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Institutional shifts and sustainable water use of the Yellow River Basin

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ABSTRACT

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

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

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INTRODUCTION

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

The Yellow River Basin (YRB), the fifth large river worldwide, is known for its irreplaceable role in the social-economic development of China, and thus also drastically interference by anthropogenic stress. Supporting 35.63% irrigation and 30% population with only 2.66% water resources of China (data from http://www.yrcc.gov.cn, last access: May 20, 2022), the overburdened Yellow River dried up in consecutive years, resulting in substantial ecological, economic and social crisis (e.g., wetland shrink, agriculture reduction, and scramble for water). Intense water use, accounting for about 80% of Yellow River surface runoff in the 1980s, was remarked as the significant reason for the degradation. Furthermore, human interferences such as soil conservation and water conservancy project boosted water withdrawal and then stressed the water scarcity of the Yellow River. In the context of future climate change, the contradiction between supplies and demands of water resources in the YRB will become more prominent. Therefore, balancing ecological and developing demands in such a human-dominated basin is a problem for China in terms of water governance throughout and for large rivers worldwide.

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

In addition to widespread recognition of the rising importance of institutions as an approach to water sustainable use within large river basins (especially transboundary rivers like the YRB), their specific effects are still in open discussion [16–18]. Effective ("matched" or "fit") institutions operate at appropriate spatial, temporal, and functional scales to manage and balance different relationships and interactions between human and water systems, therefore, supporting (but do not guarantee) sustainability of SES [7,19]. Some institutional shifts have desirable water governance outcomes (e.g., the Ecological Water Diversion Project in Heihe River Basin, China [7] and collaborative water governance systems in Europe [20]). However, shifting institutions in a large, complex river basin may create or destroy hundreds of different connections between social agents and ecological units, where matched social-ecological structures are not ubiquitous. Therefore, the role of institutional shifts in the water governance achievement of the YRB and their impacts on water use is still uncertain without an understanding of SES structures. Here, by abstracting changes in official documents following institutional shifts (the 87-WAS and the 98-UBR), we depicted the SES structures of the YRB from 1979 to 2008. Then, we use Differenced Synthetic Control (DSC) method, which considers economic growth and natural background, to estimate theoretical water use scenarios without the institutional shifts (*Methods* and *Appendix S2: Methods in details*). By further interpreting the differences of the effects in the YRB, we explored the mechanisms linking SESs structure and outcomes for a deeper understanding of institutions' role in water governance worldwide.

RESULTS

Institutional shifts and structures

The institutional shifts in 1987 (87-WAS) and 1998 (98-UBR) were two widely recognized milestones in restricting water use among national water governance practices (*Appendix* S1: Contexts of institutional shifts). Until the 87-WAS, stakeholders (the provinces in the YRB) had free access to the YR water resources for development, but there were geographic and temporal differences between freshwater demand and availability. As a compounded result of development, the provinces such as Shandong, Henan and Inner Mongolia used more water resources in the YRB with larger economies (primarily for irrigation agriculture). For shrinking water deficits, national authorities proposed in 87-WAS allocating specific water quotas between 10 provinces (or regions) along the YR basin. However, the controversial scheme helped little in turning the water depletion around until another strategy attempted to strengthen the responsibilities of the YRCC in integrated water management in 1998 (the 98-UBR). Therefore, our analysis period spans from 1979 (emergence of river depletion) to 2008 (a further polish of the 98-UBR), with the SESs shifted between three varying institutions (Figure 1).

We selected institutional regulatory documents on water use issued by national ministries (for validation to both watershed and regional agents) and extracted the interactions between the agents involved (*Appendix S1: Contexts of institutional shifts*). Before 1987, the YRCC had no links to the provinces regarding water use, and the provinces could link to the Yellow River reaches directly (Figure 1). However, according to the extracted information from the 87-WAS, the YRCC started to report water use from the provinces. Furthermore, information from the 98-UBR documents demonstrated that the provinces had to apply their plan for an annual water use licence instead of direct access to the Yellow River water. Thus, there have been links between the YRCC and the provinces since the strengthening responsibilities of the YRCC in 1998.

Institutional shifts impact on water use

Our estimation of theoretical water use suggests that the institutional shift in 1987 (87-WAS) stimulated the provinces to withdraw more water than would have been used without an institutional shift (Figure 2A). From 1988 to 1998, on average, while the estimation of annual water use only suggests 974.34 billion m^3, the observed water use of the YRB provinces reached 1038.36 billion m^3 in sum, 6.57% 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 billion m^3/yr per year, while the estimation of water use still suggests 0.82 billion m^3/yr increases (Figure 2 B). The increased water uses after 87-WAS aligns with the fact that badly drying-up of the surface streamflow from 1987 to 1998, which was an obvious touchstone of river degradation and environmental crisis (Figure 2C). On the other hand, the 98-UBR ended river depletion, despite the intensity of droughts still increasing for decades (from 0.47 after 87-WAS to 0.62 after 98-UBR on average) (Figure 2C).

Institutional effects on regulating differences

Our results also suggest differences between patterns of provinces in their responses to the two institutional regulating. During the decade after the 87-WAS, the major water-using provinces (e.g., Inner Mongolia, Henan, Shandong) had apparent accelerations (Figure 3). The proportion of increased (or decreased) water use for each province (over the estimated water use by the model) has a significant correlation (partial correlation coefficient is 0.77, $p < 0.05$) to the actual water use from the Yellow River. On everage, the major water users (Shandong, Inner Mongolia, Henan and Ningxia) used 32.14% more water uses than the prediction from 1987 to 1998. By contrast, after the 98-UBR (from 1998 to 2008), almost all provinces have seen evident (-16.54% on average) declines in water use. The only exception is Inner Mongolia, whose water use throughout still exceeded the quota, but also considerably slowdown (74.39% decreased than the decade after 87-WAS) its rising. Furthermore, the regulated water use of provinces was irrelevant (partial correlation coefficient is 0.33, $p > 0.1$) with their water use from the Yellow River in proportions.

