Supplementary Materials for

Institutional shifts and sustainable water use of the Yellow River Basin

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Abstract

The supplementary material is organized logically as follows: (1) Show the implementation of the water resource allocation system in the basin around the world and introduce the institutional changes in the Yellow River Basin in detail, aiming to explain why the Yellow River Basin is a unique quasi-natural experiment. (2) Show the technical roadmap of quantitative analysis method, and introduce the details of quantitative analysis method in detail. (3) Further extensions based on our general economic model.

S1. Detailed introduction of the institutions

We aim to abstract the water allocating institutions from the description in official documents with necessary context into SES building blocks (Figure **??**) 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 [**?**, **?**, **?**].

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

- **1982**: The provinces and the Yellow River Water Conservancy Commission (YRCC) are required to develop a water resource plan for the Yellow River [**?**, **?**].
- **1987**: Implementation of the Allocation Plan. (http://www.mwr.gov.cn, last access: May 29, 2022).
- **1998**: Implementation of unified regulation. (http://www.mwr.gov.cn, last access: May 29, 2022).
- **2008**: Provinces are asked to draw up new water resources plans for the YRB to further refine water allocations [**?**, **?**].
- **2021**: A call for redesigning the water allocation institution (http://www.ccgp.gov.cn, last access: May 29, 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.

diagrams/framework.jpg

Figure 1: Framework for understanding linkages between SES structures and outcomes. **a.** The general framework for analyzing social-ecological systems (SESs) (adapted from Ostrom [**?**]). 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)[**?**]. 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.

Table 1: Water quotas assigned in the 87-WAS

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

[a]Calculated by data from 2004 to 2017.
[b]The share is too small, thus the provinces (or region) Sichuan and Jinji not to be considered in this study.

The official documents in 1987 (http://www.mwr.gov.cn, last access: May 29, 2022) clearly convey the following key points:

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

The official documents in 1998 (http://www.mwr.gov.cn, last access: May 29, 2022) clearly convey the following key points:

- The document clearly points out that not only provinces and autonomous regions involved in water resources management (see *Article 3*), the provinces' and regions' water use shall be declared, organized, and supervised by the YRCC (*Article 11 and Chapter III to Chapter V, and Chapter VII*).
- Creating the overall plan of water use in the upper, middle, and lower reaches is identified as the first consideration of this institution (*Article 1*).
- With the same quota as used in the 1987 policy, provinces were encouraged to further distribute their quota into lower-level administrations (see *Article 6 and Article 41*).
- They emphasize that supply is determined by total quantity, and water use should not exceed the quota proposed in 1987 (see *Article 2*).

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

S2. The technical roadmap and details of quantitative analyzing

Explanatory variables are the key to constructing a robust synthetic control method. We used a total of 24 variables related to water consumption, which datasets have been used in previous studies to explain changes in water use in China [**?**]. 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 **??**).

