

# Approaching social-ecological matches of river basin systems for sustainability

Shuang Song<sup>1</sup>, Huiyu Wen<sup>2</sup>, \*Shuai Wang<sup>1</sup>, Xutong Wu<sup>1</sup>, Graeme S. Cumming<sup>3</sup> and Bojie Fu<sup>1</sup>

<sup>1</sup>State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, P.R. China.

<sup>2</sup>School of Finance, Renmin University of China, Beijing 100875, P.R. China.

<sup>3</sup>ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville 4811, QLD, Australia.

## Abstract

Increasing competition for water is leading to depletion of freshwater globally and calls for efficient institutions in water governance. Alignments of social-ecological system (SES) structures are a crucial approach to institutional matches, but an understanding of its causal links and underlying processes are still weaknesses. To fill these knowledge gaps, we select the Yellow River Basin (YRB) in China as a typical case study to quantitatively measure the effects of SES structures changing because it is one of the most anthropogenically altered large river basins. Under different water allocation institutions, its streamflow was first overdrawn, then dried up, and finally has been successfully restored. We focused on two institutional shifts, the Water Allocation Scheme that began in 1987 (87-WAS) and the Unified Basinal Regulation that took over in 1998 (98-UBR), which re-framed different SES structures. We conduct counterfactual identification on the effect of these institutional shifts, our results suggested that during the decade following the introduction of the 87-WAS, observed water use of the YRB increased by 8.57% more than expected, while 98-UBR ultimately decreased total water use. Furthermore, these heterogeneous effects of water use responses to SES structures aligned with our further theoretical marginal benefits analysis, supporting the hypothesis that SES structural changes played a vital role in sustainable water use. This quasi-natural experiment on the YRB offers profound insights into the links between SESs structures and outcomes, suggesting that fragmented ecological units linked to separated social actors should be avoided for sustainability.

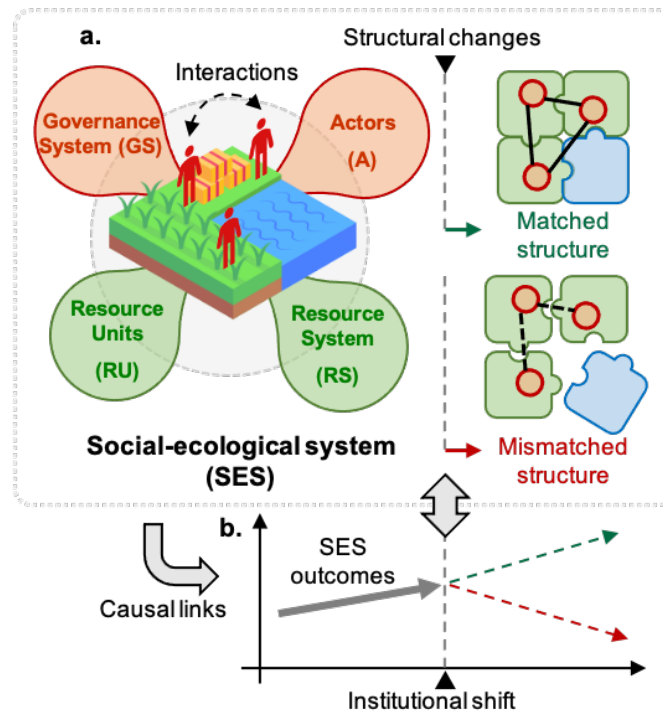
**Keywords:** Yellow River, water use, water governance, social-ecological system, institutional fit

# 27 1 INTRODUCTION

28 Widespread freshwater scarcity and overuse challenge the sustainability of large river basins, resulting in systematic  
29 risks to economies, societies, and ecosystems globally [1–4]. In the context of future climate change, the gap between  
30 supply and demand for water resources in large river basins is expected to become increasingly more prominent  
31 [5, 6]. Those river basin systems successfully supporting sustainable water resource use are structurally well-aligned  
32 with water provisioning and social-ecological demands, without inefficient competition or overuses [7]. However,  
33 balancing the water demands of ecosystems and development in heavily human-dominated river basins is a challenge  
34 because human activities and water are intertwined in their structures as complex social-ecological systems (SES)  
35 [8, 9] (Figure 1).

36 For governing river basin systems, their SES structures can be reshaped by institutions, such as policies, laws,  
37 and norms [10, 11]. Representing all relative governance practices, institutions include interplays between social  
38 actors, ecological units, or between social and ecological system elements [12, 13]. Understanding how these complex  
39 interplays are crucial for developing strategies to effectively manage natural resources and enhance the resilience of  
40 social-ecological systems [14]. Effective (“matched” or “fit”) institutions operate at appropriate spatial, temporal,  
41 and functional scales to manage and balance different relationships and interactions between human and water  
42 systems, supporting (but not guaranteeing) the sustainability of SES [7, 15] (Figure 1 a). Some institutional advances  
43 have had desirable water governance outcomes (e.g., the Ecological Water Diversion Project in Heihe River Basin,  
44 China [7], and collaborative water governance systems in Europe [16]). However, imposing institutional changes on a  
45 large, complex river basin may create or destroy hundreds of connections between social agents and ecological units,  
46 where matched social-ecological structures are not ubiquitous. Two particular weaknesses in existing knowledge of  
47 institutional matches include understanding (Figure 1 b): (i) the causal links between SES structures and outcomes;  
48 (ii) details of the underlying processes, and especially the coordination of the incentives of different participants,  
49 that result from an institutional lack of matches. These weaknesses limit understanding of institutional design and  
50 hinder approaches toward institutional matches for improving the sustainability of river basin systems.

51 To better understand how water governance institutions match their social-ecological context, we take the  
52 Yellow River Basin (YRB), China, as an example (see *Study area*) to dive into causal links between SES structures  
53 and outcomes. Specifically, we focused on two institutional shifts in water allocation of the YRB: the 1987 Water  
54 Allocation Scheme (87-WAS), and the 1998 Unified Basinal Regulation (98-UBR), which reframed SES structures  
55 significantly. The YRB provides an informative case for two main reasons: (1) The top-down institutional shifts  
56 induced sharp changes in SES structures, enabling us to estimate their net effects quantitatively. (2) Since few large



**Fig. 1** Framework for understanding linkages between SES structures and outcomes. **a.** In the general framework for analyzing social-ecological systems (SESSs), (Adapted from Ostrom, 2008 [39]). Institutional shifts can change interactions within the SES and reframe the structures. **b.** We aim to investigate causal links between matched/mismatched SES structures and their corresponding outcomes.

57 river basins have experienced such radical institutional shifts more than once, this case study provides comparable  
58 natural experiments for understanding the impacts of structural changes in SESs on natural resources.

59 We explored causal linkages between SES structures and sustainability-related outcomes by quasi-natural exper-  
60 iments (institutional shifts imposed by central government) in the YRB. Firstly, we used data on changes in official  
61 documents following two institutional shifts to describe comparable changes in the SES structures associated with  
62 the YRB from 1979 to 2008, by abstracting them into SES structures motifs (or building blocks, see *Portraying*  
63 *structures*). We then used a method called ‘Differenced Synthetic Control (DSC)’ [17], which considers economic  
64 growth and natural background, to estimate theoretical water use scenarios without institutional shifts (*Differenced*  
65 *Synthetic Control* and *Appendix B: Robustness of DSC method*). This approach allowed us to create a counterfac-  
66 tual against which to explore the mechanisms linking SESs structure and outcomes for a deeper understanding  
67 of the potential role of institutions in water governance worldwide. Finally, we further developed an approach for

68 marginal benefits analysis, to interpret the underlying processes of the match and mismatched institutions based  
69 on SESs structures (*Marginal benefits analysis*).

