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2 **Supplementary Information for**

3 **Water resource utilization regimes at a basin scale: transition framework and development** 4 **traps**

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8 **This PDF file includes:**

- 9 Supplementary text
- 10 Figs. S1 to S11
- 11 Tables S1 to S2
- 12 SI References

13 **Supporting Information Text**

14 This supplementary document consists of four *Methods* sections, 9 *SI Appendix* figures and 2 *SI Appendix* tables. Firstly,
15 we introduced our study area, the Yellow River Basin, and its subdivisions in the section Methods S1. Then, we give a
16 detailed description of used datasets and analysis their uncertainties in the section Methods S2. Further, we introduced
17 how to harmonized different datasets with various spatial and temporal scales in Methods S3. Finally, the index along with
18 corresponding indicators are introduced in the section Methods S4.

19 **Methods S1. Definition of study area**

20 **Region divisions of Yellow River Basin.** The study area is the Yellow River Basin (YRB, see Fig. S1-A), which had experienced
21 the most intense water exploitation and the most dramatic shifts of management regime in China. According to the Yellow
22 River Conservancy Commission (YRCC), an administrative government directly under the Ministry of Water Resources at
23 the basin level, the upper, middle and lower reaches of the Yellow River can be distinguished by the characteristic of river.
24 However, there is another scheme suggesting that the upstream only refers to river source areas with little human disturbance
25 and high water retention capacity. Anyhow, since the socio-economic and natural conditions were both considered in this
26 study, we integrated the two schemes above and divided the Yellow River Basin into four regions, which can be distinguished
27 by three important hydrological control stations (see Fig. S1-B). Previous studies have also shown that such a division is valid
28 when both social water use and the natural conditions of the basin are considered, as the regions exhibit strong heterogeneity
29 among themselves (see Fig. S1-C) (1):

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

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

45 Water resources make an irreplaceable contribution to the development of society in the YRB. Firstly, each aspect of
46 economic development highly depended on water resources, since the most water use patterns are positively correlated with
47 the region's key economic indicators (see Fig. S2-A, B and D).

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

- 50 • Firstly, the YRB has been subject to strong intervention by human activities since ancient times, while the last 60 years
51 have seen the most dramatic changes. Under human influence, the Yellow River's surface runoff, sediment transport,
52 and human water consumption patterns have all undergone multiple regime shifts in the last 60 years
- 53 • Secondly, landscapes in the YRB have significantly altered by human activities, which can both change the natural and
54 the social water cycle. For an example, grain for green project has produced a significant change of landscapes in the
55 middle region (MR) of YRB. With the addition forest in an erosion-prone area, water use patterns in the area and
56 surface runoff patterns in the middle and lower reaches have been radically altered.
- 57 • Thirdly, a series of management practices have promoted in order to govern the YRB. Since the establishment of the
58 Yellow River Water Conservancy Commission in XX, the agency has continued to reform and expand, eventually forming
59 a basin management agency with unified coordination, scheduling and regulatory functions. Since the promulgation of
60 the Water Law in xxx, the Ministry of Water Resources, the YRCC and other relevant agencies have issued a series of
61 policies to carry out comprehensive river basin management under the guidance of national laws (see *SI Appendix* Table
62 S2).

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

64 **Methods S2. Detailed information on datasets**

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

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

80 **Hydrological datasets.** For hydrological datasets, reservoirs data and a measured runoff data were used in this study. The
81 reservoir dataset were collected by Wang et al. (1), which introduced includes the major new reservoirs built in the Yellow
82 River Basin since 1949. Of these, we consider the reservoirs marked as pivot projects by the YRCC to be more important, as
83 they are directly involved in water resources management in the basin (<http://www.yrcc.gov.cn/hhyl/sngc/>). Annual runoff data
84 derived from hydrological station measurements.

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

91 **Methods S3. Harmonization of datasets**

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

- 94 • 1. Watersheds: Due to the fact that the subdivision of a basin is determined by hydrological subdivision, hydrological
95 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:

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

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.:

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

- 96 • 3. Province: Data at the provincial scale (i.e., GDP data of different industries) are more used for qualitative description,
97 and do not carry out horizontal proportion with data at the county scale, so the accuracy of the data is no longer
98 important. We have adopted a rough treatment. That is, according to the major provinces contained in different regions,
99 determine which region the data of that province is merged into. Referring to the traditional division practice, we made
100 the following division:

- 101 – SR: Qinghai Gansu and Sichuan,
102 – UR: Ningxia and Neimeng,
103 – MR: Shanxi and Shaanxi,
104 – DR: Shandong, Hebei and Henan.

