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Institutional effects on water use and sustainability in the Yellow River Basin

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ABSTRACT

Increasing competition for water is leading depletion of freshwater globally and calls for an urgent transformation of the governance system. 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 institutions. Focusing on two water-demand institutions, the Water Allocation Scheme since 1987 (87-WAS) and the Unified Basinal Regulation since 1998 (98-UBR), we quantitatively analyzed how the institutional shifts played a role in the YRB. Our results suggest that the observed water use of the YRB provinces had an 8.57% increase than expectation in the decade after the 87-WAS but significantly decreased by $0.49km^3$ per year after the 98-UBR. Furthermore, the 87-WAS stimulated water use in provinces with more water uses (e.g., Neimeng, Henan, and Shandong) but the 98-UBR regulated nearly all provinces. Linking our results to a mathematical marginal benefits model for a coherent interpretation, we deepen insights between the structures and outcomes in such social-ecological systems by the quasi-natural experiments of the YRB, 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, resulting in systematic risks to economies, societies, and ecosystems globally, are critical environmental challenges to sustainability [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, and limiting water use intensity will be still in the first bid 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.

In China, there were several ambitious water management practices in the last century, such as reservoir regulation, South-to-north Water Diversion Project (WDP), Water Allocation Scheme since 1987 (87-WAS), and the Unified Basinal Regulation since 1998 (98-UBR), to solve the water stress of the YRB. 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 for using 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 the complex interlinkages 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 (especially transboundary river) basins, 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, where matched human-water relationships are not ubiquitous. How and how important the institutional shifts played a role in the water governance achievement of the YRB, therefore, are still uncertain. Here, we quantitatively analyzed the impacts of two significant institutional shifts (the 87-WAS and the 98-UBR) on water uses of the YRB. By linking structures and outcomes within the coupled human and natural system, we further explored mechanisms of institutional effects in the YRB for a deeper understanding of institutions' role in water governance worldwide.

RESULTS

Institutional shifts and structures

Including the national authorities, the basin management authorities, provinces, cities, and even districts, top-down institutional structures of the YRB started to evolve up to now (S1 in Supplementary Material). 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 (known as the "87 Water Allocation Scheme, 87-WAS") and 1998 (Unified Basinal Regulation, 98-UBR) were two widely recognized milestones of water governance. Until the 87-WAS, stakeholders have free access to the YR water resources, with geographic and temporal differences between freshwater demand and availability. As the mismatch between demands and supply kept increasing, national authorities proposed in 87-WAS allocating specific water quotas between 10 provinces (or regions) along the YR basin. However, this controversial scheme helped slight turn water depletion around until a different strategy expanded the responsibilities of basinal authorities in integrated water management in 1998 (the 98-UBR). Ten years later, the YRB authorities require to further divide the provinces' quota into cities, counties, and districts. Therefore, our analysis period spans from 1975 to 2008, with the human-water system shifted between three different institutions, which were different from other large river basins in China.

Because institutions may shape the structure of SESs, describing institutional structure is a first step toward understanding the mechanisms linking structures and outcomes in SESs (Figure ?? A). For example, institutions may create a structure that encourages collaboration between the different actors managing connected ecological components (Figure ?? B), leading to sustainable outcomes. Similarly, institutions for vertical management may enhance multi-layered SES matching by coordinating horizontal relationships (Figure ?? C and D). Empirical studies have suggested that such widespread building blocks in SES are the key to the functioning of structures, and a network model is a widely used way to depict them by abstracting links and nodes. We thus 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 were links between the YRCC and the provinces. Although we abstract the two major institutional shifts from document interpretations, many studies used these two changes as baselines for the YRB's water governance history and widely recognized their importance.

ISs impact on water use of the YRB

Here, we use Differenced Synthetic Control (DSC) method, which considers economic growth and natural background, to estimate theoretical water use scenarios without basinal policy interferences (Methods; S2 in Supplementary Material). Our results suggest that the institutional shift in 1987 (87-WAS) stimulated the provinces to withdraw more water than would have been used without the interference (Figure 2A). From 1988 to 1998, while the estimation of water use only suggests $956.38 km^3$, the observed water use of the YRB provinces reached $1038.36 km^3$ 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 $0.49 km^3$ per year, while the estimation of water use still suggests $1.03 km^3$ 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 environmental crisis of river drying up was effectively resolved after the 98-UBR, though the density of droughts still increased for decades (from 0.47 after 87-WAS to 0.62 after 98-UBR on average) (Figure 2C). In line with previous literature had reported; therefore, the institution shift of 98-UBR contributed a lot to the successful water governance.