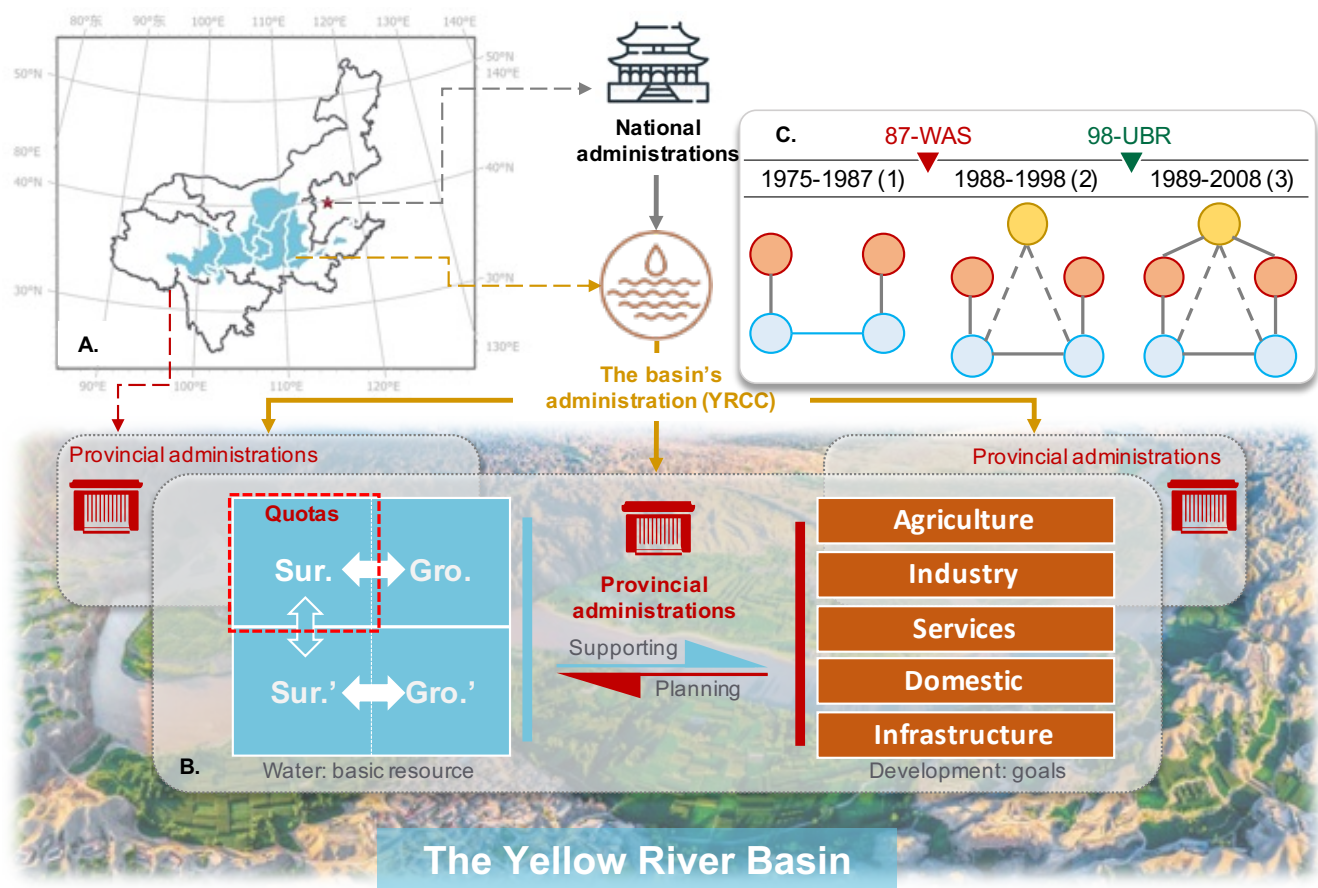
## 70 2 RESULTS

### 71 2.1 Institutional shifts and structures

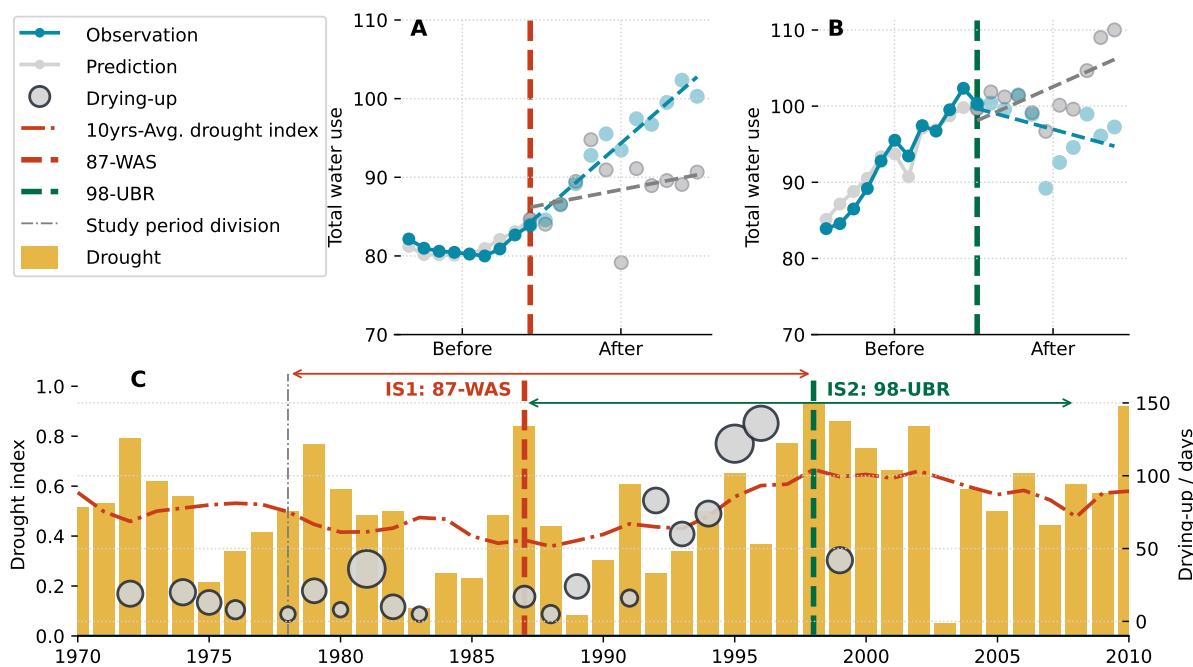
72 The institutional shifts in the YRB in 1987 (87-WAS) and 1998 (98-UBR) were two widely recognized milestones in  
73 restricting water use among YRB's water governance practices (*Study area* and *Appendix A: Contexts of institutional*  
74 *shifts*). Until the 87-WAS, stakeholders (the provinces in the YRB) had free access to the YR water resources  
75 for development, but there were geographic and temporal differences between freshwater demand and availability.  
76 The YRCC had no links to the provinces regarding water use before 1987, and the provinces could link directly  
77 to the Yellow River reaches (Figure 2 C). To shrink water deficits, in 87-WAS, national authorities proposed  
78 in 87-WAS allocating specific water quotas between 10 provinces (or regions) along the YR basin (Table A1).  
79 Simultaneously, according to the extracted information from documents of the 87-WAS issued by national ministries,  
80 the YRCC started to report water use in each reach. As it was the first time the responsibility of the YRCC  
81 involved water use, this introduced new links between the YRCC and the ecological nodes (Figure 2 C). However,  
82 the controversial 87-WAS did not resolve water depletion. In 1998, another strategy (98-UBR) was developed to  
83 strengthen the responsibilities of the YRCC for integrated managing water use. Information from the 98-UBR  
84 documents demonstrated that the provinces had to apply their plan for an annual water use license to YRCC  
85 instead of direct access to the Yellow River water. Thus, the YRCC has been linked to the provinces since 1998  
86 (Figure 2 C). As result, the two institutional shifts reshaped SES structures, leading to three general structures  
87 linked by social actors and ecological nodes (Figure 2 C).

### 88 2.2 Institutional shifts impact on water use

89 Our estimation of theoretical water use suggests that the institutional shift in 1987 (87-WAS) stimulated the  
90 provinces to withdraw more water than would have been used without an institutional shift (Figure 3A). From 1988  
91 to 1998, on average, while the estimation of annual water use only suggests 974.34 billion  $m^3$ , the observed water  
92 use of the YRB provinces reached 1038.36 billion  $m^3$  (an increase of 6.57%). However, after the institutional change  
93 in 1998 (98-UBR), trends of increasing water use appeared to be effectively suppressed. From 1998 to 2008, the  
94 total observed water use decreased by 0.49 billion  $m^3/yr$  per year, while the estimation of water use still suggests



**Fig. 2** 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 A: Contexts of institutional shifts](#) Table A1). 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.** Provincial administrative agencies are the major stakeholders. Since the 87-WAS, with surface water withdrawal from the Yellow River restricted by specific quotas, each stakeholder plan and use water resources for development. However, the natural hydrological processes are connected. Although the institutions focus mainly on 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. The YRCC only monitors water withdrawals at that time. **C.** Institutional shifts and following structures changes (details in [Appendix A: Contexts of institutional shifts](#)). (1) From 1979 to 1987, water resources were freely accessible to each stakeholder (denoted by red circles) from the 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 for water use licenses from the YRCC (the connections between the red and yellow circles).

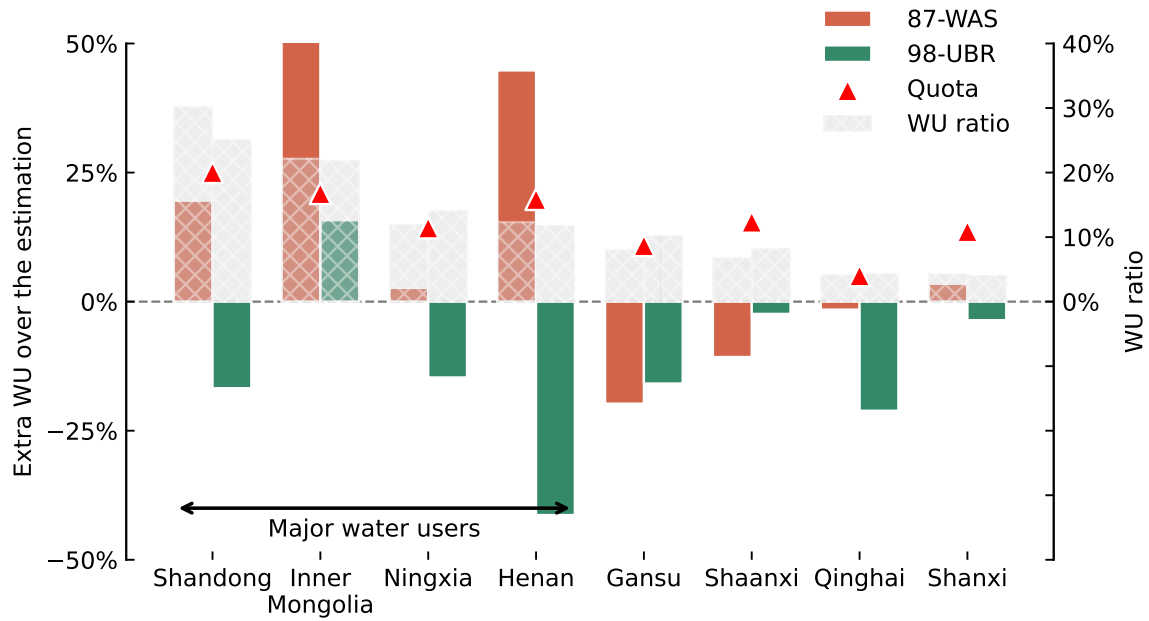


**Fig. 3** Effects of two institutional shifts on water resources use and allocation in the Yellow River Basin (YRB). **A.** water uses of the YRB before and after the institutional shift in 1987 (87-WAS); **B.** water uses of the YRB before and after the institutional shift in 1998 (98-UBR). Blue lines are statistics derived from water use data; grey lines are estimates 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 drying upstream.

0.82 billion  $m^3/yr$  increases (Figure 3 B). The increased water uses after 87-WAS aligns with the severe drying-down of the surface streamflow from 1987 to 1998, an obvious indicator of river degradation and environmental crisis (Figure 3C). On the other hand, the 98-UBR ended river depletion, despite subsequent increases in drought intensity (from 0.47 after 87-WAS to 0.62 after 98-UBR on average) (Figure 3C).

## 2.3 Heterogeneous effects and interpretation

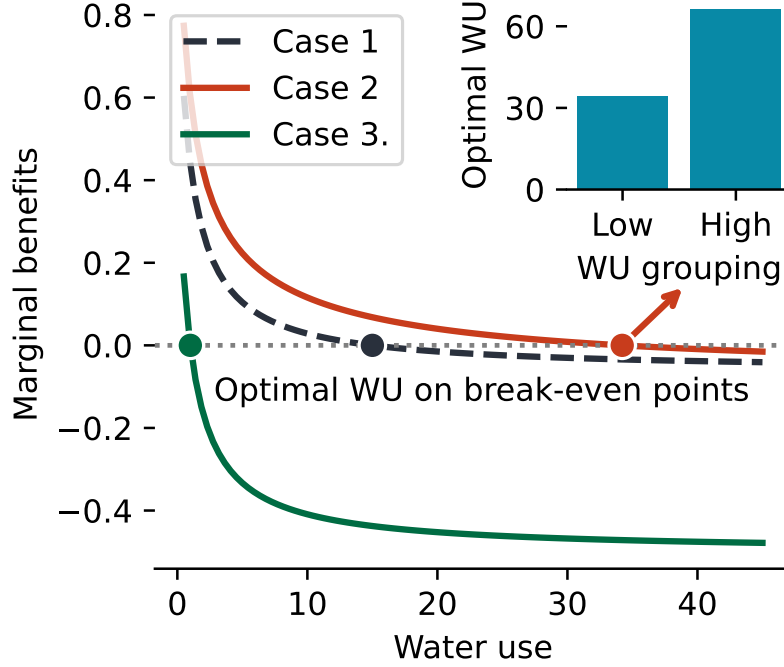
Our results also suggest differences between patterns of provinces in their responses to the two institutional regulating. During the decade after the 87-WAS, the major water-using provinces (e.g., Inner Mongolia, Henan, Shandong) had apparent accelerations (Figure 4). The proportion of increased (or decreased) water use for each province (over the estimated water use by the model) correlated significantly (partial correlation coefficient is 0.77,  $p < 0.05$ ) with actual water use from the Yellow River. On average, the major water users (Shandong, Inner Mongolia, Henan, and Ningxia) used 32.14% more water than predicted from 1987 to 1998. By contrast, after the 98-UBR (from 1998 to



**Fig. 4** Regulating differences for provinces in the YRB. Red (the 87-WAS) and green (the 98-UBR) bars denote an increased or decreased ratio for actual water use relative to the estimate from the model in the decade after the institutional shift. The grey bars indicate the proportions of actual water use for each province relative to their total water use in the decade after the institutional shift. The triangles mark the water quotas assigned under the institution, converted to ratios by dividing by their sum.

