Approaching social-ecological matches of river basin systems for sustainability

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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

1 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]. In the context of future climate change, the gap between supply and demand for water resources in large river basins is expected to become increasingly more prominent [5, 6]. Those river basin systems successfully supporting sustainable water resource use are structurally well-aligned with water provisioning and social-ecological demands, without inefficient competition or overuses [7]. However, balancing the water demands of ecosystems and development in heavily human-dominated river basins is a challenge because human activities and water are intertwined in their structures as complex social-ecological systems (SES) [8, 9].

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

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

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   In methodology, we explored causal linkages between SES structures and sustainability-related outcomes by

60 quasi-natural experiments (institutional shifts imposed by central government) in the YRB. Firstly, we used data on

61 changes in official documents following two institutional shifts (the 87-WAS and the 98-UBR) to describe comparable

62 changes in the SES structures associated with the YRB from 1979 to 2008, by abstracting them into SES structures

63 motifs (or building blocks, see *Portraying structures*). We then used a method called 'Differenced Synthetic Control

64 (DSC)' [17], which considers economic growth and natural background, to estimate theoretical water use scenarios

65 without institutional shifts (*Differenced Synthetic Control* and *Appendix B: Robustness of DSC method*). This

66 approach allowed us to create a counterfactual against which to explore the mechanisms linking SESs structure and

67 outcomes for a deeper understanding of the potential role of institutions in water governance worldwide. Finally,

68 we further developed an approach for marginal benefits analysis, to interpret the underlying processes of the match

69 and mismatched institutions based 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 1 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 1 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
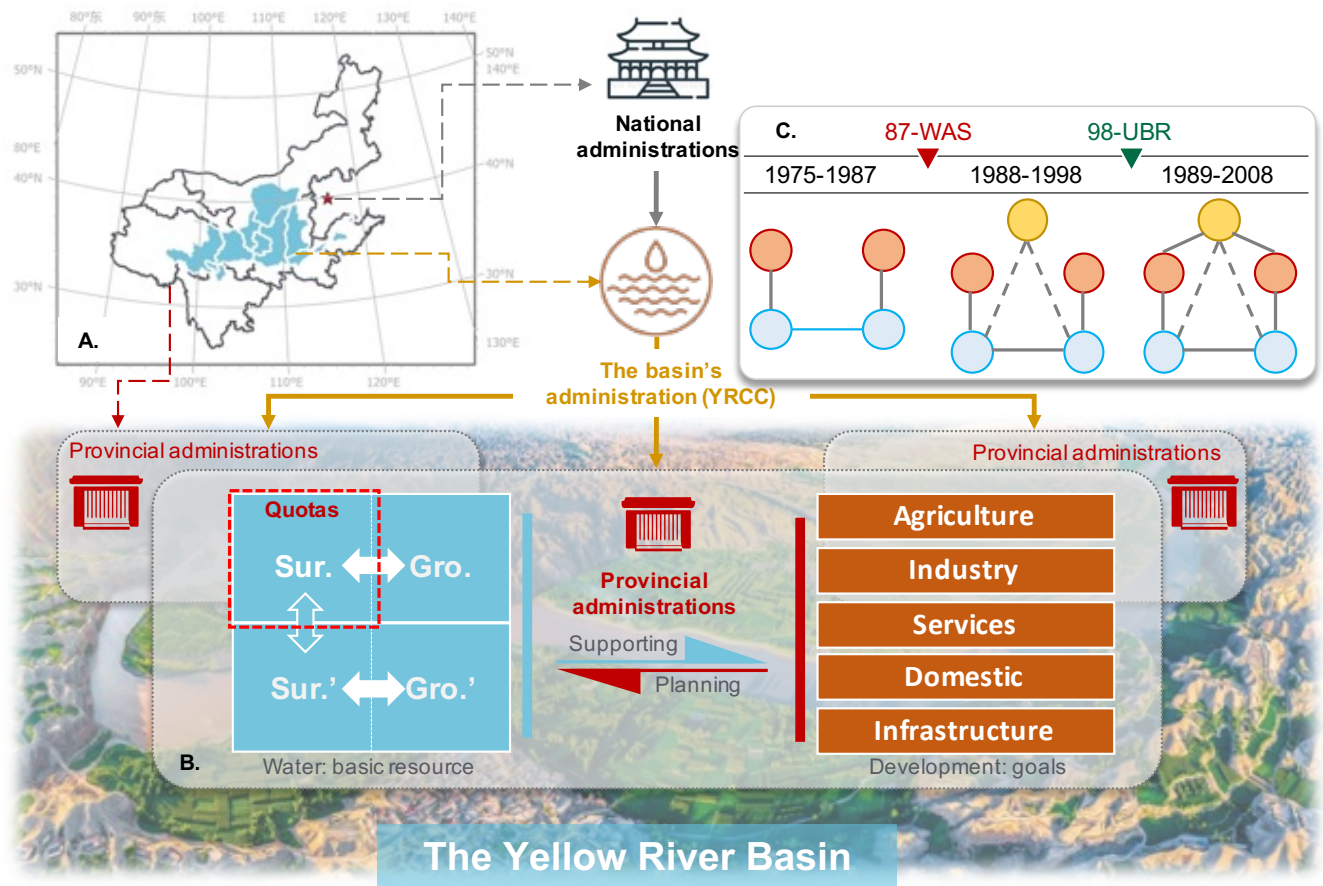
Fig. 1 Institutional shifts and related SES structures in the Yellow River Basin (YRB). **A.** The YBR crosses 10 provinces or the same-level administrative regions, 8 of which are highly relying on the water resources from the YRB (see *Appendix A: Contexts of institutional shifts* Table A1). The national 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).

(Figure 1 C). As result, the two institutional shifts reshaped SES structures, leading to three general structures linked by social actors and ecological nodes (Figure 1 C).
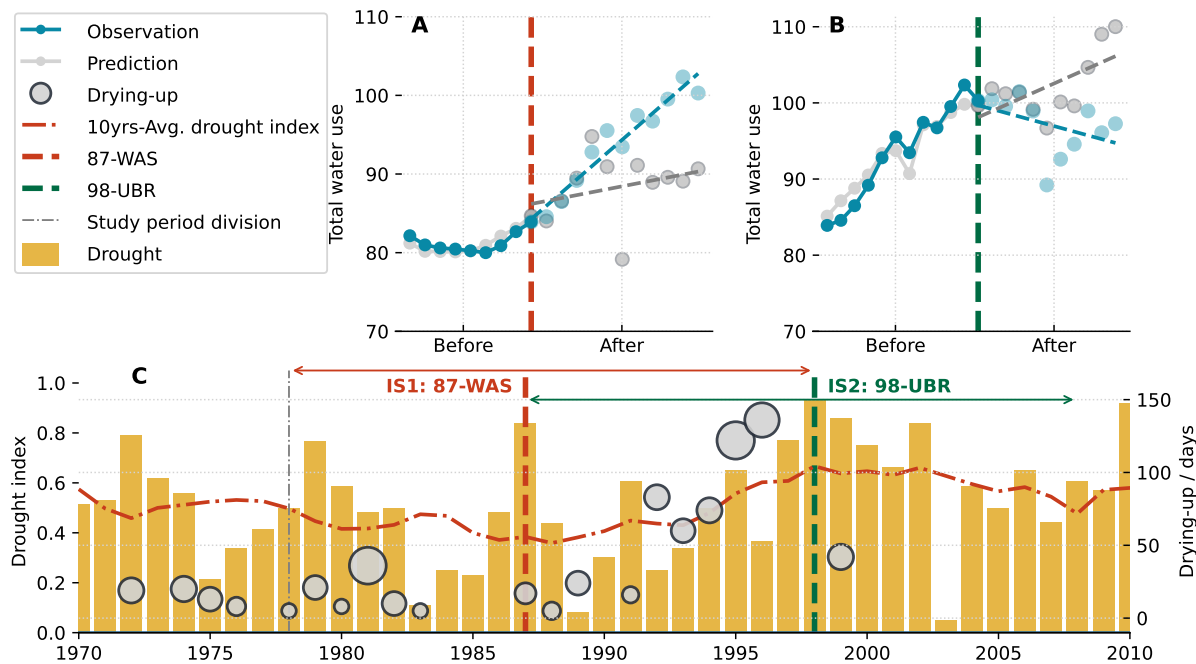
2.2 Institutional shifts impact on water use

Fig. 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). 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.

