# Supplementary Information for

## Water resource utilization regimes at a basin scale: transition framework and development traps

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**This PDF file includes:**

## Supporting Information Text

This supplementary document consists of three sections and 10 figures. Firstly, we introduced our study area, the Yellow River Basin, in the section Methods S1. Definition of study area. Then, we give a detailed description of used datasets and analysis their uncertainties in the section Methods S2. Detailed information on dataset and processing. Finally, the index along with corresponding indicators are introduced in the section Methods S3. Water Utility Regime Index.

## Methods S1. Definition of study area

**Region divisions of Yellow River Basin.** The study area is the Yellow River Basin (YRB, see Fig. S1-A), which has experienced the most intense water exploitation and the most dramatic shifts of management regime in China. According to the Yellow River Conservancy Commission (YRCC), an administrative government directly under the Ministry of Water Resources at the basin level, the upper, middle and lower reaches of the Yellow River can be distinguished by characteristic of river. However, there is another scheme suggesting that the upstream only refers to river source areas with little human disturbance and high water retention capacity. Anyhow, since the socio-economic and natural conditions were considered in this study, we integrated the two schemes above and divided the Yellow River Basin into four regions, which can be distinguished by three important hydrological control stations (see Fig. S1-B). Previous studies have also shown that such a division is valid when both social water use and the natural conditions of the basin are considered, as the regions exhibit strong heterogeneity among themselves (see Fig. S1-C):

- **Source Region (SR):** Over 50% of natural runoff was produced in this region. The most ecology function here is water conservation, as sparsely populated and less economically developed.
- **Upper Region (UR):** With the highest per capita irrigated land area, there are numbers of large irrigation lands in this region. However, because of backward production methods, efficiency of irrigation are used to be very low.
- **Middle Region (MR):** Crossing Loess Plateau, famous rich-sand area, Yellow River loads most of its sediments here with the highest soil erosion risk. To reverse this situation, the grain for green project changed the water utilization here strikingly.
- **Lower Region (LR):** With dense population and the traditional agricultural trajectory, lower region used to be the largest water use region. However, as the industrial transformation going, proportion of agriculture keeps decreasing, but LR is still the largest water use region in each aspect.

In general, there are inter-regional differences in the economic layout, distribution of water resources, distribution of water consumption, and population distribution of the Yellow River Basin (see Fig. S2). On the basis of these fundamental differences, social development and watershed management continue to influence and reshape their changes, making the Yellow River Basin the world's most intimately connected and dramatically changing large river basin. Thus, as a case study for analysing the evolution of the human-water relationship, it possesses typicality.

**Importance of water resource to society within the YRB.** Water resources make an irreplaceable contribution to the development of society in the YRB. Firstly, each aspect of economic development highly depended on water resources, since the most water use patterns are positively correlated with the region's key economic indicators (see Fig. S3-A). Secondly, their relationships have noticeably changed over the study period. In particular, the major water-consuming sectors have undergone particularly dramatic changes (see Fig. S3-B).

**Changes brought from human activities on the YRB.** Humans are constantly modifying the water cycle processes in the watersheds as society develops.

- Firstly, the YRB has been subject to strong intervention by human activities since ancient times, while the last 60 years have seen the most dramatic changes. Under human influence, the Yellow River's surface runoff, sediment transport, and human water consumption patterns have all undergone multiple regime shifts in the last 60 years (see Fig. S4).
- Secondly, landscapes in the YRB have significantly altered by human activities, which can both change the natural and the social water cycle (see Fig. S5). For an example, grain for green project has produced a significant change of landscapes in the middle region (MR) of YRB. With the addition of xxx hectares of forest in an erosion-prone area, water use patterns in the area and surface runoff patterns in the middle and lower reaches have been radically altered.
- Thirdly, a series of management practices have promoted in order to govern the YRB (see Fig. S6). Since the establishment of the Yellow River Water Conservancy Commission in XX, the agency has continued to reform and expand, eventually forming a basin management agency with unified coordination, scheduling and regulatory functions. Since the promulgation of the Water Law in xxx, the Ministry of Water Resources, the YRCC and other relevant agencies have issued a series of policies to carry out comprehensive river basin management under the guidance of national laws.

Historic and recent river basin management practices have strong impacts on water utilization.

## Methods S2. Detailed information on datasets

Multiple types of dataset were used in this study (see Table S1).

**Statistical datasets.** For statistics, we used GDP data, water resources uses data extracted from the 2nd National Water Resources Assessment Program (1) and statistical yearbook data of YRB. GDP data from the China Macro data in the Wind database, which firstly aggregated from annual reports of the provinces. Water resources uses dataset was published by Zhou et al. (1), which records water utilization in different sectors along with social-economic situations in perfects level. This dataset was mainly extracted by 2nd National Water Resources Assessment Program launched in 2002, led by the National Development and Reform Commission and the Ministry of Water Resources (see ref (1) and http://www.mwr.gov.cn/english/publs/ for more details). Since then, the statistics from the survey using the same criteria have been supplemented and harmonized to the 2013 administrative divisions. The data covers a total of subcategories of water use under four broad categories: agriculture, industry, urban and rural, but does not distinguish between surface water and groundwater. There is uncertainty at the county scale for each disaggregated water use sector, but because the data are corrected for statistical information using the water balance method, the data are adequate for the regional scale and the four broad water use categories used in this study. Finally, in order to make a simple distinction between the proportion of surface water and groundwater extraction where needed, we use basin-scale water resources annual reporting data. Yearbook data of YRB documenting surface water resources and groundwater resource extraction in each watershed and province.