2008), almost all provinces have seen declines ( $-16.54\%$  on average) in water use. Furthermore, the regulated water use of provinces was unrelated (partial correlation coefficient is 0.33,  $p > 0.1$ ) to their proportional water use from the Yellow River.

For interpretation of the pattern, we compared the theoretical marginal returns and optimal water use under three different structural cases (case 1 to case 3, corresponding to different SES structures in Figure 2 C, see [Marginal benefits analysis](#) Figure 5, detailed derivation in [Appendix C: Optimization model for water use](#)). Assuming that water is the factor input with decreasing marginal output of each province, results show that varying incentives for water use in each province derive from the relationship between the benefits and costs of water use. As a benchmark, case 1 analogy to a decentralized stakeholders situation and lead to medium-level water use. In case 2, each stakeholder expects that current water use helps bargain for a favorable water quota in the face of institutional shift (see [Appendix C: Optimization model for water use](#)), which can intensify the incentive to use water, leading to higher water use. Furthermore, the water users with higher capability are more stimulated by the institutional



**Fig. 5** The proposed relationship of marginal benefits and water use of individual province under varying cases (case 1 to case 3, corresponding to the different SES structures in Figure 2 C) Major water users' theoretically optimal water use is also larger (see [Marginal benefits analysis](#) and [Appendix C: Optimization model for water use](#)).

118 shift and away from the theoretically optimal water use under a unified allocation. After water-use decisions are  
 119 consolidated into unified management (case 3), marginal benefits analysis suggests the lowest water use among the  
 120 cases.

### 121 3 DISCUSSION

122 The influences of institutions on the outcomes of social-ecological systems (SESs) were widely reported worldwide,  
 123 but few attempts to quantify their net effects [18]. Our results show that while 98-UBR decreased water use in the  
 124 YRB, 87-WAS increased it by 8.57%. The results challenged previous analyses (i.e., suggesting that 87-WAS "had  
 125 little practical effect") because theoretically, there should be few gaps between actual and synthetic water use in the  
 126 YRB if no effect is present [19, 20]. However, the significant net effect indicated by our analysis suggests 87-WAS  
 127 was followed by more water use even after controlling for environmental and economic variables (see [Appendix B:](#)  
 128 [Robustness of DSC method](#) Table B1). On the contrary, the 98-UBR reduced water competition, so many studies  
 129 attributed the restoration mainly to the successful introduction of this institution [21–23].



130 The above comparison suggests that the 87-WAS, whose results were contrary to the purpose of the institution,  
131 is similar to many other SES governance failures, supporting that mismatched socio-ecological structures can dete-  
132 rioration of common resources [24–26]. The increased water use after 87-WAS aligns with concerns about frequently  
133 scrambling for water in some provinces during this period [27, 28]. Although reasons for the non-ideal effect of 87-  
134 WAS had been widely discussed [22] (such as enforcement, feasibility, and equity), however, structural change has  
135 received limited attention. Our results show that the correlation between current water use and changed (increased  
136 or decreased) water use was significant after 87-WAS (Figure 4). This “major users use more” pattern supports  
137 the hypothesis that separated stakeholders (individual provinces) will respond to structure by maximizing utility  
138 (interpreted in our structure-based model, see Figure 5).

139 The validity of our theoretical analysis is supported by two facts: (1) The water quotas of 87-WAS (or the initial  
140 water rights) went through a stage of “bargaining” among stakeholders (from 1982 to 1987) [7, 29], where each  
141 province attempted to demonstrate its development potential related to water use. The bargaining was also a process  
142 for matching water shares to economic volume because the major water users (like Shandong and Henan) needed  
143 more water than their original quota (if only considering economic potentials when designing the institution) [30].  
144 (2) Provinces with higher current water use might have greater bargaining power in water use allocation because  
145 of information asymmetry between decision-makers and stakeholders. Therefore, stakeholders had considerable  
146 incentives to prevent water quotas from hindering their economic potential, which aligned with their appeals to the  
147 higher central government for larger shares [7, 29].

148 On the other hand, social-ecological matches can also be supported by structure effects. After 98-UBR, the  
149 YRCC could adjust water use quotas to match river conditions for the whole YRB. When the YRCC began to  
150 coordinate among stakeholders, the external appeals of provinces for larger quotas turned into internal innovation  
151 to improve water efficiency (e.g., drastically increased water-conserving equipment) [31, 32]. During this period,  
152 proportional decreased water use of provinces indicated a positive result of the regulation (see [Heterogeneous effects](#)  
153 [and interpretation](#)). The 98-UBR thus led to expected institutional outcomes at a basin scale, indicating that  
154 successful governance of SES emerged by indirectly (or vertically) creating links between different stakeholders. Our  
155 model demonstrates that in this case, a unified scale-matched institution was indispensable for sustainable water  
156 use.

157 The structural building blocks we depicted here (Figure 2) have also been reported in other SESs worldwide  
158 [14, 33, 34]. Before 98-UBR, SES structure (i.e., fragment ecological units linked to separate social actors) was more  
159 likely to be mismatched because isolated actors generally struggle to maintain interconnected ecosystems holistically  
160 [25, 35–37]. Institutional re-alignments since 98-UBR improved the authority of the YRCC and helped it match the

scale of resource provisioning in the YRB, leading to enhanced social-ecological fit and better outcomes [7, 18]. The comparison demonstrates again the challenge of finding win-win situations in coupled human-nature systems [38], and the need to more deeply understand the role of social-ecological structures [36, 37].

Our approach has some inevitable limitations. First, the contributions of economic growth and institutional shifts are difficult to distinguish because of intertwined causality (institutional changes can also influence the relative economic variables); and second, when applying the DSC method, it is difficult to rule out the effects of other policies over the same time breakpoints (1987 and 1998). Our quasi-experiment approach nonetheless provides evidence supporting the view that there was a change in water use trajectory following the YRB's unique institutional shifts and offers insights into water governance (and particularly the importance of having a scale-matched, basin-wide authority for water allocation solutions [13, 39, 40]). Moreover, the ultimate success of the 98-UBR institutional shift theoretically and practically proved the importance of social-ecological fit. 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. From these perspectives, two scenarios based on the marginal benefit analysis (see [Appendix D: Model extensions](#)) can inspire institutional design on how to reduce mismatches. For example, water rights transfers may be another way to build horizontal links between stakeholders that also have the potential to result in better water governance. In addition, policymakers can propose more dynamic and flexible institutions to increase the adaptation of stakeholders to a changing SES context [40].

The structural building blocks that led to different outcomes are recurring motifs in global SESs, so our proposed mechanism is crucial to governing such coupled systems. Calls for a redesign of water allocation institutions in the YRB in recent years also illustrate the importance of institutional solutions for sustainability (see [Appendix A: Contexts of institutional shifts](#)) [41]. Given the changing environmental context, outdated and inflexible water quotas can no longer meet the demands of sustainable development [29]. Thus, the Chinese government has embarked on a plan to redesign its decades-old water allocation institution (see [Appendix A: Contexts of institutional shifts](#)). Our analysis suggests that these initiatives can benefit by actively incorporating social-ecological matched building blocks when developing new institutions [13]. Moreover, our research provides a cautionary tale of how institutions can create perverse incentives [38], while insights from the YRB can provide guidelines for SESs management worldwide [42, 43].

## 188 4 CONCLUSION

189 Intense water use in one of the most anthropogenically altered large river basins, the Yellow River Basin (YRB),  
190 once led to drying up. Alterations of institutions eventually successfully restored water governance practices on a  
191 decadal time scale. We propose that the institutional shifts in the YRB (87-WAS and 98-UBR) framed two different  
192 SES structures and depicted them as widespread building blocks. We quantitatively estimate the net effects of these  
193 changes in the YRB and analyze the reasons from SES structural perspectives. Our results show that the historical  
194 records, the responses from stakeholders to structural changes, and the theoretical analysis from the marginal  
195 benefits analysis all support that fragmented ecological units linked to separate social actors frames a mismatched  
196 SES structure. Through the quasi-natural experiments of the YRB, we demonstrate that social-ecological fits can  
197 lead to successful SESs management worldwide with better sustainability outcomes.

## 198 5 MATERIALS AND METHODS

199 We first abstract the SES structures of water used in the YRB from 1979 to 2008, where two institutional shifts split  
200 the period into three pieces. To process the data, we use the Principal Components Analysis (PCA) method to reduce  
201 the dimensionality of variables affecting the total water use. We then estimated the net effects of two institutional  
202 shifts on total water use, changing trends, and differences of the YRB's provinces, by Differenced Synthetic Control  
203 (DSC) method [17]. Finally, for theoretical discussion, we developed a marginal benefit analysis based on identified  
204 SES structures to provide the observed pattern of water use changes with a theoretical interpretation.

### 205 5.1 Study area

206 The Yellow River Basin (YRB), the fifth-largest river basin worldwide, is known for its vital role in the socio-  
207 economic development of China. It supports 35.63% of China's irrigation and 30% of its population while containing  
208 only 2.66% of its water resources (data from <http://www.yrcc.gov.cn>, last access: July 13, 2022). In the 1980s, intense  
209 water use, accounting for about 80% of Yellow River surface runoff, combined with other forms of human interference  
210 (e.g., soil conservation and water conservancy projects), caused consecutive drying events and substantial ecological,  
211 economic, and social crises (e.g., wetland shrinkage, agriculture reduction, and a scramble for water). In response,  
212 Chinese authorities implemented several ambitious water management practices in the YRB to relieve water stress,  
213 such as reservoir regulation, the South-to-north Water Diversion Project (WDP), the 1987 Water Allocation Scheme  
214 (87-WAS), and the 1998 Unified Basinal Regulation (98-UBR) [7, 44]. Those efforts led to ecological restoration  
215 of wetlands and the estuarine delta. Drying up has been avoided for over 20 years, which is widely considered

a substantial management achievement. Instead of relying on engineering to increase water supply, institutional strategies like the 87-WAS (which assigned water quotas for provinces in the YRB) and the 98-UBR (under which provinces had to obtain permits from the Yellow River Conservancy Commission, YRCC, authority at a basin-level) focused mainly on limiting demand for water [28, 45]. While researchers have carefully evaluated and quantified the effects of engineering solutions on water supply[44], there have been few attempts to assess institutional contributions to successful water governance in the YRB.

