
[3]School of Finance, Renmin University of China, Beijing 100875, P.R. China;
[4]ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville 4811, QLD, Australia;
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*Corresponding authors. Email: shuaiwang@bnu.edu.cn.

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ABSTRACT

Increasing competition for water is leading to depletion of freshwater globally and calls for an urgent transformation of the governance system. To quantitatively analyse how institutions contributed to water governance, we focus on institutional shifts of the Yellow River Basin (YRB), one of the most anthropogenic interfered large river basins overburdened in water use, then drying up, but finally successfully restored. Our results suggest that two institutional shifts, the Water Allocation Scheme since 1987 (87-WAS) and the Unified Basinal Regulation since 1998 (98-UBR), framed different structures of social-ecological systems (SESs) in regional and basinal water use. During the decade after the 87-WAS, the observed water use of the YRB had an 8.57% increase than an expectation. However, the 98-UBR significantly decreased total water use by 4.9 billion m^3/yr. Specifically, the 87-WAS stimulated water use in provinces with more water uses (e.g., Inner Mongolia, Henan, and Shandong), but the 98-UBR regulated nearly all provinces. Linking our results to a mathematical marginal benefits model, we suggest that the outcomes with regional variations come from the effects of SES structural changes. These quasi-natural experiments of the YRB deepened insights on SESs structures and outcomes, thus providing a valuable guideline for SESs worldwide facing water depletion.

Keywords: Yellow River, water use, water governance, social-ecological system, institutional fit

INTRODUCTION

Widespread freshwater scarcity and overuse challenge the sustainability of large river basins, resulting in systematic risks to economies, societies, and ecosystems globally [1–4]. With steadily increasing demand, competition for water causes depletion of freshwater globally and calls for an urgent transformation of the governance system by considering water use conservation [5–7]. Despite worldwide trying to govern water, however, degradation of large river basins is not easily reversible because of few alignments between practice and theory in successful water governance cases. [8–10].

The Yellow River Basin (YRB), the fifth large river worldwide, is known for its irreplaceable role in the social-economic development of China, and thus also drastically interference by anthropogenic stress. Supporting 35.63% irrigation and 30% population with only 2.66% water resources of China (data from http://www.yrcc.gov.cn, last access: 28 February 2021), the overburdened Yellow River dried up in consecutive years, resulting in substantial ecological, economic and social crisis (e.g., wetland shrink, agriculture reduction, and scramble for water). Intense water use, accounting for about 80% of Yellow River surface runoff in the 1980s, was remarked as the significant reason for the degradation. Furthermore, human interferences such as soil conservation and water conservancy project boosted water withdrawal and then stressed the water scarcity of the Yellow River. In the context of future climate change, the contradiction between supplies and demands of water resources in the YRB will become more prominent. Therefore, balancing ecological and developing demands in such a human-dominated basin is a problem for China in terms of water governance throughout and for large rivers worldwide.

Chinese authorities implemented several ambitious water management practices in the YRB in the last century to relieve the water stress, such as reservoir regulation, South-to-north Water Diversion Project (WDP), and Water Allocation Scheme since 1987 (87-WAS), and the Unified Basinal Regulation since 1998 (98-UBR). Through those efforts, ecological restoration of wetland and estuary delta in the YRB without drying up for over 20 is widely considered a considerable river management achievement. Different from the engineering of WDP provides further water supply or reservoir matches water supply and demands, institutional strategies like the 87-WAS (assign water quotas for provinces in the YRB) and the 98-UBR (the provinces had to be allowed to use water by the Yellow River Conservancy Commission, YRCC) mainly focused on limiting demands of water use. Such institutions (policies, laws, and norms) can influence regional sustainability by changing the structure of the coupled human and natural system, including interplays between social actors, ecological units, or between social and ecological system elements [11–14]. Understanding those complex interlinkages, therefore, is crucial for developing strategies to effectively manage natural resources and enhance the resilience of social-ecological systems (SES) [15]. However, while literature had well evaluated and quantified the effects of engineering solutions beforehand, there are few attempts to assess institutional contributions to successful water governance.