**Hydrological datasets.** For hydrological datasets, reservoirs data and a measured runoff data were used in this study. The reservoir dataset were collected by Wang et al. (2), which introduced includes the major new reservoirs built in the Yellow River Basin since 1949. Of these, we consider the reservoirs marked as pivot projects by the YRCC to be more important, as they are directly involved in water resources management in the basin (http://www.yrcc.gov.cn/hhyl/sngc/). Annual runoff data derived from hydrological station measurements.

**Political datasets.** For the policy data set, we select the laws and policies related to the Yellow River basin promulgated and implemented by departments at and above the river Basin level (such as Yellow River Conservancy Commission) in the Comprehensive Planning for the Yellow River Basin (such as national ministries and commissions) (3). In addition, we also obtain the organizational evolution of the Yellow River Water Conservancy Commission as a watershed management unit from the book Organizational Evolution of the Yellow River Water Conservancy Commission to reflect the implementation of watershed management measures (4).

## Methods S3. Harmonization of datasets

Due to the wide sources of our data set and the different spatial scales, we need to reconcile the data on the regional scale (SR, UR, MR and DR), and have different processing methods according to the spatial scale of the data.

- 1. Watersheds: Due to the fact that the subdivision of a basin is determined by hydrological subdivision, hydrological annual data and measured runoff data can be directly divided according to their corresponding hydrological stations.

- 2. Perfects: At the scale of cities and counties, we respectively calculate the area occupied by cities and counties in different watershed districts, and select the largest region. If this area accounts for more than 95% of the area of the county, the city is considered to belong to this region, that is:

$$S_{ij} = MAX(S_i j / S_i)$$

  where $i$ refers a certain perfect and $j$ refers a region within YRB, i.e. SR, UR, MR, or DR. $S_i$ refers the area of perfect $i$, and $S_{ij}$ refers intersecting area between perfect $i$ and region $j$. We define perfect $i$ belongs to region $j$ if their intersecting area over 95% of $S_i$, i.e.:

$$MAX(S_{ij}) > 0.95 * S_i$$

- 3. Province: Data at the provincial scale (i.e., GDP data of different industries) are more used for qualitative description, and do not carry out horizontal proportion with data at the county scale, so the accuracy of the data is no longer important. We have adopted a rough treatment. That is, according to the major provinces contained in different regions, determine which region the data of that province is merged into. Referring to the traditional division practice, we made the following division:
  - SR: Qinghai Gansu and Sichuan,
  - UR: Ningxia and Neimeng,
  - MR: Shanxi and Shaanxi,
  - DR: Shandong, Hebei and Henan

Finally, when we process the location data (such as the location data of reservoir construction), we judge the province it belongs to according to its location, and then process it according to the regional classification method on the provincial scale. After the above processing, all the data can be well coordinated at the regional scale.

## Methods S4. Water Utility Regime Index

The steady-state index of water resources utilization considers the three most important dimensions of human utilization of water resources at the watershed scale, corresponding to the three questions of "how much water", "how to use" and "for whom, for where" respectively. In order for these dimensions to be quantified, we found or invented a total of three metrics corresponding to the trend indicating their change: SFV Index, Non-provisioning Share and Allocational Entropy Metric.

**Stress: SFV-index.** There is how much water can be used in a certain basin? How much stresses has societies put on the water resources of the basin? Various metrics, therefore, proposed for water stress (e.g. water scarcity, water stresses index, scarcity-flexibility-variability index), where the dimensions of human impact are increasingly valued. Among of them, by taking changes of water flexibility and variability into account, the scarcity-flexibility-variability (SFV) index focus more on dynamic responses to water resources in developing perspective, which considered a valid metric of temporal changes in water stresses.