105 Finally, when we process the location data (such as the location data of reservoir construction), we judge the province it
106 belongs to according to its location, and then process it according to the regional classification method on the provincial scale.
107 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 Allocation Entropy Metric.

Stress: SFV-index. There is how much water can be used in a certain basin? How many 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 (5).

To apply this method, we need to combine three metrics following:

First for scarcity, $A_{i,j}$ is the total water consumption as a proportion of regional multi-year average runoff volume, in year j and region i :

$$A_{i,j} = \frac{WU_{i,j}}{R_{i,avg}}$$

Second for flexibility, $B_{i,j}$ is the inflexible water use $WU_{inflexible}$ (i.e. for thermal power plants or humans and livestock) as a proportion of average multi-year runoff, in year i and region j :

$$B_{i,j} = \frac{WU_{inflexible}}{R_{i,avg}}$$

Finally for variability, the capacity of the reservoir and the positive effects of storage on natural runoff fluctuations are also considered.

$$C_i = C1_i * (1 - C2_i)$$

$$C1_{i,j} = \frac{R_{i,std}}{R_{i,avg}}$$

$$C2_i = \frac{RC_i}{R_{i,avg}}, \text{ if } RC < R_{i,avg}$$

$$C2_i = 1, \text{ if } RC \geq R_{i,avg}$$

In all the equations above, $R_{i,avg}$ is the average runoff in region i , RC_i is the total storage capacities of reservoirs in the region i , $R_{i,std}$ is the standard deviation of runoff in the region i .

Finally, assuming three metrics (scarcity, flexibility and variability) have the same weights, we can calculate *SFV* index after normalizing them:

$$V = \frac{A_{normalize} + B_{normalize} + C_{normalize}}{3}$$

$$a = \frac{1}{V_{max} - V_{min}};$$

$$b = \frac{1}{V_{min} - V_{max}} * V_{min}$$

$$SFV = a * V + b$$

Priority: Non-provisioning share. How to use water resources? There has been 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 provisions 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 provisions and services. Today, the world’s non-provisioning form of water supply to human beings are increasing more than 20 times faster growth, including industry, services 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 a metric to indicate priority of water utility:

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

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 *indirect* 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 provisioning water. Correspondingly, non-provisioning 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 provisioning water is often the key to support the production of agricultural products, while non-provisioning 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 trade-off 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 priority with water.

Configuration: Allocation Entropy Metric. Where to use water resources? The allocation of water resources has always been a difficult problem, requiring trade-offs 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 configuration 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 configuration 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_{ij} are proportions of water use in sector j and region i :

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

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

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 labour, 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 labour 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.