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 (an increase of 6.57%). However, after the institutional change in 1998 (98-UBR), trends 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

95 0.82 billion m^3/yr increases (Figure 2 B). The increased water uses after 87-WAS aligns with the severe drying-
96 down of the surface streamflow from 1987 to 1998, an obvious indicator of river degradation and environmental
97 crisis (Figure 2C). On the other hand, the 98-UBR ended river depletion, despite subsequent increases in drought
98 intensity (from 0.47 after 87-WAS to 0.62 after 98-UBR on average) (Figure 2C).

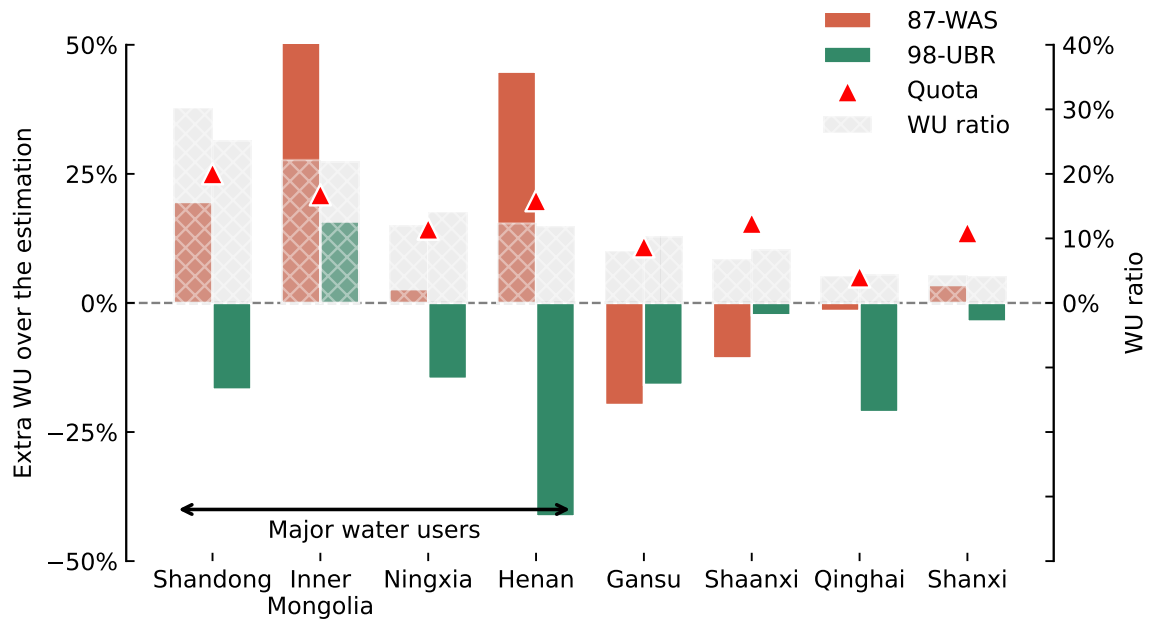## 2.3 Heterogeneous effects and interpretation

Fig. 3 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.

100 Our results also suggest differences between patterns of provinces in their responses to the two institutional
101 regulating. During the decade after the 87-WAS, the major water-using provinces (e.g., Inner Mongolia, Henan,
102 Shandong) had apparent accelerations (Figure 3). The proportion of increased (or decreased) water use for each
103 province (over the estimated water use by the model) correlated significantly (partial correlation coefficient is 0.77,
104 $p < 0.05$) 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 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.
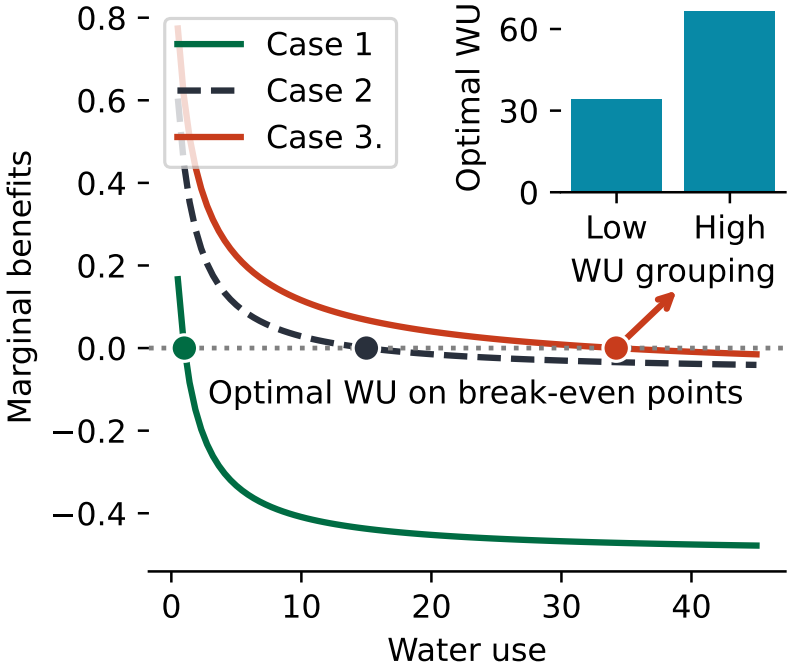

Fig. 4 The proposed relationship of marginal benefits and water use of individual province under varying cases (case 1 to case 3, corresponding to the different SES structures in Figure 1) Major water users' theoretically optimal water use is also larger (see Marginal benefits analysis and *Appendix C: Optimization model for water use*).

For interpretation of the pattern, we compared the theoretical marginal returns and optimal water use under three different structural cases (analogy to Figure 1 C, see Marginal benefits analysis Figure 4, 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. Until water-use decisions are consolidated into unified management, each stakeholder's expectation that current water use helps bargain for a favorable water quota may intensify the incentive to use water, leading to higher water use. Furthermore, water users with higher capability are more stimulated by institutional shifts and away from the theoretically optimal water use under a unified allocation.

3 DISCUSSION

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

The above comparison suggests that the 87-WAS, whose results were contrary to the purpose of the institution, is similar to many other SES governance failures, supporting that mismatched socio-ecological structures can deterioration of common resources [24–26]. The increased water use after 87-WAS aligns with concerns about frequently scrambling for water in some provinces during this period [27, 28]. Although reasons for the non-ideal effect of 87-WAS had been widely discussed [22] (such as enforcement, feasibility, and equity), however, structural change has received limited attention. Our results show that the correlation between current water use and changed (increased or decreased) water use was significant after 87-WAS (Figure 3). This "major users use more" pattern supports the hypothesis that separated stakeholders (individual provinces) will respond to structure by maximizing utility (interpreted in our structure-based model, see Figure 4).