**Tendentiousness: Non-provisioning share.** How to use water resources? XXX et al. put forward the virtual water theory by considering the water consumption in consumer goods, and found that the supply of water resources as food and consumption products is the main use of water resources, and can flow with trade. However, with the change of water resource utilization mode, the water footprint research on the basis of water footprint further generalizes the concept of water-related products and services. Today, the world's non-product form of water supply to human beings has reached XX%, including XXXXXX and other ways, the human society is occurring from "consumption of water" to "use of water" tilt. Here, we use Non-Provisioning Shares (NPS) of used water resources as an metric to indicate tendentiousness of water utility:

$$NPS_{ij} = \frac{WU_{indirect,i,j}}{WU_{direct,i,j} + WU_{undirect,i,j}}$$

where $i$ refers a certain year and $j$ refers a certain region. Thus, $WU_{i,j}$ means the water use in $i$ year and region $j$, where *direct* part and *undirect* part indicate provisioning sectors and non-provisioning sectors respectively. In this study, we consider water for livestock, water for rural or urban residents and water for agriculture as supply water. Correspondingly, non-supply water is often industrial water, mainly energy water. Extensive studies have shown that there is a wide connection between water, food and energy, which is a manifestation of water supply tendency, in which supply water is often the key to support the production of agricultural products, while non-supply water is more involved in industrial and other social processes. For China as a whole, if only agricultural production is considered, China is the recipient country of virtual water trade. But if industrial consumption is taken into account, China is exporting virtual water. However, as a river basin with high degree of water resource scarcity, the tradeoff between the two has always been treated with greater value; thus, the adoption of this ratio as an indicator can simply, directly and effectively reflect the change of tendentientitreating with water.

**Pattern: Allocational Entropy Metric.** Where to use water resources? The allocation of water resources has always been a difficult problem, requiring tradeoffs between upstream and downstream and between different water sectors, but there is still a lack of relevant indicators to quantify. Here we have designed a "distribution entropy index", which can simply and directly express the pattern of water allocation (which tends to be more evenly distributed or more focused on a certain region). We imitate the idea of information entropy in physics. When the distribution of information (here is water resource) is more equal, its entropy increases; when the distribution is more inclined to a certain region, the certainty of development in that region increases, resulting in the overall entropy decrease. The indicators will be different areas (SR, UR, MR, DR) and different departments (agriculture, industry, service industry, human settlements) of Water consumption of Water Use (WU) as observations, calculation completely when the average allocation of Water resources allocation of Water resources as the maximum entropy, and the actual Water distribution of the ratio of the maximum entropy and the actual entropy, to show the pattern of Water resources allocation how much deviation from the average allocation, i.e.:

$$ratio = \frac{Entropy}{Entropy_{max}}$$

where $Entropy$ and $Entropy_{max}$ are entropy and maximum entropy of water distributions, respectively. They can be calculated by:

$$Entropy = \sum_{i=1}^{n} \sum_{j=1}^{m} -log(p_{ij}) * p_{ij}$$

$$Entropy_{max} = n * \sum_{j=1}^{m} -\frac{p_j}{n} * log(\frac{p_j}{n})$$

where $p_j$ and $p_i j$ are proportions of water use in sector $j$ and region $i$:

$$p_j = \frac{\sum_{i=1}^{n} WU_j}{\sum_{i=1}^{n} WU}$$

$$p_{ij} = \frac{WU_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{m} WU_{ij}}$$

where $n$ is the total number of regions ($n = 4$ here, see supplementary Methods. S1) and $m$ is the total number of sectors ($m = 4$ here, see supplementary Methods. S2).

The above indicators take into account the distribution between regions and between industries, but with the development of the basin, the trend of the two is different. For river basin is located in the same country, from the exploitation of water resources for development between regional opportunities are equal, the actual use of water resources depends more on their own economic strength, so consider don't ideal is conditioned by the actual economic situation, between the four areas of water resources should be fair (on average) distribution (entropy). But at the same time, due to the wide existence of geographical differences and division of labor, different regions have their comparative advantages, which is the key factor restricting which water resources are allocated to in the water industry theoretically. Therefore, the distribution of water resources among departments in a specific region will show an overall trend of increasing differences (entropy reduction) in an ideal situation. At the same time, the division of labor will emerge along with the comparative advantage, so that different regions have their own advantageous departments (compared with the average level of the river basin).

Finally, we consider the indexes of the three dimensions in the same weight after standardization to form the Water Utility Regime Index.