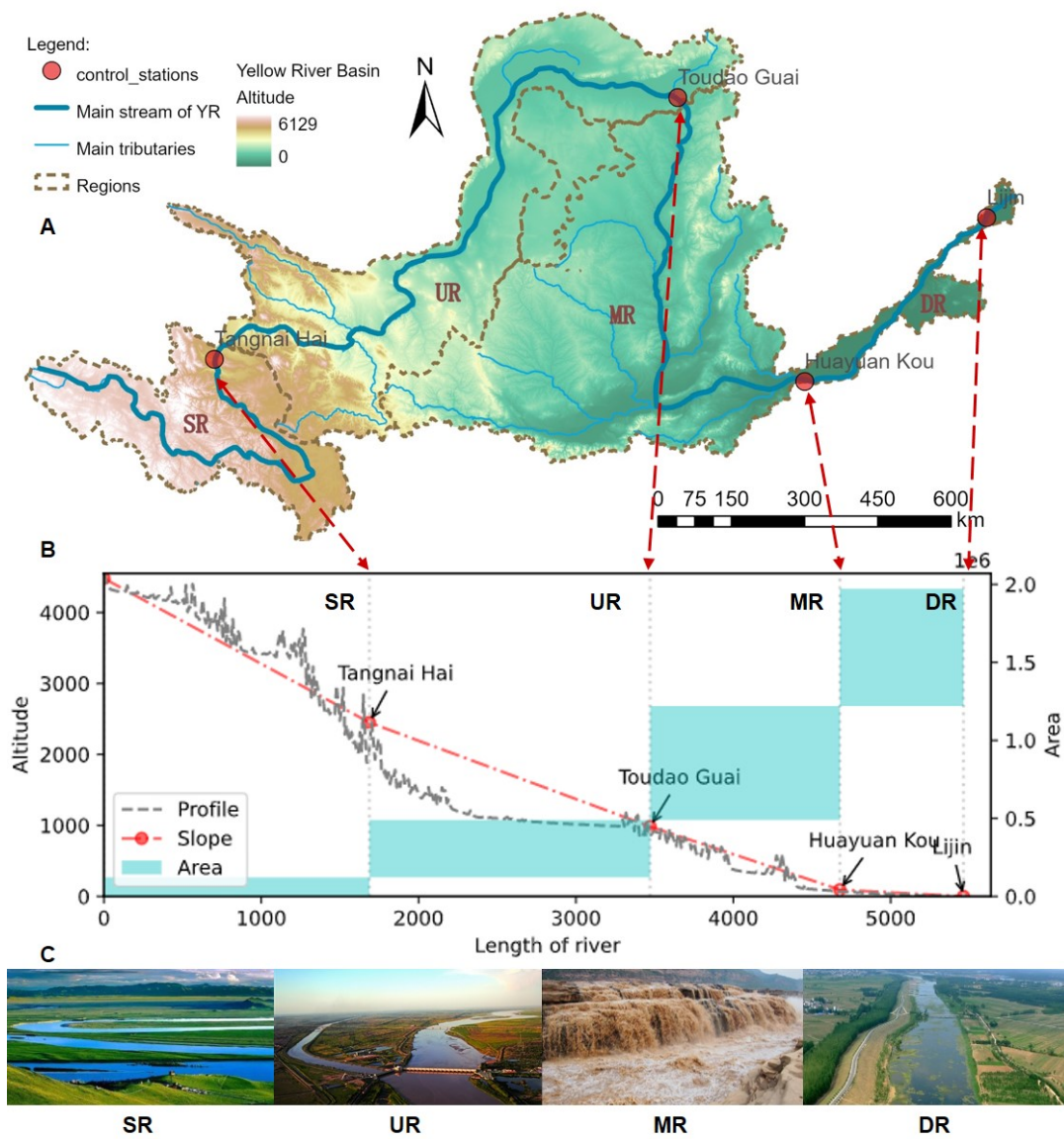


Fig. S1. The study area. **A.** Diagram of the YRB and the subdivision of the basin (SR: Source Region, UR: Upper Region, MR: Middle Region, DR: Downstream region). **B.** Profile of main channel of the Yellow River. **C.** Typical landscapes in different regions in the YRB.

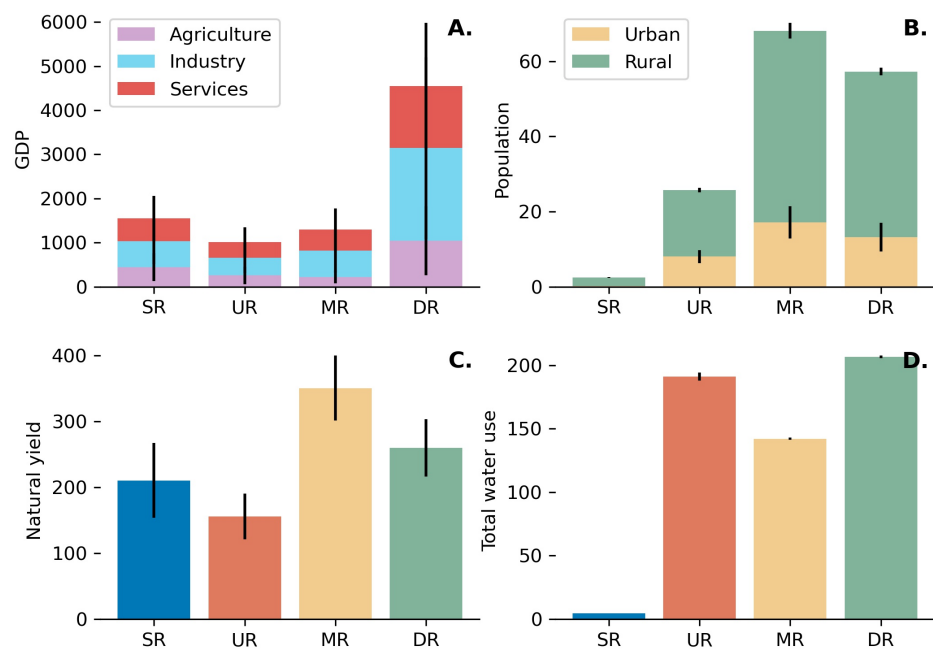


Fig. S2. Basic socio-economic status and water resource conditions of different regions in the YRB, the average from 1980 to 2000 shown. **A.** Proportion of GDP in different industries (primary, secondary or tertiary industry) in different regions. **B.** Population of urban or rural area in different regions. **C.** Natural water yield in different regions. **D.** Total water use in different regions.