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

On the other hand, social-ecological matches can also be supported by structure effects. After 98-UBR, the YRCC could adjust water use quotas to match river conditions for the whole YRB. When the YRCC began to coordinate among stakeholders, the external appeals of provinces for larger quotas turned into internal innovation

147 to improve water efficiency (e.g., drastically increased water-conserving equipment) [31, 32]. During this period,
148 proportional decreased water use of provinces indicated a positive result of the regulation (see Heterogeneous effects
149 and interpretation). The 98-UBR thus led to expected institutional outcomes at a basin scale, indicating that
150 successful governance of SES emerged by indirectly (or vertically) creating links between different stakeholders. Our
151 model demonstrates that in this case, a unified scale-matched institution was indispensable for sustainable water
152 use.

153   The structural building blocks we depicted here (Figure 1) have also been reported in other SESs worldwide
154 [14, 33, 34]. Before 98-UBR, SES structure (i.e., fragment ecological units linked to separate social actors) was more
155 likely to be mismatched because isolated actors generally struggle to maintain interconnected ecosystems holistically
156 [25, 35–37]. Institutional re-alignments since 98-UBR improved the authority of the YRCC and helped it match the
157 scale of resource provisioning in the YRB, leading to enhanced social-ecological fit and better outcomes [7, 18]. The
158 comparison demonstrates again the challenge of finding win-win situations in coupled human-nature systems [38],
159 and the need to more deeply understand the role of social-ecological structures [36, 37].

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

174   The structural building blocks that led to different outcomes are recurring motifs in global SESs, so our proposed
175 mechanism is crucial to governing such coupled systems. Calls for a redesign of water allocation institutions in the
176 YRB in recent years also illustrate the importance of institutional solutions for sustainability (see *Appendix A:*
177 *Contexts of institutional shifts*) [41]. Given the changing environmental context, outdated and inflexible water quotas

178 can no longer meet the demands of sustainable development [29]. Thus, the Chinese government has embarked on
179 a plan to redesign its decades-old water allocation institution (see *Appendix A: Contexts of institutional shifts*).
180 Our analysis suggests that these initiatives can benefit by actively incorporating social-ecological matched building
181 blocks when developing new institutions [13]. Moreover, our research provides a cautionary tale of how institutions
182 can create perverse incentives [38], while insights from the YRB can provide guidelines for SESs management
183 worldwide [42, 43].

4 CONCLUSION

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

5 MATERIALS AND METHODS

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

5.1 Study area

202 The Yellow River Basin (YRB), the fifth-largest river basin worldwide, is known for its vital role in the socio-
203 economic development of China. It supports 35.63% of China's irrigation and 30% of its population while containing
204 only 2.66% of its water resources (data from http://www.yrcc.gov.cn, last access: July 3, 2022). In the 1980s, intense

205 water use, accounting for about 80% of Yellow River surface runoff, combined with other forms of human interference

206 (e.g., soil conservation and water conservancy projects), caused consecutive drying events and substantial ecological,

207 economic, and social crises (e.g., wetland shrinkage, agriculture reduction, and a scramble for water). In response,

208 Chinese authorities implemented several ambitious water management practices in the YRB to relieve water stress,

209 such as reservoir regulation, the South-to-north Water Diversion Project (WDP), the 1987 Water Allocation Scheme

210 (87-WAS), and the 1998 Unified Basinal Regulation (98-UBR) [7, 44]. Those efforts led to ecological restoration

211 of wetlands and the estuarine delta. Drying up has been avoided for over 20 years, which is widely considered

212 a substantial management achievement. Instead of relying on engineering to increase water supply, institutional

213 strategies like the 87-WAS (which assigned water quotas for provinces in the YRB) and the 98-UBR (under which

214 provinces had to obtain permits from the Yellow River Conservancy Commission, YRCC, authority at a basin-level)

215 focused mainly on limiting demand for water [28, 45]. While researchers have carefully evaluated and quantified the

216 effects of engineering solutions on water supply[44], there have been few attempts to assess institutional contributions

217 to successful water governance in the YRB.

5.2 Portraying structures

218

219 We apply the network [13] approach to portray SES structures by abstracting relationships between ecological units

220 (river reaches), stakeholders (provinces), and the administrative unit (the YRCC) into general building blocks (or

221 motifs) (see Figure A1), from the official documents. Empirical studies have suggested that such widespread building

222 blocks in SES are the key to the functioning of structures. The network-based approach is to abstract connections

223 between entities into links and nodes [14, 33, 46]. In this study, we examined the official documents of the two

224 institutional shifts of concern (87-WAS and 98-UBR, see *Appendix Appendix A: Contexts of institutional shifts* for

225 details). Besides the ecologically connected river reaches, the agents (provinces and the YRCC) are abstracted as

226 nodes, and their required interactions regarding water use are summarized as links. The 1987-WAS requires the

227 YRCC to monitor each river's reach, while the 1998-UBR requires direct interactions (through water use licenses)

228 between the YRCC and the provinces. Therefore, we linked the YRCC unit to each ecological unit after 87-WAS

229 and each province unit after the 98-UBR. We tested whether focusing on SES structures rather than institutional

230 details could reasonably explain the differences caused by institutional shifts in the YRB.

5.3 Dataset and preprocessing

231

232 We choose datasets and variables to compare on actual and estimated water use of the YRB. The actual water

233 uses are accessible in China's provincial annual water consumption dataset from the National Water Resources

234 Utilization Survey, whose details are accessible from Zhou (2020) [47]. To estimate the water use of the YRB by
235 assuming there were no effects from institutional shifts, we focused on variables from five categories (environmental,
236 economic, domestic, and technological) water use factors. Their specific items and origins are listed in Table B1.

237   Among the total 31 data-accessible provinces (or regions) assigned quotas in the 87-WAS and the 98-UBR, we
238 dropped Sichuan, Tianjin, and Beijing because of their trivial water use from the YRB (see *Appendix* Table A1).
239 We then divided the dataset into a "target group" and a "control group", treating provinces involved in water quota
240 as the target group ($n = 8$) and other provinces as the control group ($n = 20$) for applying the DSC.

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

5.4 Differenced Synthetic Control

248

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

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

258   In practice, all treated units (i.e., provinces) were affected by institutional shifts in 1987 and 1998, each taken as
259 the "shifted" time t_0 within two individually analyzed periods T: 1979-1998; 1987-2008. We include each province
260 in the YRB ($n = 8$, see *Dataset and preprocessing*) as the treated unit separately, as multiple treated units approach
261 had been widely applied [50]. Then, we consider the $J + 1$ units observed in time periods $T = 1, 2 \cdots, T$ with
262 the remaining $J = 20$ units are untreated provinces from outside. We define T_0 to represent the number of pre-
263 treatment periods $(1, \cdots, t_0)$ and T_1 the number post-treatment periods $(t_0, \cdots, T)$, such that $T = T_0 + T_1$. The

treated unit is exposed to the institutional shift in every post-treatment period T_0, 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 $\mathbf{W} * (\mathbf{V})$. Therefore, we choose $\mathbf{V}^*$ to be the $\mathbf{V}$ that results in $\mathbf{W} * (\mathbf{V})$ that minimizes the following expression:

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

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 $\mathbf{Z}_0$ 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 1), 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: Optimization model for water use*, and some simple model-based extensions are involved in *Appendix Appendix D: Model extensions*.