DISCUSSION

In addition to quantitatively demonstrating the regulatory effect of 98-UBR by previous studies, our study also found that 87-WAS would increase overall water use of the YRB. The results challenged the previous analyses (who suggested that the 87-WAS "has little effect") because the difference between prediction and observation will be trivial when the institutional shift was just a blank policy by applying the DSC method [21,22]. Fixing the environmental background, the forecast by DSC takes economic factors into account under the assumptions that the production function between economic volume and water uses remained unchanged (**methods** and *Appendix S2: Methods in details*). After 87-WAS, the growth of economic volume (both in agriculture, industry and services) in the YRB broke the parallel trend with other regions since 1979 (*Appendix S3* Figure 6), though domestics water and environmental context remained their trends. Furthermore, construction of water-saving facilities (especially in agriculture) after the 87-WAS may contribute to the water use changing per unit of production (*Appendix S2: Methods in details* Figure 6). These facts of saving water and speeding up water use simultaneously, are in line with the sigh from then: the tragedy of frequently scrambling for water appeared in some provinces [23]. Since the 98-UBR improved tragedy of water competition greatly by water licences, therefore, many studies attributed the restoration from river depletion mainly to the successful institutional shift [24–26].

Although previous studies summarised reasons for the non-ideal effect of 87-WAS [25], few chanegs of those aspects in the 98-UBR indicate that influences from the structural changes were underestimated. As we have depicted in Figure 1, the institutional shifts twice framed the structure of SESs in the YRB and led to different building blocks, which were also reported in various types of SESs worldwide [15,27,28]. The empirical studies in many different fields also indicate that the structure before 98-UBR (i.e., fragment ecological units are linked to separate social actors) is likely to be mismatched as isolated actors struggle with holistically maintain-

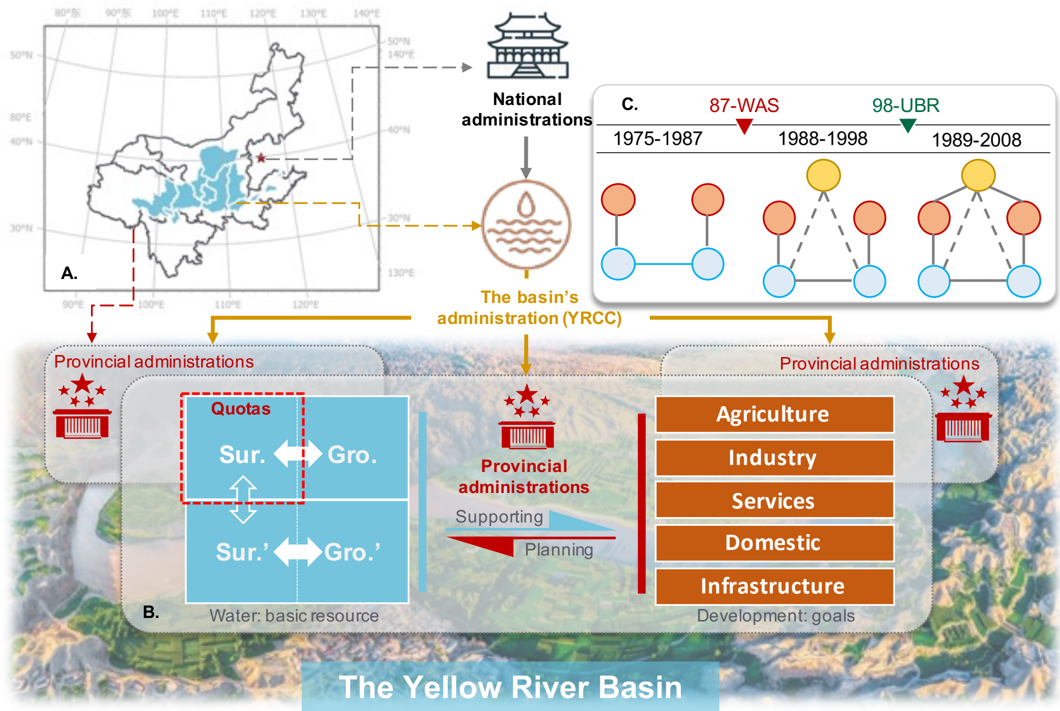

Figure 1. Institutional shifts and related SES structures in the Yellow River Basin (YRB). **A.** The YBR crosses 10 provinces or the same-level administrative regions, 8 of which are highly relying on the water resources from the YRB (see *Appendix S1: Contexts of institutional shifts* Table 1). The national administrations are the ultimate authority in issuing water governance policies, which are often implemented by basin-level agency (the Yellow River Conservancy Commission, YRCC) and each province-level agency. **B.** Since the YRCC does not use but monitor water, the provincial administrative agencies are the major stakeholders. Since the 87-WAS, with surface water withdraw from the Yellow River restricted by specific quotas, each stakeholder seperatly develop by planning and using fundamental water resources. However, the natural hydrological processes are connected. Although the institutions focus mainly on the surface water (Sur.), it can also influence groundwater inside (Gro.) or water resources outside (Sur. and Gro.'), through systematic socio-hydrological processes within the YRB. **C.** Institutional shifts and following structures changes (details in *Appendix S1: Contexts of institutional shifts*). (1) From 1979 to 1987, water resources were freely accessible to each stakeholder (denoted by red circles) from connected ecological unit (the reach of Yellow River, denoted by the blue circles). (2) After 1987-WAS, the YRCC (the yellow circles) was monitoring (the dot-line links) river reaches with the water use quota. (3) Since the 98-UBR, stakeholders have to apply water use licences from the YRCC (the connections between the red and yellow circles).

ing interconnected ecosystems [29–32]. On the contrary, the YRCC, whose authority matched the YRB in scale after the 98-UBR, led to a well-recognized structure for institutional alignments to social-ecological fit and good outcomes. The effect of the institutional shifts once again demonstrated that it is not easy to have a win-win situation of environment and interests in complex coupled human-nature systems [33] which calls for exceptional understanding and caution to the structure of hampering sustainability [30,32].