## 5.2 Portraying structures

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 [14, 33, 46]. We apply the network approach [13] to portray SES structures by abstracting relationships between ecological units (river reaches), stakeholders (provinces), and the administrative unit (the YRCC) into general building blocks (or motifs) (see Figure ??), from the official documents. Empirical studies have suggested that such widespread building blocks in SES are the key to the functioning of structures. The network-based approach is to abstract connections between entities into links and nodes [14, 33, 46]. In this study, we examined the official documents of the two institutional shifts of concern (87-WAS and 98-UBR, see *Appendix A: Contexts of institutional shifts* for details). Besides the ecologically connected river reaches, the agents (provinces and the YRCC) are abstracted as nodes, and their required interactions regarding water use are summarized as links. The 1987-WAS requires the YRCC to monitor each river’s reach, while the 1998-UBR requires direct interactions (through water use licenses) between the YRCC and the provinces. Therefore, we linked the YRCC unit to each ecological unit after 87-WAS and each province unit after the 98-UBR. We tested whether focusing on SES structures rather than institutional details could reasonably explain the differences caused by institutional shifts in the YRB.

## 5.3 Dataset and preprocessing

We choose datasets and variables to compare on actual 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) [47]. To estimate the water use of the YRB by assuming there were no 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 B1.

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 of their trivial water use from the YRB (see *Appendix Table A1*).

245 We then divided the dataset into a “target group” and a “control group”, treating provinces involved in water quota  
246 as the target group ( $n = 8$ ) and other provinces as the control group ( $n = 20$ ) for applying the DSC.

247 Using the normalized data of all variables, we performed the PCA reduction to capture 89.63% explained variance  
248 by 5 principal components *Appendix Appendix B: Robustness of DSC method*. Bayan had proved that combining  
249 PCA and DSC can raise the robustness of causal inference [48]. We first applied the Zero-Mean normalization (unit  
250 variance), as the variables’ units are far different. Then, we apply PCA to the multi-year average of each province,  
251 using the Elbow method to decide the number of the principal components (*Appendix Appendix B: Robustness of*  
252 *DSC method Figure B5*). Finally, we transform the dataset and input the dimensions-reduced output into the DSC  
253 model.

## 254 5.4 Differenced Synthetic Control

255 Using the Differenced Synthetic Control (DSC) method, we estimate water use without the effect of the institutional  
256 shift. The DSC method is an effective identification strategy for estimating the net effect of historical events or  
257 policy interventions on aggregate units (such as cities, regions, and countries) by constructing a comparable control  
258 unit [19, 20, 49].

259 This method aims to evaluate the effects of policy change that are not random across units but focuses on some  
260 of them (i.e., institutional shifts in the YRB here). By re-weighting units to match the pre-trend for the treated and  
261 control units, the DSC method imputes post-treatment control outcomes for the treated unit(s) by constructing a  
262 synthetic version of the treated unit(s) equal to a convex combination of control units. Therefore, the synthetic and  
263 actual version difference can be estimated as a net effect for a treated unit.

264 In practice, all treated units (i.e., provinces) were affected by institutional shifts in 1987 and 1998, each taken as  
265 the “shifted” time  $t_0$  within two individually analyzed periods  $T$ : 1979-1998; 1987-2008. We include each province  
266 in the YRB ( $n = 8$ , see *Dataset and preprocessing*) as the treated unit separately, as multiple treated units approach  
267 had been widely applied [50]. Then, we consider the  $J + 1$  units observed in time periods  $T = 1, 2 \dots, T$  with  
268 the remaining  $J = 20$  units are untreated provinces from outside. We define  $T_0$  to represent the number of pre-  
269 treatment periods  $(1, \dots, t_0)$  and  $T_1$  the number post-treatment periods  $(t_0, \dots, T)$ , such that  $T = T_0 + T_1$ . The  
270 treated unit is exposed to the institutional shift in every post-treatment period  $T_0$ , unaffected by the institutional  
271 shift in all preceding periods  $T_1$ . Then, any weighted average of the control units is a synthetic control and can be  
272 represented by a  $(J * 1)$  vector of weights  $\mathbf{W} = (w_1, \dots, w_J)$ , with  $w_j \in (0, 1)$ . Among them, by introduce a  $(k * k)$   
273 diagonal, semidefinite matrix  $\mathbf{V}$  that signifies the relative importance of each covariate, the DSC method procedure  
274 for finding the optimal synthetic control ( $W$ ) is expressed as follows:

$$\mathbf{W}^*(\mathbf{V}) = \underset{\mathbf{W} \in \mathcal{W}}{\text{minimize}} (\mathbf{X}_1 - \mathbf{X}_0 \mathbf{W})' \mathbf{V} (\mathbf{X}_1 - \mathbf{X}_0 \mathbf{W}) \quad (1)$$

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  $\mathbf{W}^*(\mathbf{V})$ . Therefore, we choose  $\mathbf{V}^*$  to be the  $\mathbf{V}$  that results in  $\mathbf{W}^*(\mathbf{V})$  that minimizes the following expression:

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

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  $\mathbf{Z}_0$  be a  $(k * T_0)$  matrix containing the outcome for each control unit in the pre-treatment period, and  $k$  is the 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 [51, 52].

## 5.5 Marginal benefits analysis

To infer the mechanisms underlying the results, we developed an marginal benefits analysis based on marginal revenue to analyze how the institutional shift could have led to differences in water use.

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

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

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

Under the above-simplified assumptions, we demonstrate three cases -corresponding to the abstracted SES structures (Figure 2 C), inference of how SES structure alters the expected marginal benefits and costs of provinces making decisions. As one of the possible interpretations 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 Appendix C*:

297 *Optimization model for water use*, and some simple model-based extensions are involved in *Appendix Appendix D:*  
298 *Model extensions*.

## 299 References

- 300 [1] Distefano, T. & Kelly, S. Are we in deep water? Water scarcity and its limits to economic growth **142**, 130–147.  
301 <https://doi.org/10.1016/j.ecolecon.2017.06.019> .
- 302 [2] Dolan, F. *et al.* Evaluating the economic impact of water scarcity in a changing world **12** (1), 1915. [https:](https://doi.org/10.1038/s41467-021-22194-0)  
303 [//doi.org/10.1038/s41467-021-22194-0](https://doi.org/10.1038/s41467-021-22194-0) .
- 304 [3] Xu, Z. *et al.* Assessing progress towards sustainable development over space and time **577** (7788), 74–78.  
305 <https://doi.org/10.1038/s41586-019-1846-3> .
- 306 [4] Mekonnen, M. M. & Hoekstra, A. Y. Four billion people facing severe water scarcity **2** (2), e1500323. [https:](https://doi.org/10.1126/sciadv.1500323)  
307 [//doi.org/10.1126/sciadv.1500323](https://doi.org/10.1126/sciadv.1500323) .
- 308 [5] Flörke, M., Schneider, C. & McDonald, R. I. Water competition between cities and agriculture driven by  
309 climate change and urban growth **1** (1), 51–58. <https://doi.org/10.1038/s41893-017-0006-8> .
- 310 [6] Yoon, J. *et al.* A coupled human–natural system analysis of freshwater security under climate and population  
311 change **118** (14), e2020431118. <https://doi.org/10.1073/pnas.2020431118> .
- 312 [7] Wang, S. *et al.* Alignment of social and ecological structures increased the ability of river management **64** (18),  
313 1318–1324. <https://doi.org/10.1016/j.scib.2019.07.016> .
- 314 [8] Huggins, X. *et al.* Hotspots for social and ecological impacts from freshwater stress and storage loss **13** (1),  
315 439. <https://doi.org/10.1038/s41467-022-28029-w> .
- 316 [9] Konar, M., Garcia, M., Sanderson, M. R., Yu, D. J. & Sivapalan, M. Expanding the Scope and Foundation of  
317 Sociohydrology as the Science of Coupled Human-Water Systems **55** (2), 874–887. [https://doi.org/10.1029/](https://doi.org/10.1029/2018WR024088)  
318 [2018WR024088](https://doi.org/10.1029/2018WR024088) .
- 319 [10] Young, O. R., King, L. A. & Schroeder, H. (eds) *Institutions and Environmental Change: Principal Findings,*  
320 *Applications, and Research Frontiers* (MIT Press).

- 321 [11] Cumming, G. S. *et al.* Advancing understanding of natural resource governance: A post-Ostrom research  
322 agenda **44**, 26–34. <https://doi.org/10.1016/j.cosust.2020.02.005> .
- 323 [12] Lien, A. M. The institutional grammar tool in policy analysis and applications to resilience and robustness  
324 research **44**, 1–5. <https://doi.org/10.1016/j.cosust.2020.02.004> .
- 325 [13] Bodin, O. Collaborative environmental governance: Achieving collective action in social-ecological systems  
326 **357** (6352), eaan1114. <https://doi.org/10.1126/science.aan1114> .
- 327 [14] Kluger, L. C., Gorris, P., Kochalski, S., Mueller, M. S. & Romagnoni, G. Studying human–nature relationships  
328 through a network lens: A systematic review **2** (4), 1100–1116. <https://doi.org/10.1002/pan3.10136> .
- 329 [15] Epstein, G. *et al.* Institutional fit and the sustainability of social–ecological systems **14**, 34–40. <https://doi.org/10.1016/j.cosust.2015.03.005> .
- 330
- 331 [16] Green, O., Garmestani, A., van Rijswijk, H. & Keessen, A. EU Water Governance: Striking the Right Balance  
332 between Regulatory Flexibility and Enforcement? **18** (2). <https://doi.org/10.5751/ES-05357-180210> .
- 333 [17] Arkhangelsky, D., Athey, S., Hirshberg, D. A., Imbens, G. W. & Wager, S. Synthetic Difference-in-Differences  
334 **111** (12), 4088–4118. <https://doi.org/10.1257/aer.20190159> .
- 335 [18] Cumming, G. S. & Dobbs, K. A. Quantifying Social-Ecological Scale Mismatches Suggests People Should Be  
336 Managed at Broader Scales Than Ecosystems S2590332220303511. [https://doi.org/10.1016/j.oneear.2020.07.](https://doi.org/10.1016/j.oneear.2020.07.007)  
337 [007](https://doi.org/10.1016/j.oneear.2020.07.007) .
- 338 [19] Abadie, A., Diamond, A. & Hainmueller, J. Comparative Politics and the Synthetic Control Method: Com-  
339 parative Politics and the Synthetic Control Method **59** (2), 495–510. <https://doi.org/10.1111/ajps.12116>  
340 .
- 341 [20] Hill, A. D., Johnson, S. G., Greco, L. M., O’Boyle, E. H. & Walter, S. L. Endogeneity: A Review and  
342 Agenda for the Methodology-Practice Divide Affecting Micro and Macro Research **47** (1), 105–143. <https://doi.org/10.1177/0149206320960533> .
- 343
- 344 [21] Chen, C., Jia-jia, G. & Da-jun, S. Water resources allocation and re-allocation of the yel-  
345 low river basin **43** (04), 799–812. URL <https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=>



346 CJFD&dbname=CJFDLAST2021&filename=ZRZY202104015&uniplatform=NZKPT&v=tQHwxd2\_  
 347 O0DqVtXGxGXcwW5OsqQTjg6OYnfyCjw5KZ9N0rc-WLgZBBQvZ0UYeVHC .