In addition to widespread recognition of the rising importance of institutions as an approach to water sustainable use within large river basins (especially transboundary rivers like the YRB), their specific effects are still in open discussion [16–18]. Effective ("matched" or "fit") institutions operate at appropriate spatial, temporal, and functional scales to manage and balance different relationships and interactions between human and water systems, therefore, supporting (but do not guarantee) sustainability of SES [7,19]. Some institutional shifts have desirable water governance outcomes (e.g., the Ecological Water Diversion Project in Heihe River Basin, China [7] and collaborative water governance systems in Europe [20]). However, shifting institutions in a large, complex river basin may create or destroy hundreds of different connections between social agents and ecological units, where matched social-ecological structures are not ubiquitous. Therefore, the role of institutional shifts in the water governance achievement of the YRB and their impacts on water use is still uncertain without an understanding of SES structures. Here, by abstracting changes in official documents following institutional shifts (the 87-WAS and the 98-UBR), we depicted the SES structures of the YRB from 1975 to 2008. Then, we use Differenced Synthetic Control (DSC) method, which considers economic growth and natural background, to estimate theoretical water use scenarios without the institutional shifts (**Methods**; *S2 in Supplementary Material*). By further interpreting the differences of the effects in the YRB, we explored the mechanisms linking SESs structure and outcomes for a deeper understanding of institutions' role in water governance worldwide.

RESULTS

Institutional shifts and structures

As a pioneer in water governance shifting in China, the YRB started to explore the initial water allocating scheme in the 1970s. The institutional shifts in 1987 (87-WAS) and 1998 (98-UBR) were two widely recognized milestones of water governance. Until the 87-WAS, stakeholders (the provinces in the YRB) had free access to the YR water resources for development, but there were geographic and temporal differences between freshwater demand and availability. As a compounded result of development, the provinces such as Shandong, Henan and Inner Mongolia used more water resources in the YRB with larger economies (primarily for irrigation agriculture). For shrinking water deficits, national authorities proposed in 87-WAS allocating specific water quotas between 10 provinces (or regions) along the YR basin. However, the controversial scheme helped little in turning the water depletion around until another strategy attempted to strengthen the responsibilities of the YRCC in integrated water management in 1998 (the 98-UBR). Therefore, our analysis period spans from 1975 (emergence of river depletion) to 2008 (a further polish of the 98-UBR), with the SESs shifted between three varying institutions which were different from other large river basins in China.

We selected institutional regulatory documents on water use issued by national ministries (for validation to both watershed and regional agents) and extracted the interactions between the agents involved (*Supplementary Material S2*). Before 1987, the YRCC had no links to the provinces regarding water use, and the provinces could link to the Yellow River reaches directly (Figure 1). However, according to the extracted information from the 87-WAS, the YRCC started to report water use from the provinces. Furthermore, information from the 98-UBR documents demonstrated that the provinces had to apply their plan for an annual water use licence instead of direct access to the Yellow River water. Thus, there have been links between the YRCC and the provinces since the strengthening responsibilities of the YRCC in 1998.

Institutional shifts impact on water use

Our estimation of theoretical water use suggests that the institutional shift in 1987 (87-WAS) stimulated the provinces to withdraw more water than would have been used without an institutional shift (Figure 2A). From 1988 to 1998, on average, while the estimation of annual water use only suggests 956.38 billion m^3, the observed water use of the YRB provinces reached 1038.36 billion m^3 in sum, 8.57% increased. However, after the institution shifted again in 1998 (98-UBR), the trend of increasing water use appeared to be effectively suppressed. From 1998 to 2008, the total observed water use decreased by 4.9 billion m^3/yr per year, while the estimation of water use still suggests 10.3 billion m^3/yr increases (Figure 2 B). The increased water uses after 87-WAS aligns with the fact that badly drying-up of the surface streamflow from 1987 to 1998, which was an obvious touchstone of river degradation and environmental crisis (Figure 2C). On the other hand, the 98-UBR ended river depletion, despite the density of droughts still increasing for decades (from 0.47 after 87-WAS to 0.62 after 98-UBR on average) (Figure 2C).

Institutional effects on regulating differences

Our results also suggest differences between patterns of provinces in their responses to the two institutional regulating. During the decade after the 87-WAS, the major water-using provinces (e.g., Inner Mongolia, Henan, Shandong) had apparent accelerations (Figure 3). The proportion of increased (or decreased) water use for each province (over the estimated water use by the model) has a significant correlation (partial correlation coefficient is 0.84, $p < 0.05$) to the actual water use from the Yellow River. In particular, Inner Mongolia and Shandong, both provinces that exceeded the prescribed water uses of the 87-WAS, used 44.25% and 25.69% more water uses than the prediction from 1987 to 1998, respectively. By contrast, after the 98-UBR, except Shanxi (whose water quota has always been far abundant over its actual water use since the 87-WAS) had an evident (17.53%) increase in water use, almost all provinces have seen evident declines in water use (−12.5% on average). Furthermore, the regulated water use of provinces was not correlated (−0.03) with their water use from the Yellow River in proportions.

