Importance of social-ecological fit for water management in large river basins: An analysis of institutional shifts in the Yellow River Basin

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Abstract

Increasing competition for water is challenging management institutions of large river basins around the world. Institutions that successfully support sustainable water resource use are structurally well-aligned with water provisioning and social-ecological demands. However, what constitutes a well-aligned institution in this context is poorly understood. We analyzed institutional shifts in water resource allocation, exploiting two quasi-natural experiments of the Yellow River Basin, China. Using a synthetic control identification strategy, we analyzed an institution that was intended to prevent water overuse but instead resulted in a social-ecological structural mismatch, leading to a 164% increase beyond the expected total water use. We applied a novel economic model that suggested that this "sprint effect" (i.e., rapid competing in resource use) and the resulting ecological crisis were driven by incentive distortions in water allocation bargaining, which in turn, led to each province trying to pre-emptively increase their water quotas for long-term gain. Our analysis highlights the need to carefully evaluate institutional fit in the management of water in large river basins, particularly to avoid the possibility of incentive distortion.

1 Introduction

Emerging competition for water is an urgent problem in water governance, with widespread water scarcity and overuse resulting in huge impacts on economies, societies, and ecosystems [1, 2, 3, 4, 5]. Water is the key exclusive and competitive resource that couples socioeconomic and ecological systems (known as common-pool resources, CPRs) [6, 7, 8, 9]. Conflicts of interest often occur in allocation and competitions of water resources, with water governance policies often leading to long-term changes in human–water relationships and the redistribution of benefits [10, 11, 12]. Although governments in many of the world's large river basins have tried to resolve competition for water through the deliberate design of new institutions, general principles underlying the successes and failures of these initiatives are poorly documented and understood.

Institutions (such as policies, laws, and norms) can influence regional sustainability by changing social-ecological system (SES) structure and dynamics [13, 14, 15]. These include inter-relationships and interactions between social actors, between ecological units, or between social and ecological system elements [16, 17]. Effective ("matched") institutions operate at appropriate spatial, temporal, and functional scales to manage and balance these different relationships and interactions [18, 19]. From the perspective of SES outcomes, matched institutions support (but do not guarantee) sustainability [20, 10].

Some kinds of institutions have been shown to support desirable outcomes in water-centered SESs (e.g., the Ecological Water Diversion Project in Heihe River Basin, China [10] and in collaborative water governance systems in Europe [21]). At the same time, undesired and unsustainable outcomes (e.g., failures in environmental regulation of highly polluting industries or the development of "tragedy of the commons" situations when pursuing more water resources), with considerable ecological degradation, have attracted much attention [22, 23, 8]. Despite widespread recognition of the rising importance of integrated water resource management in solving water competition in the world's large river basins, relatively few studies have explored the mechanisms by which SESs respond to new institutions [24, 25, 26]. Two particular weaknesses in existing knowledge include understanding (1) the causal links between SES structures and outcomes; and (2) details of the underlying processes, especially the coordination of the incentives of different participants, that result from an institutional lack of fit. These weaknesses limit our understanding of institutional design, and they may reduce the speed and transfer of new knowledge and experience related to improving the sustainability of comprehensive water resources management.

In order to disentangle the relationship between SES structure and outcomes, we analyzed a case study to show how an institutional shift led to a structural mismatch that triggered unsustainable water use and unintended ecological deterioration. Two rapid shifts in institutional structure that occurred in 1987 and 1998 (see Supplementary Material S1) provide unique settings to exploit quasi-natural experiments of a large river basin, the Yellow River Basin (YRB) in China [27]. After a period of severe drying up, an institutional shift implemented in 1987 represented the beginning of attempts to control water use in the YRB through the use of quotas, with the goals of alleviating conflicts between supply and demand and achieving sustainable development.

Our results show that this initiative actually accelerated water withdrawals, resulting in an unintended "sprint effect", where institutional mismatches created an even stronger incentive for each resource user to withdraw resources until the next major institutional shift in 1998. Our analysis contributes to a deeper understanding of the mechanisms underlying the relationships among institutions, SES structures, and outcomes. By highlighting potential concerns for ecosystem collapse under structural mismatches, our findings are consistent with the urgent calls for a more dynamic design for water use allocation to achieve sustainability.