348 [22] Hu An-gang, W. Y.-h. Institutional failure is an important reason for the depletion of the yellow river (63),  
 349 31. <https://doi.org/10.16110/j.cnki.issn2095-3151.2002.63.035> .

350 [23] Xin-dai, A., Qing, S. & Yong-qi, C. Prospect of water right system establish-  
 351 ment in yellow river basin (19), 66–69. URL <https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CJFD&dbname=CJFD2007&filename=SLZG200719038&uniplatform=NZKPT&v=5q38Jxp-3Q0FuG3N3kMKdCVt0LTbHDN93vRDqJTzRQsrS0ejKhJTBGXaCwppoYC> .  
 352  
 353

354 [24] Kellenberg, D. K. An empirical investigation of the pollution haven effect with strategic environment and trade  
 355 policy **78** (2), 242–255. <https://doi.org/10.1016/j.jinteco.2009.04.004> .

356 [25] Cai, H., Chen, Y. & Gong, Q. Polluting thy neighbor: Unintended consequences of China’s pollution reduction  
 357 mandates **76**, 86–104. <https://doi.org/10.1016/j.jeem.2015.01.002> .

358 [26] Barnes, M. L. *et al.* Social-ecological alignment and ecological conditions in coral reefs **10** (1), 2039. <https://doi.org/10.1038/s41467-019-09994-1> .  
 359

360 [27] Shou-long, M. Institutional analysis under the depletion of the yellow river (20), 58–61. URL [https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CJFD&dbname=CJFD2000&filename=ZWQW200020021&uniplatform=NZKPT&v=2rrGzyi0e\\_w91jdi27jR8I9gdp\\_Btpa0PKT3pUMZ0ofAYfVyv\\_Xr7VeoiesoGTxP](https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CJFD&dbname=CJFD2000&filename=ZWQW200020021&uniplatform=NZKPT&v=2rrGzyi0e_w91jdi27jR8I9gdp_Btpa0PKT3pUMZ0ofAYfVyv_Xr7VeoiesoGTxP) .  
 361  
 362

363 [28] Bouckaert, F. W., Wei, Y., Pittock, J., Vasconcelos, V. & Ison, R. River basin governance enabling pathways  
 364 for sustainable management: A comparative study between Australia, Brazil, China and France. *Ambio* **51** (8),  
 365 1871–1888 (2022). <https://doi.org/10.1007/s13280-021-01699-4> .

366 [29] Wang, Y. *et al.* Review of the implementation of the yellow river water allocation scheme for thirty years  
 367 **41** (9), 6–19. <https://doi.org/10.3969/j.issn.1000-1379.2019.09.002> .

368 [30] Qi-ting, Z., Bin-bin, W., Wei, Z. & Jun-xia, M. A method of water distribution in transboundary rivers and  
 369 the new calculation scheme of the yellow river water distribution **42** (01), 37–45. <https://doi.org/10.18402/resci.2020.01.04> .  
 370

- 371 [31] Krieger, J. H. Progress in Ground Water Replenishment in Southern California **47** (9), 909–913. <https://doi.org/10.1002/j.1551-8833.1955.tb19237.x>, <https://arxiv.org/abs/41254171> .
- 372
- 373 [32] Ostrom, E. *Governing the Commons: The Evolution of Institutions for Collective Action* Political Economy  
374 of Institutions and Decisions (Cambridge University Press).
- 375 [33] Guerrero, A., Bodin, Ö., McAllister, R. & Wilson, K. Achieving social-ecological fit through bottom-up  
376 collaborative governance: An empirical investigation **20** (4). <https://doi.org/10.5751/ES-08035-200441> .
- 377 [34] Bodin, Ö. & TengÖ, M. Disentangling intangible social–ecological systems **22** (2), 430–439. [https://doi.org/](https://doi.org/10.1016/j.gloenvcha.2012.01.005)  
378 [10.1016/j.gloenvcha.2012.01.005](https://doi.org/10.1016/j.gloenvcha.2012.01.005) .
- 379 [35] Sayles, J. S. & Baggio, J. A. Social–ecological network analysis of scale mismatches in estuary watershed  
380 restoration **114** (10), E1776–E1785. <https://doi.org/10.1073/pnas.1604405114> .
- 381 [36] Sayles, J. S. Social-ecological network analysis for sustainability sciences: A systematic review and innovative  
382 research agenda for the future 19. <https://doi.org/10.1088/1748-9326/ab2619> .
- 383 [37] Bergsten, A. *et al.* Identifying governance gaps among interlinked sustainability challenges **91**, 27–38. <https://doi.org/10.1016/j.envsci.2018.10.007> .
- 384
- 385 [38] Hegwood, M., Langendorf, R. E. & Burgess, M. G. Why win–wins are rare in complex environmental  
386 management 1–7. <https://doi.org/10.1038/s41893-022-00866-z> .
- 387 [39] Ostrom, E. A General Framework for Analyzing Sustainability of Social-Ecological Systems **325** (5939),  
388 419–422. <https://doi.org/10.1126/science.1172133> .
- 389 [40] Reyers, B., Folke, C., Moore, M.-L., Biggs, R. & Galaz, V. Social-Ecological Systems Insights for Navigating  
390 the Dynamics of the Anthropocene **43** (1), 267–289. <https://doi.org/10.1146/annurev-environ-110615-085349> .
- 391 [41] Yu, W. *et al.* Adaptability assessment and promotion strategy of the Yellow River Water Allocation Scheme  
392 **30** (5), 632–642 .
- 393 [42] Muneeppeerakul, R. & Anderies, J. M. Strategic behaviors and governance challenges in social-ecological systems  
394 **5** (8), 865–876. <https://doi.org/10.1002/2017EF000562> .

- 395 [43] Leslie, H. M. *et al.* Operationalizing the social-ecological systems framework to assess sustainability **112** (19),  
396 5979–5984. <https://doi.org/10.1073/pnas.1414640112> .
- 397 [44] Long, D. *et al.* South-to-North Water Diversion stabilizing Beijing’s groundwater levels **11** (1), 3665. <https://doi.org/10.1038/s41467-020-17428-6> .
- 398
- 399 [45] Speed, R. & Asian Development Bank. *Basin Water Allocation Planning: Principles, Procedures, and*  
400 *Approaches for Basin Allocation Planning* (Asian Development Bank, GIWP, UNESCO, and WWF-UK). URL  
401 <http://www.adb.org/sites/default/files/pub/2013/basic-water-allocation-planning.pdf>.
- 402 [46] Bodin, Ö., Barnes, M. L., McAllister, R. R., Rocha, J. C. & Guerrero, A. M. Social–Ecological Network  
403 Approaches in Interdisciplinary Research: A Response to Bohan *et al.* and Dee *et al.* **32** (8), 547–549. <https://doi.org/10.1016/j.tree.2017.06.003> .
- 404
- 405 [47] Zhou, F. *et al.* Deceleration of China’s human water use and its key drivers **117** (14), 7702–7711. <https://doi.org/10.1073/pnas.1909902117> .
- 406
- 407 [48] Bayani, M. Robust Pca Synthetic Control (3920293). URL <https://papers.ssrn.com/abstract=3920293> .
- 408 [49] Abadie, A., Diamond, A. & Hainmueller, J. Synthetic Control Methods for Comparative Case Studies: Esti-  
409 mating the Effect of California’s Tobacco Control Program **105** (490), 493–505. [https://doi.org/10.1198/jasa.](https://doi.org/10.1198/jasa.2009.ap08746)  
410 [2009.ap08746](https://doi.org/10.1198/jasa.2009.ap08746) .
- 411 [50] Abadie, A. Using Synthetic Controls: Feasibility, Data Requirements, and Methodological Aspects **59** (2),  
412 391–425. <https://doi.org/10.1257/jel.20191450> .
- 413 [51] Billmeier, A. & Nannicini, T. Assessing Economic Liberalization Episodes: A Synthetic Control Approach  
414 **95** (3), 983–1001. <https://doi.org/10.1162/REST.a.00324> .
- 415 [52] Smith, B. The resource curse exorcised: Evidence from a panel of countries **116** (C), 57–73. [https://doi.org/](https://doi.org/10.1016/j.jdeveco.2015.04.001)  
416 [10.1016/j.jdeveco.2015.04.001](https://doi.org/10.1016/j.jdeveco.2015.04.001) .
- 417 [53] Wang, Z. & Zheng, Z. Things and current significance of the yellow river water allocation scheme in 1987  
418 **41** (10), 109–127. <https://doi.org/10.3969/j.issn.1000-1379.2019.10.019> .

## 419 A Appendix A: Contexts of institutional shifts

420 Water allocation institutions are widespread in large river basin management programs throughout the world (see  
421 *Appendix Figure A1*) [45]. This was the first basin in China for which a water resource allocation institution was  
422 created, and institutional shifts can be traced through several documents released by the Chinese government (at  
423 the national level)[29]:

- 424 • **1982:** The provinces and the Yellow River Water Conservancy Commission (YRCC) are required to develop a  
425 water resource plan for the Yellow River [29, 53].
- 426 • **1987:** Implementation of the Allocation Plan. ([http://www.gov.cn/zhengce/content/2011-03/30/content\\_3138.](http://www.gov.cn/zhengce/content/2011-03/30/content_3138.htm#)  
427 [htm#](http://www.gov.cn/zhengce/content/2011-03/30/content_3138.htm#), last access: July 13, 2022).
- 428 • **1998:** Implementation of unified regulation. ([http://www.mwr.gov.cn/ztpd/2013ztbd/2013fxkh/fxkhswcbcs/](http://www.mwr.gov.cn/ztpd/2013ztbd/2013fxkh/fxkhswcbcs/cs/ffg/201304/t20130411_433489.html)  
429 [cs/ffg/201304/t20130411\\_433489.html](http://www.mwr.gov.cn/ztpd/2013ztbd/2013fxkh/fxkhswcbcs/cs/ffg/201304/t20130411_433489.html), last access: July 13, 2022).
- 430 • **2008:** Provinces are asked to draw up new water resources plans for the YRB to further refine water allocations  
431 [29, 53].
- 432 • **2021:** A call for redesigning the water allocation institution ([http://www.ccg.gov.cn/cggg/zygg/gkzb/](http://www.ccg.gov.cn/cggg/zygg/gkzb/202107/t20210721_16591901.htm)  
433 [202107/t20210721\\_16591901.htm](http://www.ccg.gov.cn/cggg/zygg/gkzb/202107/t20210721_16591901.htm), last access: July 13, 2022).