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A Appendix A: Contexts of institutional shifts

We aim to abstract the water allocating institutions from the description in official documents with necessary context into SES building blocks (Figure A1) 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].
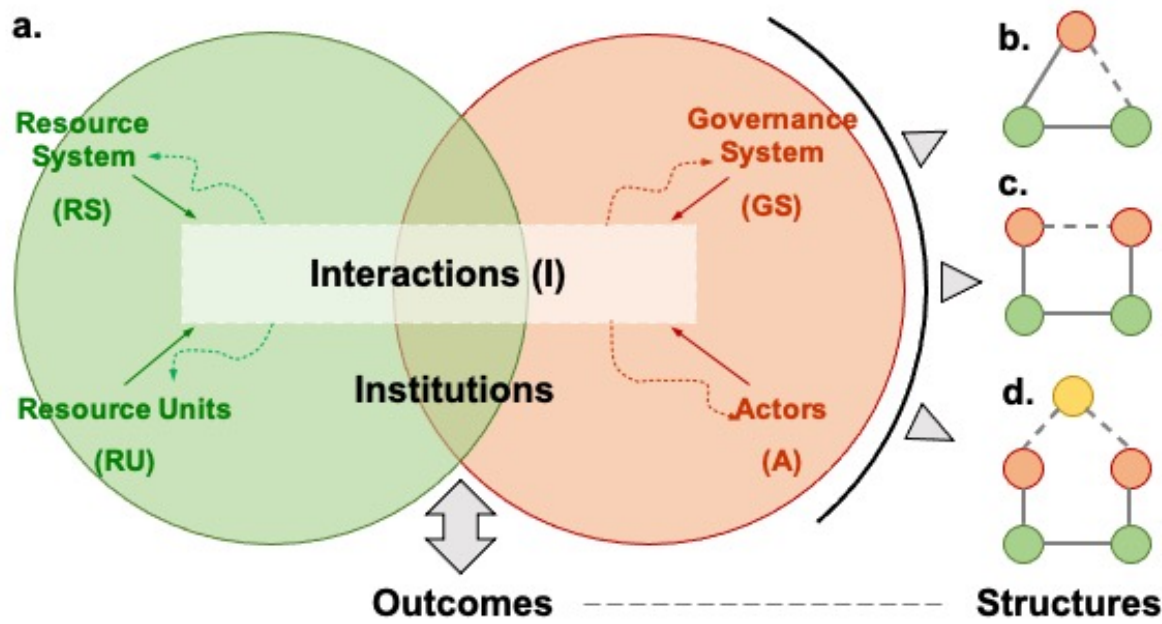
Supplementary Figure A1 Framework for understanding linkages between SES structures and outcomes. **a.** The general framework for analyzing social-ecological systems (SESs) (adapted from Ostrom [39]). Institutions embedded in SESs may reshape structures by changing the interactions between core subsystems, resulting in different outcomes. Three typical types of abstracted SES structures are shown as **b.**, **c.** and **d.** (adapted from Bodin, 2017)[13]. 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 gray lines link two units. According to empirical evidence, the gray dashed lines show aligned SES structures that are more likely to achieve a desirable outcome.

Water allocation institutions are widespread in large river basin management programs throughout the world (see *Appendix* Figure A2) [45]. 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)[29]:

- **1982**: The provinces and the Yellow River Water Conservancy Commission (YRCC) are required to develop a water resource plan for the Yellow River [29, 53].
- **1987**: Implementation of the Allocation Plan. (http://www.gov.cn/zhengce/content/2011-03/30/content_3138.htm#, last access: July 3, 2022).
- **1998**: Implementation of unified regulation. (http://www.mwr.gov.cn/ztpd/2013ztbd/2013fxkh/fxkhswcbcs/cs/flfg/201304/t20130411_433489.html, last access: July 3, 2022).
- **2008**: Provinces are asked to draw up new water resources plans for the YRB to further refine water allocations [29, 53].
- **2021**: A call for redesigning the water allocation institution (http://www.ccgp.gov.cn/cggg/zygg/gkzb/202107/t20210721_16591901.htm, last access: July 3, 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.gov.cn/zhengce/content/2011-03/30/content_3138.htm#, last access: July 3, 2022) convey the following key points:

- The policy is aimed at related provinces (or regions at the same administrative level).
- Depletion of the river is identified as the first consideration of this institution.
- Provinces are encouraged to develop their 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/ztpd/2013ztbd/2013fxkh/fxkhswcbcs/cs/flfg/201304/t20130411_433489.html, last access: July 3, 2022) convey the following key points:

- The document 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*).

451 • They emphasize that supply is determined by total quantity, and water use should not exceed the quota
452 proposed in 1987 (see *Article 2*).
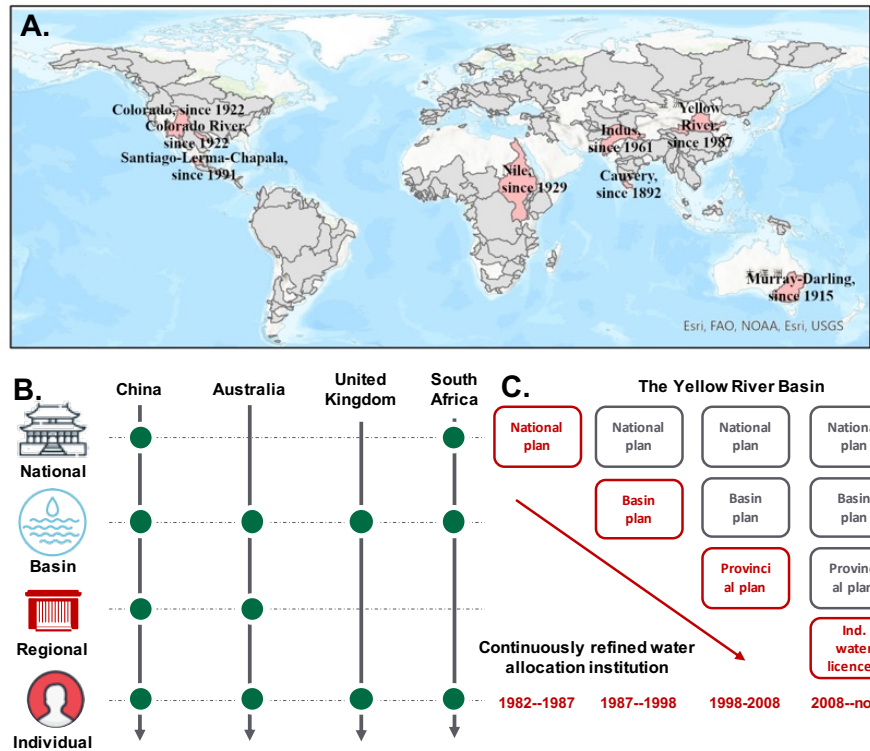
Supplementary Figure A2 Overview of water allocation institutions. **A.** Major river basins in the world with water resource allocation systems (shaded red); the YRB first proposed a resource allocation scheme in 1987 (designed since 1983) and then changed to a unified regulation scheme in 1998 (designed 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.