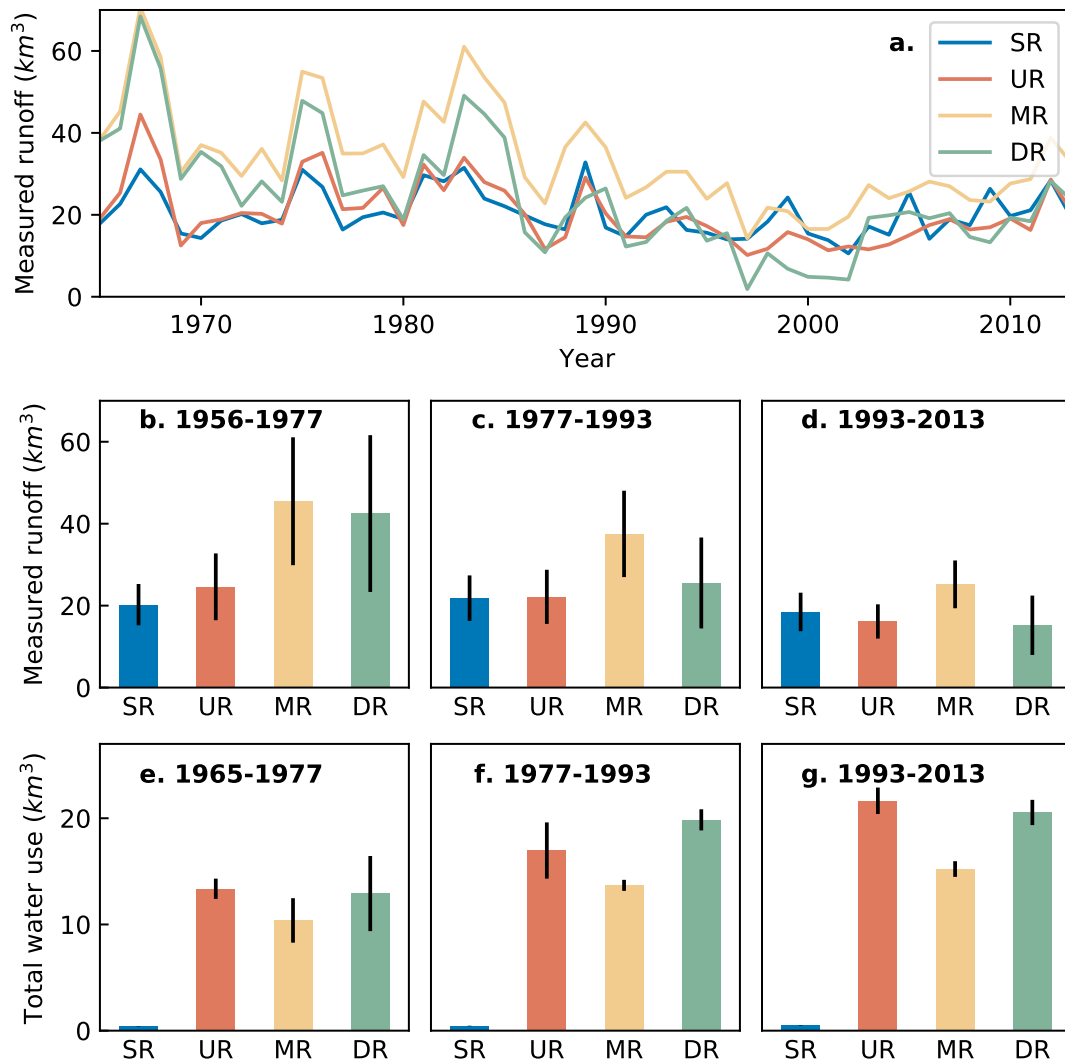


Fig. S3. Water resources in different regions. **A**, changing trend of measured runoff, **B**, **C** and **D** average measured runoff within different periods. **E**, **F** and **G** average total water consumptions within different periods.

