Supplementary Materials for
Institutional shifts and water sustainability 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 *Supplementary Material Figure 1*) [**?**]. The Yellow River Basin (YRB) in China has a typical top-down approach to institutional reform, which produces rapid institutional impacts and allows researchers to quantitatively estimate the net impact of changes in high-level institutional design on water use (see *Supplementary Material Figure 2*). 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: April 5, 2022).
- **1998**: Implementation of unified regulation. (http://www.mwr.gov.cn, last access: April 5, 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: April 5, 2022).

The 1982 document marked the beginning of the attempt to design a water allocation institution, and the 2008 document marked the maturity of the system (complete establishment of basin-level, provincial, and district water allocation and unified regulation). Currently, a major overhaul is in the planning stages. Major shifts of the institution can be analyzed by using the 1987 and 1998 documents. It is worth noting that, although the essential reason for these institutions was the mismatch between the spatial and temporal distribution of water resources as well as social and economic water demands, the direct reason for their introduction was the drying-up of the Yellow River [**?**].

The official documents in 1987 clearly convey the following key points: http://www.mwr.gov.cn, last access: April 5, 2022.

- The policy is aimed at related provinces (or regions), and the YRCC is not mentioned.
- Drying-up 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 clearly convey the following key points: http://www.mwr.gov.cn, last access: April 5, 2022.

- 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*).

On the basis of the above analysis, we abstracted the operational structure of the water resource allocation institution of the YRB as shown in Figure 2 of the main text, focusing on the period between 1975 and 2008. By comparing the net effects of three different institutional structures split by the two institutional shifts, we were able to reach a stronger understanding of the influence of structural alignments under the same basin (previous structure-based analysis usually focus on a certain type of systems but with different geographic contexts).

S2. The technical roadmap and details of quantitative analyzing

To quantify and interpret the institutional effects, we followed the technical route illustrated in *Supplementary Material Figure 3*. It was a two-step process in which we (i) created a comparable control group and an expectation (a "null model") to analyze the impact of the institutional shifts on water use by using synthetic control and placebo matching methods, and (ii) created a general economic model based on marginal revenue to explain the "sprint effect" we observed and designed scenarios for further analysis.

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 (see the *Methods in the main text*). All variables used are listed in Table 1. These variables refer to major economic factors (agriculture, industry,