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

B Appendix B: Robustness of DSC method

456 Explanatory variables are the key to constructing a robust synthetic control method. We used a total of 24 variables
457 related to water consumption Table B1, which datasets have been used in previous studies to explain changes in

Table A1 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.

458 water use in China [47]. In addition, we selected 5 principal components as input by the elbow method because

459 selection in autocorrelated variables reduces dimensions and then enhances the robustness of the DSC (Figure B5).

460   There are two approaches to validity testing of the DSC: (1) comparing the post-treated and pre-treated recon-

461 structions and (2) testing robustness through placebo analysis. For (1), differences between each province and their

462 synthetic are significant in post-treated periods and small in pre-treated periods (Figure B1 and figure B2), which

463 show good reconstructions of their water use changes' estimation. For (2), we applied the in-place placebo analysis

464 described by [49]. In most provinces, ratios of post-MSPE to pre-MSPE are higher than the median of other placebo

465 units, which suggests the institutional shifts in treated time (1987 and 1998 here) influenced them more than most

466 of the other provinces (figure B3, figure B4, Table B2).

C Appendix C: Optimization model for water use

Setup

469 To understand the mechanisms through which the SES structure impacts provincial water use, we developed a

470 dynamic marginal benefits analysis to analyze how institutional mismatch could have led to the changes in water use,

471 especially among provinces with high incentives for excess water use. Specifically, we modeled individual provincial

472 decision-making in water resources before quota execution.

473   We proposed three intuitive and general assumptions:
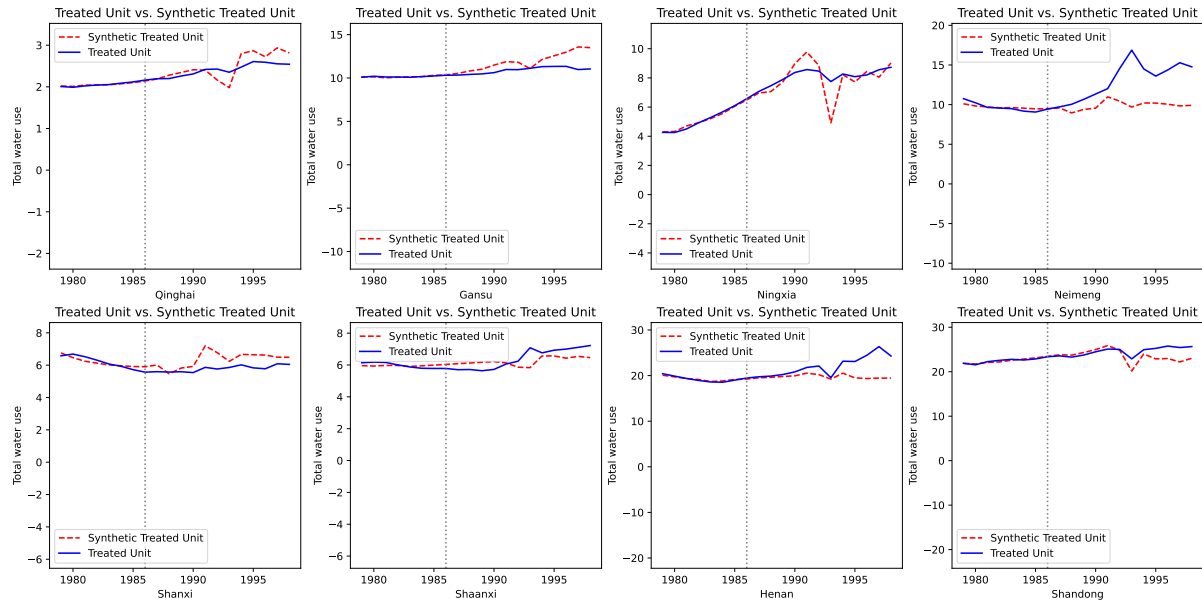
Supplementary Figure B1 Comparations between YRB' provinces and their synthetic controls around the 87-WAS.
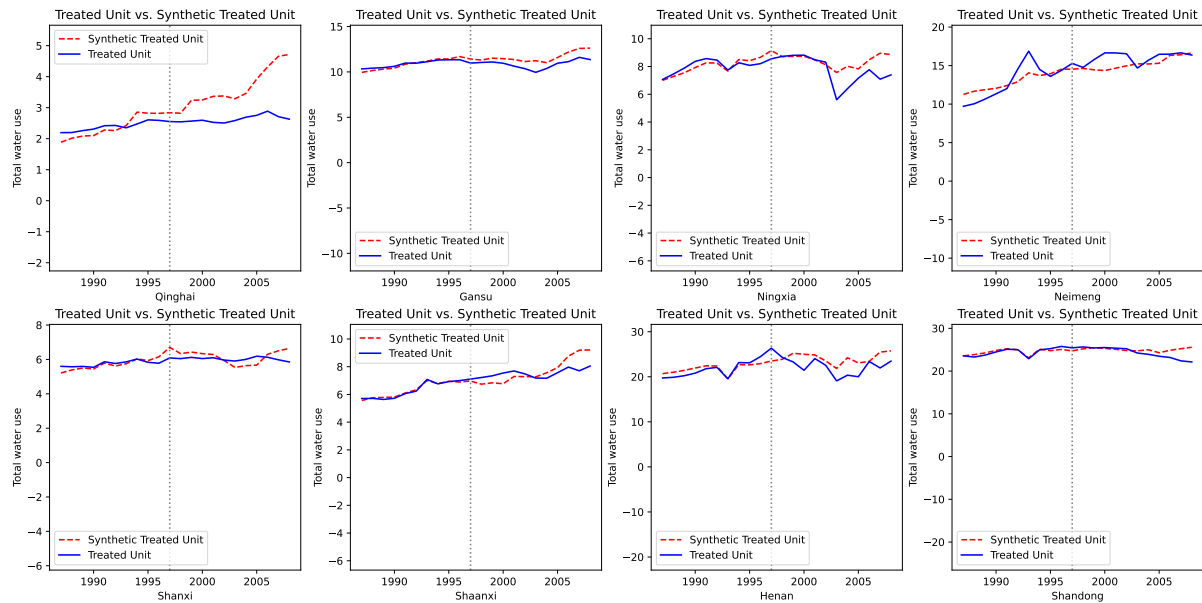
Supplementary Figure B2 Comparations between YRB' provinces and their synthetic controls around the 98-UBR.
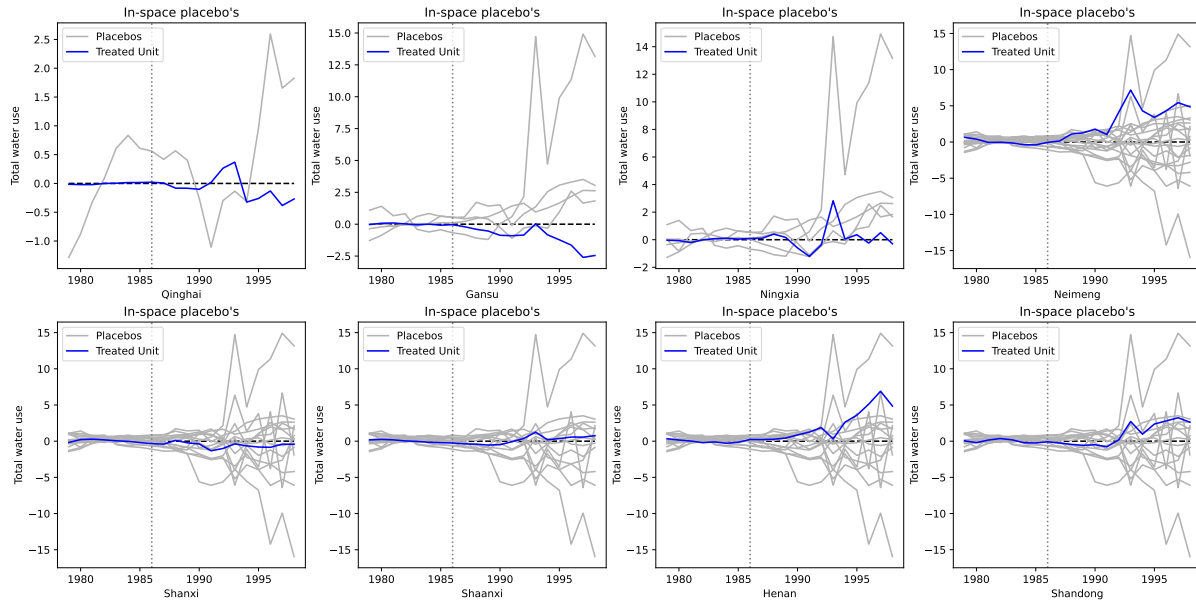
Supplementary Figure B3 Gaps in change in water use between provinces outside the YRB and their synthetic control, around the 87-WAS, excluding the provinces with high pre-treatment RMSPE (more than 3 times of treated units' RMSPE).
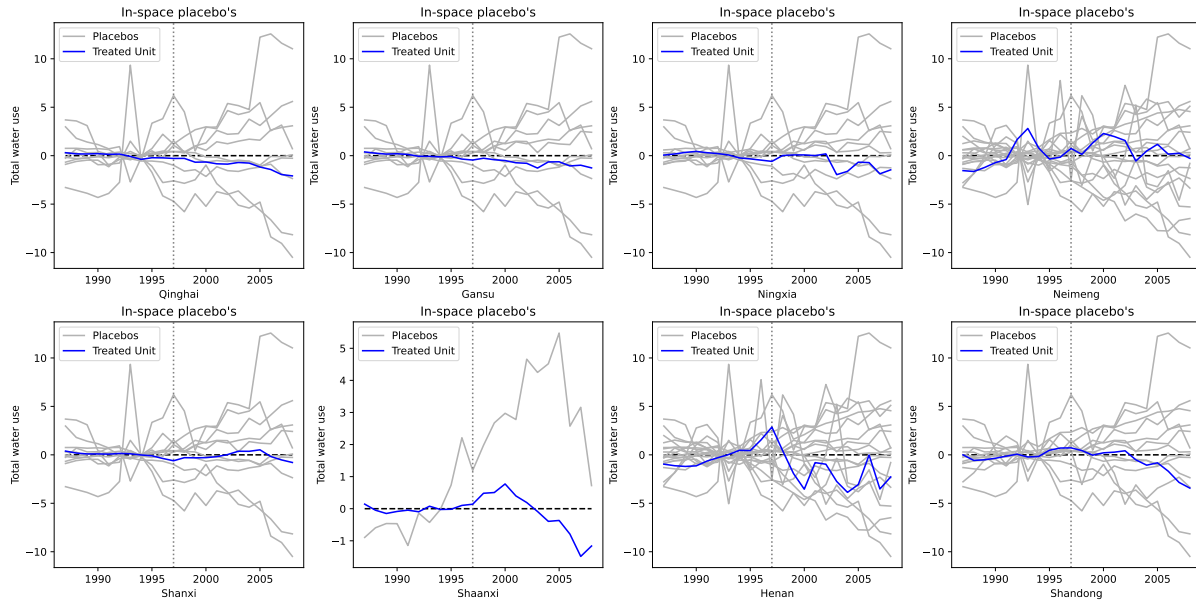
Supplementary Figure B4 Gaps in change in water use between provinces outside the YRB and their synthetic control, around the 98-UBR, excluding the provinces with high pre-treatment RMSPE (more than 3 times of treated units' RMSPE)