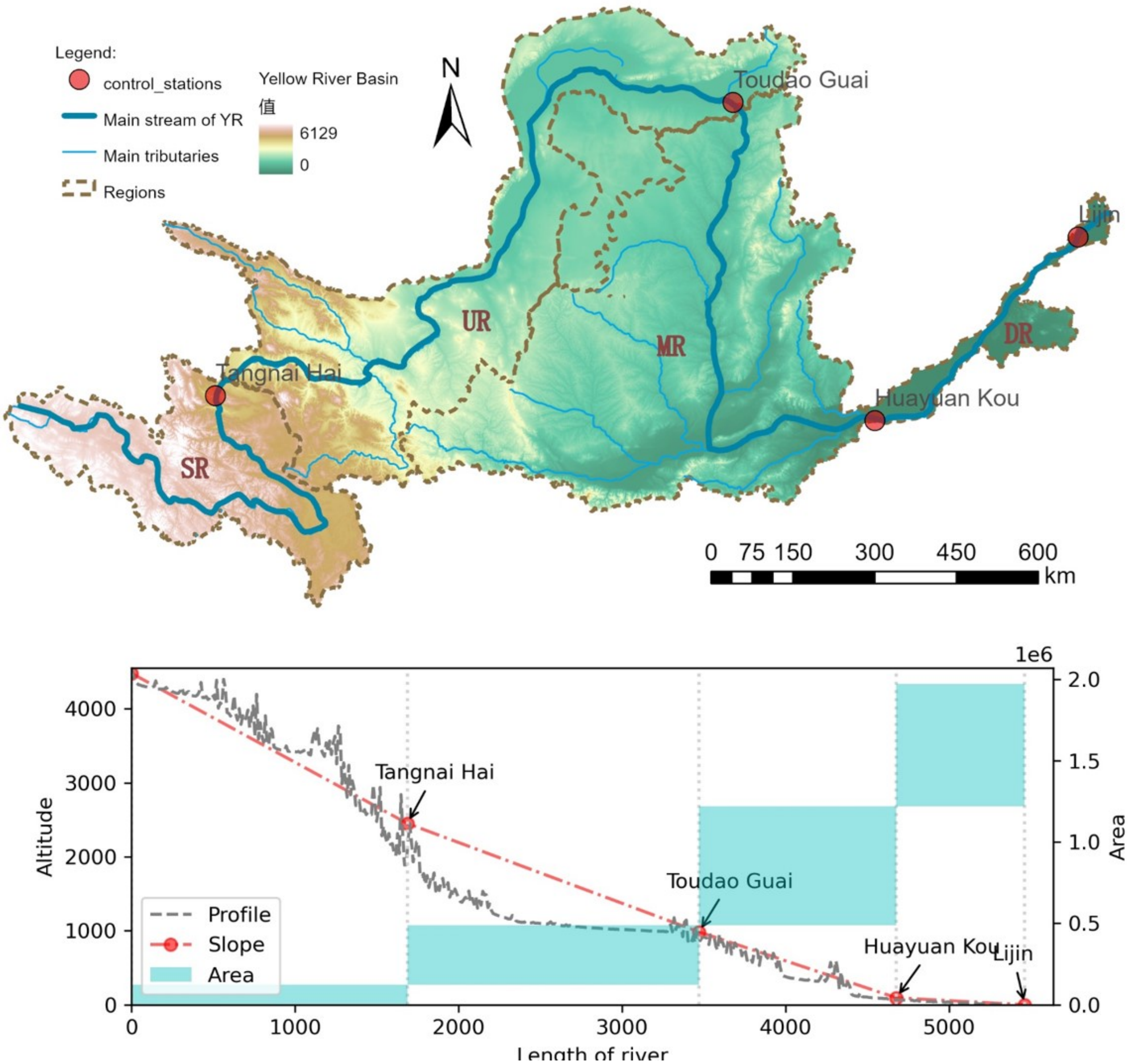


**Fig. S1.** Yellow River Basin

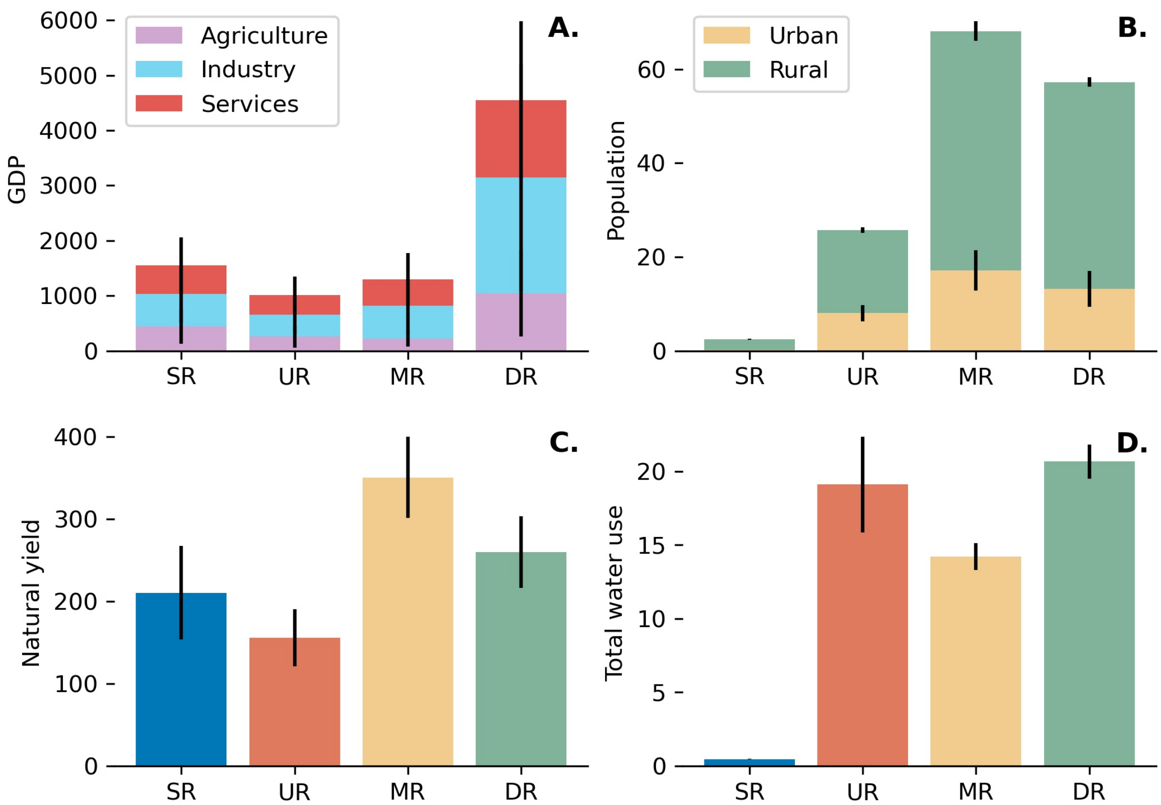


**Fig. S2.** Different regions

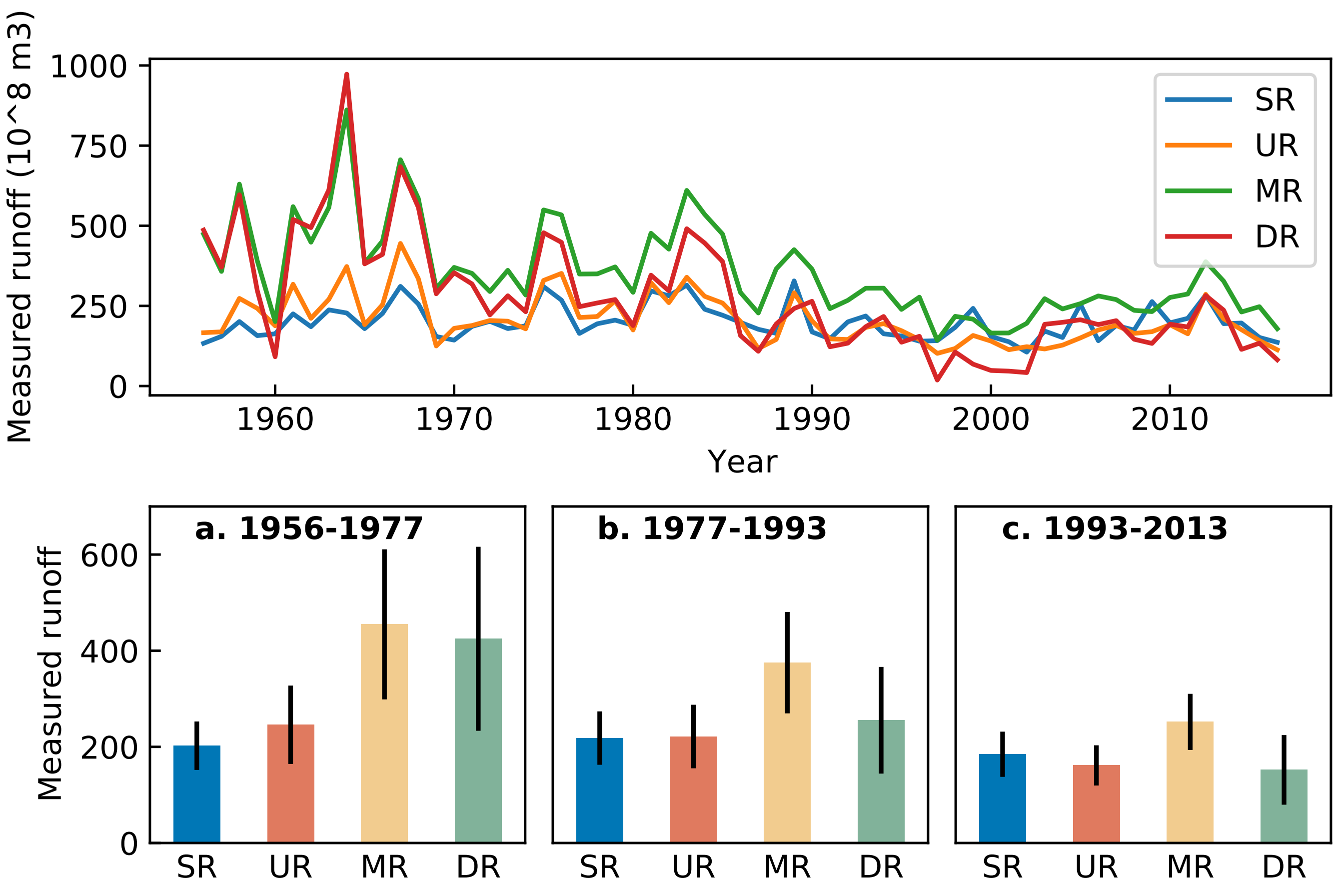


**Fig. S3.** Natural measured runoff of Yellow River within different periods.

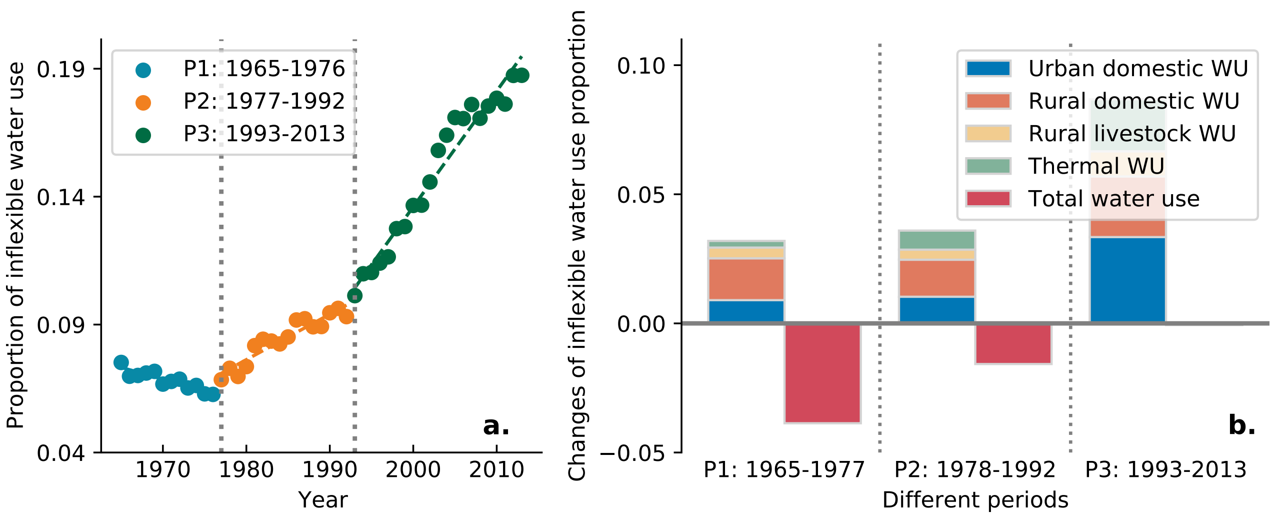


**Fig. S4.** Flexibility

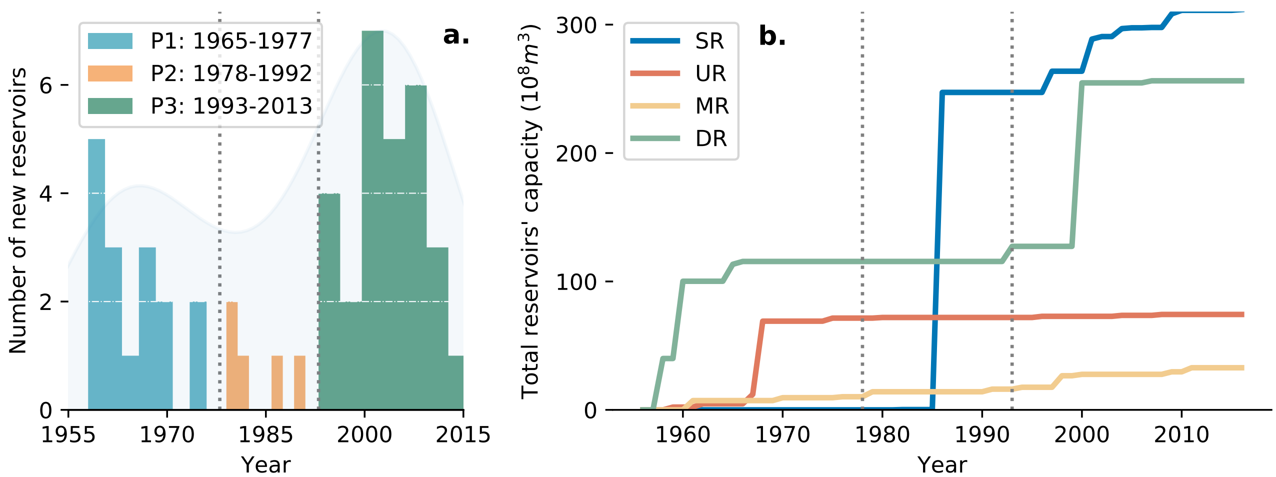