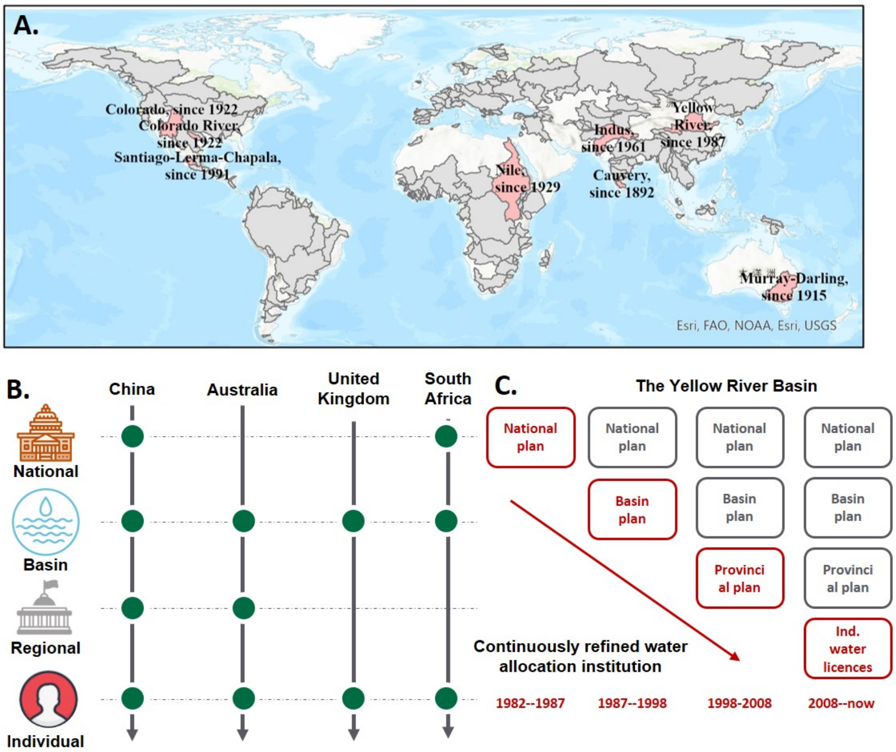

Figure 1: Overview of water allocation institutions. **A.** Major river basins in the world with existing water resource allocation systems (shaded red); the YRB first proposed a resource allocation scheme in 1987 (designed in 1983) and then changed to a unified regulation scheme in 1998 (designed in 1997 but implemented in 1998). **B.** Different water resource allocation system design patterns; the YRB is typical of a top-down system with multiple levels. **C.** The four periods of institutional evolution of water allocation of the YRB.

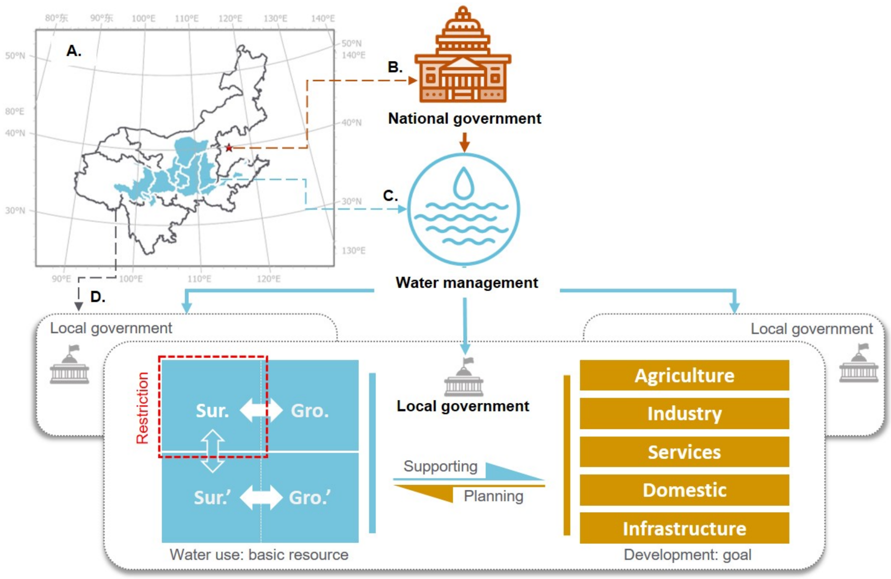

Figure 2: A top-down water resources allocation scheme in China (a case study of the YRB). **A.** A total of 10 provinces or regions withdraw surface water resources from the Yellow River, of which 8 are highly dependent on the river (see *Supplementary Material S2*). **B.** The Chinese government is the ultimate authority in issuing watershed management policies, which are often quickly implemented from top down. **C.** The basin-level agency (here, the YRCC) is primarily responsible for the river-related management of the basin in accordance with national policy guidelines. **D.** The water management system directly affects the process by which local governments (major stakeholders) plan and use water resources for development. Although only surface water (Sur.) is usually traced and restricted, it can also influence groundwater through related hydro-processes such as recharge.

