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Institutional shifts and water sustainability of 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.

Keywords: water use, water management, social-ecological system, common pool resources, institutional analysis, collaborative governance

INTRODUCTION

Widespread freshwater scarcity and overuse, resulting in systematic risks on economies, societies, and ecosystems globally, are critical environmental challenges to sustainable development [1–4]. With steadily increasing demand, competition for water is an urgent problem in water governance, where policies often lead to long-term changes in human–water relationships and the redistribution of benefits [5–7]. Despite governments worldwide trying to resolve competition for water through deliberate institutions at large river basins, cascading effects of these initiatives are poorly understood [8–10].

Institutions (such as policies, laws, and norms) can influence regional sustainability by changing the structure of the coupled system, including interplays between social actors, between 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) [?]. Effective ("matched") institutions operate at appropriate spatial, temporal, and functional scales to manage and balance these different relationships and interactions, therefore, supporting (but do not guarantee) sustainability of SES [7,15]. Water governance tends to shift for institutional solutions within a complex basinal system, where societal drivers impact through water use and related technical interventions [?]. Some institutional shifts were reported to have desirable water governance outcomes (e.g., the Ecological Water Diversion Project in Heihe River Basin, China [7] and in collaborative water governance systems in Europe [16]). However, shifting institutions in a large, complex river basin may create or destroy hundreds of different connections, where matched human-water relationships are not universal. Therefore, despite widespread recognition of the rising importance of institutions as an approach to water sustainable use within large river (especially transboundary river) basins, broader cascading effects of these changes are still in open discussion [17–19].

Supporting 35.63% irrigation and *xx*% population with only 2.66% of water resources in China (data from http://www.yrcc.gov.cn, last access: 28 February 2021), the overburdened Yellow River (YR) once dried up in consecutive years but successfully recovered through an institutional solution since 1998. Before the remarkable achievement in the restoration of river depletion, on the contrary, the first temptation to restrict water uses in the YR in 1987 (known as the “87 Water Allocation Scheme, 87-WAS”) was recognized as a not fulfilling expectations institutional shift. Until the 87-WAS, stakeholders have free access to the YR water resources, with geographic and temporal differences between freshwater demand and availability. As mismatch between demands and supply kept increasing, national authorities proposed in 87-WAS allocating certain water quota between 10 provinces (or regions) along the YR basin. However, this controversial scheme helped little in turn water depletion around until a different strategy (Unified Basinal Regulation, 98-UBR) expanded responsibilities of basinal authorities in integrated water management, 1998, and started progress in the restoration.

The shifts of the water governance institution of YR refactored the interplays between humans and water with long-term cascading effects, leaving two quasi-natural experiments for understanding the interactions. By Differenced Synthetic Control method, our analysis on net effects of institutional shift shows that institutional mismatches contributed to acceleration water withdrawals for resource users after 98-WAS. As few large river basins have experienced such radical structural changes several times, our quantitative analysis of institutional shifts in the YR induces a valuable understanding of water sustainable governance by decoupling natural and human interferences. By highlighting potential concerns for ecosystem collapse under structural mismatches, our findings align with the urgent calls for a more dynamic design for water governance institutions to achieve sustainability.

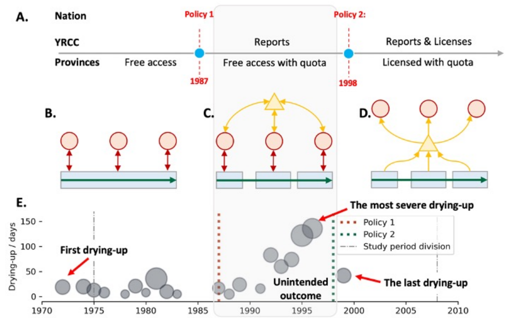

Figure 1. Institutional shifts and related SES structures in the Yellow River Basin (YRB). See Supplementary Material S1 for detailed introduction for the institutions. A. The national government changed YRB management policies and institutions in 1987 and 1998. As a result, the Yellow River Conservancy 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.

RESULTS AND DISCUSSION

Cascading effects of the institutional shifts

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, then found a successful solution of dring-up in 1998, and promoted completely since

2008. Throughout, the institutional shifts in 1987 (87-WAS) and 1998 (98-UBR) were two widely recognized milestones of water governance (Figure 1 and S1 in Supplementary Material). Our analysis period, therefore, spans from 1975 to 2008, with the human-water system shifted between three different institutional structures (Figure 1).

Here, we use Differenced Synthetic Control method, which considers economic growth and natural background, to estimate theoretical water uses scenarios without these 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). However, after the institution shifted again in 1998 (98-UBR), the trend of increasing water use appeared to be effectively suppressed, with total observed water consumption decreasing by 260% relative to the estimation (Figure 2 B). The increased water uses after 87-WAS align 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, although the density of droughts increased in the decade after the 98-UBR, the environmental crisis of river drying-up was effectively resolved (Figure 2C). As literature has suggested, this institution shift contributed a lot to the successful water governance.