DISCUSSION

In addition to quantitatively demonstrating the regulatory effect of 98-UBR by previous studies, our study also found that 87-WAS would increase overall water use of the YRB. The results challenged the previous analyses suggesting that the 87-WAS "has little effect" because the difference between prediction and observation will be trivial when the institutional shift was just a blank policy by applying the DSC method. Fixing the environmental background, the forecast by DSC takes economic factors into account under the assumptions that the production function between economic volume and water uses remained unchanged (*S2 in Supplementary Material*). As the accumulations of economy volume (GDP in different sectors) in the YRB maintained a parallel trend with other regions throughout (*S3 in Supplementary Material* Figure **??**), differences after the institutional shifts suggest water use changing per unit of production, especially in agriculture (*S3 in Supplementary Material* Figure **??**). This fact is in line with the sigh from then: although the key to alleviating the drought is saving water in the irrigated areas, the tragedy of frequently scrambling for water appeared in some provinces Since the 98-UBR improved tragedy of water competition greatly, many studies attributed the restoration from river depletion mainly to the successful institutional shift.

Although previous studies summarised reasons for the non-ideal effect of 87-WAS, few improvements in the 98-UBR indicate that they underestimated influences from the structural changes (*S3 in Supplementary Material* Figure **??**). As we have depicted (Figure 1), the institutional shifts twice framed the structure of SESs in the YRB and led to different building blocks, which were also reported in various types of SESs worldwide. The empirical studies in many different fields also indicate that the structure before 98-UBR (i.e., fragment ecological units are linked to separate social actors) is likely to be mismatched as isolated stakeholders struggle with holistically maintaining interconnected ecosystems [21–24]. On the contrary, the YRCC, whose authority matched the YRB in

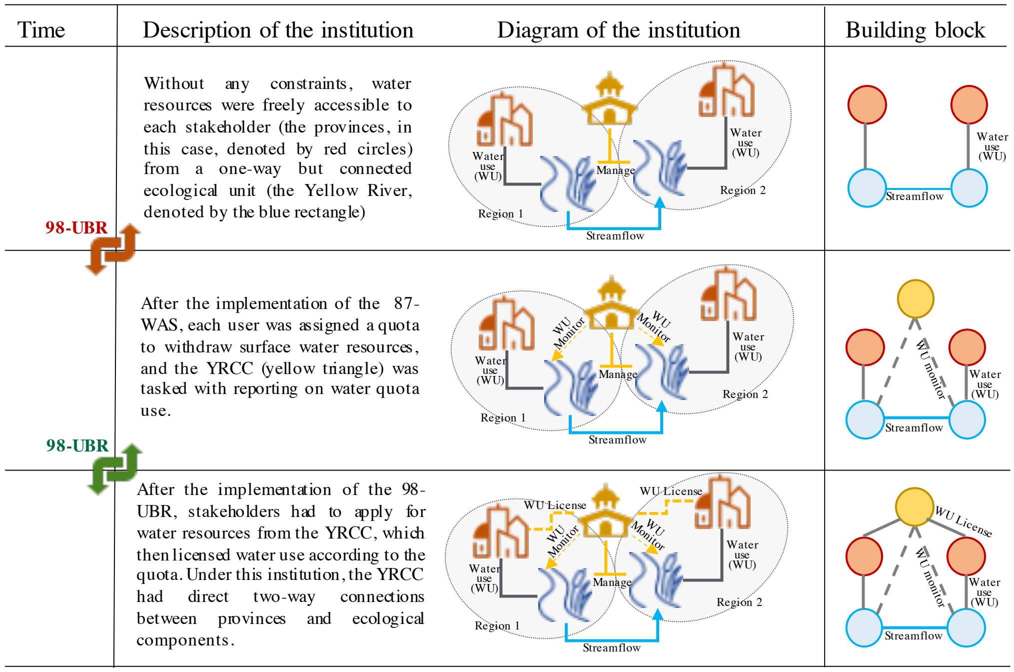

Figure 1. Institutional shifts and related SES structures in the Yellow River Basin (YRB). See *Supplementary Material S1* for detailed introduction for the institutions.