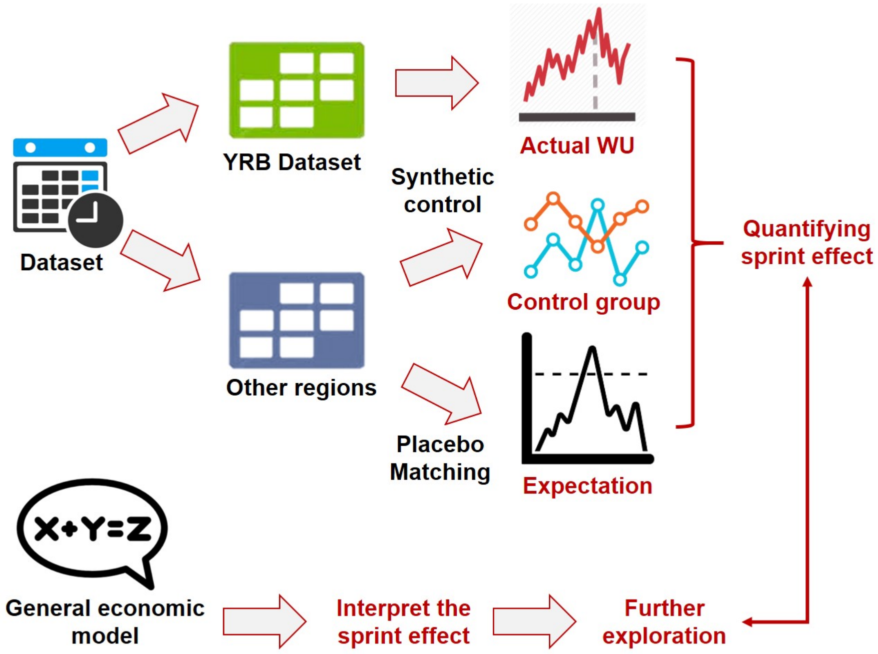

Figure 3: Technical roadmap for quantitatively analyzing the "sprint effect". WU is the the core variable we concerned -total water uses of the Yellow River Basin.

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 4 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 4B). To estimate the expected water use changes, we used the placebo test method as a null model (see the *Methods*), which gives a comparable baseline for matched datasets. Figure 5 indicates that the matched dataset is similar to the actual data both in values and change trends. This means that the differences between the predictions made from actual data and from the matched data by the synthetic control method are more likely to be result of the impacts of institutional shifts.

S3. Results appendix

S4. Theoretical model

Using the general economic model (see the *Methods 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 Nontransferable, 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 sprint effect and potential solutions. We argue that the sprint effect of water use remains robust even

Table 1: Variables and their categories for water use predictions

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

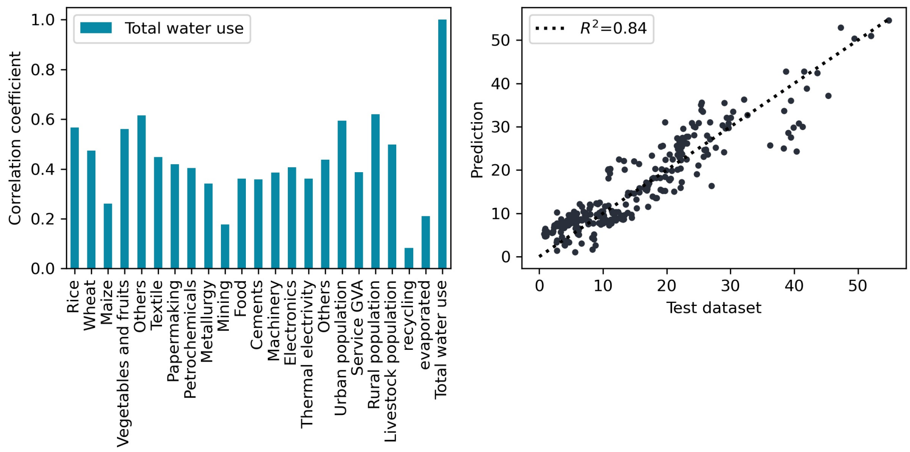

Figure 4: **A.** Correlation between independent variables and the dependent variable (water use). **B.** Linear relationship between the independent variables and the dependent variable trained by a linear model.