2 Institutions and SES structures

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 1A). For example, institutions may create a structure that encourages collaboration between the different actors managing connected ecological components (Figure 1B), leading to sustainable outcomes. Similarly, institutions for vertical management may enhance multi-

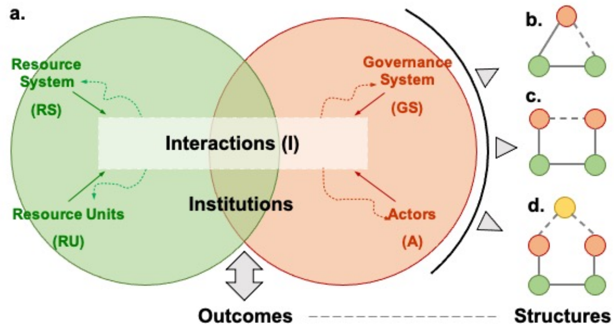

Figure 1: Framework for understanding linkages between SES structures and outcomes. **a.** The general framework for analyzing social-ecological systems (SESs) (adapted from Ostrom [7]). Institutions embedded in SESs may reshape structures by changing the interactions between core subsystems, resulting in different outcomes. Three typical types of abstracted SES structures are shown as **b.**, **c.** and **d.** (adapted from Bodin, 2017)[16]. Red circles indicate social actors, and green ones indicate ecological components. Connection (ties between two ecological components), collaboration (ties between two social actors), or management (ties between a social actor and an ecological component) exist when two units are linked by gray lines. The gray dashed lines show aligned SES structures that are more likely to result in a desirable outcome according to empirical evidence.

layered SES matching by coordinating horizontal relationships (Figure 1C and D). In practice, institutional changes in a large, complex river basin will create or destroy hundreds of different connections. The broader impacts of these local changes can be seen in the overall behavior of the system. We thus 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 [10, 11]; top-down regulations can trigger immediate institutional shifts and sharp SES structural changes [11, 28]. 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 improves the clarity of the causal link between SES structure and outcome. Second, by comparing the net effects of three different institutional structures split by two institutional shifts in the YRB, we can also reach a stronger understanding of the influence of structural alignments under a fixed basin. 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 SES institutional structure.

3 Context of institutional shifts

The Yellow River, whose basin is the cradle of Chinese civilization, is the fifth-longest river in the world. It supports 9.7% of China's irrigation, with only 2.6% of its total water resources (data from http://www.yrcc.gov.cn, last access: 28 February 2021). However, after years of free access to water by provinces along the river (Figure 2 A and B), surface water consumption of the Yellow River was close to 80% of its runoff by the 1980s and rising [29, 30]. Reductions in runoff after 1972 damaged the ecology of the YRB and restricted its economic development [29]. Therefore, through typical top-down institutional structures in China (see *Supplementary Material S1*), relatively integrated water allocation regulations were successively proposed across different levels in the YRB. These include the national government, the basin management agency, provinces, cities, and even districts. These policies at different stages of institutional development triggered abrupt changes in the SES structure of the YRB with different outcomes.

In 1982, the Chinese government issued instructions to the Yellow River Water Conservancy Commission (YRCC), the basin agency of the YRB, requiring it to design a water allocation scheme and at the same time requiring the provinces along the Yellow River to carry out water resources planning (see *Supplementary Material S1*) [31]. The Chinese government started to assign water quotas to the relevant provinces in 1987, but did not create a unit to coordinate water division between them (Figure 2 **A** and **C**). The mandate of the YRCC during this period was only to report on and analyze water consumption in the YRB [31]. However, since reductions in river flow indicated an unintended SES outcome (Figure 2 E), the Chinese government pushed for a policy reform in 1998 that required all provinces to apply for licenses to use water from the YRCC, allowing the council to directly regulate their water use (see *Supplementary Material S1* and Figure 2 A and D). The 1998 policy succeeded in curbing water extraction (Figure 2 E), and it was further refined in 2008. The relevant provinces created a more detailed allocation plan and finally formed the present water allocation institutions of the YRB (see *Supplementary Material S1*). Therefore, in our study period (from 1975 to 2008), the system shifted between three different SES structures (Figure 2 **B** to **D**). The sharp and unintended decline in the ecological condition of the Yellow River from 1987 to 1998 indicates an institutional mismatch during this period (Figure 2 the shadowed time periods).