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 (see REFERENCESsec:model Figure 4). 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 case (detailed derivation in *Appendix S3: Optimization model for water use*). 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 (Figure 4 A). Before the 98-UBR, the separated ecological units (river reaches) link to stakeholders (related provinces) who use water to pursue their benefits. 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

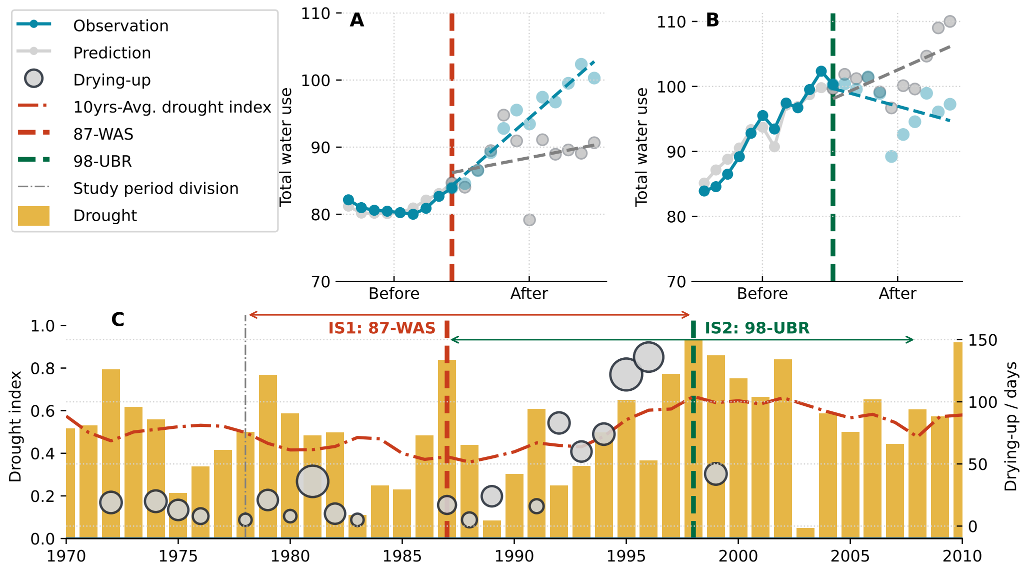

Figure 2. Effects of two institutional shifts on water resources use and allocation in the Yellow River Basin (YRB). **A.** water uses of the YRB before and after the institutional shift in 1987 (87-WAS); **B.** water uses of the YRB before and after the institutional shift in 1998 (98-UBR). While the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

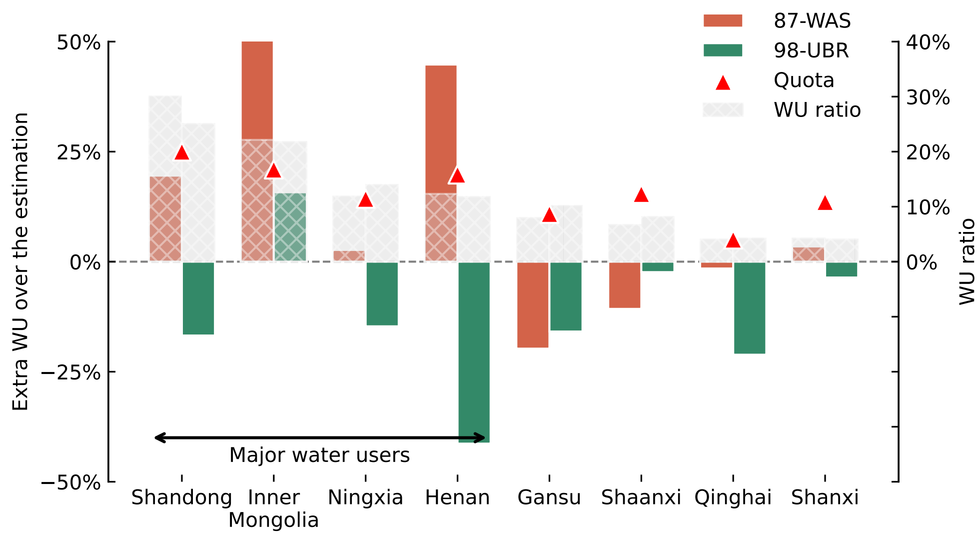

Figure 3. Regulating differences for provinces in the YRB. Red and green bars denote actual water use over the estimation from the model in a decade after the institutional shift -the 87-WAS and the 98-UBR, respectively. The grey bars indicate the proportions of actual water use for each province to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

(*Appendix S3: Optimization model for water use*). Therefore, isolated stakeholders reacted to the similar marginal cost, and smaller water users have a threshold, 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 (*Appendix S3: Optimization model for water use*). 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,

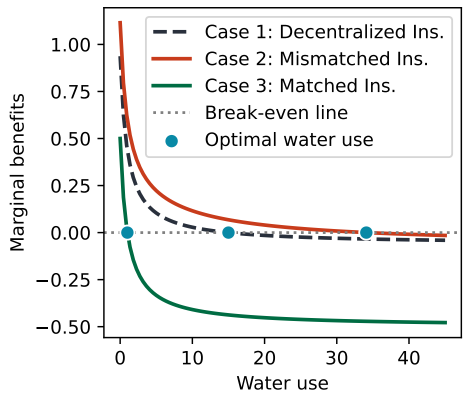

Figure 4. **A.** The relationship of marginal benefits and water use of province i at $t = 0$ for three different cases (case 1 to case 3, corresponding to the different SES structures in Figure 1, assuming $F(x) = ln(1 + x)$, $N = 8$, $P = 1$, $C = 0.5$, and $\beta = 0.4$ as an example (see *Economic model* The horizontal coordinate of each intersection of marginal benefits and the break-even line represents the optimal water use under each case.

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) [7,34], 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*) [35,36]. Then, the YRCC, the authority for approving water applications from all stakeholders, could adjust water use quotas according to the river conditions of the whole basin. The 98-UBR led to a structure for achieving social-ecological fits in both basins (between YRCC and the YRB) and regions (between provincial economy and their water shares).

LIMITATION, INSIGHTS AND IMPLICATIONS

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

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

Calls for a redesign of water allocation institutions in the YRB in recent years also illustrate the importance of institutional solutions to sustainability (see *Appendix S1: Contexts of institutional shifts*) [37]. Given recent changes in the YRB, outdated and inflexible water quota can no longer meet the new demands of economic development [34]. As a result, the Chinese government has embarked on a plan to redesign its decades-old water allocation institution (see *Appendix S1: Contexts of institutional shifts*). These initiatives can benefit from our analysis by actively incorporating social-ecological matched building blocks when developing a new institutional shift toward sustainability. Moreover, our research provides a cautionary tale of how institutions can be double-edged, while insights from the YRB can be a valuable guideline for SESs worldwide [12,38–40].

CONCLUSION

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

MATERIALS AND METHODS

We first abstract the SES structures of water using in the YRB from 1979 to 2008, where two institutional shifts split the period into three pieces. We then estimated the net effects of two institutional shifts on total water uses, changing trends, and differences of the YRB's provinces, by Differenced Synthetic Control (DSC) method [41]. For the stability of DSC model, we use Principal Components Analysis (PCA) method to reduce the dimensionality of many variables affecting the total water use. Finally, for discussion, we created an economic model based on marginal revenue to provide the observed water use changes a theoretical interpretation.