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

438 The official documents in 1987 ([http://www.gov.cn/zhengce/content/2011-03/30/content\\_3138.htm#](http://www.gov.cn/zhengce/content/2011-03/30/content_3138.htm#), last  
439 access: July 13, 2022) convey the following key points:

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

444 The official documents in 1998 ([http://www.mwr.gov.cn/ztpd/2013ztbd/2013fxkh/fxkhswcbcs/cs/ffg/201304/](http://www.mwr.gov.cn/ztpd/2013ztbd/2013fxkh/fxkhswcbcs/cs/ffg/201304/t20130411_433489.html)  
445 [t20130411\\_433489.html](http://www.mwr.gov.cn/ztpd/2013ztbd/2013fxkh/fxkhswcbcs/cs/ffg/201304/t20130411_433489.html), last access: July 13, 2022) convey the following key points:

- 446 • The document points out that not only provinces and autonomous regions involved in water resources man-

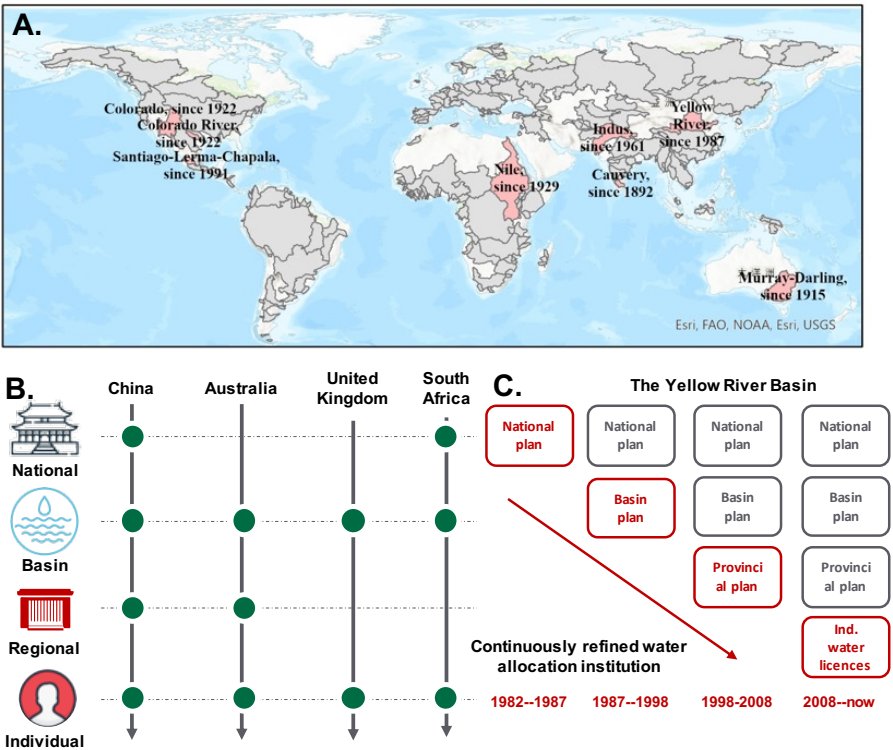
447 agement (see *Article 3*), the provinces' and regions' water use shall be declared, organized, and supervised by

448 the YRCC (*Article 11 and Chapter III to Chapter V, and Chapter VII*).
- 449 • Creating the overall plan of water use in the upper, middle, and lower reaches is identified as the first

450 consideration of this institution (*Article 1*).
- 451 • With the same quota as used in the 1987 policy, provinces were encouraged to further distribute their quota

452 into lower-level administrations (see *Article 6 and Article 41*).
- 453 • They emphasize that supply is determined by total quantity, and water use should not exceed the quota

454 proposed in 1987 (see *Article 2*).



**Supplementary Figure A1** 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) [45]. **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 A1** Water quotas assigned in the 87-WAS

Items (water volume, billion $m^3$ )	Qinghai	Sichuan	Gansu	Ningxia	Inner Mon- golia	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 <sup>a</sup>	25.80	36.58	61.97	21.16	11.97	34.30	77.87	5.85 <sup>a</sup>
Proportion of water from the Yellow River in total water consumption	48.12%	0.10 <sup>b</sup> %	30.79%	58.45%	47.82%	73.55%	44.39%	24.77%	34.41%	3.11% <sup>b</sup>

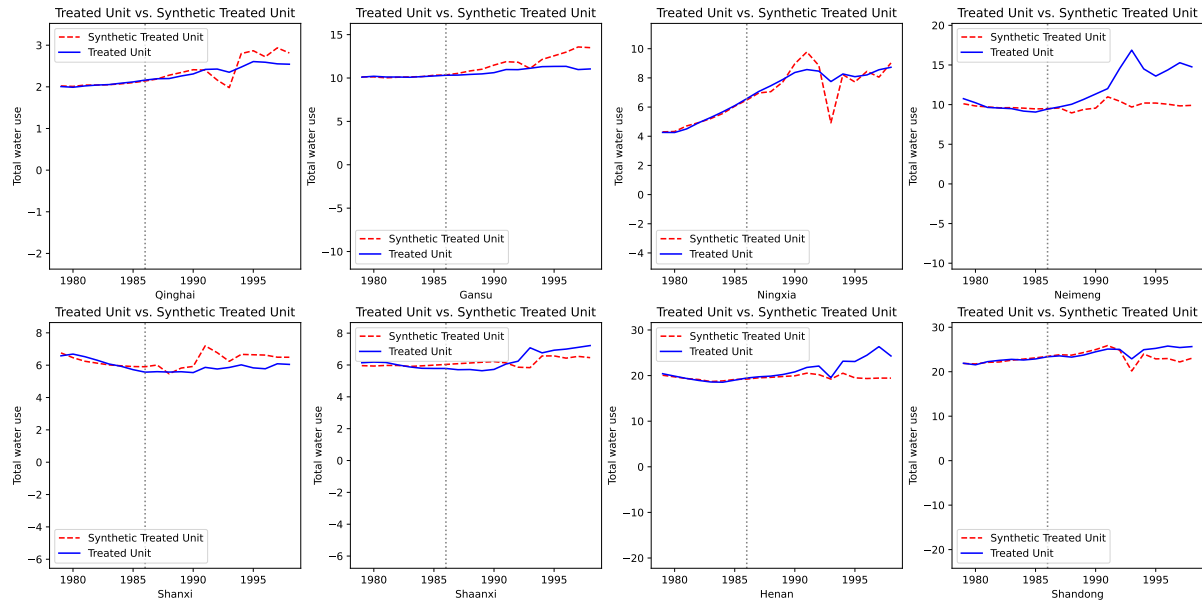
[a]Calculated by data from 2004 to 2017.

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

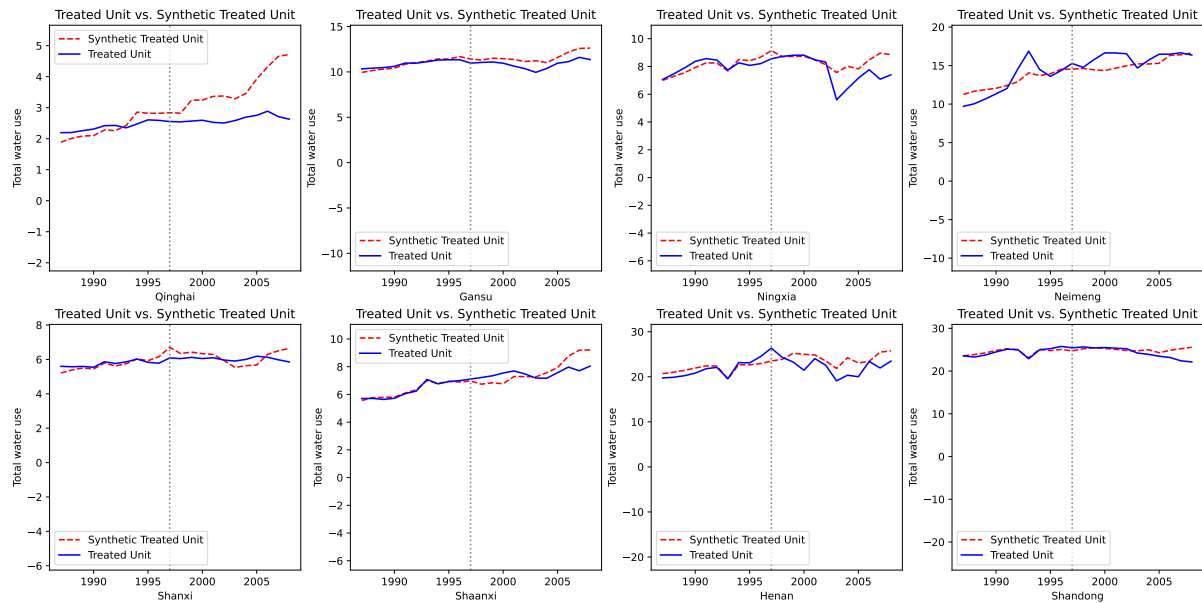
Based on the above documents, we abstracted the structural changes of SES (see *Appendix S2*) after the two institutional changes, as shown in Figure 2 C.

## B Appendix B: Robustness of DSC method

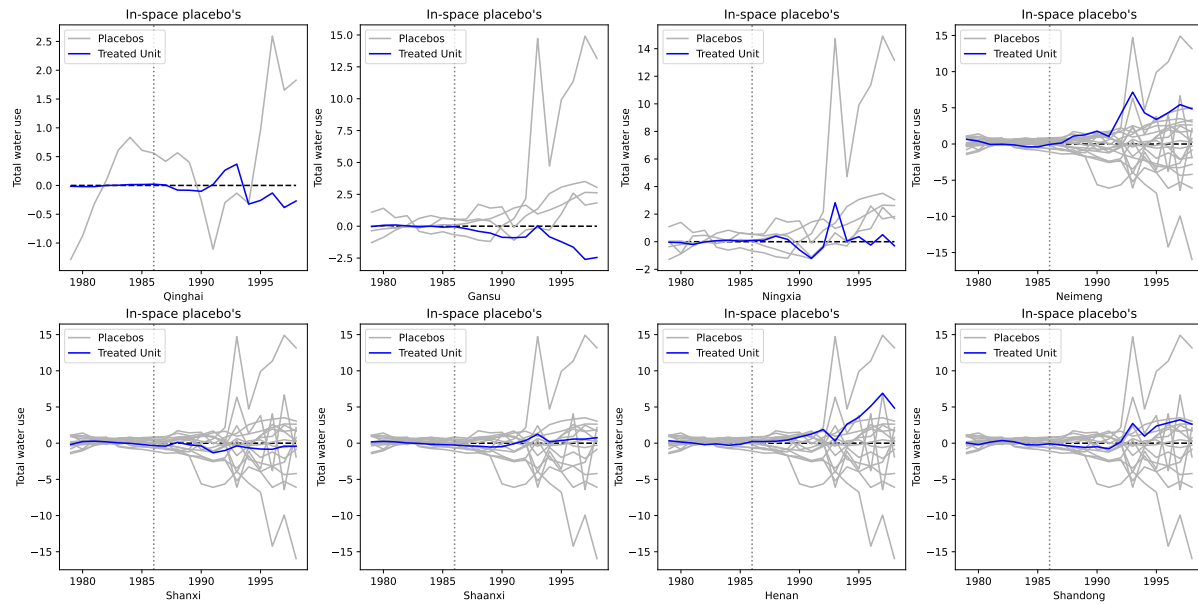
Explanatory variables are the key to constructing a robust synthetic control method. We used a total of 24 variables related to water consumption Table B1, which datasets have been used in previous studies to explain changes in water use in China [47]. In addition, we selected 5 principal components as input by the elbow method because selection in autocorrelated variables reduces dimensions and then enhances the robustness of the DSC (Figure B5). There are two approaches to validity testing of the DSC: (1) comparing the post-treated and pre-treated reconstructions and (2) testing robustness through placebo analysis. For (1), differences between each province and their synthetic are significant in post-treated periods and small in pre-treated periods (Figure B1 and figure B2), which show good reconstructions of their water use changes' estimation. For (2), we applied the in-place placebo analysis described by [49]. In most provinces, ratios of post-MSPE to pre-MSPE are higher than the median of other placebo units, which suggests the institutional shifts in treated time (1987 and 1998 here) influenced them more than most of the other provinces (figure B3, figure B4, Table B2).