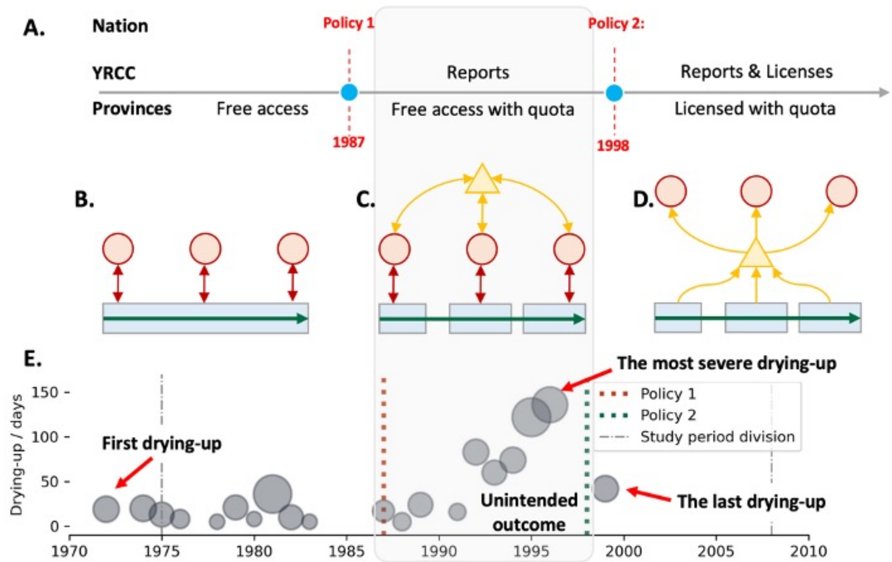

Figure 2: Institutional shifts and related SES structures in the Yellow River Basin (YRB). See *Supplementary Material S1* for detailed introduction for the institutions. **A.** The national government changed YRB management policies and institutions in 1987 and 1998. As a result, the Yellow River Conservancy Commission (YRCC) and the provinces acted differently in different periods. Three different SES structures existed successively in the YRB. **B.** 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). **C.** 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. **D.** 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. **E.** A timeline of the Yellow River and drying conditions. The size of the circles indicates the length of section that dried up (km), and the y-axis indicates the length of the drying period. Both policy 1 and policy 2 were put forward to solve this ecological crisis. The mismatch created by policy 1 is clearly correlated with the unintended outcomes shown in the second (gray-shaded) period.

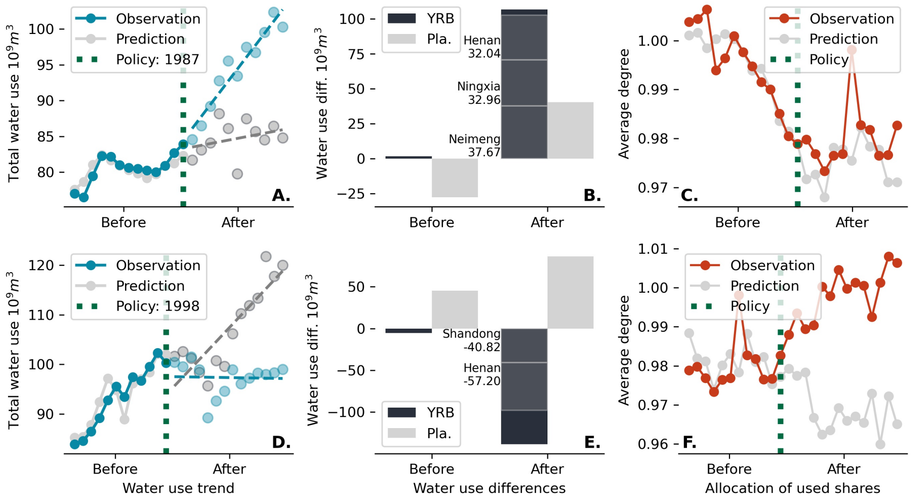

Figure 3: Effects of two institutional shifts on water resources use and allocation in the Yellow River Basin (YRB). (**A** to **C**: Entering the mismatched SES structure in 1987; **D** to **E**: exiting the mismatch in 1998. **A** and **D**: Impact of the first institutional shift on water use trends in the YRB. Blue points are actual water use, and gray points are predicted use under a scenario without any institutional shift (see *Methods*). **B** and **E**: Impact of the institutional shift on total water use. Dark bars indicate the difference between the actual and predicted water use in specific study periods. Gray bars are the expected water use, simulated by setting up placebo experiments (null models, see *Methods*). **C** and **F**: Impact of institutional shift on water allocation equity (see *Methods*). Red lines indicate the index calculated from actual water use data; gray lines indicate predicted water use under a scenario with unconstrained water use.