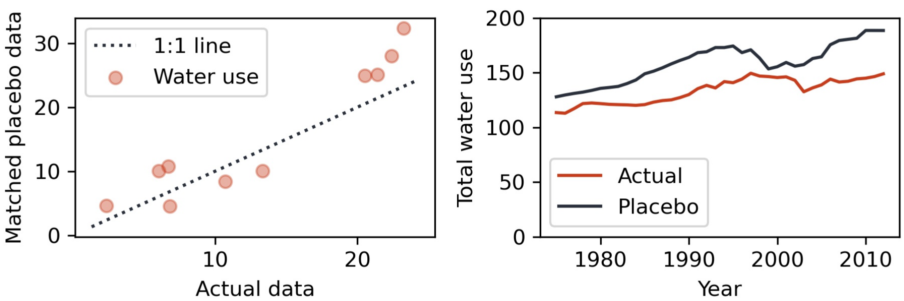

Figure 5: **A.** A comparison of the matched placebo dataset and the actual YRB dataset for each province. **B.** Trend of total water use ($10^8 m^3$) for the matched placebo and actual datasets.

if a complete and equitable system.

Growth in technology

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 the

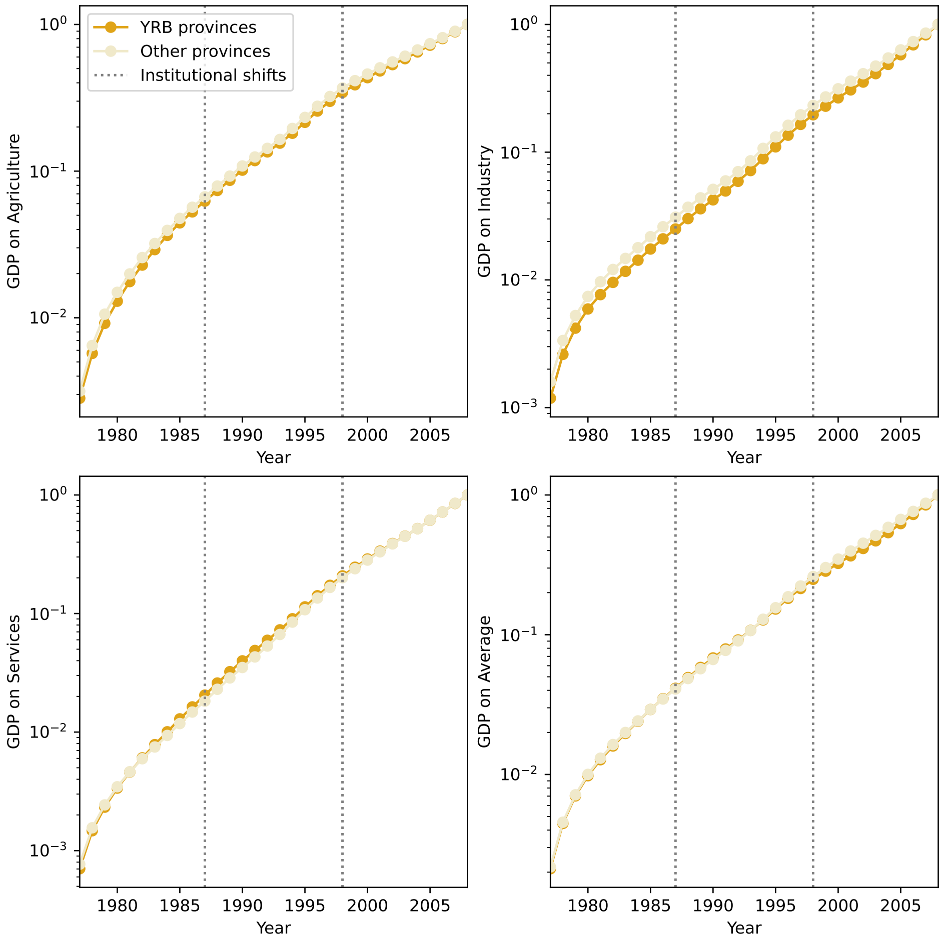

Figure 6: test

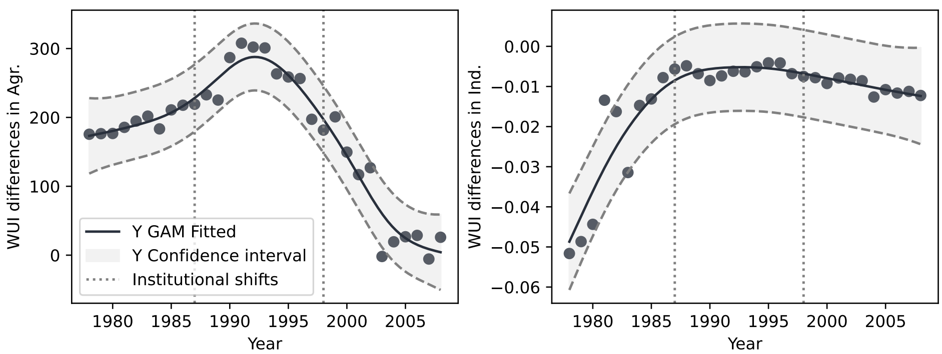

Figure 7: test

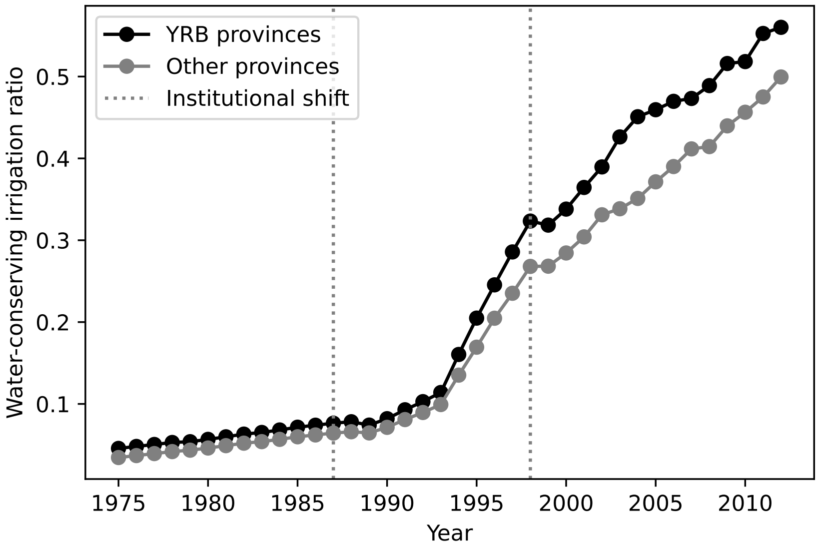

Figure 8: test

following finite-period water use optimization:

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

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

We depict the relation between multi-period benefits and water use x_{i0} in Figure 9to illustrate the optimal water use pattern under technology growth. The higher marginal benefits of water might create enough incentive to offset the nontransferable costs of water overuse at $t = 0$, because a higher allocated quota provides growth option value. Because provincial decisions are under a longer time horizon, there is a greater sprint effect due to the higher accumulated yield.

Economic benefits and ecological costs with different discount rate

Assume that there is high discount rate for economic 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 $\beta^{ecology}$ and $\beta^{ecology}$. It means that present economic profits are significantly concerned but future ecological costs are widely ignored. (In fact, if GDP are the core standard to judge officers' performance, this is an assumption cloth to the reality.) For simplicity, consider the following finite-period water use optimization, notes the water use of province i at period t:

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

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

We depict the relation between multi-period benefits and water use xi0 in different time horizons in Figure 10, Using a higher discount rate for ecological costs might create enough incentive to set off the nontransferable unit