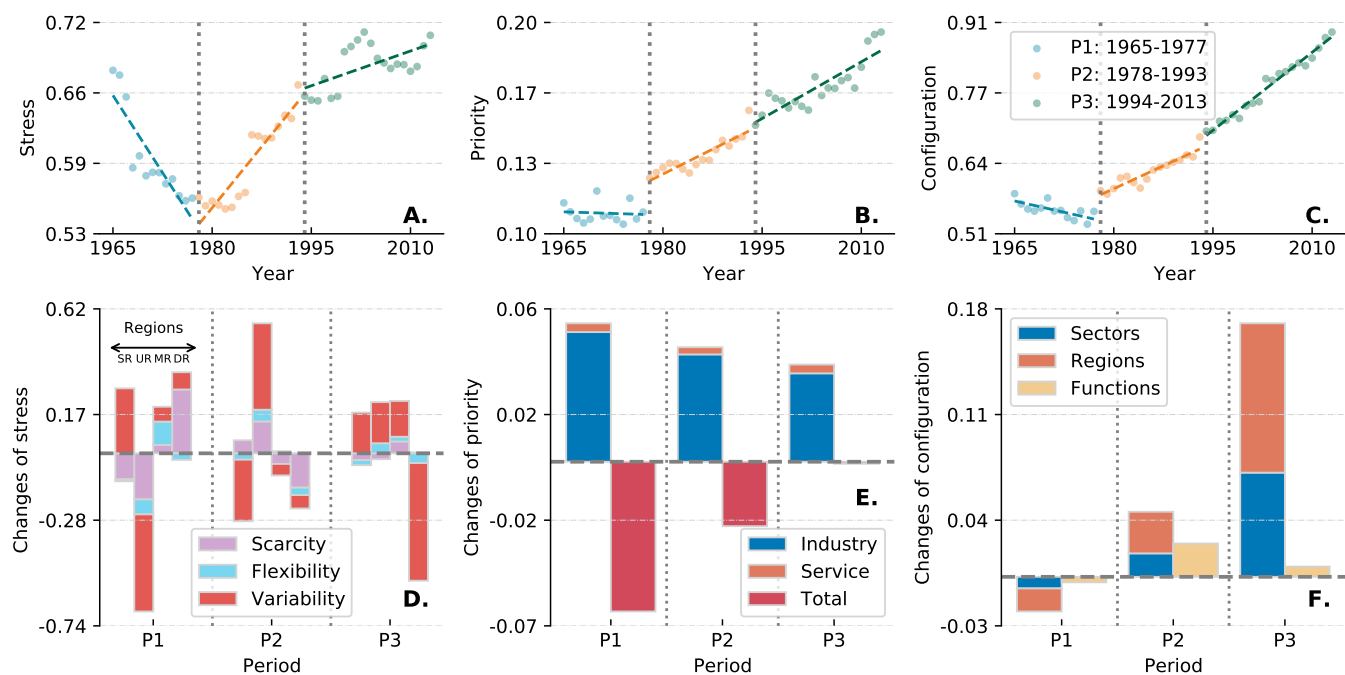


Fig. S4. Changes in different dimensions of water resources utilization regimes and their main contributors. **A.** changes of water utilization stress, indicated by unstandardized scarcity-flexibility-variability water stresses index (SFV-index, see *Methods* and *SI Appendix Method S4*). **B.** changes of water utilization priority, indicated by non-provisioning water shares (see *SI Appendix Methods S4*). **C.** changes of water utilization configuration, indicated by unstandardized distribution information entropy index (*Methods* and *SI Appendix Method S4*). **D.** Main impact factors to water utilization stresses in each period or region, and their change contributions to unstandardized SFV-index. **E.** Main impact water uses to water utilization priority, and their change contributions to non-provisioning water shares. **F.** Main impact factors to water utilization configurations, and their change contributions of related unstandardized distribution information entropy index (*Methods* and *SI Appendix Method S4*).