Portraying structures

We apply network approach to portray SES structures by abstracting relationships between ecological units (river reaches), stakeholders (provinces), govern unit (the YRCC) into general building blocks (or motifs) (see Figure 8), from the official documents. For example, institutions may create a horizontal connected structure that encourages collaboration between the different stakeholders managing ecological components (Figure 8 c). Similarly, institutions for vertical management may enhance multi-layered SES matching by coordinating through the higher-level governing node (Figure 8 d). Empirical studies have suggested that such widespread building blocks in SES are the key to the functioning of structures, and a network-based description is a widely used way to depict them by abstracting links and nodes [15,27,42]. In this study, we examined the official documents of the two institutional shifts of concern (87-WAS and 98-UBR, see *Appendix S1: Contexts of institutional shifts* for details), in which the agents are abstracted as nodes and the required interactions between agents are abstracted as links. The resulting structure is mainly used to inference the mechanism of institutional impact in the discussion, and to give an overview understanding of the institutional shifts. We try to approve that focusing on SES structures rather than institutional details, can well interpret the differences caused by institutional shifts in the YRB, and keeps consistent with previous studies theoretically.

Differenced Synthetic Control

We estimate water use without institutional shifts effect by using the Differenced Synthetic Control (DSC) method. The DSC method 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 [21,22,43]. This method aims to evaluate the effects of policy change that are not random across units but focus on some of the units (i.e., institutional shifts in the YRB here). By re-weighting units to match the pre-trend for the treated and control units, the DSC method imputes post-treatment control outcomes for the treated unit(s) by constructing a synthetic version of the treated unit(s) equal to a convex combination of control units with a new estimator with improved bias properties.

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" time t_0 within two individually analyzed periods T: 1979-1998; 1987-2008. Including each province in the YRB ($n = 8$, see *Dataset and preprocessing*) as the only treated unit, we consider the $J + 1$ units observed in time periods $T = 1, 2 \cdots, T$ with the remaining $J = 20$ units are untreated provinces from outside. We define T_0 to represent the number of pre-treatment periods $(1, \cdots, t_0)$ and T_1 the number post-treatment periods $(t_0, \cdots, T)$, such that $T = T_0 + T_1$. That is, treated unit is exposed to the institutional shift in every post-treatment period T_0, and unaffected by the institutional shift in all preceding periods T_1. Then, any weighted average of the control units is a synthetic control and can be represented by a $(J * 1)$ vector of weights $\mathbf{W} = (w_1, ..., w_J)$, with $w_j \in (0, 1)$. Among them, by introduce a $(k * k)$ diagonal, semidefinite matrix $\mathbf{V}$ that signifies the relative importance of each covariate, the DSC method procedure for finding the optimal synthetic control (W) is expressed as follows:

$$\mathbf{W}^*(\mathbf{V}) = \underset{\mathbf{W} \in \mathcal{W}}{\text{minimize}} \, (\mathbf{X_1} - \mathbf{X_0}\mathbf{W})' \, \mathbf{V} \, (\mathbf{X_1} - \mathbf{X_0}\mathbf{W}) \tag{1}$$

where $\mathbf{W}^*(V)$ is the vector of weights $\mathbf{W}$ that minimizes the difference between the pre-treatment characteristics of the treated unit and the synthetic control, given $\mathbf{V}$. That is, $\mathbf{W}^*$ depends on the choice of $\mathbf{V}$ –hence the notation $\mathbf{W} * (\mathbf{V})$. We choose $\mathbf{V}^*$ to be the $\mathbf{V}$ that results in $\mathbf{W} * (\mathbf{V})$ that minimizes the following expression:

$$\mathbf{V}^* = \underset{\mathbf{V} \in \mathcal{V}}{\text{argmin}} \, (\mathbf{Z}_1 - \mathbf{Z}_0\mathbf{W}^*(\mathbf{V}))' \, (\mathbf{Z}_1 - \mathbf{Z}_0\mathbf{W}^*(\mathbf{V})) \tag{2}$$

That is the minimum difference between the outcome of the treated unit and the synthetic control in the pre-treatment period, where $\mathbf{Z}_1$ is a $(1 * T_0)$ matrix containing every observation of the outcome for the treated unit in the pre-treatment period. Similarly, let $\mathbf{Z}_0$ is a $(k * T_0)$ matrix containing the outcome for each control unit in the pre-treatment period, k is number of variables in the datasets. The DSC method generalizes the difference-in-differences estimator and allows for time-varying individual-specific unobserved heterogeneity, with double robustness properties [44,45].

Dataset and preprocessing

We choose dataset and variables to compare on actural and estimated water use of the YRB. The actual water uses are accessible in China's provincial annual water consumption dataset from the National Water Resources Utilization Survey, whose details are accessible from Zhou (2020) [46]. To estimate the water use of the YRB by assuming there were not effects from institutional shifts, we focused on variables from five categories (environmental, economic, domestic, and technological) water use factors. Their specific items and origins are listed in Table 2.

Among the total 31 data-accessible provinces (or regions) assigned quotas in the 87-WAS and the 98-UBR, we dropped Sichuan, Tianjin and Beijing because their trivial water use from the YRB (see *Appendix* Table 1). We then divided the dataset into a "target group" and a "control group", treating provinces involved in water quota as the target group ($n = 8$) and other provinces as the control group ($n = 20$), for applying the DSC.

Using the normalized data of all variables, we performed the PCA reduction to capture 89.63% explained variance by 5 pricipal components Appendix S2: Methods in details. Bayan had proved that combining PCA and DSC can rise robustness of causal inference [47]. Here, we first applied the Zero-Mean normalization (unit variance), as the variables' unit are far different. We use Elbow method to choose number of the pricipal components, as Appendix S2: Methods in details Figure 7 shows, 5 components well reduced the dimensions of the dataset with 89.63% variance explaination.

Economic model

In order to inference the mechanisms underlying the results, we developed a economic model based on marginal revenue to analyze how institutional shift could have led to differences in water use.