Regional differences in responses to the ISs

Differences between stakeholders in responses to institutional shifts are vital to understanding the mechanism between structures and outcomes. Our results show that the proportion of accelerated water use in each province after the decade of 87-WAS (the proportion of actual water use exceeding the predicted water use by the model) has a significant correlation ($p < 0.05$, see Methods) to the Yellow River water use in each province (Figure 3A). Furthermore, while no evident impacts for most provinces (no more than 10% differences, the apparent acceleration effects were only prominent in the big water-using provinces (e.g., Neimeng, Henan, and Shandong. Figure 3B). In particular, Neimeng 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. Furthermore, the satisfaction of each province with the water allocation stipulated by the 87-WAS (expressed by the difference between the actual water allocation of each province and the expected planning value) has little significant correlation to the acceleration. By contrast, after the 98-UBR, except Shaanxi (which has always been abundant in water quota) had an evident (17.53%) increase in water use, almost all provinces have seen significant declines in water use (-12.5% on average). However, neither the satisfaction nor Yellow

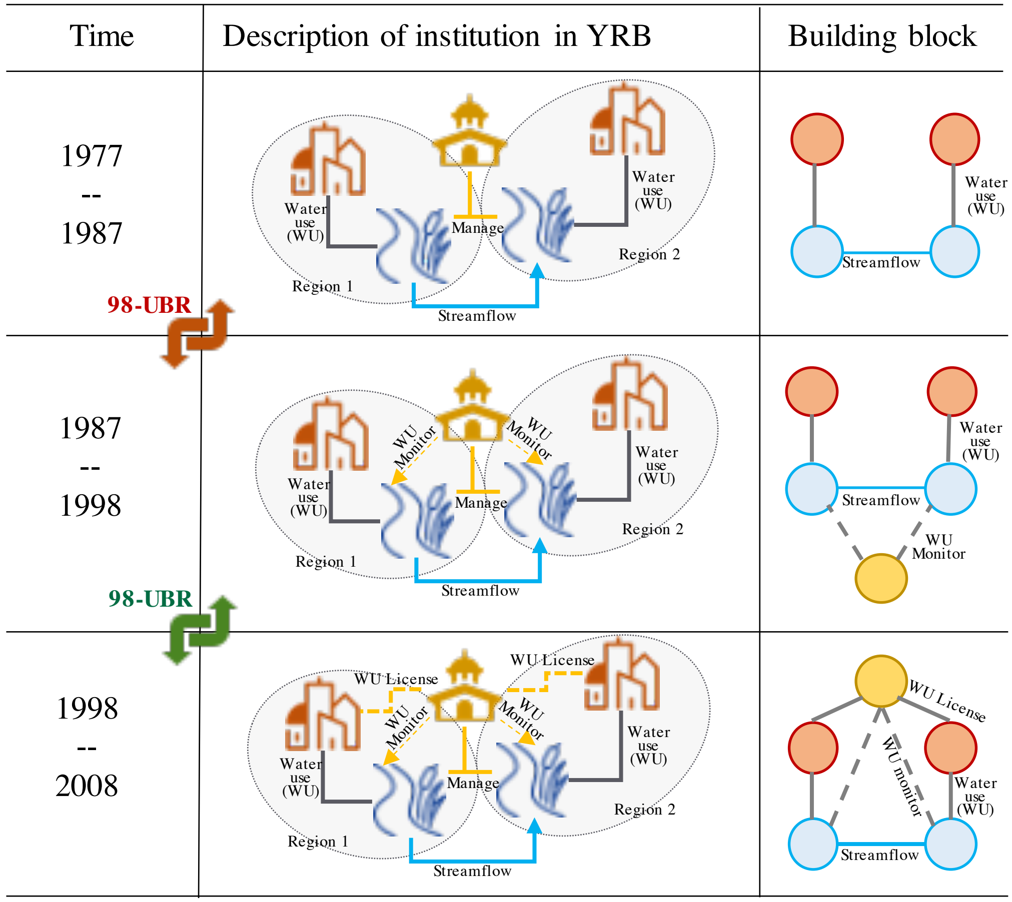

Figure 1. Institutional shifts and related SES structures in the Yellow River Basin (YRB). See Supplementary Material S1 for detailed introduction for the institutions. 1975–1987: Without any constraints, water resources were freely accessible to each stakeholder (the provinces in this case, denoted by red circles) from a one-way but connected ecological unit (the Yellow River, denoted by the blue rectangle). 1987–1998: After the implementation of policy 1 in 1987, each user was assigned a quota to withdraw surface water resources, and the YRCC (yellow triangle) was tasked with reporting on water quota use. 1998–2008: After the implementation of policy 2, stakeholders had to apply for water resources from the YRCC, which then licensed water use according to the quota. Under this institution, the YRCC had direct two-way connections between provinces and ecological components.