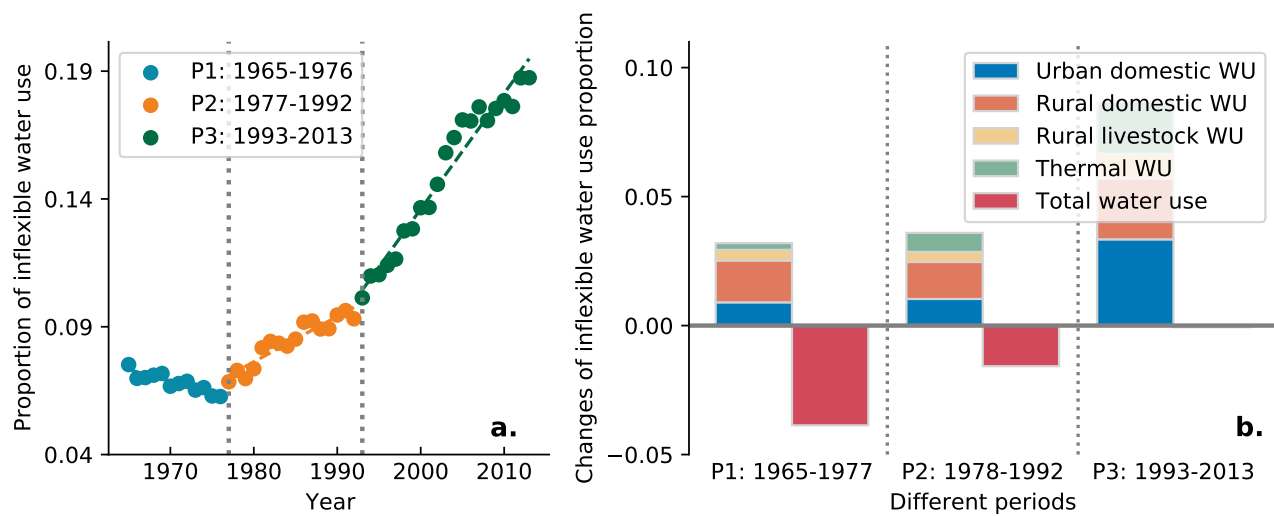


Fig. S5. Flexibility and its change contributions of water utilization. **A.** Proportion of inflexible water uses. **B.** Change contributions of inflexible water uses.

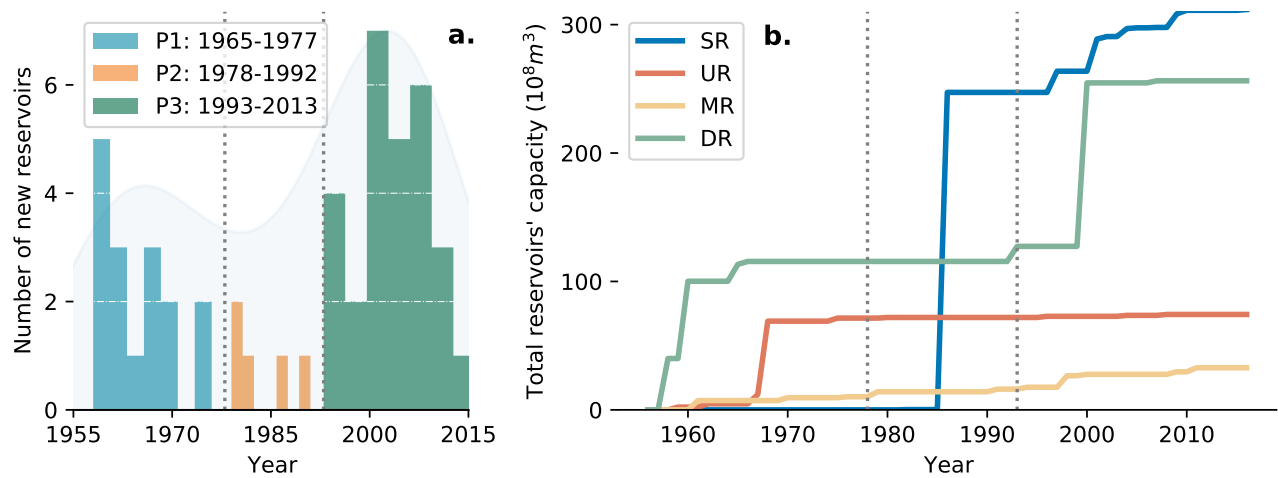


Fig. S6. Reservoirs and their storage. **A**, number of new reservoirs in different periods. **B**, total storage capacities in different regions.