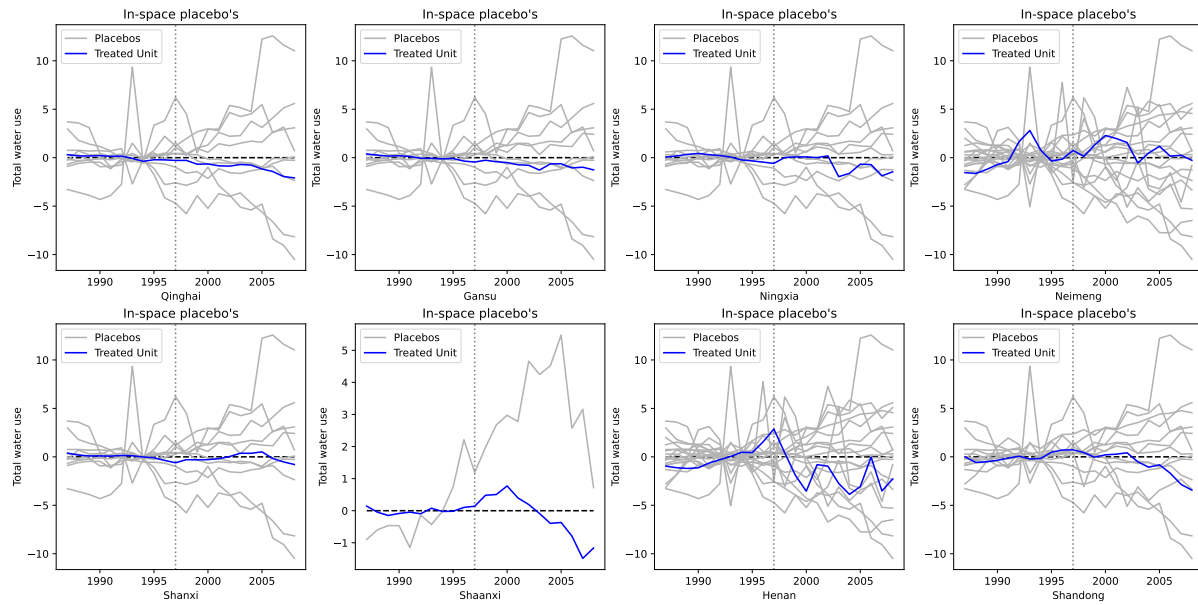
**Supplementary Figure B1** Comparisons between YRB' provinces and their synthetic controls around the 87-WAS.



**Supplementary Figure B2** Comparisons between YRB' provinces and their synthetic controls around the 98-UBR.



**Supplementary Figure B3** Gaps in change in water use between provinces outside the YRB and their synthetic control, around the 87-WAS, excluding the provinces with high pre-treatment RMSPE (more than 3 times of treated units' RMSPE).



**Supplementary Figure B4** Gaps in change in water use between provinces outside the YRB and their synthetic control, around the 98-UBR, excluding the provinces with high pre-treatment RMSPE (more than 3 times of treated units' RMSPE)



**Table B1** Variables and their categories for water use predictions

Sector	Category	Unit	Description	Variables
Agriculture	Irrigation Area	thousand ha	Area equipped for irrigiation by different crop:	Rice, Wheat, Maize, Fruits, Others.
				Textile, Papermaking, Petrochemicals, Metallurgy, Mining, Food, Cements, Machinery, Electronics, Thermal electrivity, Others.
Industry	Industrial gross value added	Billion Yuan	Industrial GVA by industries	Ratio of industrial water recycling, Ratio of industrial water evaporated.
	Industrial water use efficiency	%	The ratio of recycled water and evaporated water to total industrial water use	
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
Environment	Temperature	$K$	Near surface air temperature	Temperature
	Precipitation	$mm$	Annual accumulated precipitation	Precipitation

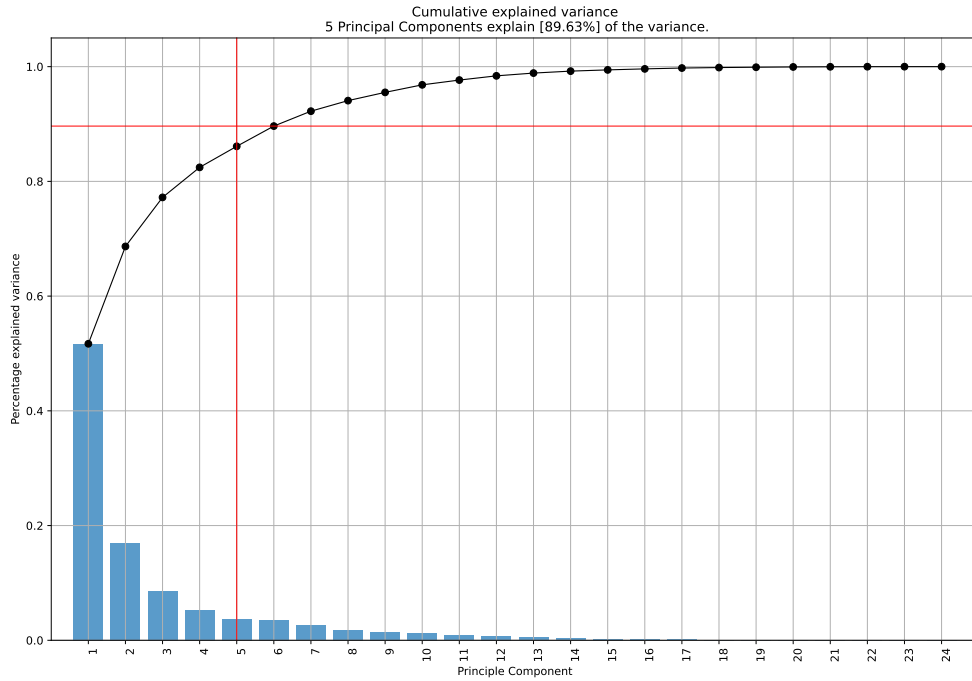
C Appendix C: Optimization model for water use

Setup

To understand the mechanisms through which the SES structure impacts provincial water use, we developed a dynamic marginal benefits analysis to analyze how institutional mismatch could have led to the changes in 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,



**Supplementary Figure B5** Choose number of principal components by Elbow method, 5 principal components already capture 89.63% explained variance.

**Table B2** Pre and post treatment root mean squared prediction error (RMSPE) for YRB's provinces

Provinces	1987-WAS				1998-UBR			
	Pre-RMSPE	Post-RMSPE	Ratio	Significant <sup>a</sup>	Pre-RMSPE	Post-RMSPE	Ratio	Significant <sup>a</sup>
Qinghai	0.016	0.231	14.606	True	0.230	1.170	5.096	True
Gansu	0.056	1.307	23.265	True	0.244	0.841	3.448	True
Ningxia	0.097	0.944	9.697	True	0.332	1.091	3.284	True
Neimeng	0.335	3.846	11.479	True	1.320	1.183	0.896	False
Shanxi	0.208	0.675	3.241	False	0.264	0.401	1.520	False
Shaanxi	0.181	0.572	3.164	False	0.096	0.724	7.579	True
Henan	0.210	3.207	15.292	True	1.222	2.479	2.029	False
Shandong	0.209	1.840	8.785	True	0.431	1.517	3.516	True

[a] Larger post/pre RMSPE than the median of the placebos.

479  $F'(0) = \infty$ ,  $F'(\infty) = 0$ ,  $F'(x) > 0$ , and  $F''(x) < 0$ . The production output is under perfect competition, with a  
480 constant unit price of  $P$ .

481 **Assumption 5.** (Ecological cost allocation) Under the assumption that the ecology is a single entity for the whole  
482 basin involved in  $N$  provinces, the cost of water use is equally assigned to each province under any water use. The  
483 unit cost of water is a constant  $C$ .

484 **Assumption 6.** (Multi-period settings) There are infinite periods with a constant discount factor  $\beta$  lying in  $(0,1)$ .  
485 There is no cross-period smoothing in water use.

486 Under the above assumptions, we can demonstrate three cases to simulate the water use decision-making and  
487 water use patterns in a whole basin.

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

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

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

492 
$$AF'(x) = \frac{C}{P},$$

493 where  $A_H$  and  $A_L$  denote high-incentive and low-incentive provinces, respectively.

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

495 
$$x_{it}^* = x_i^*$$

496 **Case 2.** *Mismatched institution:* This case corresponds to an SES structure where fragmented stakeholders are  
497 linked to unified river reaches.

498 The water quota is determined at  $t=0$  and imposed in  $t=1, 2, \dots$ . Under the subjective expectation of each province  
499 that current water use may influence the future water allocation determined by high-level authorities, the total quota  
500 is a constant denoted as  $Q$ , and the quota for province  $i$  is determined in a proportional form:

501 
$$Q_i = Q \cdot \frac{x_i}{x_i + \sum x_{-i}}.$$

502 Under a scenario with decentralized decision-making with a water quota, given other provinces' decisions on  
503 water use remain unchanged, the optimal water use of province  $i$  at  $t=0$  satisfies:

504 
$$AF'(x_{i,0}) = \frac{C}{P \cdot N} - \frac{\beta}{1-\beta} \cdot A \cdot f\left(Q \cdot \frac{x_{i,0}}{x_{i,0} + \sum x_{-i,0}}\right) \cdot Q \cdot \frac{\sum x_{-i,0}}{(x_{i,0} + \sum x_{-i,0})^2},$$

505 where  $A_H$  denotes a high-incentive province and  $A_L$  denotes a low-incentive province.

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

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

510 
$$F'(x) = \frac{C}{P}.$$

511 We propose Proposition 1 and Proposition 2:

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

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

516 Proposition 2: Water overuse is higher among provinces with high water use incentives than low- water use  
517 incentives under a mismatched institution.

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

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

524 Appendix: Water Use Optimization

525 **Case 1. Centralized decision**

526 When the  $N$  provinces decide on water uses as a unity, the marginal cost is  $C$ , equal to its fixed unit cost. The  
527 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.,  $AF'(x) = \frac{C}{P}$ ,  
528 where  $A$  denotes  $A_H$  for a high-incentive province and  $A_L$  for a low-incentive province.

529 **Case 2. Decentralized decision**

530 When each of the  $N$  provinces independently decides on its water use, the marginal cost of water use would be  
531  $\frac{C}{N}$  as a result of cost-sharing with others. Hence, the optimal water use in province  $i$  at period  $t$ , denoted as  $\hat{x}_i^*$ ,  
532 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,  $\hat{x}_{it}^* > x_i^*$ .