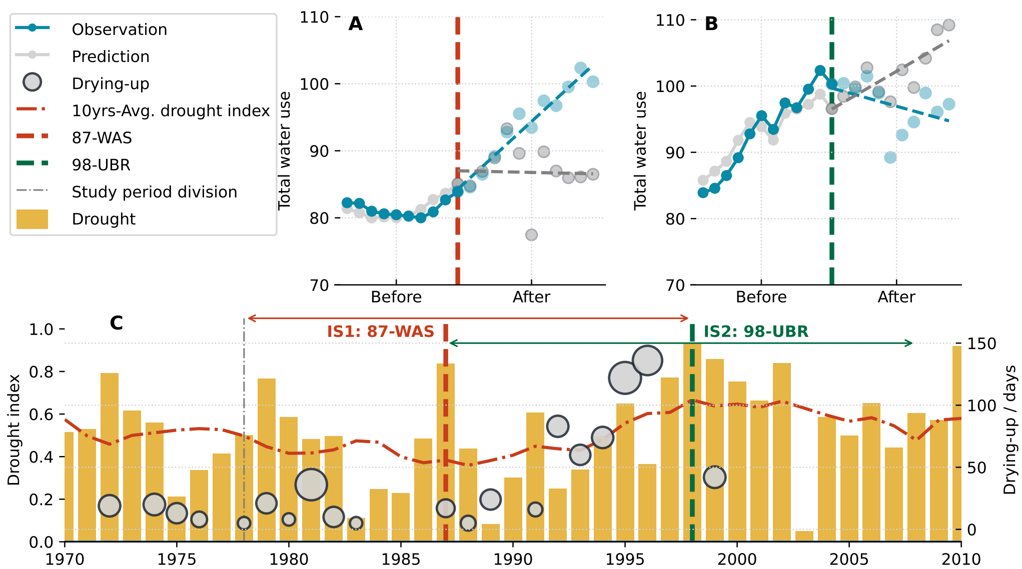

Figure 2. Effects of two institutional shifts on water resources use and allocation in the Yellow River Basin (YRB). **A.** water uses of the YRB before and after the institutional shift in 1987 (87-WAS); **B.** water uses of the YRB before and after the institutional shift in 1998 (98-UBR). While the blue lines are statistic water use data, the grey ones are the estimation from the Differenced Synthetic Control method with economic and environmental background controlled. **C.** Drought intensity in the YRB and drying up events of the Yellow River. The size of the grey bubbles denotes the length of a drying upstream.

scale after the 98-UBR, led to a well-recognized structure for institutional alignments to social-ecological fit and good outcomes. The effect of the institutional shifts once again demonstrated that it is not easy to have a win-win situation of environment and interests in complex coupled human-nature systems [25] which calls for exceptional understanding and caution to the structure of hampering sustainability [22,24].

Differences in the pattern of the response by provinces can demonstrate the influence of social-ecological structures led by the institutional shifts. We analyzed mathematically why the mismatched structure made limited water use holistically elusive in the institution shift of the 87-WAS but finally achieved by the 98-UBR (*method* and *Supplementary Material S4*). By taking the structure before and after the two in-