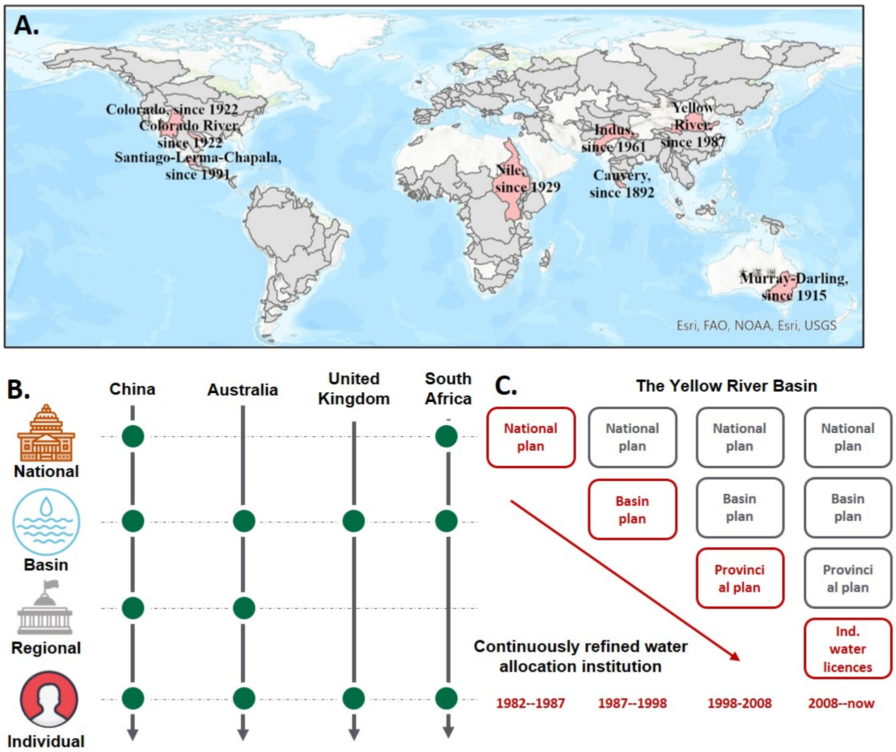

Figure 2: Overview of water allocation institutions. **A.** Major river basins in the world with water resource allocation systems (shaded red); the YRB first proposed a resource allocation scheme in 1987 (designed since 1983) and then changed to a unified regulation scheme in 1998 (designed in 1997 but implemented in 1998) [**?**]. **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.

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 **??** and figure **??**), which show good reconstructions of their water use changes' estimation. For (2), we applied the in-place placebo analysis described by [**?**]. 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 **??**, figure **??**, Table **??**).

S3. Results appendix

S4. Theoretical model

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

We proposed three intuitive and general assumptions.

Assumption 1 *(Water-dependent production) Because of irreplaceability, water is assumed to be the only input of the production function with two types of production efficiency. The production function of a high-incentive province* outputs/87panel.pdf

Figure 3: Comparations between YRB' provinces and their synthetic controls around the 87-WAS.

outputs/98panel.pdf

Figure 4: Comparations between YRB' provinces and their synthetic controls around the 98-UBR.

outputs/87placebo.pdf

Figure 5: 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).

outputs/98placebo.pdf

Figure 6: 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)

outputs/elbow.pdf

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

Table 2: Variables and their categories for water use predictions

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

Table 3: Pre and post treatment mean squared prediction error (MSPE) for YRB's provinces

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

is $A_H F(x)$, and the production function of a low-incentive province is $A_L F(x)$ ($A_H > A_L$). F(x) is continuous, $F'(0) = \infty$, $F'(\infty) = 0$, $F'(x) > 0$, and $F''(x) < 0$. The production output is under perfect competition, with a constant unit price of P.

Assumption 2 *(Ecological cost allocation) Under the assumption that the ecology is a single entity for the whole basin involved in N provinces, the cost of water use is equally assigned to each province under any water use. The unit cost of water is a constant C.*

Assumption 3 *(Multi-period settings) There are infinite periods with a constant discount factor β lying in (0,1). There is no cross-period smoothing in water use.*

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

We propose Proposition 1 and Proposition 2:

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

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

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

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

Extensions of the model are shown in Supplementary Material S3.

Appendix: Water Use Optimization

Centralized decision

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

Decentralized decision

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

Forward-looking decentralized decision under quota restrictions

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

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

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

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

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

The optimal water use in province i at t=0 $\widetilde{x}^*_{i,0}$ satisfies $P \cdot A \cdot F'(x_{i,0}) = \frac{C}{N} - \frac{\beta}{1-\beta} \cdot P \cdot A \cdot f(Q \cdot \frac{x_{i,0}}{x_{i,0}+\sum x_{-i,0}}) \cdot Q \cdot \frac{\sum x_{-i,0}}{(x_{i,0}+\sum x_{-i,0})^2}$, i.e., $A \cdot F'(x_{i,0}) = \frac{C}{P \cdot N} - \frac{\beta}{1-\beta} \cdot A \cdot f(Q \cdot \frac{x_{i,0}}{x_{i,0}+\sum x_{-i,0}}) \cdot Q \cdot \frac{\sum x_{-i,0}}{(x_{i,0}+\sum x_{-i,0})^2}$.

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

Proof of Proposition 1:

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

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

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

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

Proof of Proposition 2:

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

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

S5. Further analysis regarding the general economic model

Further analysis of the general economic model

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

Forward-looking decentralized decision, taken ecology cost into considerations

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

(a) technology growth

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

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

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

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

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

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

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

outputs/Fig3.jpg

Figure 8: 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 $Q = 8$.

outputs/Fig4.jpg

Figure 9: 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 $Q = 8$.