Table B1 Variables and their categories for water use predictions

| Sector	Category	Unit	Description	Variables
Agriculture	Irrigation Area	thousand ha	Area equipped for 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
Environment	Temperature	K	Near surface air temperature	Temperature
	Precipitation	mm	Annual accumulated precipitation	Precipitation

474 **Assumption 4.** *(Water-dependent production) Because of irreplaceability, water is assumed to be the only input of*
475 *the production function with two types of production efficiency. The production function of a high-incentive province*
476 *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,*
477 *$F'(0) = \infty$, $F'(\infty) = 0$, $F'(x) > 0$, and $F''(x) < 0$. The production output is under perfect competition, with a*
478 *constant unit price of P.*

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

482 **Assumption 6.** *(Multi-period settings) There are infinite periods with a constant discount factor β lying in (0,1).*
483 *There is no cross-period smoothing in water use.*
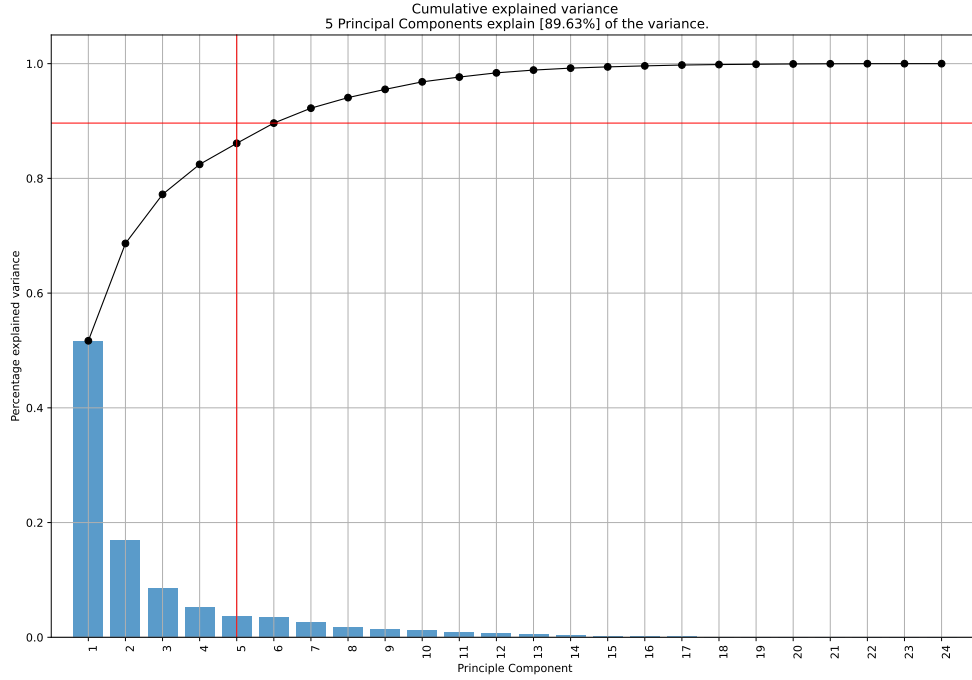
Supplementary Figure B5 Choose number of pricipal components by Elbow method, 5 pricipal components already capture 89.63% explained variance.

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

	1987-WAS				1998-UBR			
Provinces	Pre-RMSPE	Post-RMSPE	Ratio	Significant[a]	Pre-RMSPE	Post-RMSPE	Ratio	Significant[a]
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.