Assumption 1. *(Water-dependent production) Because of irreplaceability, water is assumed to be the only input of the production function with two types of production efficiency.*

Assumption 2. *(Ecological cost allocation) Under the assumption that the ecology is a single entity for the whole basin involved, the cost of water use is equally assigned to each province.*

Assumption 3. *(Multi-period settings) There are multiple settings periods with a constant discount factor for expectation of future water use.*

Under the above simplified assumptions, we demonstrate three cases -corresponding the abstracted SES structures (Figure 1), inference how SES structure alters the expected marginal benefits and costs of provinces making decisions. As one of the possible interpretation for the causality between SES structure and institutional effects, the derivation of the model based on the above three assumptions can be found in *Appendix S3: Optimization model for water use*, and some simple model-based extensions are involved in *Appendix S4: Model extensions*.

S1: Contexts of institutional shifts

Water allocation schemes are widespread in large river basin management programs throughout the world (see *Appendix* Figure 5) [48]. This was the first basin in China for which a water resource allocation institution was created, and institutional shifts can be traced through several documents released by the Chinese government (at the national level) [34]:

- **1982**: The provinces and the Yellow River Water Conservancy Commission (YRCC) are required to develop a water resource plan for the Yellow River [34,49].
- **1987**: Implementation of the Allocation Plan. (http://www.mwr.gov.cn, last access: May 20, 2022).
- **1998**: Implementation of unified regulation. (http://www.mwr.gov.cn, last access: May 20, 2022).
- **2008**: Provinces are asked to draw up new water resources plans for the YRB to further refine water allocations [34,49].
- **2021**: A call for redesigning the water allocation institution (http://www.ccgp.gov.cn, last access: May 20, 2022).

Since 1982, administrations attemptted to design a quota institution, and the 2008 document marked the maturity of the scheme (complete establishment of basin-level, provincial, and district water quotas). Between the period, two significant institutional shits can be analyzed by using the 1987 (87-WAS) and 1998 (98-UBR) documents.

The official documents in 1987 (http://www.mwr.gov.cn, last access: May 20, 2022) clearly convey the following key points:

- The policy is aimed at related provinces (or regions in the same administrative level).
- Depletion of the river is identified as the first consideration of this institution.
- Provinces are encouraged to develop their own water use plans based on a quota system.
- Water in short supply is a common phenomenon in relevant provinces (regions).

The official documents in 1998 (http://www.mwr.gov.cn, last access: May 20, 2022) clearly convey the following key points:

- The document clearly points out that not only provinces and autonomous regions involved in water resources management (see *Article 3*), the provinces' and regions' water use shall be declared, organized, and supervised by the YRCC (*Article 11 and Chapter III to Chapter V, and Chapter VII*).
- Creating the overall plan of water use in the upper, middle, and lower reaches is identified as the first consideration of this institution (*Article 1*).
- With the same quota as used in the 1987 policy, provinces were encouraged to further distribute their quota into lower-level administrations (see *Article 6 and Article 41*).

- They emphasize that supply is determined by total quantity, and water use should not exceed the quota proposed in 1987 (see *Article 2*).

Based on the above documents, we abstracted the structural changes of SES (see *Appendix S2*) after the two institutional changes, as shown in Figure 1 C.

S2: Methods in details

The Differenced Synthetic Control (DSC) method estimates water use y' by assuming that the control group (provinces out of the YRB) and experiment group (provinces in the YRB) keep their changing trends after an institutional shift in t_0, i.e., $f_{t<t_0}(X) = f_{t>t_0}(X)$. Therefore, when comparing the actual water use y and the estimated water use y' after institutional shifts, if $y'_{t<t_0} \approx y_{t<t_0}$ but $y'_{t>t_0} \neq y_{t>t_0}$, there are two cases: (1) changing trends of independent variables X are different between control groups and experiment groups; (2) functions of variables are different between pre- and post- institutional shift periods i.e., $f_{t<t_0}(X) \neq f_{t>t_0}(X)$. Corresponding to the problem of this study, they mean: (1) Institutional shift changes the trend of independent variables (environment, economy, technology); (2) Institutional shift makes difference of water use caused by the change of unit independent variable combination different.

In practice, both two factors may contribute simultaneously. Here, we analyze the differences between the YRB (affecting the actual water consumption) and other provinces (used by DSC generating synthetic control group) for the representative independent variables in each category of Table 2 by calculating their differences in ratio $Diff_{ratio}$:

$$Diff_{ratio} = \frac{\vec{var}_t^{YRB} - \vec{var}_t^{others}}{\frac{1}{T} * \sum_t^T (var_t^{YRB} - var_t^{others})} \tag{3}$$

where $\vec{var}$ is a vector of specific independent variable in $X_{t,var}$, $t \in [1979, 2008]$.

For the first case, in terms of environmental factors, the differences between provinces in the YRB and other Chinese provinces has not changed significantly throughout (i.e., kept parallel, Figure 6 A and B). However, the economic factors (both in agriculture, industry, and services) had significant changes after the first institutional shift (the 87-WAS) (Figure 6 C, D and E), but not in population (Figure 6 F).

For the second case, since water the production functions of water use are mainly dependent on its efficiency, which is influenced by water-saving facilities a lot, we analyze the differences between water conservation infrastructures (WCI) ratio and industrial water recycling (IWR) ratio. While an abruptly changing trend occurred after the 87-WAS for WCI, ratio of IWR rised its differences between the YRB provinces and other provinces (without abrupt change) until the 98-UBR (Figure 6 G and H).

As results, the differences between the DSC estimated YRB's water use and its actual water use are contributed by both abrupt changes of independent variables and functions. Furthermore, the economic variables (agriculture, industry, and services) contributed much more rather than environmental variables or population.

S3: Optimization model for water use

Setup. In order to understand the mechanisms through which the SES structure impacts provincial water use, we developed a dynamic economic model to analyze how institutional mismatch could have led to the changes of water use, especially among provinces with high incentives for excess water use. Specifically, we modeled individual provincial decision-making in water resources before quota execution.

We proposed three intuitive and general assumptions.

