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

Water allocation schemes 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 6, 2022).
- **1998**: Implementation of unified regulation. (http://www.mwr.gov.cn, last access: May 6, 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 6, 2022).

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

The official documents in 1987 (http://www.mwr.gov.cn, last access: May 6, 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 6, 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*).

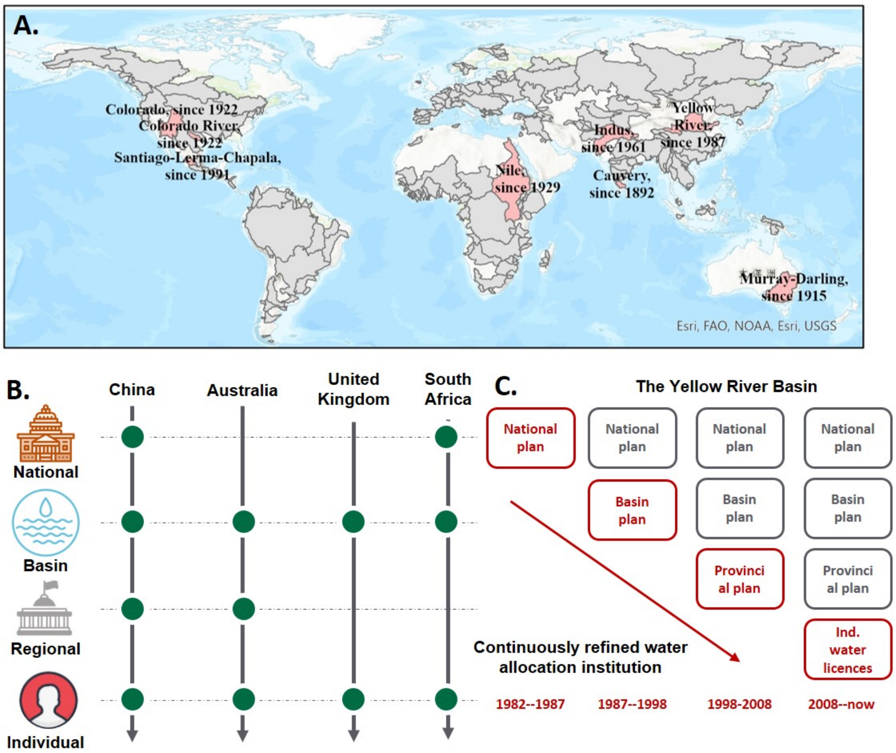

Figure 1: Overview of water allocation institutions. **A.** Major river basins in the world with water resource allocation systems (shaded red); the YRB first proposed a resource allocation scheme in 1987 (designed since 1983) and then changed to a unified regulation scheme in 1998 (designed in 1997 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.

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.

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.

S2. The technical roadmap and details of quantitative analyzing

In order to use the synthetic control method to predict the trend of water use without institutional change, socioeconomic data affecting water use were used as the input independent variables. All variables used are listed in Table ??. These variables refer to major economic factors (agriculture, industry, service industry, and domestic) that provincial units need to take into account when using water resources; their correlation coefficients with the dependent variable (water resource use) are shown in Figure ?? A.

In addition, the synthetic control method assumes that a linear combination of independent variables can effectively predict the dependent variables. We therefore divided the dataset into two groups, training samples (80%) and test samples (20%), and used the training samples to build a multivariate linear model to predict the water consumption. We then used the test dataset to test the model-fitting effect. Results show that the goodness of fit R^2 exceeded 0.8; thus, the dependent variable is well-explained by the linear combination of independent variables, and the dataset can be used in the synthetic control method (Figure ??B).

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

S3. Results appendix

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

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

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

where $\vec{var}$ is a vector of specific independent variable in $X_{t,var}$, $t \in [1975, 2008]$.

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

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

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

Table 3: 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.
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Domestic	Urban population	Million Capita	Population living in urban regions.	Urban pop
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	Livestock population	Billion KJ	Livestock commodity calories summed from 7 types of animal.	Livestock