Furthermore, 87-WAS did not “have no effect” as previous analyses suggested because water uses will be closer to what our models predicted when the shift was a blank policy. Besides environmental background, our forecast takes economic factors into account under the assumptions that the production function between economic volume and water uses remained unchanged (S2 in Supplementary Material). However, the production efficiency of unit water resources kept similar trends between provinces of the YRB and others (Figure S3 in Supplementary Material), which means that the accelerated growth of basinal water uses was not the inevitable result of economic growth. However, our results suggest that water use (especially for irrigation) in the YRB was more likely to be partly stimulated by the shift in 1987 besides economic growth. This accelerated growth in water use was contrary to the original intention of the 87-WAS in conserving the limited water.

The cascading effects of the two institutional shifts were very different, while their reframed SES structures have direct differences. In our study period, the institution shifted between three different structures (XXX, XXX, and XXX) (Figure 1). However, the YRCC, whose primary official response to the river before 1998, the mandate was to conserve the riverway environment, construct and maintain infrastructures, and report on and analyze water consumption (after the 87-WAS) in the YRB, i.e., connecting the ecological nodes (different river reaches) horizontally [?]. Thus, 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 sections. Empirical studies in many different fields indicate that this structure is likely to be mismatched, as isolated stakeholders struggle with holistically maintaining interconnected ecosystems [?,?,?,?]. The cascading effect of the 87-WAS once again demonstrates that the more stakeholders, the more difficult it is to have a win-win situation of environment and interests [?] which calls for exceptional understanding and caution to the structure of hampering sustainability [?,?].

Mechanism of institutional shift effects

Next, we explored the mechanisms linking the structures and the outcomes. Differences in provincial responses to 87-WAS are vital to understanding the mechanism of institutional shifts’ impacts. Our results show that the proportion of accelerated water consumption in each province (the proportion of actual water consumption exceeding the predicted water consumption by the model) has a significant correlation to the Yellow River water consumption in each province (Figure 3A). However, the apparent acceleration effect of the 87-WAS was only prominent in the significant water-using provinces (Neimeng, Henan, and Shandong), and there were no evident impacts for most provinces (Figure 3B). In particular, Shandong and Inner Mongolia, both of which exceed the prescribed water uses of the 87-WAS, used xx% and XX% more water uses than predicted by

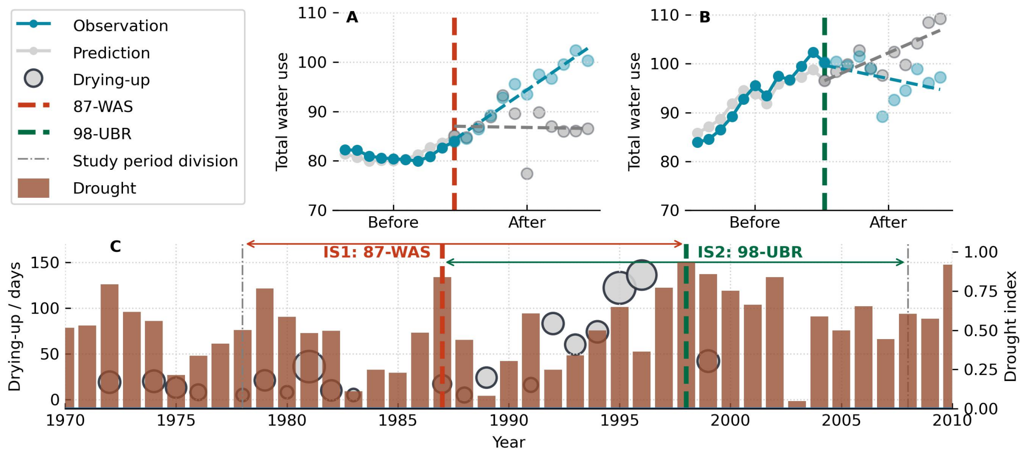

Figure 2. Effects of two institutional shifts on water resources use and allocation in the Yellow River Basin (YRB). A. water uses of the YRB before and after the institutional shift in 1987 (87-WAS); B. water uses of the YRB before and after the institutional shift in 1998 (98-UBR). While the blue lines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

the model from 1987 to 1998, respectively.

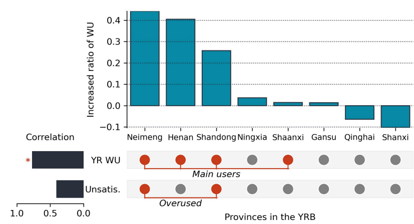

Figure 3. A. The partial correlation coefficient between wate uses (WU) of Yellow River (YR), unsatisfied ratio (compared with requirements in water plan and supply in the 87-WAS), and the average accelerated ratio. B. Average accelerated ratio of water uses for each province in the YRB during the decade 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.