4 Sprint effect induced by an institutional mismatch

Our results suggest that the institutional shift in 1987 stimulated the provinces to use far more water than would have been used without policy effects (Figure 3A), with an observed increase of 164% over the expectation(Figure 3B). However, the relative share of water use was not changed, denoting proportionally similar water use increases among the different regions (Figure 3C). After the SES structure changed again in 1998, the trend of increasing water use appeared to be effectively suppressed (Figure 3 D), with total observed water consumption decreasing by 260% relative to expectations(Figure 3 E). At this stage, however, the reduction in water use came mainly from the provinces with large water consumption, such as Henan and Shandong (Figure 3 E), so the proportion of water used by regions became more similar (Figure 3 F). In conclusion, the water allocation policy curbed water use in 1998, whereas the 1987–1998 institutional mismatch stimulated a notable increase in total water use in all related provinces. Over this decade, “sprint” responses (i.e., rapid increases in resource use [32]) to institutional change appear to have created a race in which each province began to use more water than they needed.

5 Incentive distortion causes the sprint effect

Theoretically, our economic model suggests that different kinds of institutional shifts should lead to different optimal water uses (Figure 4). Furthermore, our analysis indicated that the cause of the sprint effect in this case was incentive distortion. Compared with the decentralized water allocation institution in place before 1987, the presence of central management (by the YRCC in this case, after 1998) can effectively reduce marginal ecological costs (see Table 1 the **methods** for a detailed mathematical formula). The unintended sprint effect (from 1987 to 1998) was caused by both declining marginal costs (a shift from a fixed unit cost to an irrelevant cost) and increasing marginal returns due to future water use benefits (see Table 1 the **methods** for a detailed mathematical formula). The institution thus triggered an incentive distortion that ran counter to the intention of sustainable water use. Further, the strength of the sprint effect was positively correlated with the size and time horizon of the water use quota (Figure 4 **Panel B**).

Table 1: Summary of marginal returns and marginal costs for each case

	Case 1: Decentralized Ins.	Case 2: Mismatched Ins.	Case 3: Matched Ins.
Marginal return	$P * F'(X)$	$P * F'(X) + V(X)^*$	$P * F'(X)$
Marginal cost	C/N	$Irrelevant$	C

*Note: $V(X)$ denotes a shadow value.

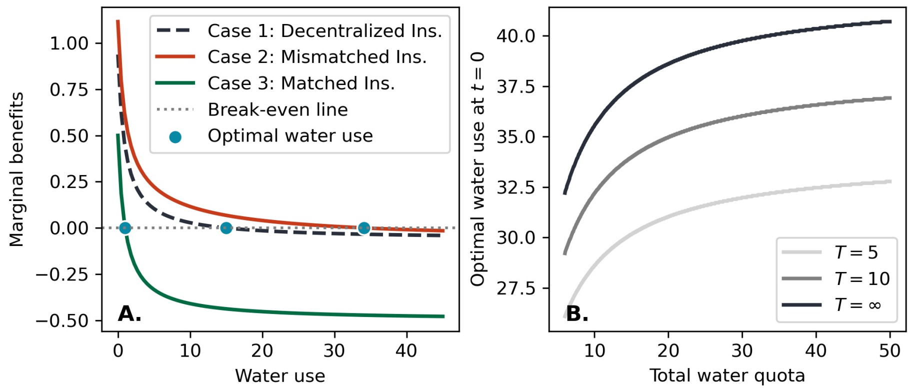

Figure 4: **A.** The relationship of marginal benefits and water use of province i at t = 0 for three different cases (case 1 to case 3, corresponding to the different SES structures in Figure 2, assuming $F(x) = ln(1 + x)$, $N = 8$, $P = 1$, $C = 0.5$, and $\beta = 0.4$ as an example (see *Methods*In Case 3, water use by others is taken as a given, equal to the optimal water use for Case 2. The horizontal coordinate of each intersection of marginal benefits and the break-even line represents the optimal water use under each case. **Panel B.** The relation between optimal water use of province i and total quota for Case 3, under time horizon of $T = 5$, $T = 10$, and an infinite T, respectively. The settings are the same as in **A**.