484   Under the above assumptions, we can demonstrate three cases to simulate the water use decision-making and

485   water use patterns in a whole basin.

486   Under the above assumptions, we can demonstrate three cases consisting of local governments in a whole basin

487   to simulate their water use decision-making and water use patterns.

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

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

490 $AF'(x) = \frac{C}{P}$,

491   *where A_H and A_L denote high-incentive and low-incentive provinces, respectively.*

492   *When the decisions in different periods are independent, for $t = 0, 1, 2 \cdots$, then:*

493 $x_{it}^* = x_i^*$

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

495   *The water quota is determined at t=0 and imposed in t=1,2,... Under the subjective expectation of each province*

496   *that current water use may influence the future water allocation determined by high-level authorities, the total quota*

497   *is a constant denoted as Q, and the quota for province i is determined in a proportional form:*

498 $Q_i = Q \cdot \dfrac{x_i}{x_i + \sum x_{-i}}$.

499   *Under a scenario with decentralized decision-making with a water quota, given other provinces' decisions on*

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

501 $AF'(x_{i,0}) = \dfrac{C}{P \cdot N} - \dfrac{\beta}{1-\beta} \cdot A \cdot f(Q \cdot \dfrac{x_{i,0}}{x_{i,0} + \sum x_{-i,0}}) \cdot Q \cdot \dfrac{\sum x_{-i,0}}{(x_{i,0} + \sum x_{-i,0})^2}$,

502   *where A_H denotes a high-incentive province and A_L denotes a low-incentive province.*

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

504   *managed.*

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

506   *and controls the water use in each province), the optimal water use x_i^* of province i satisfies:*

507 $F'(x) = \frac{C}{P}$.

508   We propose Proposition 1 and Proposition 2:

509   Proposition 1: Compared with the decentralized institution, a matched institution with unified management

510   decreases total water use.

511   The optimal water use under the three cases implies that mismatched institutions cause incentive distortions

512   and lead to resource overuse.

513   Proposition 2: Water overuse is higher among provinces with high water use incentives than low- water use

514   incentives under a mismatched institution.

515   The intuition for this proposition is straightforward in that all provinces would use up their allocated quota

516   under a relatively small Q. As production efficiency increases, the marginal benefits of a unit quota increase, and

517   the quota would provide higher future benefits for a pre-emptive water use strategy. Provinces with high production

518   efficiency have higher optimal water use values under the decentralized decision. The divergence in water use would

519   be exaggerated when the water quota is expected to be implemented with greater competition.

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

521   Appendix: Water Use Optimization

522   **Case 1.** *Centralized decision*

523   *When the N provinces decide on water uses as a unity, the marginal cost is C, equal to its fixed unit cost. The*

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

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

526   **Case 2.** *Decentralized decision*

527   *When each of the N provinces independently decides on its water use, the marginal cost of water use would be*

528   *$\frac{C}{N}$ as a result of cost-sharing with others. Hence, the optimal water use in province i at period t, denoted as $\hat{x}_i^*$,*

529   *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, $\hat{x}_{it}^* > x_i^*$.*

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

531   *When the water quota would constrain future water use, the dynamic optimization problem of province i is shown*

532   *as follows. In $t = 1, 2, \cdots$, there would be no relevant cost when the quota is bound that each province takes ongoing*

533   *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*

534   *total water use in Case 2 since a "too large" quota doesn't make sense for ecological policies.*

535 $$max \quad P \cdot A \cdot F(x_{i,0}) - \frac{C \cdot \sum x_{i,0} + x_{-i,0}}{N} + \beta P \cdot A \cdot F(x_{i,1}) + \beta^2 P \cdot A \cdot F(x_{i,2}) + ...$$

536 $$= P \cdot A \cdot F(x_{i,0}) - C \cdot \frac{x_{i,0} + \sum x_{-i,0}}{N} + \frac{\beta}{1-\beta} P \cdot A \cdot F(Q \cdot \frac{x_{i,0}}{x_{i,0} + \sum x_{-i,0}})$$

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

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

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

540 $Q \cdot \frac{\sum x_{-i,0}}{(x_{i,0}+\sum x_{-i,0})^2}$, *i.e.,* $A \cdot F'(x_{i,0}) = \frac{C}{P \cdot N} - \frac{\beta}{1-\beta} \cdot A \cdot f(Q \cdot \frac{x_{i,0}}{x_{i,0}+\sum x_{-i,0}}) \cdot Q \cdot \frac{\sum x_{-i,0}}{(x_{i,0}+\sum x_{-i,0})^2}$.

541   *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*

542 *use decisions are exactly symmetric, total water use would increase when each province has higher incentives for*

543 *current water use.*

544   *Proof of Proposition 1:*

545   *Because $F' > 0$ and $F''(x) < 0$ is monotonically decreasing, based on a comparison of costs and benefits for*

546 *stakeholders (provinces) in the three cases,*

547 $\widetilde{x}_i^* > \hat{x}_i^* > x_i^*$.

548   *The result of $\hat{x}_i^* > x_i^*$ indicates that individual rationality would deviate from collective rationality under unclear*

549 *property rights where a water user is fully responsible for the relevant costs. The result of $\hat{x}_i^* > x_i^*$*

550   *The difference between x_i^* and $\hat{x}_i^*$ stems from two parts: the effect of the marginal returns and the effect of the*

551 *marginal costs. First, the "shadow value" provides additional marginal returns of water use in $t = 0$, which increases*

552 *the incentives of water overuse by encouraging bargaining for a larger quota. Second, the future cost of water use*

553 *would be degraded from $\frac{P}{N}$ to an irrelevant cost.*

554   *Proof of Proposition 2:*

555   *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*

556 *other provinces' water use are taken as given.*

557   *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*

558 *water overuse derived from an expectation of water quota allocation. The incentive of water overuse increases by A.*

559 # D   Appendix D: Model extensions

560 Using the marginal benefits analysis (see the Methods section in the main text), we also explored the response of

561 stakeholders to water quota policies. We considered two additional scenarios for stakeholders: technology growth and

562 one that felt different valuations through time (via the discount rate) of economic benefits and ecological costs. In

563 the following scenarios, the cost is assumed to be untransferable, which could be fully allocated to the one incurring

564 the water use. Explaining plausible scenarios for these stakeholders will help us better understand the causes of

565 water overuse and potential solutions. We argue that water overuse remains robust even if a complete and equitable

566 system.