River water use correlates with the declines after the 98-UBR.

DISCUSSION

Besides environmental background, our 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). It means the forecast of water use includes the part caused by the increased economic volume, while the outcomes of the economy (GDP in different sectors) of the YRB maintained a parallel trend with other regions during the period (S3 in Supplementary Material Figure ??). Therefore, 87-WAS did not "have little effect" as previous analyses suggested (cites) but led to increased water use because the difference between prediction and observation will be trivial when the shift was just a blank policy by applying the DSC method. Water-use intensity is another crucial factor in interpreting the differences besides the economic factors (e.g., irrigated areas and industrial outcomes) considered and controlled by the method. In addition to the expansion of irrigation area after the 87-WAS, water uses per unit of irrigation area also rapidly widened the gap with the average level of the rest provinces. However, the industry water use intensity hardly changed (S3 in Supplementary Material Figure ??). As a previous report sigh: although the key to alleviating the drought is saving water in the irrigated areas, the tragedy of scrambling for water appeared in provinces and irrigated ar-

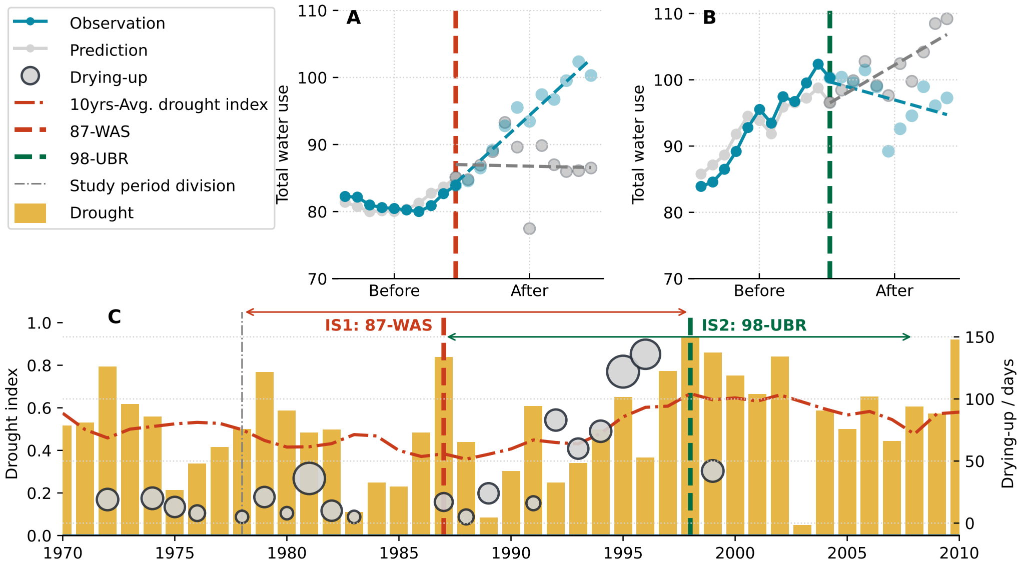

Figure 2. Effects of two institutional shifts on water resources use and allocation in the Yellow River Basin (YRB). A. water uses of the YRB before and after the institutional shift in 1987 (87-WAS); B. water uses of the YRB before and after the institutional shift in 1998 (98-UBR). While the blue lines 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.