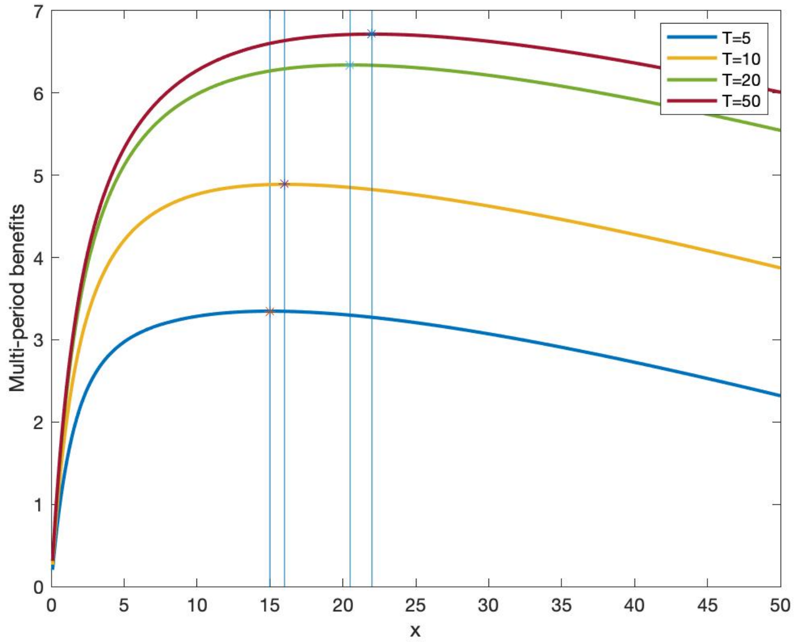

Figure 9: Multi-period benefits and optimal water use under technology growth and a quota system. The figure depicts the relationship of multi-period benefits of province i and water use under Case 3 with technology growth under T periods. Assume $F(x) = \ln(1 + x)$, $N = 8$, $P = 1$, $C = 0.5$, $\beta = 0.7$, $g = 0.2$, and $Q = 8$. The horizontal axis coordinates of $*$ denotes optimal water use at $t = 0$ under each time horizon in decision-making.

cost of C. Because the provincial decision is often under a longer horizon than that in baseline results in Figure 4 of the main text, there is a greater sprint effect as a result of higher accumulated yields.

S5. Further analysis regarding the general economic model

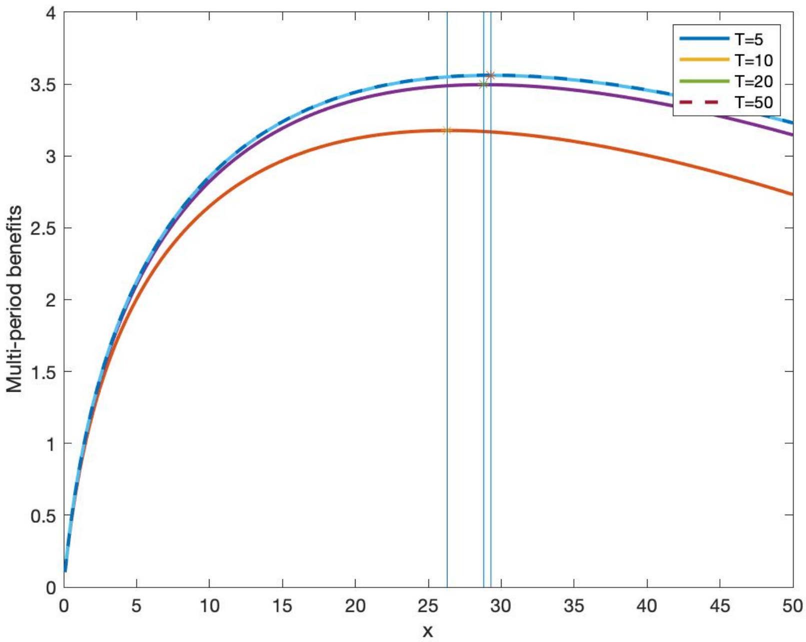

Figure 10: Multi-period benefits and optimal water use when economic benefits have a high discount rate, ecological costs have a low discount rate, and a quota is implemented. The figure depicts the relation between multi-period benefits of province i and water use under Case 3 under T periods. Assume $F(x) = \ln(1+x)$, $N = 8$, $P = 1$, $C = 0.5$, $\beta_{economy} = 0.7$, $\beta_{ecology} = 0.3$, and $Q = 8$. The horizontal axis coordinates of $*$ denotes optimal water use at $t = 0$ under each time horizon in decision-making.