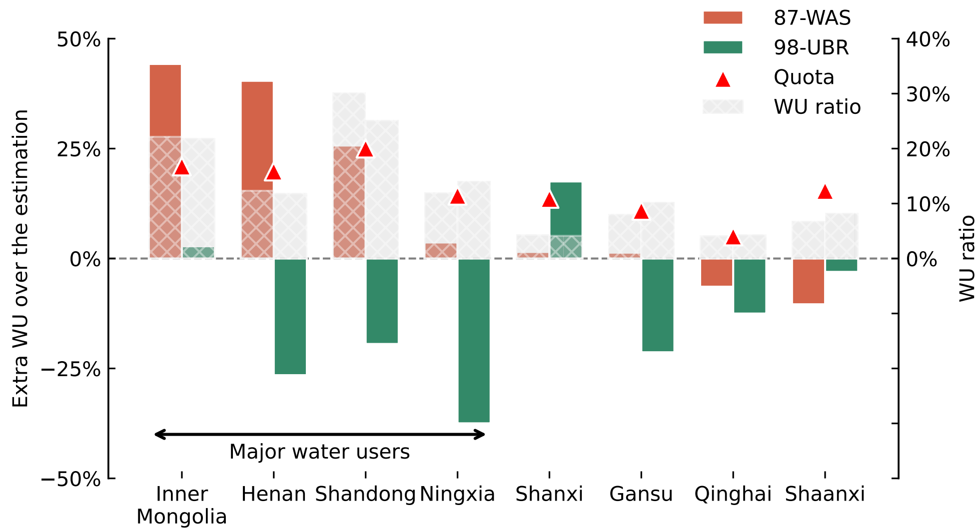

Figure 3. Regulating differences for provinces in the YRB. Red and green bars denote actual water use over the estimation from the model in a decade after the institutional shift -the 87-WAS and the 98-UBR, respectively. The grey bars indicate the proportions of actual water use for each province to total water use of the provinces in a decade after the institutional shift. The triangles mark the water quotas assigned in the institution, scaled into ratios by the same total actual water use, too.

stitutional shifts as different basic assumptions (before 87-WAS: free access to water; after 87-WAS but before 98-UBR: decisions on water use under quotas; after 98-UBR: unified regulation), we use the marginal benefit model to analyze the theoretical optimal water consumption of stakeholders in each scenario. The analysis of the model also shows that 98-UBR can reduce the overall water use of the basin while 87-WAS can increase the water use of the basin when the same parameters are guaranteed but the institutional structure changes. Before the 98-UBR, the model assumes that the separated ecological units (river reaches) link to stakeholders (related provinces) who use water to pursue their marginal benefits but have a potential political cost if they exceed the quota 87-WAS. Our model suggests that for users who are already economically efficient (who are already using more water), greater marginal returns from water induce the acceleration of extracting resources for future economic growth (*Supplementary Material S4*). Therefore, isolated stakeholders reacted to the similar marginal cost, and smaller water users have a threshold because of the political cost, so 87-WAS triggered an increased water use for the significant users. On the contrary, the presence of central management (by the YRCC in this case, after 1998) can effectively reduce marginal ecological costs holistically as stakeholders only take corresponding responsibilities (follow the quota as possible as they can) to the YRCC (*Supplementary Material S4*). As a result, unified regulating acted the core role after the 98-UBR and reduced water use of all stakeholders (provinces) by irregular ratios.

The alignments of differences in institutional structures and outcomes here echo the hypothesis that successful governance of SES emerged by indirectly (or vertically) creating links between different stakeholders (in the YRB cases, through administration). When links The water quotas of 87-WAS (or the initial water rights) in our case studies went through a stage of "bargaining" among stakeholders (from 1982 to 1987) [7,26], where each province attempted to demonstrate its development potential related to water use. The bargaining itself was also a process towards matches between their economic volume and water shares, as studies show that the large water users (like Shandong and Henan) need more water than their quota (in the 87-WAS) if only considering the economic equity when designing the institution. Furthermore, with information asymmetry between upper-level decision-makers and lower-level stakeholders in water use allocation, those with more current water use might have greater bargaining power. In practice, therefore, although the affected provinces may not have directly encouraged excessive resource use because of the institutional shift, they had a more considerable incentive to show their economic potential That aligns with the historical records that, even after the 87-WAS had already confirmed the quotas, provinces, especially water-intensive ones, challenged it by appearing to the higher central government for larger quotas. On the contrary, after YRCC as governing agent coordinated between stakeholders since 98-UBR, the external appeal of provinces for larger quotas turned into internal innovation to improve water efficiency (e.g., drastically increased water-conserving equipment, *Supplementary Material S3*) [27,28]. Then, the YRCC, the authority for approving water applications from all stakeholders, could adjust water use quotas according to the river conditions of the whole basin. The 98-UBR led to a structure for achieving social-ecological fits in both basins (between YRCC and the YRB) and regions (between provincial economy and their water shares).

LIMITATION, INSIGHTS AND IMPLICATIONS

Matching social and ecological scales appears widespread as building blocks (or motifs) in successfully governed SES, whether in fisheries, forests, or groundwater management. Since the building blocks introduced by 87-WAS and 98-UBR are recurring motifs in many SES, our proposed mechanism is crucial to understanding such coupled systems. We explored these causal linkages between the SES structures and sustainability (outcomes) by quasi-natural experiments (the institutional shifts) of the YRB, which provides an informative case study for two main reasons. First, different from gradual changes following bottom-up emergence, the top-down institutional shifts induced sharp changes in SES structures in the YRB, enabling us to estimate their net effects quantitatively. Second, as few basins experienced such radical institutional shifts more than once, the YRB provides comparable settings for understanding the impacts of structural changes in SESs. However, one of the inevitable limitations of our method is that it is difficult to rule out the effects of other policies over the same time breakpoints. Since scholars have reached a consensus on the importance of the two institutional shifts of 87-WAS and 98-UBR, the differences in their results still provide important insights for understanding water governance.