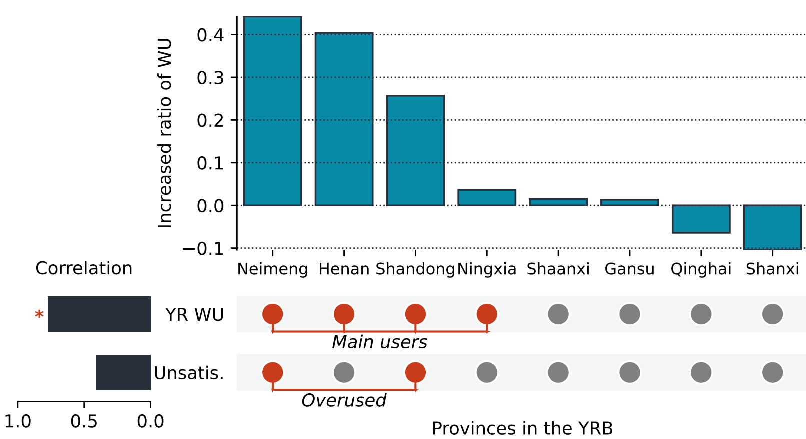

Figure 3. A. The partial correlation coefficient between wate uses (WU) of Yellow River (YR), unsatisfied ratio (compared with requirements in water plan and supply in the 87-WAS), and the average accelerated ratio. B. Average accelerated ratio of water uses for each province in the YRB during the decade after 87-WAS (from 1987 to 1998). Mian users: Major water consumption provinces (over the median). Overused: violate the 87-WAS in average water uses.

eas In terms of the average ratio of water-saving irrigation area (refer to drip or sprinkler irrigation systems and canal lining), although there was a significant increase in the whole country after 1987, the YRB did not rapidly open a noticeable gap until about 1994 (Figure ??). As a result, despite the irrigation area expanding, scrambling for water resources without any incentive to optimize production per unit of water resources accelerated holistic water use. This accelerated water use was contrary to the original intention of the 87-WAS in conserving the limited water, and the failure was a barrier to the sustainability

Previous studies have summarised factors that contribute to the non-ideal effect of 87-WAS: (1) The YRCC had no right to punish the provinces for over-exploitation; (2) the water quotas were annual values, causing provinces to rob water in the dry season; (3) The YRCC can make statistics on water use in the mainstream but cannot on the tributaries, so provinces water use underreport However, the effects of the two institutional shifts (the 87-WAS and the 98-UBR) were significantly different, which the above reasons cannot fully explain. Between the 98-UBR and the further refinement of the unified regulation in 2008, there was still a lack of a temporary water allocation scheme and effective monitoring of tributaries. Moreover, without any actual punishment, provinces with high water consumption (such as Inner Mongolia and Shandong) continued to exceed the quota after 98-UBR. As we have analyzed (Figure 1), the difference between the two institutional shifts is mainly reflected in the structure of linkages between social actors. Until the institutional shift of 98-UBR, with no necessity to apply for a water permit from YRCC, there were no horizontal connections (cooperations or agreements) between the various stakeholders (provinces) directly connected to the ecological units. Make it clear that the YRCC was responsible for regulating provincial water use; that is, each province has made it clear that in the long run, water resources are not "internal" but "dependent" on YRCC. In that way, the YRCC, whose authority scale matches the whole river basin, also took the primary responsibilities to the river, and literature recognized the structure as a social-ecological fit that usually led to good outcomes. 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]. 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 institutional 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 (Figure ??). 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