Assumption 4. *(Water-dependent production) Because of irreplaceability, water is assumed to be the only input of the production function with two types of production efficiency. The production function of a high-incentive province is $A_H F(x)$, and the production function of a low-incentive province is $A_L F(x)$ ($A_H > A_L$). F(x) is continuous, $F'(0) = \infty$, $F'(\infty) = 0$, $F'(x) > 0$, and $F''(x) < 0$. The production output is under perfect competition, with a constant unit price of P.*

Assumption 5. *(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 6. *(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 use.*

Under the above assumptions, we can demonstrate three cases to simulate the water use

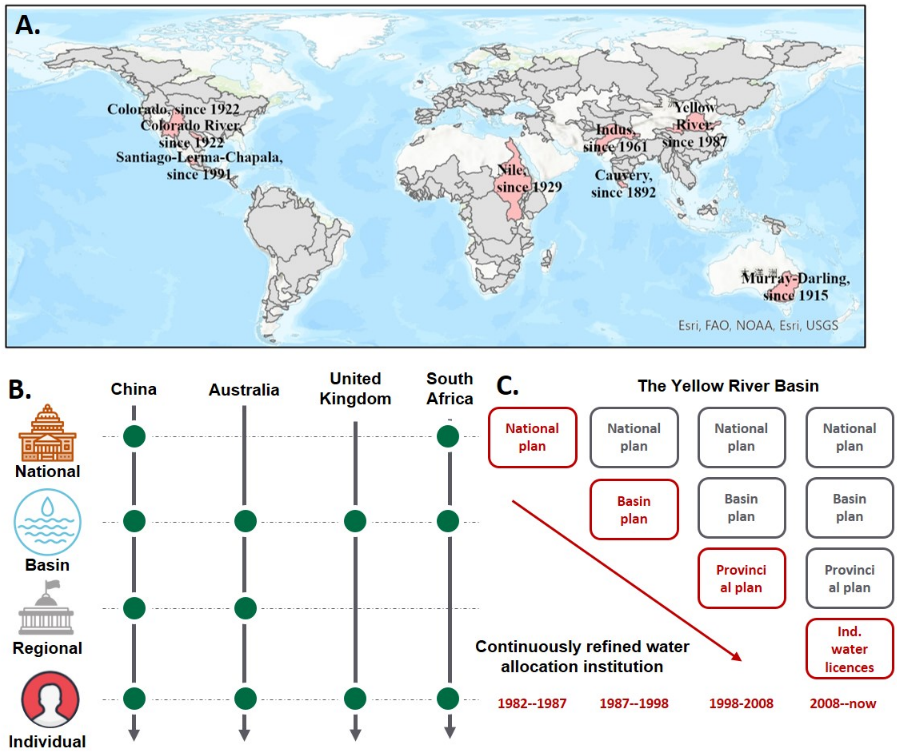

Figure 5. Overview of water allocation institutions. **A.** Major river basins in the world with water resource allocation systems (shaded red); the YRB first proposed a resource allocation scheme in 1987 (designed since 1983) and then changed to a unified regulation scheme in 1998 (designed in 1997 but implemented in 1998) [48]. **B.** Different water resource allocation system design patterns; the YRB is typical of a top-down system. **C.** The four periods of institutional evolution of water allocation of the YRB.

Table 1. Water quotas assigned in the 87-WAS

Items (water volume, billion m^3)	Qinghai	Sichuan	Gansu	Ningxia	Inner Mongolia	Shanxi	Shaanxi	Henan	Shandong	Jinji
Demands in water plan	35.7	0	73.5	60.5	148.9	115	60.8	111.8	84	6
Quota designed in 1983	14	0	30	40	62	43	52	58	75	0
Quota assigned in 1987	14.1	0.4	30.4	40.0	58.6	38.0	43.1	55.4	70.0	20
Average water consumption from the Yellow River from 1987-2008	12.03	0.25[a]	25.80	36.58	61.97	21.16	11.97	34.30	77.87	5.85[a]
Proportion of water from the Yellow River in total water consumption	48.12%	0.10[b]%	30.79%	58.45%	47.82%	73.55%	44.39%	24.77%	34.41%	3.11%[b]

[a]Calculated by data from 2004 to 2017.

[b]The share is too small, thus the provinces (or region) Sichuan and Jinji not to be considered in this study.

decision-making and water use patterns in a whole basin.

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

Case 1. *Dentralized decision: This case corresponds to a situation without any high-level water allocation institution.*

When each province independently decides on its water use, the optimal water use x_i^* in province i satisfies:

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

where A denotes A_H for a high-incentive province and A_L for a low-incentive province.

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

$$x_{it}^* = x_i^*$$

Case 2. *Mismatched decision: This case corresponds to a mismatched institution.*

The water quota is determined at t=0 and imposed in t=1,2,... Under the subjective expectation of each province that current water use may influence the future water allocation determined by high-level authorities, 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, given other provinces' decisions on water use remain

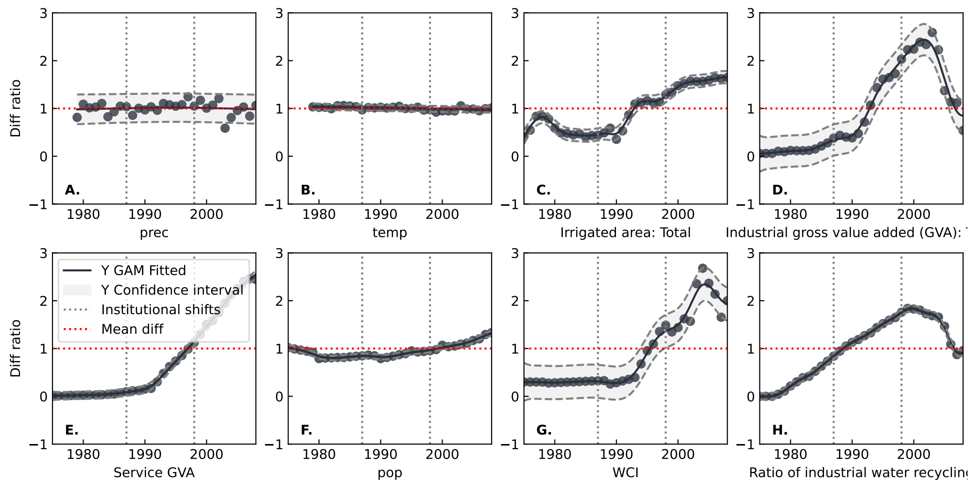

Figure 6. Differences ratio of different variables: **A.** precipitation, **B.** temperature, **C.** total irrigated areas, **D.** industrial gross value added (industrial GVA), **E.** services GVA, **F.** population, **G.** water conservation irrigation (WCI) ratio, and **H.** industrial water recycling (IWR) ratio.