Our results and discussion deepen the understanding of SES structure and strengthen the basic understanding that the mismatched structure (isolated stakeholders with the fragmentation of ecology) is not conducive to institutional solutions. Moreover, we report how another institutional shift contributed to successful water governance -the subsequent success of 98-UBR has proved the importance of social-ecological fit again, theoretically and practically. For sustainability in the future, therefore, it is necessary to emphasize the necessity of strengthening connections between stakeholders by agents consistent with the scale of the ecological system (in this case, the basinal scale and the YRCC). From these starting points, several other scenarios given by a marginal benefit model (see *Supplementary Material S4*) can provide plausible insights into water governance. For example, water rights transfers can be another way to emerge horizontal links between stakeholders that also have the potential to result in better water governance. In addition, the policymakers can propose more dynamic and flexible institutions to increase the adaptation of stakeholders to respond to changing SES context.

Calls for a redesign of water allocation institutions in the YRB in recent years also illustrate the importance of institutional solutions to sustainability (see *Supplementary Material S1*) [29]. Given recent changes in the YRB, outdated and inflexible water quota can no longer meet the new demands of economic development [26]. As a result, the Chinese government has embarked on a plan to redesign its decades-old water allocation institution (see *Supplementary Material S1*). These initiatives can benefit from our analysis by actively incorporating social-ecological matched building blocks when developing a new institutional shift toward sustainability. Moreover, our research provides a cautionary tale of how institutions can be double-edged, while insights from the YRB can be a valuable guideline for SESs worldwide [12,30–32].

MATERIALS AND METHODS

We estimated and analyzed the net effects of two SES structural changes of water use. The actual water use of the Yellow River Basin was peroxided by the sum of the water use of the target group provinces. To quantify water use, we used synthetic control methods to estimate possible trends of water use in the absence of institutional shifts. Finally, we created an economic model based on marginal revenue to provide a theoretical explanation for the observed "sprint effect" phenomenon. A brief technical overview is given in *Supplementary Material S2*.

Dataset and variables

We used China's provincial annual water consumption dataset from 1978 to 2012. This publicly available dataset was obtained from the National Water Resources Utilization Survey; details are accessible from Zhou (2020) [33]. A total of 10 provinces or regions have been directly affected by the water allocation institutional shifts in the YRB, accounting for 8.6% of the total population of China (in 1990). Eight provinces have been particularly affected because of their greater dependence on the water resources from the Yellow River (see *Supplementary Material S2*). Therefore, we divided the dataset into a "target group" and a "control group", treating provinces that were greatly affected as the target group ($n = 8$) and provinces that were not affected by the institutional shifts as the potential control group ($n = 20$).

We focused on total water use in the YRB. The actual water uses are given by the dataset, but when the synthetic control method is used to predict the water use of the control group, other independent influences need to be considered. Thus, we used economic features that are highly related to water use to extrapolate demand (e.g., agriculture, industry, service industry, and domestics, see *Supplementary Material S2, Table 1*

Difference Synthetic Control

Synthetic control is an effective identification strategy for estimating the net effect of historical events or policy interventions on aggregate units (such as cities, regions, and countries) by constructing a comparable control unit [34–36]. In this study, we used a comparative event approach and compared actual post-institutional shift induced water use changes with an appropriate counterfactual of what the water use change would have been. The counterfactual was built as the optimally weighted average of provinces not exposed to the institutional shifts. The synthetic control method generalizes the difference-in-differences estimator and allows for time-varying individual-specific unobserved heterogeneity [37,38]. In practice, each of the units (i.e., provinces) in the treated group were affected by institutional shifts in 1987 and 1998, each of which was taken as the "shifted" point t_0 and the two steady institutions as t for analyzing in each shift. The synthetic control method generates the control unit by assigning a weight matrix W to units of the potential control group, so that the treated unit and its control unit are similar in each variable before t_0, i.e.,

$$\min(V_i^{t<t_0} - W_i * F_{control}^{t<t_0})$$

where V_i is a vector that indicates all features of a unit i of the treated group, and $F_{control}$ is a matrix that consists of all features and units of the potential control group. W_i is the weight matrix for target unit i. We minimized the root mean square error (RMSE) by using the Synth package in R [**?**,**?**]. All codes are accessible in the repository.