Agents matching the ecological scale appear widespread as motifs in SES of successful governance, whether in fisheries, forests, or groundwater management, suggesting that reducing independent stakeholders linked to fragmentation is an essential primary mechanism for a structure to produce good results. Since the structures introduced by 87-WAS and 98-UBR are recurring motifs in many SES, our proposed mechanism is crucial to understanding such coupled systems. Furthermore, we explored the causal linkages between the SES structures and sustainability (outcomes) in quasi-natural experiments of the YRB, which provides an informative case study for two main reasons. First, the sharp structural shifts in YRB management enabled us to quantitatively estimate the net effects of changes in high-level institutional design on water use. Institutions that determine water allocation include bottom-up agreements or social norms as well as top-down quotas or regulations, with different effects on SES structure [7,29]; top-down regulations can trigger immediate institutional shifts and sharp SES structural changes [29,30]. In comparison with investigations of more gradual changes induced by bottom-up institutional shifts, exploring the impacts of a top-down change substantially diminishes potential problems of omitted variables in the quantitative analysis of SES and clarifies the causal link between SES structure and outcome. Second, we can better understand the influence of structural alignments under a fixed basin by comparing the net effects of three different institutional structures split by two institutional shifts in the YRB. Although socioeconomic units within a basin benefit from water resources in large river basins all over the world, and many locations have shown increased levels of regulation, few basins have experienced such radical SES structural changes several times (see Supplementary Material S1). Thus, the YRB provides a valuable setting for understanding the direct impacts of changes in the SES institutional structure. Finally, one of the limitations of our method is that it is difficult to rule out the effects of other policies over the same time breakpoints. However, 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 formed by isolated stakeholders is not conducive to institutional solutions; -and then reported how another social-ecological fit structure contributed to successful water governance and sustainability. Moreover, the subsequent success of 98-UBR has proved the importance of institutional scale matching both theoretically and practically. Therefore, it is necessary to emphasize the establishment of potentially connected building blocks between stakeholders by agents consistent with the scale of the ecological system (in this case, the basinal scale and the YRCC). Furthermore, we applied several scenarios based on the marginal benefit model (see Supplementary Material S4) for some further insights into sustainable water governance. For example, water rights transfers can be another way to emerge horizontal links between stakeholders that also have the potential in resulting in better water governance. In addition, the policymakers can also propose a more dynamic and flexible institution by increasing the frequency of quota updates that responds to changing conditions and will adapt more effectively to its SES context.

Calls for a redesign of water allocation institutions in the YRB in recent years also illustrate the importance of dynamic quota setting (see Supplementary Material S1) [31]. Following the institutional reforms of 1998, the Yellow River has not dried up since 1999. However, given recent changes in the YRB, its rigid resource allocation scheme can no longer meet the new demands of economic development [26]. As a result, the Chinese government has embarked on an ambitious plan to redesign its decades-old water allocation institution (see Supplementary Material S1). These initiatives can benefit from our analysis by actively considering and incorporating social-ecological complexity and incentive structures when developing new approaches that avoid unsustainable outcomes. Our research provides a cautionary tale of how institutions can be a double-edged sword in attaining sustainability. Therefore, insights from the YRB can be a valuable guideline for SESs around the world facing similar governance problems [12,32–34].

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) [35]. 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 [36–38]. 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 [39,40]. 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 factor 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:

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

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

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 straight-forward 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 institutions. Focusing on two water-demand institutions, the Water Allocation Scheme since 1987 (87-WAS) and the Unified Basinal Regulation since 1998 (98-UBR), we quantitatively analyzed how and how important the institutional shifts played a role in the water governance achievement of the YRB.

First, by abstracting institutions into building blocks of a social-ecological system (SES), we explored the linkages within the YRB before and after two institutional shifts. Then, we applied Differenced Synthetic Control method to quantify their impacts on water use of the YRB. The observed water use of the YRB provinces had an 8.57% increase than our estimation in the decade after the 87-WAS but significantly decreased by $0.49 km^3$ per year after the 98-UBR (the model still suggests a $1.03 km^3$ annual increases). Finally, by analyzing the differences in stakeholders' responses to the institutional shifts, we found that 87-WAS stimulated water use in provinces with more water uses (e.g., Neimeng, Henan, and Shandong)

98-UBR regulated nearly all provinces.

Since the above results closely align with our mathematical marginal benefits model, we can link the structures (widespread building blocks) and outcomes (goals of the institution, i.e., limiting water demands) by the quasi-natural experiments of the YRB. We demonstrate again that social-ecological fits lead to successful governance, whether in fisheries, forests, or groundwater management; reducing independent stakeholders linked to fragmentation is an essential primary mechanism for a structure to produce good results. Therefore, insights from the YRB can be a valuable guideline for SESs worldwide facing similar water governance problems.

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