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

534 When the water quota would constrain future water use, the dynamic optimization problem of province  $i$  is shown  
 535 as follows. In  $t = 1, 2, \dots$ , there would be no relevant cost when the quota is bound that each province takes ongoing  
 536 costs of  $\frac{P \cdot Q}{N}$  regardless of the allocation. Therefore, it is sufficient to consider only the total water quota is less than  
 537 total water use in Case 2 since a “too large” quota doesn’t make sense for ecological policies.

$$538 \quad \max \quad P \cdot A \cdot F(x_{i,0}) - \frac{C \cdot \sum x_{i,0} + x_{-i,0}}{N} + \beta P \cdot A \cdot F(x_{i,1}) + \beta^2 P \cdot A \cdot F(x_{i,2}) + \dots$$

$$539 \quad = P \cdot A \cdot F(x_{i,0}) - C \cdot \frac{x_{i,0} + \sum x_{-i,0}}{N} + \frac{\beta}{1-\beta} P \cdot A \cdot F\left(Q \cdot \frac{x_{i,0}}{x_{i,0} + \sum x_{-i,0}}\right)$$

$$540 \quad \text{First-order condition: } P \cdot A \cdot F'(x_{i,0}) - \frac{C}{N} + \frac{\beta}{1-\beta} [P \cdot A \cdot f\left(Q \cdot \frac{x_{i,0}}{x_{i,0} + \sum x_{-i,0}}\right) \cdot Q \cdot \frac{\sum x_{-i,0}}{(x_{i,0} + \sum x_{-i,0})^2}] = 0$$

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

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

$$543 \quad Q \cdot \frac{\sum x_{-i,0}}{(x_{i,0} + \sum x_{-i,0})^2}, \text{ i.e., } A \cdot F'(x_{i,0}) = \frac{C}{P \cdot N} - \frac{\beta}{1-\beta} \cdot A \cdot f\left(Q \cdot \frac{x_{i,0}}{x_{i,0} + \sum x_{-i,0}}\right) \cdot Q \cdot \frac{\sum x_{-i,0}}{(x_{i,0} + \sum x_{-i,0})^2}.$$

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

547 *Proof of Proposition 1:*

548 Because  $F' > 0$  and  $F''(x) < 0$  is monotonically decreasing, based on a comparison of costs and benefits for  
 549 stakeholders (provinces) in the three cases,

$$550 \quad \tilde{x}_i^* > \hat{x}_i^* > x_i^*.$$

551 The result of  $\hat{x}_i^* > x_i^*$  indicates that individual rationality would deviate from collective rationality under unclear  
 552 property rights where a water user is fully responsible for the relevant costs. The result of  $\hat{x}_i^* > x_i^*$

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

557 *Proof of Proposition 2:*

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

560 The difference between  $\tilde{x}_i^*$  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  
 561 water overuse derived from an expectation of water quota allocation. The incentive of water overuse increases by  $A$ .

## 562 D Appendix D: Model extensions

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

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

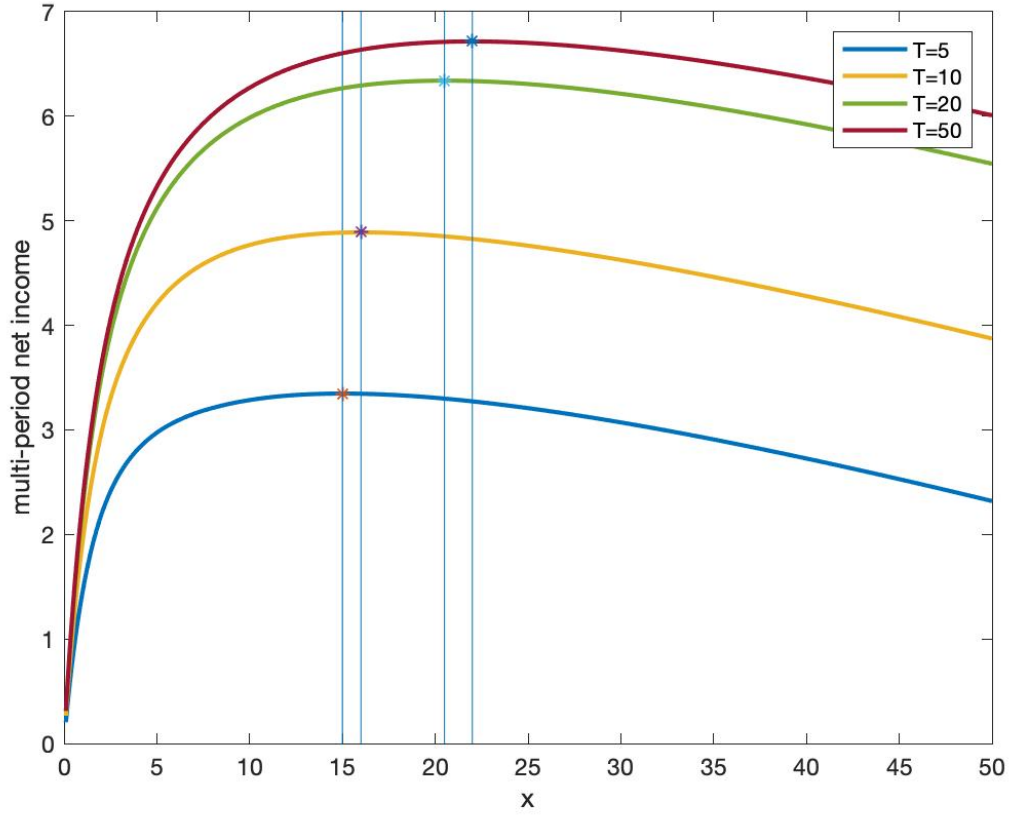
571 Even if the negative externality of water overuse is eliminated by “fair” ecology cost of  $\frac{x_{i,0}}{x_{i,0} + \sum x_{-i,0}} \cdot Q \cdot C$ , it is  
 572 possible that the future growth opportunities and “remote” ecological costs provide enough incentive for the sprint.  
 573 Water overuse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

575 (a) *technology growth*

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

$$\begin{aligned} 579 \quad & \max \quad P \cdot (1+g)^t \ln(1+x_{i,0}) - \frac{C}{N} + \beta^t \sum_{t=1}^T [P \cdot (1+g)^t \ln(x_{i,t}+1) - C \cdot x_{i,t}] \\ 580 \quad & \text{s.t.} \quad x_{i,t} \leq Q \cdot \frac{x_{i,0}}{x_{i,0} + \sum x_{-i,0}} \quad \text{for } \forall t \end{aligned}$$

581 We depict the relationship between multi-period profit and water use  $x_{i,0}$  in different horizons in Figure D1 ,  
 582 and thus find out the optimal water use pattern under technology growth. The higher marginal water output might  
 583 create enough incentive to offset the untransferable cost since a higher allocated quota provides growth option value.  
 584 On the other hand, as the provincial decision is under a longer horizon, there is a more significant sprint effect due  
 585 to higher accumulated yield and relatively tighter water use constraints over time.



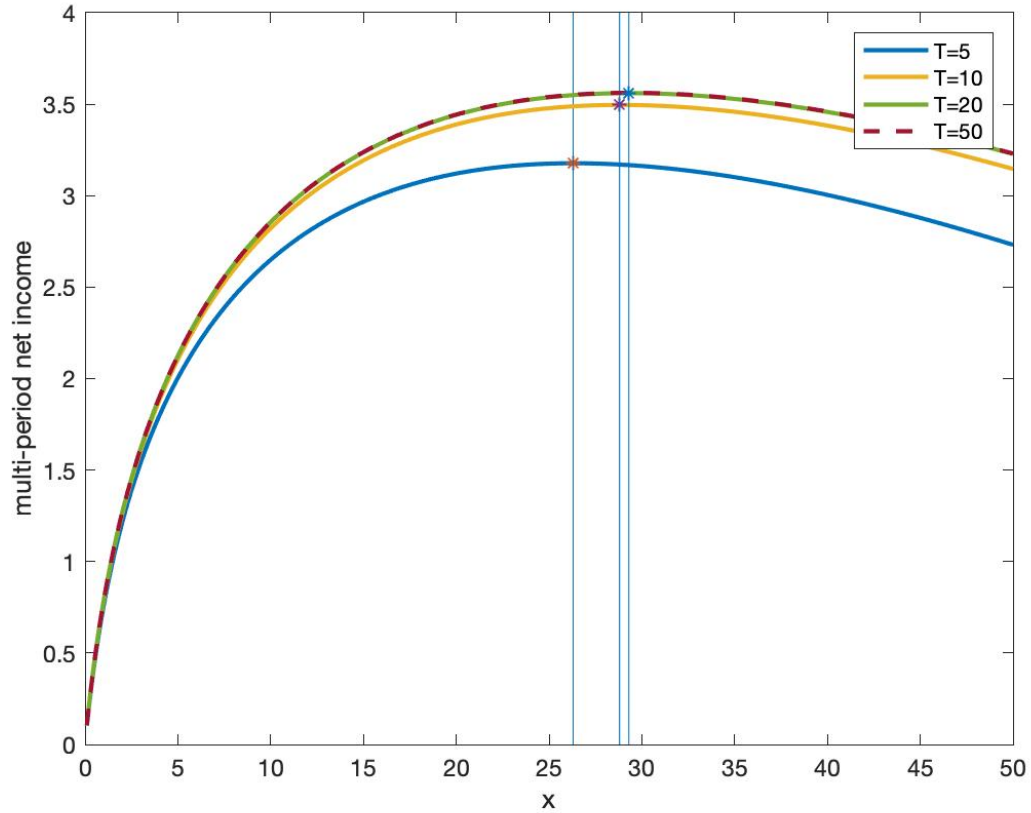
**Supplementary Figure D1** Multi-period optimization of optimal water use under technology growth. The figure depicts the relationship of multi-period benefits of province  $i$  and water use under Case 3 with technology growth. Assume  $F(x) = \ln(1 + x)$ ,  $N = 8$ ,  $P = 1$ ,  $C = 0.5$ ,  $\beta = 0.7$ ,  $g = 0.2$ , and  $Q = 8$ .

586 (b) Economic benefits and “remote” ecological costs with different discount factors

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

$$\begin{aligned}
 591 \quad & \max \quad P \cdot \ln(1 + x_{i,0}) - \frac{C}{N} + \beta_1^t \sum_{t=1}^T [P \cdot \ln(x_{i,t} + 1)] - \beta_2^t \sum_{t=1}^T [C \cdot x_{i,t}] \\
 592 \quad & \text{s.t.} \quad x_{i,t} \leq Q \cdot \frac{x_{i,0}}{x_{i,0} + \sum x_{-i,0}} \quad \text{for } \forall t
 \end{aligned}$$

593 We depict the relationship of multi-period net income and water use  $x_{i,0}$  in different horizons in Figure D2 ,  
594 and thus find out the optimal water use pattern under “remote” ecological costs. The higher discounted ecological  
595 costs might create enough incentive to set off the untransferable cost. On the other hand, as the provincial decision  
596 is under a longer horizon, a more significant sprint effect is due to a higher accumulated yield.



**Supplementary Figure D2** 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  $Q = 8$ .