Then, we analyzed mathematically why the mismatched structure made win-wins elusive in the institution shift of 87-WAS (method and Supplementary Material S4). Theoretically, our model suggests that different kinds of institutional shifts should lead to different optimal water uses (Figure ??). The unintended accelerations 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 (Supplementary Material S4). For users who are already economically efficient, the "sprint effect" of extracting resources for future economic growth is is induced by greater marginal returns. The institution (87-WAS) thus triggered an incentive distortion that ran counter to the intention of sustainable water use. On the contrary, the presence of central management (by the YRCC in this case, after 1998) can effectively reduce marginal ecological costs (Supplementary Material S4).

Linking structures to outcomes are in need of advancement when understanding a SES. Here, we have shown how a mismatched structure induced by institutional shift can lead to accelerated depletion of water resources (i.e., the "sprint effect") caused by incentive distortion. The "sprint effect" is a particular case faced by CPR systems, where institutional mismatches create an even stronger incentive (with distortion) for each resource user to withdraw resources [?,?,?]. Previous studies have suggested that institutions are often the key to avoiding 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 [?,?,?]. The initial formulation of the water quota in our case studies went through a stage of "bargaining" among stakeholders (from 1982 to 1987) [?,?], where each province attempted to demonstrate its development potential related to water use. 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. 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 [?,?]. 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) [?, ?]. Adoption of an overall quota plays a vital role in preventing overuse of CPRs [?]. However, the adverse 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 [?]. 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).

Novel insights and policy implications

However, if an institution allowed stakeholders to compensate for the shadow value (i.e., potential returns sacrificed due to water constraints and water scarcity) [?] 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.

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). 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 [?,?]; top-down regulations can trigger immediate institutional shifts, and sharp SES structural changes [?,?]. 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 better understand 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.

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) [?]. 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 [?]. 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 [?,?,?,?]. 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.

MATERIALS AND METHODS

Detailed methods are given inthe online supplementary material.

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.

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) [?]. 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.

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 [?]. 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 [?,?]. 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.

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.

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:

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

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

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 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

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REFERENCES

1. Distefano T and Kelly S. Are we in deep water? Water scarcity and its limits to economic growth ; 142: 130–147.
2. Dolan F, Lamontagne J, Link R et al. Evaluating the economic impact of water scarcity in a changing world ; 12: 1915.
3. Xu Z, Chau SN, Chen X et al. Assessing progress towards sustainable development over space and time ; 577: 74–78.

4. Mekonnen MM and Hoekstra AY. Four billion people facing severe water scarcity ; 2: e1500323.
5. Gleick PH and Palaniappan M. Peak water limits to freshwater withdrawal and use ; 107: 11155–11162.
6. Ziolkowska JR and Peterson JM. Competition for Water Resources: Experiences and Management Approaches in the US and Europe (Elsevier).
7. Wang S, Fu B, Bodin O et al. Alignment of social and ecological structures increased the ability of river management ; 64: 1318–1324.
8. Giuliani M and Castelletti A. Assessing the value of cooperation and information exchange in large water resources systems by agent-based optimization ; 49: 3912–3926.
9. Falkenmark M, Wang-Erlandsson L and Rockström J. Understanding of water resilience in the Anthropocene ; 2: 100009.
10. Jaeger WK, Amos A, Conklin DR et al. Scope and limitations of drought management within complex human-natural systems ; 2: 710–717.
11. Young OR, King LA and Schroeder H, editors. Institutions and Environmental Change: Principal Findings, Applications, and Research Frontiers (MIT Press).
12. Cumming GS, Epstein G, Anderies JM et al. Advancing understanding of natural resource governance: A post-Ostrom research agenda ; 44: 26–34.
13. Lien AM. The institutional grammar tool in policy analysis and applications to resilience and robustness research ; 44: 1–5.
14. Bodin . Collaborative environmental governance: Achieving collective action in social-ecological systems ; 357: eaan1114.
15. Epstein G, Pittman J, Alexander SM et al. Institutional fit and the sustainability of social–ecological systems ; 14: 34–40.
16. Green O, Garmestani A, van Rijswick H et al. EU Water Governance: Striking the Right Balance between Regulatory Flexibility and Enforcement? ; 18.
17. Agrawal A. Sustainable Governance of Common-Pool Resources: Context, Methods, and Politics ; 32: 243–262.
18. Persha L, Agrawal A and Chhatre A. Social and Ecological Synergy: Local Rulemaking, Forest Livelihoods, and Biodiversity Conservation ; .
19. Agrawal A. Common Property Institutions and Sustainable Governance of Resources ; 29: 1649–1672.