In accordance with the idea of dimensionality reduction, we constructed a series of comparable control units that were most similar in characteristics to the treated units. Because the units of the control group were not affected by the institutional shifts, after giving the same weight to the total water use of the control group $M_i * WU_{control}$, the result $W_i * WU_{control}$ could be considered a reasonable estimation of the untreated situation. The net effect of the water allocation institutional shift was then estimated by calculating the difference of water uses after the institutional shift between the treated group and the control group, compared with the water use difference before the shift.

Economic model

In order to understand the mechanisms underlying the empirical results, we developed a dynamic economic model to analyze how institutional change could have led to the sprint effect in water use. Specifically, we modeled individual provincial decision-making in water resources before quota execution. The analysis result implied that the underlying driver of CPR overuse was incentive distortion.

In developing the model, we highlighted the main features of the YRB, as well as the water use institutions of 1987 and 1998. We proposed three intuitive and general assumptions.

Assumption 1. *(Water-dependent production) For simplicity, water is assumed to be the only input of the homogenous production function $F(x)$ of each province because of its irreplaceability. $F(x)$ is continuous and satisfies the Inada Conditions, i.e., $F'(x) > 0, F''(x) < 0$ (the diminishing marginal returns assumption), $F'(0) = \infty, F'(\infty) = 0$. The production output is under perfect competition, with a constant unit price of P.*

Assumption 2. *(Ecological cost allocation) Under the assumption that the ecology is a single entity for the whole basin involved in N provinces, the cost of water use is equally assigned to each province under any water use. The unit cost of water is a constant C.*

Assumption 3. *(Multi-period settings) There are infinite periods with a constant discount fac-*

tor β lying in (0,1). There is no cross-period smoothing in water uses.

Under the above assumptions, we can demonstrate three cases consisting of local governments in YRB to simulate their water use decision-making and water use patterns.

Case 1. *Decentralized institution: This case corresponds to a situation without any high-level water allocation institution (i.e., before 1987, see Figure 1 B).*

When each province independently decides on its water use, the optimal water use $\hat{x}_i^*$ in province i satisfies:

$$F'(x) = \frac{C}{P \cdot N}$$

When the decisions in different periods are independent, for $t = 0, 1, 2 \ldots$, then:

$$\hat{x}_{it}^* = \hat{x}_i^*$$

Case 2. *Mismatched institution This case corresponds to a mismatched institution (i.e., 1987 ∼ 1998, see Figure 1 C).*

The water quota is determined at $t = 0$ and imposed in $t = 1, 2, \ldots$ The total quota is a constant denoted as Q, and the quota for province i is determined in a proportional form:

$$Q_i = Q \cdot \frac{x_i}{x_i + \sum x_{-i}}$$

Under a scenario with decentralized decision-making with a water quota institution, given other provinces' water use decisions remain unchanged, the optimal water use $\widetilde{x}_{i0}^*$ of province i at $t = 0$ satisfies:

$$F'(x_{i,0}) = \frac{C}{P \cdot N} - \frac{\beta}{1-\beta} \cdot f(Q \cdot \frac{x_{i,0}}{x_{i,0} + \sum x_{-i,0}}) \cdot Q \cdot \frac{\sum x_{-i,0}}{(x_{i,0} + \sum x_{-i,0})^2}.$$

When future water use is constrained by a water quota, the dynamic optimization problem of province i is shown as follows:

$$max \quad P \cdot F(x_{i,0}) - \frac{C \cdot \sum x_{i,0} + x_{-i,0}}{N} + \beta P \cdot F(x_{i,1}) + \beta^2 P \cdot F(x_{i,2}) + \ldots$$

$$= P \cdot F(x_{i,0}) - C \cdot \frac{x_{i,0} + \sum x_{-i,0}}{N} + \frac{\beta}{1-\beta} P \cdot F(Q \cdot \frac{x_{i,0}}{x_{i,0} + \sum x_{-i,0}})$$

First-order condition: $P \cdot F'(x_{i,0}) - \frac{C}{N} + \frac{\beta}{1-\beta}[P \cdot f(Q \cdot \frac{x_{i,0}}{x_{i,0}+\sum x_{-i,0}}) \cdot Q \cdot \frac{\sum x_{-i,0}}{(x_{i,0}+\sum x_{-i,0})^2}] = 0$

where $f(\cdot)$ is the differential function of $F(\cdot)$.