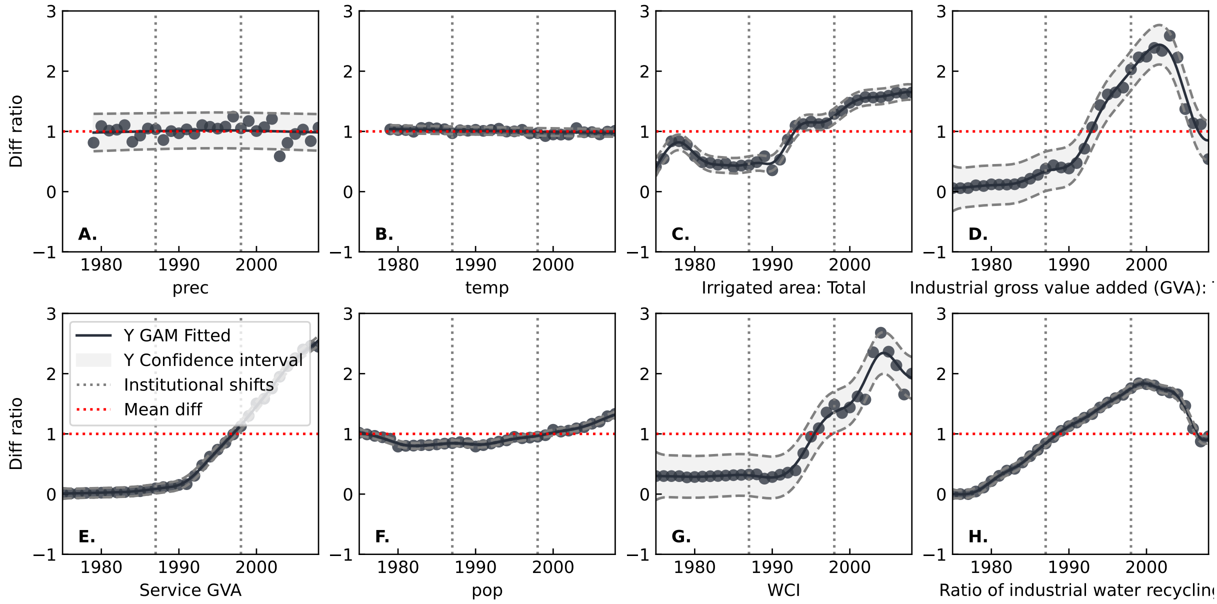

Figure 2: Differences ratio of different variables: **A.** precipitation, **B.** temperature, **C.** total irrigated areas, **D.** industrial gross value added (industrial GVA), **E.** services GVA, **F.** population, **G.** water conservation irrigation (WCI) ratio, and **H.** industrial water recycling (IWR) ratio.

S4. Theoretical model

Setup In order to understand the mechanisms underlying the empirical results, we developed a dynamic economic model to analyze how institutional mismatch could have led to the sprint effect 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 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 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.*

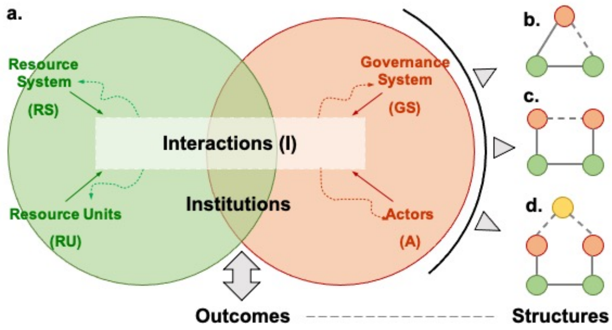

Figure 3: Framework for understanding linkages between SES structures and outcomes. **a.** The general framework for analyzing social-ecological systems (SESs) (adapted from Ostrom [**?**]). Institutions embedded in SESs may reshape structures by changing the interactions between core subsystems, resulting 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 two units are linked by gray lines. The gray dashed lines show aligned SES structures that are more likely to result in a desirable outcome according to empirical evidence.

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 $t = 0, 1, 2, \ldots$, 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 *Appendix S5.*

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.

Optimal water use under different institutions

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

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:

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

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

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:

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

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

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

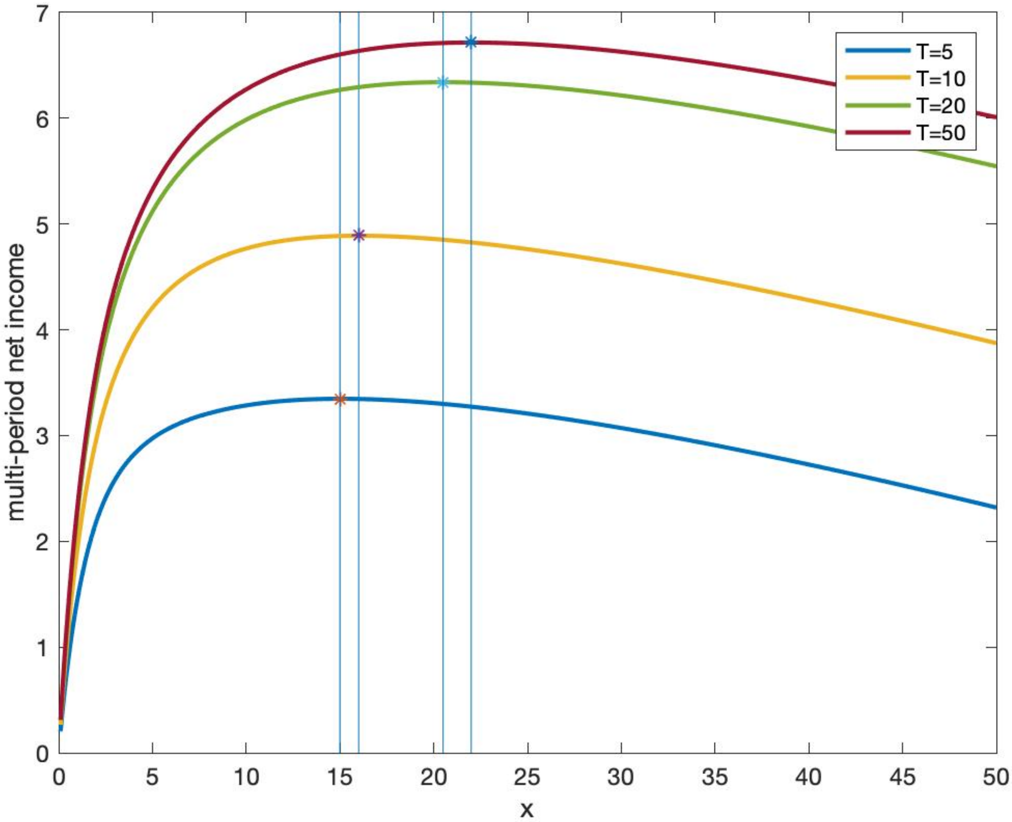

Figure 4: Multi-period optimization of optimal water use under technology growth. The figure depicts the relationship of multi-period benefits of province i and water use under Case 3 with technology growth. Assume $F(x) = ln(1+x)$, $N = 8$, $P = 1$, $C = 0.5$, $\beta = 0.7$, $g = 0.2$, and $Q = 8$.

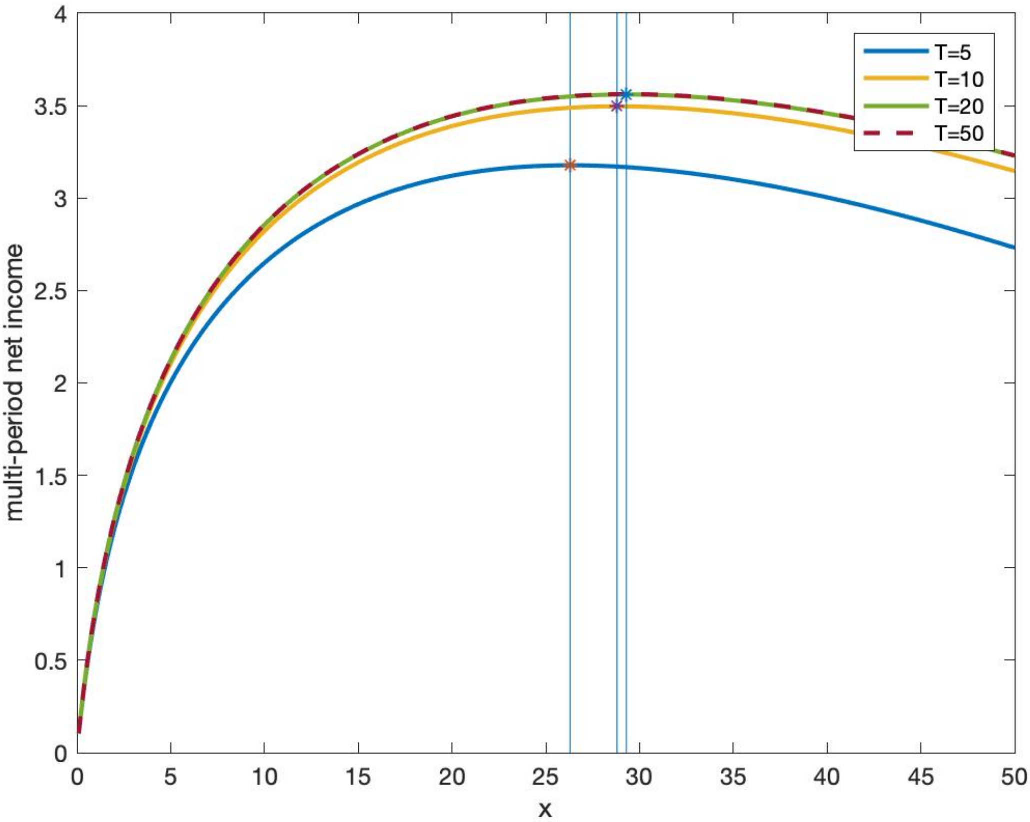

Figure 5: Multi-period optimization of water use under "remote" ecological cost. The figure depicts the relationship of multi-period benefits of province i and water use under Case 3 with "remote" ecological cost. Assume $F(x) = ln(1+x)$, $N=8$, $P=1$, $C=0.5$, $\beta_{economy}=0.7$, $\beta_{ecology}=0.3$, and $Q=8$.