6 Discussion

We have shown how a mismatched allocation institution can lead to an accelerated depletion of water resources (i.e., the “sprint effect”) caused by incentive distortion. The sprint effect is a special case faced by CPR systems, where institutional mismatches create an even stronger incentive (with distortion) for each resource user to withdraw resources [33, 7, 8]. Previous studies have suggested that institutions are often the key to avoid the collapse of a CPR system, but the emergence of a sprint effect shows that an institution with structural mismatches can also be the trigger that accelerates system collapse [34, 16, 10]. The initial formulation of the water quota in our case studies went through a stage of “bargaining” among stakeholders (from 1982 to 1987) [31, 35], where each province attempted to demonstrate its development potential related to water use. In water use allocation with information asymmetry between upper-level decision-makers and lower-level stakeholders, those with more current water use might have greater bargaining power. After 1987, the logical next step for provinces was to attempt to justify bargaining for larger quotas rather than immediately adopt resource-conserving transformations. In practice, although the affected provinces may not have directly encouraged excessive resource use, they had a greater incentive to give the green light to resource withdrawals because of incentive distortions [36, 37]. As a result, while competing for potential water quotas, the provinces tended to hide the ecological costs behind economic development.

There is no doubt that with increasingly fierce competition for water, more and more SESs are developing new institutions for water allocation (whether through self-organization or government intervention) [38, 6]. Adoption of an overall quota plays an important role in preventing overuse of CPRs [39]. However, the negative effects of incentive distortion imply a trade-off between long-term SES benefits and current stability, and the proportion of available resources allocated under quota schemes matters when institutions change [40]. According to our analysis of plausible scenario assumptions based on our general economic model, the sprint effect will be reinforced when stakeholders anticipate that technological advances will amplify the benefits of water quotas in the future (see *Supplementary Material S3*). However, if an institution allowed stakeholders to compensate for the shadow value (i.e., potential returns sacrificed due to water constraints and water scarcity) [41] of future water use, incentive distortion would be less devastating (e.g., through water rights transfer). Policymakers can also weaken the sprint effect by increasing the frequency of quota updates, supporting the idea that a more dynamic institution that responds to changing conditions (see *Supplementary Material S3*) will adapt more effectively to its social-ecological 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*) [42]. 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 [35]. The Chinese government has embarked on an ambitious plan to redesign its decades-old water allocation institution (see *Supplementary Material S1*). Other SESs around the world face similar problems in establishing successful resource allocation institutions [43, 44, 14, 45]. 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 act as a double-edged sword when trying to attain sustainability.

7 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. In addition, as a robustness test, we conducted a matched placebo test (creating a "null model") to exclude the effects of other factors that were contemporaneous with the 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*.

7.1 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) [46]. 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 two features of water use in the YRB: total water use and diversification of water allocation. 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* To measure resource allocation diversification between the upper, middle, and lower reaches, we used "entropy" as a simple index,

$$Index_{entropy} = \sum_{i} p_i * log(p_i)$$

Where p_i is the proportion of water uses for region i to the total water uses in the basin. A larger index value indicates the proportion of water resources actually used is closer to the average among the upper, middle, and lower reaches.

7.2 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 [47]. 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 [48, 49]. 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 [50, 51]. 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.

7.3 Placebo Test

For robustness, we conducted a placebo test because the synthetic control method neglects the influences of overall changes in factors in the same year by simply dividing time periods according to institutional shifts. Three steps were required to apply the placebo test: (1) For each province in the target group, we calculated the Euclidean distance of vectors between all provinces in the potential control group. (2) After ranking the distances, the three provinces with the most similar economic context were used to generate an average paired treatment target unit. (3) We performed the same synthetic control analysis for this paired target (i.e., the potential control group excluding the three provinces in step 2). In this way, we theoretically constructed a pseudo-treated unit and performed the same synthetic control treatments. Because these placebo tests were directed at units unaffected by the institutional shifts, the results can be regarded as a reasonable baseline expectation or null model from which to assess the changes caused by other factors.

7.4 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 2 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.,* $1987 \sim 1998$, *see Figure 2 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., $1998 \sim 2008$, *see Figure 2 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 [52], because of the common-pool characteristics of water [9, 7].

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*.

8 Info.

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[Competing Interests] The authors declare that they have no competing interests.

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[Author contributions]Shuai Wang and Bojie Fu designed this research, Shuang Song performed the research and analyzed data, and Huiyu Wen designed the economic model. Shuang Song and Huiyu Wen wrote the paper, and Graeme S. Cumming revised the manuscript and offered important advice.

[Code availability] All codes and datasets used in this research are accessible at https://github.com/SongshGeo/sochyd-transboundary-HESS. They will be made open source after this project is completed.

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