The optimal water use in province i at t=0 $\widetilde{x}_{i,0}^*$ satisfies $P \cdot F'(x_{i,0}) = \frac{C}{N} - \frac{\beta}{1-\beta} \cdot P \cdot f(Q \cdot \frac{x_{i,0}}{x_{i,0}+\sum x_{-i,0}}) \cdot Q \cdot \frac{\sum x_{-i,0}}{(x_{i,0}+\sum x_{-i,0})^2}$, *i.e.,* $F'(x_{i,0}) = \frac{C}{P \cdot N} - \frac{\beta}{1-\beta} \cdot f(Q \cdot \frac{x_{i,0}}{x_{i,0}+\sum x_{-i,0}}) \cdot Q \cdot \frac{\sum x_{-i,0}}{(x_{i,0}+\sum x_{-i,0})^2}$.

Case 3. *Matched institution*

This case corresponds to the institution under which the YRCC centrally managed water allocation between provinces (i.e., 1998 ∼ 2008, see Figure 1 D).

When the N provinces decide on water uses as unified whole (e.g., the central government completely decides and controls on the water use in each province), the optimal water use x_i^* of province i satisfies:

$$F'(x) = \frac{C}{P}$$

We propose Proposition 1 and Proposition 2:

Proposition 1: Compared with the decentralized institution, a matched institution with unified management decreases total water use.

Because F' is monotonically decreasing, based on a comparison of costs and benefits for stakeholders (provinces) in the three cases,

$$\widetilde{x}_i^* > \hat{x}_i^* > x_i^*$$

The result of $\hat{x}_i^* > x_i^*$ indicates that individual rationality would deviate from collective rationality when property rights are unclear [**?**], because of the common-pool characteristics of water [**?**,**?**].

The difference of $\widetilde{x}_i^*$ and $\hat{x}_i^*$ stems from two parts: the marginal returns effect and the marginal costs effect. First, the "shadow value" provides additional marginal returns of water use in $t = 0$, wwhich increases the incentives of water overuse by encouraging bargaining for a larger quota. Second, the future cost of water use would be degraded from $\frac{P}{N}$ to an irrelevant cost.

The optimal water use under the three cases implies that mismatched institutions cause incentive distortions and lead to resource overuse.

Proposition 2: The quota determination of the mismatched institution increases the incentives of current water use.

The intuition for this proposition is straightforward in that all provinces would use up their allocated quota under a relatively small Q. As Q increases, the quota would provide higher future benefits for a pre-emptive water use strategy. Since the provincial water use decisions are exactly symmetric, total water use would increase when each province has higher incentives for current water use. This situation corresponds to a "sprint" effect, where the total water use dramatically increases in the "sprint" period.

Extensions of the model are shown in *Supplementary Material S3*.

CONCLUSION

Intense water use in one of the most anthropogenic interfered large river basins, the Yellow River Basin (YRB), once led to overburdened drying up but finally had a successful restoration by sequential water governance practices. Focusing on two water-demand institutions, 87-WAS and the 98-UBR, we quantitatively analyzed how institutional shifts played a role in the water governance achievement of the YRB. Shifting throughout different SES structures framed by them, the observed water use of the YRB provinces had an 8.57% increase than expected during the decade after the 87-WAS. Then, water use significantly decreased by $4.9 billion m^3$ per year since the 98-UBR, while the model still suggests a $10.3 billion m^3$ annual increase in expectation. Finally, as differences in stakeholders' response to the institutional shifts, water use rises after the 87-WAS in provinces with more water uses (e.g., Inner Mongolia, Henan, and Shandong) while shrunk in nearly all provinces after the 98-UBR. Since the above results closely align with interpretations from a mathematical marginal benefits model, we can link the structures (widespread building blocks) and outcomes (goals of the institution, i.e., limiting water demands) by these quasi-natural experiments of the YRB. We demonstrate that social-ecological fits lead to successful governance where reducing independent stakeholders linked to fragmentation is an essential primary mechanism for good SES outcomes.

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