**Fig. S5.** Reservoirs and accumulated storage

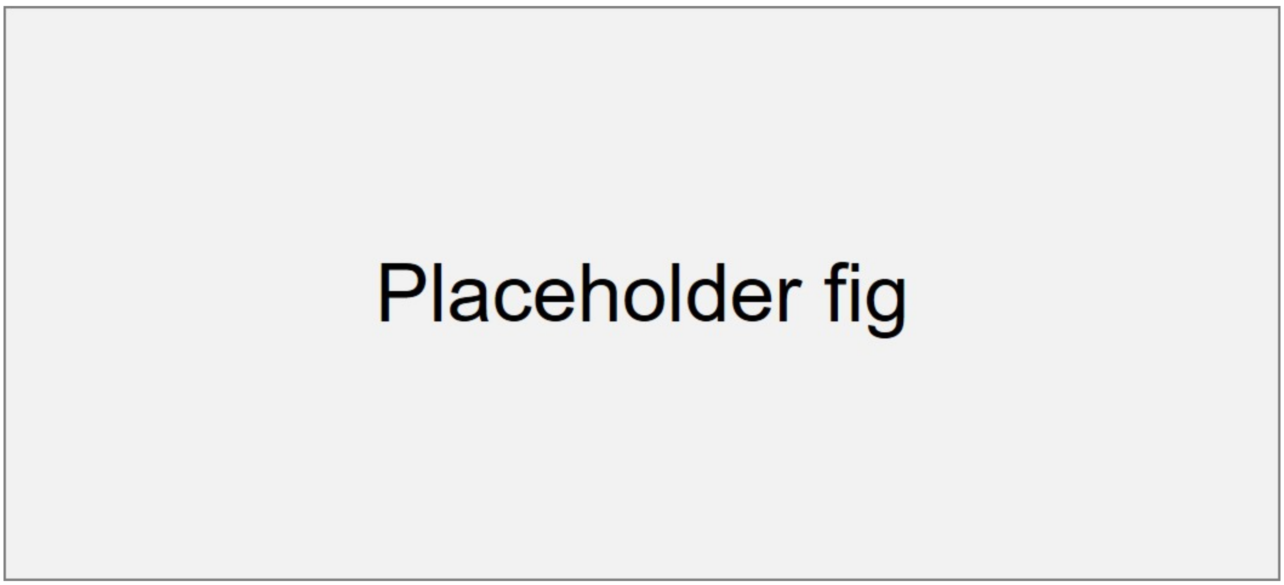


**Fig. S6.** technological solutions and water conservation practices

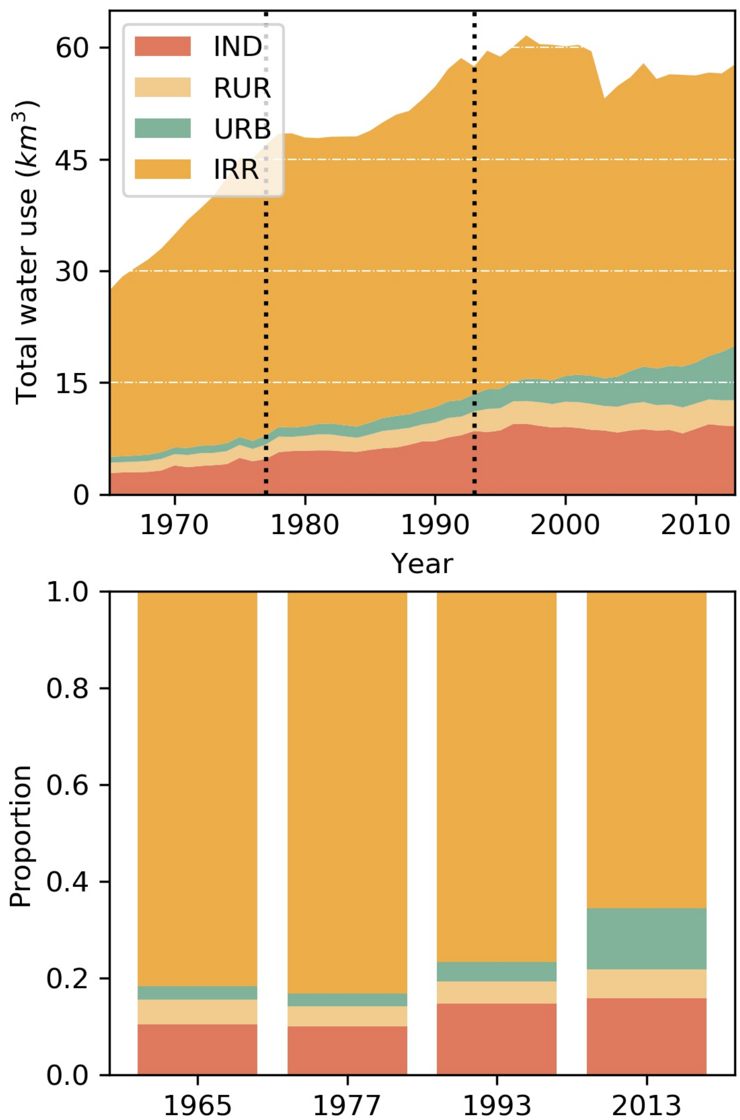


**Fig. S7.** Proportions of water use between the different sectors

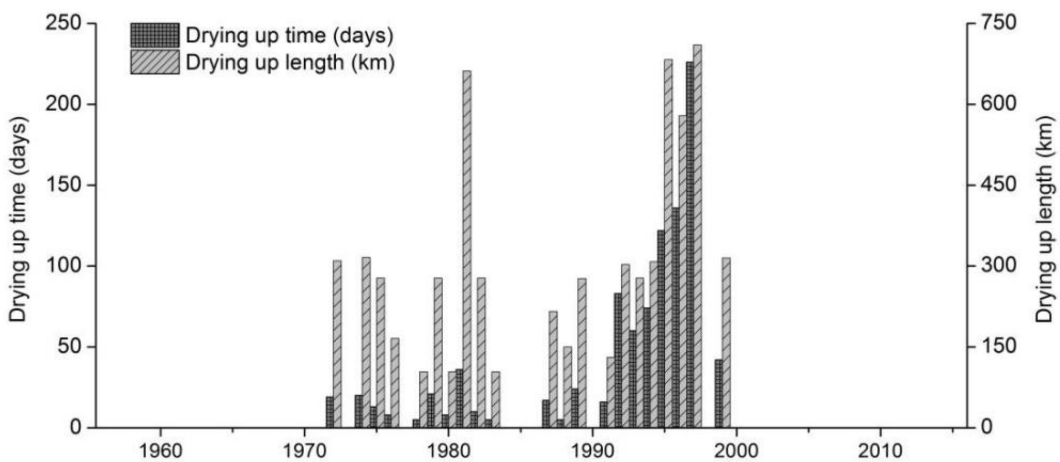


**Fig. S8.** Severe runoff outages and groundwater depletion

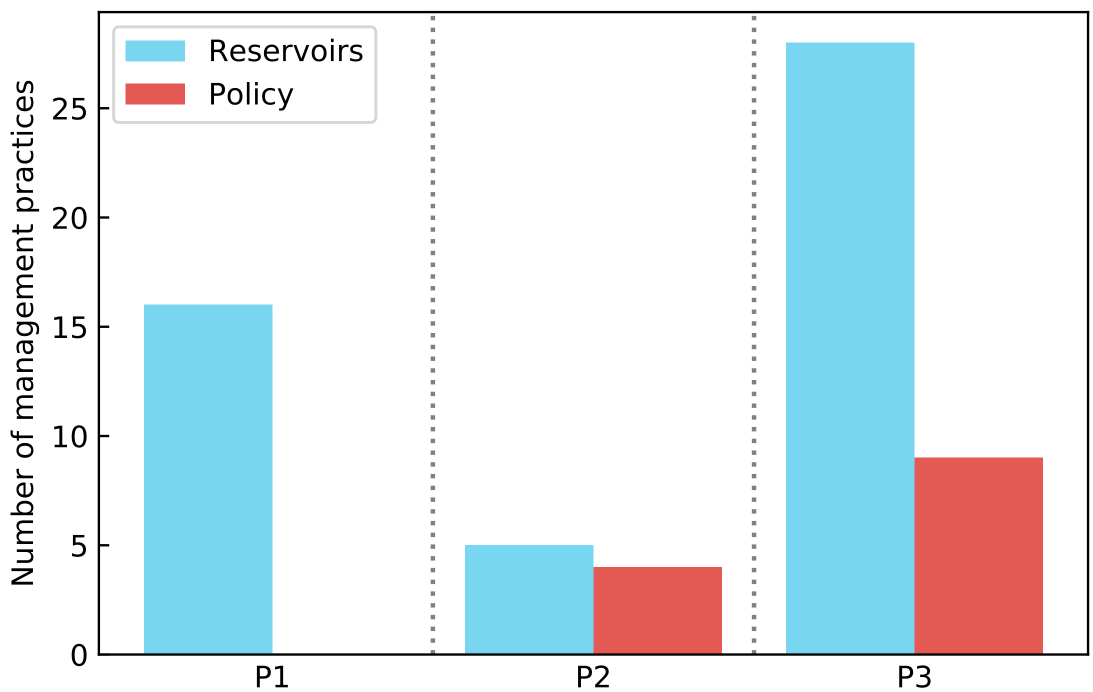


**Fig. S9.** Number of management practices in different periods, including policy and reservoirs.

**Table S1. Used datasets and their sources.**

| Dataset | Type | Spatial scale | Time limit | Source |
|---|---|---|---|---|
| 1. Water use | Statistical | Perfects | 1965-2013 | 2nd National Water Resources Assessment Program |
| 2. GDP | Statistical | Province | 1949-2019 | Wind database |
| 3. Groundwater and surface water use | Statistical | Watershed | 2003-2019 | Yearbooks of YRB by the YRCC. |

**Table S2. Policies and regulations above YRB level.**

| Name | Year | Agency |
|---|---|---|
| 1. Water Law of PRC | 1988 | NPC [a] |
| 2. Water Law of PRC -revised 1 | 2009 | NPC |
| 3. Water Law of PRC -revised 2 | 2016 | NPC |

[a] National People's Congress of PRC

## References


1. F Zhou, et al., Deceleration of China's human water use and its key drivers. *Proc. Natl. Acad. Sci.*, 201909902 (2020).
2. Y Wang, W Zhao, S Wang, X Feng, Y Liu, Yellow River water rebalanced by human regulation. *Sci. Reports* **9**, 9707 (2019).
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