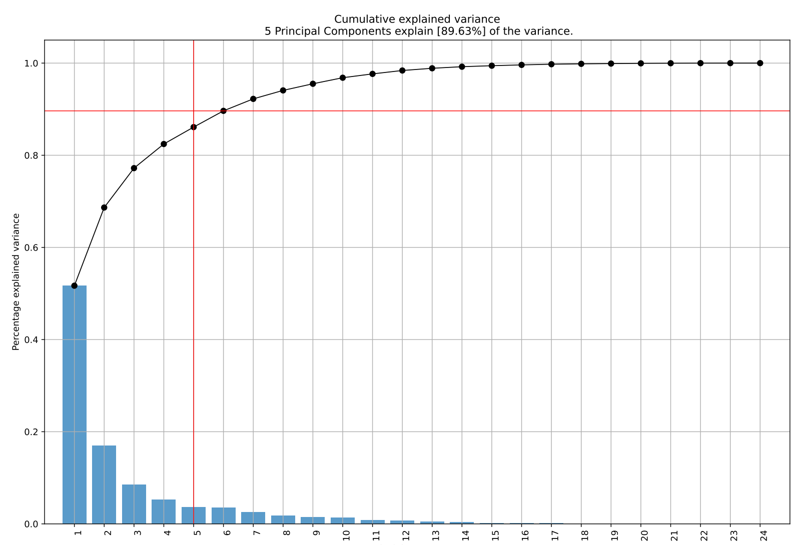

Figure 7. Choose number of pricipal components by Elbow method, 5 pricipal components already capture 89.63% explained variance.

Table 2. Variables and their categories for water use predictions

Economic sector	Category	Unit	Description	Variables
Agriculture	Irrigation Area	thousand ha	Area equipped for irrgiation by different crop:	Rice, Wheat, Maize, Fruits, Others.
Industry	Industrial gross value added	Billion Yuan	Industrial GVA by industries	Textile, Papermaking, Petrochemicals, Metallurgy, Mining, Food, Cements, Machinery, Electronics, Thermal electrivity, Others.
	Industrial water use efficiency	%	The ratio of recycled water and evaporated water to total industrial water use	Ratio of industrial water recycling, Ratio of industrial water evaporated.
Services	Services gross value added	Billion Yuan	GVA of service activities	Services GVA
Domestic	Urban population	Million Capita	Population living in urban regions.	Urban pop
	Rural population	Million Capita	Population living in rural regions.	Rural pop
	Livestock population	Billion KJ	Livestock commodity calories summed from 7 types of animal.	Livestock

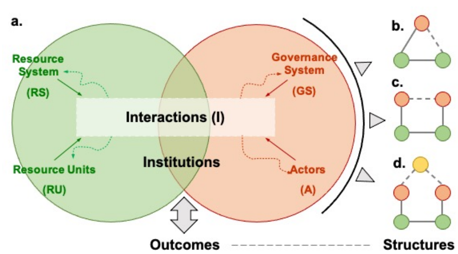

Figure 8. Framework for understanding linkages between SES structures and outcomes. **a.** The general framework for analyzing social-ecological systems (SESs) (adapted from Ostrom [50]). Institutions embedded in SESs may reshape structures by changing the interactions between core subsystems, resulting in different outcomes. Three typical types of abstracted SES structures are shown as **b.**, **c.** and **d.** (adapted from Bodin, 2017) [14]. 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.

unchanged, the optimal water use of province i at t=0 satisfies:

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

where A denotes A_H for a high-incentive province and A_L for a low-incentive province.

Case 3. *Matched institution: This case corresponds to the institution under which water use in a basin is centrally managed.*

When the N provinces decide on water use as a unified whole (e.g., the central government completely decides and controls 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.

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

Proposition 2: The water overuse is higher among provinces with high water use incentives than that with low water use incentives under a mismatched institution.

The intuition for this proposition is straightforward in that all provinces would use up their allocated quota under a relatively small Q. As production efficiency increases, the marginal benefits of a unit quota increase, and the quota would provide higher future benefits for a preemptive water use strategy. Provinces with high production efficiency have higher optimal values of water use under the decentralized decision, and the divergence in water use would be exaggerated during the period that the water quota is expected to be implemented and water use is in greater competition.

Extensions of the model are shown in Supplementary Material S3.

Appendix: Water Use Optimization

Case 1. *Centralized decision*

When the N provinces decide on water uses as a unity, the marginal cost is C, equal to its fixed unit cost. The water use of province i aims to maximize $P \cdot A \cdot F(x) - C$. *Hence,* x_i^* *satisfies* $P \cdot A \cdot F'(x) = C$, *i.e.,* $AF'(x) = \frac{C}{P}$, *where A denotes* A_H *for a high-incentive province and* A_L *for a low-incentive province.*

Case 2. *Decentralized decision*

When each of the N provinces independently decides on its water use, the marginal cost of water use would be $\frac{C}{N}$ *as a result of cost-sharing with others. Hence, the optimal water use in province i at period t, denoted as* $\hat{x}_i^*$, *satisfies* $P \cdot A \cdot F'(x_{it}) = \frac{C}{N}$, *i.e.,* $A \cdot F'(x) = \frac{C}{P \cdot N}$. *Since* F' *is monotonically decreasing,* $\hat{x}_{it}^* > x_i^*$.

Case 3. *Forward-looking decentralized decision under quota restrictions*

When the future water use would be constrained by the water quota, the dynamic optimization problem of province i is shown as follows. In t=1,2,..., there would be no relevant cost when the quota is bound that each province takes constant costs of $\frac{P \cdot Q}{N}$ *regardless of the allocation. It is sufficient to consider only the total water quota is smaller than total water use in Case 2 since a "too large" quota doesn't make sense for ecological policies.*

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

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

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

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

Since $F' > 0$ *and* $F'' < 0$, $\widetilde{x}_i^* > \hat{x}_i^* > x_i^*$, *taken others' water use* $x_{-i,0}$ *as given. Since the provincial water use decisions are exactly symmetric, total water use would increase when each province has higher incentives for current water use.*

Proof of Proposition 1:

Because $F' > 0$ *and* $F''(x) < 0$ *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 under unclear property rights where a water user is fully responsible for the relevant costs. The result of* $\hat{x}_i^* > x_i^*$

The difference between x_i^* *and* $\hat{x}_i^*$ *stems from two parts: the effect of the marginal returns and the effect of the marginal costs. First, the "shadow value" provides additional marginal returns of water use in t = 0, which 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.*

Proof of Proposition 2:

Since $A_H > A_L$, $F'(x_H) < F'(x_L)$, *Eq.(xxx) implies a positive relation between* x_{i0} *and A, when* β, P, C, Q, *and other provinces' water use are taken as given.*

The difference between $\widetilde{x}_i^*$ *and* $\hat{x}_i^*$ *(i.e.,* $\frac{\beta}{1-\beta} \cdot A \cdot f(Q \cdot \frac{x_{i,0}}{x_{i,0} + \sum x_{-i,0}}) \cdot Q \cdot \frac{\sum x_{-i,0}}{(x_{i,0} + \sum x_{-i,0})^2}$*) represents the incentive of water overuse derived from an expectation of water quota allocation. The incentive of water overuse increases by A.*

Fig. 1. *Optimal water use under different institutions*

Notes: The figure depicts the relationship of marginal return deducted from marginal cost and water use of province i *at t=0 under centralized decisions, decentralized decisions, and decentralized decisions under quota restrictions, for a province with high water use incentive in Panel (A), and for a province with low water use incentive in Panel (B). Assume* $F_H(x) = A_H ln(1+x), F_L(x) = A_L ln(1+x), A_H = 1, A_L = 0.8, N = 8, P = 1, C = 0.5, \beta = 0.7$, *and* $Q = 8$. *In Case 3, others' water use is taken as given, equal to the optimal water use under Case 2. The horizontal coordinate of each intersection of marginal return minus the marginal cost and break-even line represents the optimal water use under each case.*

S4: Model extensions

Further analysis of the general economic model

Using the general economic model (see the Methods section in the main text), we also explored the response of stakeholders to water quota policies. We considered two additional scenarios for stakeholders, one that considered technology growth and one that considered different valuations through time (via the discount rate) of economic benefits and ecological costs. In the following scenarios, the cost is assumed to be untransferable, which could be fully allocated to the one incurring the water use. Explaining plausible scenarios for these stakeholders will help us better understand the causes of the water overuse and potential solutions. We argue that the water overuse remains robust even if a complete and equitable system.

Case 4. *Forward-looking decentralized decision, taken ecology cost into considerations*

Even if the negative externality of water overuse is eliminated by"fair" ecology cost of $\frac{x_{i,0}}{x_{i,0}+\sum x_{-i,0}} \cdot Q \cdot C$, *it is possible that the future growth opportunities and "remote" ecological costs provide enough incentive for the sprint. The water overuse has the value of future economical benefits by slacking the water use constraint in the future. The heterogeneous production efficiency is omitted in this section, and we set A=1.*

(a) technology growth

Assume that there is an exogenous technology growth rate of g in the scenario of N provinces bargaining for water use under total quota Q, with unit price of output P, unit cost C, and discount factor β. For simplicity, consider a finite-period water use optimization:

$$max \quad P \cdot (1+g)^t ln(1+x_{i,0}) - \frac{C}{N} + \beta^t \sum_{t=1}^{T} [P \cdot (1+g)^t ln(x_{i,t}+1) - C \cdot x_{i,t}]$$

$$s.t. \quad x_{i,t} \leq Q \cdot \frac{x_{i,0}}{x_{i,0}+\sum x_{-i,0}} \quad for \quad \forall t$$

We depict the relationship of multi-period profit and water use $x_{i,0}$ *in different horizons in Figure 9,and thus find out the optimal water use pattern under technology growth. The higher marginal output of water might create enough incentive to set off the untransferable cost since a higher allocated quota provides growth option value. As the provincial decision is under a longer horizon, there is a greater sprint effect due to higher accumulated yield and relatively tighter water use constraints over time.*

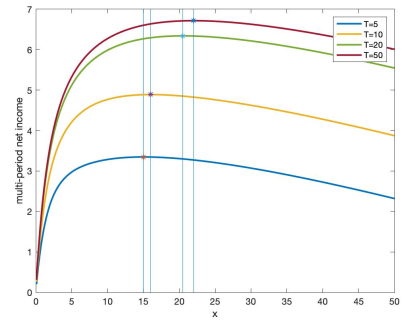

Figure 9. Multi-period optimization of optimal water use under technology growth. The figure depicts the relationship of multi-period benefits of province i and water use under Case 3 with technology growth. Assume $F(x) = ln(1+x)$, $N = 8$, $P = 1$, $C = 0.5$, $\beta = 0.7$, $g = 0.2$, and $Q = 8$.

(b) Economic benefits and "remote" ecological costs with different discount factors

Assume that there is a high discount rate for economical benefits and a low discount rate for ecological costs, in the scenario of N provinces bargaining for water use under total quota Q, with unit price of output P, unit cost C, discount factor $\beta^{economy}$ *and* $\beta^{ecology}$ ($\beta^{economy} > \beta^{ecology}$). *For simplicity, consider the following finite-period water use optimization, noting the water use of province i at period t:*

$$max \quad P \cdot ln(1+x_{i,0}) - \frac{C}{N} + \beta_1^t \sum_{t=1}^{T} [P \cdot ln(x_{i,t}+1)] - \beta_2^t \sum_{t=1}^{T} [C \cdot x_{i,t}]$$

$$s.t. \quad x_{i,t} \leq Q \cdot \frac{x_{i,0}}{x_{i,0}+\sum x_{-i,0}} \quad for \quad \forall t$$

We depict the relationship of multi-period net income and water use $x_{i,0}$ *in different horizons in Figure 10, and thus find out the optimal water use pattern under "remote" ecological costs. The higher discounted ecological costs might create enough incentive to set off the untransferable cost. As the provincial decision is under a longer horizon, there is a greater sprint effect due to a higher accumulated yield.*

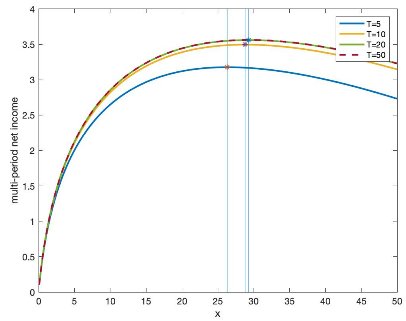

Figure 10. Multi-period optimization of water use under "remote" ecological cost. The figure depicts the relationship of multi-period benefits of province i and water use under Case 3 with "remote" ecological cost. Assume $F(x) = ln(1 + x)$, $N = 8$, $P = 1$, $C = 0.5$, $\beta_{economy} = 0.7$, $\beta_{ecology} = 0.3$, and $Q = 8$.

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