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

568 *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*

569 *possible that the future growth opportunities and "remote" ecological costs provide enough incentive for the sprint.*

570 *Water overuse has the value of future economic benefits by slacking the water use constraint in the future. The*

571 *heterogeneous production efficiency is omitted in this section, and we set A=1.*

572 *(a) technology growth*

573 *Assume that there is an exogenous technology growth rate of g in the scenario of N provinces bargaining for*

574 *water use under total quota Q, with unit price of output P, unit cost C, and discount factor β. For simplicity,*

575 *consider a finite-period water use optimization:*

576 $max \quad P \cdot (1+g)^t ln(1+x_{i,0}) - \frac{C}{N} + \beta^t \sum_{t=1}^{T} [P \cdot (1+g)^t ln(x_{i,t}+1) - C \cdot x_{i,t}]$

577 $s.t. \quad x_{i,t} \leq Q \cdot \frac{x_{i,0}}{x_{i,0}+\sum x_{-i,0}} \quad for \quad \forall t$

578 *We depict the relationship between multi-period profit and water use $x_{i,0}$ in different horizons in Figure D1 ,*

579 *and thus find out the optimal water use pattern under technology growth. The higher marginal water output might*

580 *create enough incentive to offset the untransferable cost since a higher allocated quota provides growth option value.*

581 *On the other hand, as the provincial decision is under a longer horizon, there is a more significant sprint effect due*

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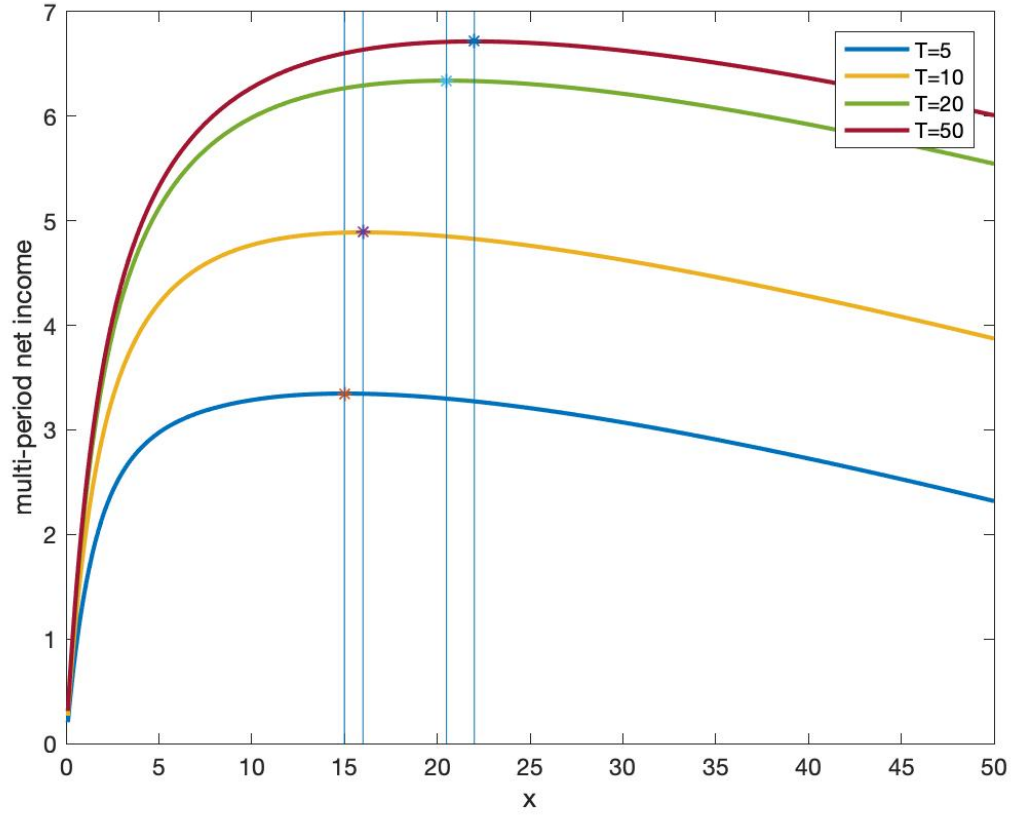
Supplementary Figure D1 Multi-period optimization of optimal water use under technology growth. The figure depicts the relationship of multi-period benefits of province i and water use under Case 3 with technology growth. Assume $F(x) = ln(1+x)$, $N = 8$, $P = 1$, $C = 0.5$, $\beta = 0.7$, $g = 0.2$,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

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

584   *Assuming that there is a high discount rate for economic benefits and a low discount rate for ecological costs,*

585   *in the scenario of N provinces bargaining for water use under total quota Q, with unit price of output P, unit cost*

586   *C, discount factor $\beta^{economy}$ and $\beta^{ecology}$ ($\beta^{economy} > \beta^{ecology}$). For simplicity, consider the following finite-period*

587   *water use optimization, noting the water use of province i at period t:*

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

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

590   *We depict the relationship of multi-period net income and water use $x_{i,0}$ in different horizons in Figure D2 ,*

591   *and thus find out the optimal water use pattern under "remote" ecological costs. The higher discounted ecological*

592   *costs might create enough incentive to set off the untransferable cost. On the other hand, as the provincial decision*

593   *is under a longer horizon, a more significant sprint effect is due to a higher accumulated yield.*
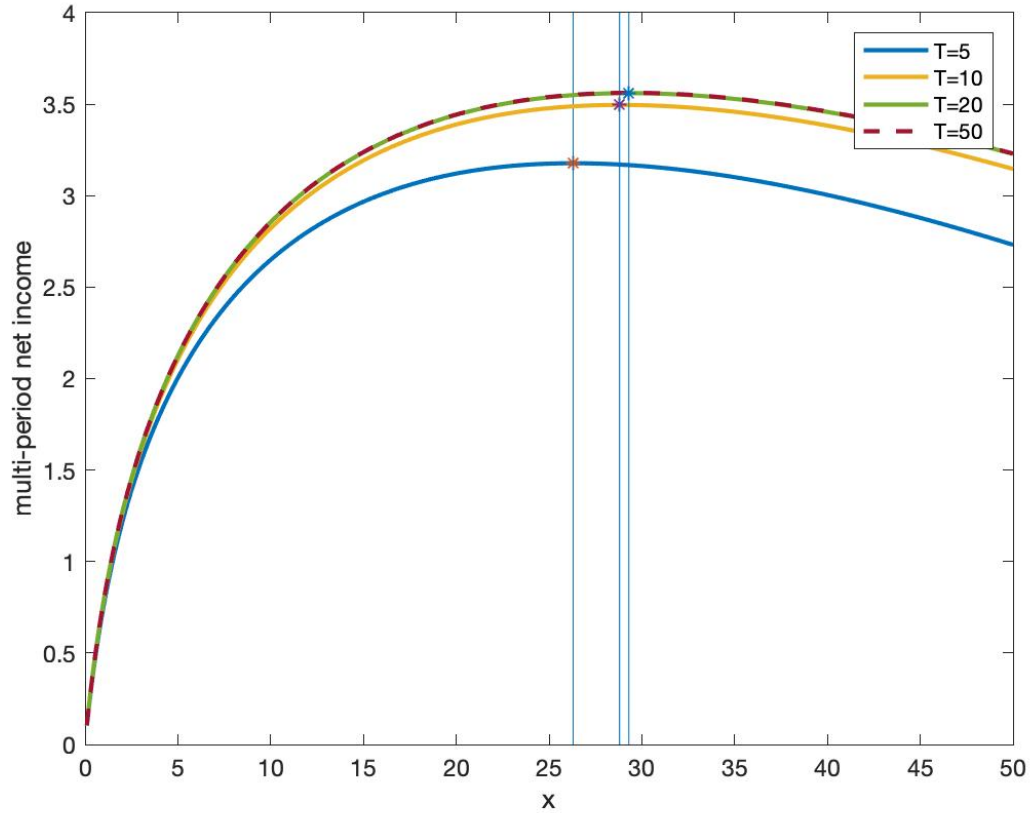
Supplementary Figure D2   Multi-period optimization of water use under "remote" ecological cost. The figure depicts the relationship of multi-period benefits of province i and water use under Case 3 with "remote" ecological cost. Assume $F(x) = ln(1 + x)$, $N = 8$, $P = 1$, $C = 0.5$, $\beta_{economy} = 0.7$, $\beta_{ecology} = 0.3$, and $Q = 8$.