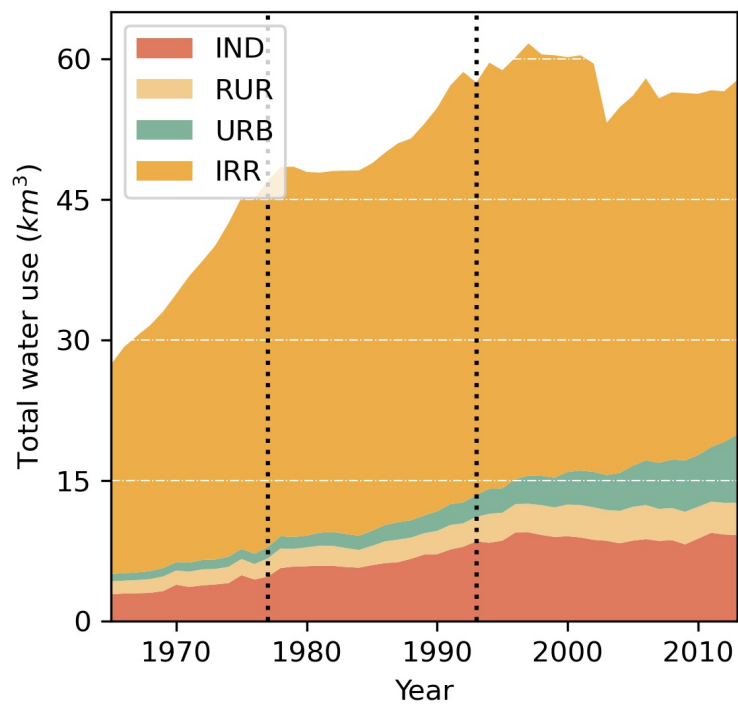


Fig. S7. Proportions of total water use between the different sectors

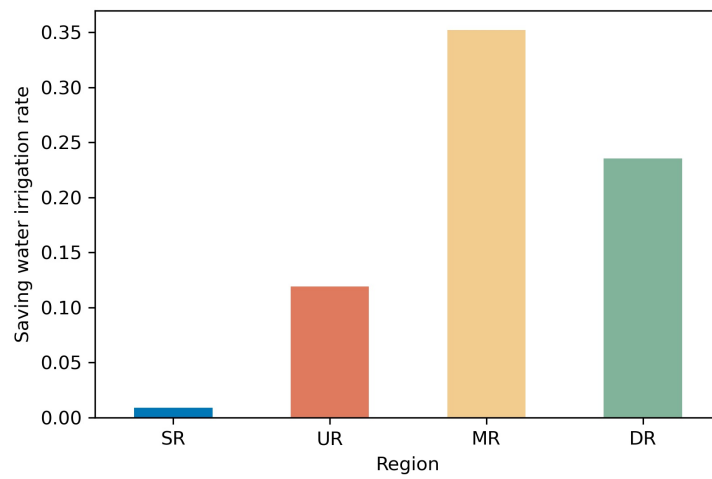


Fig. S8. Saving water irrigated area ratio in 2013.

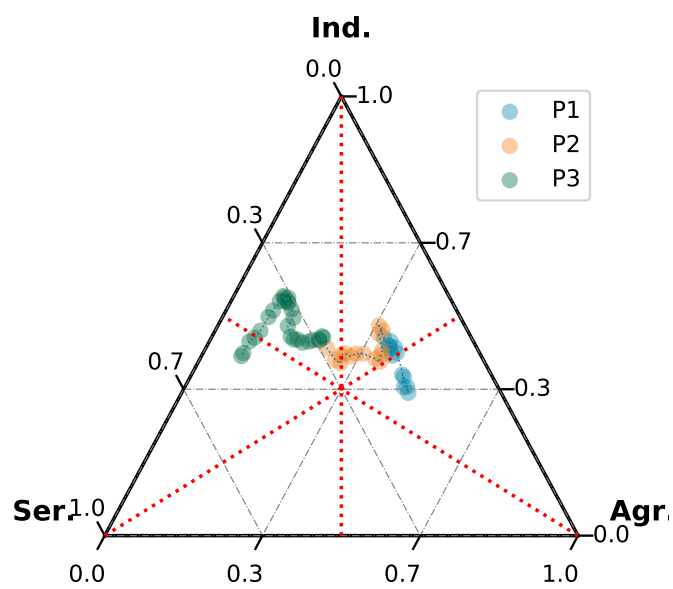


Fig. S9. Net contribution of agriculture, industry and services to GDP in different years.

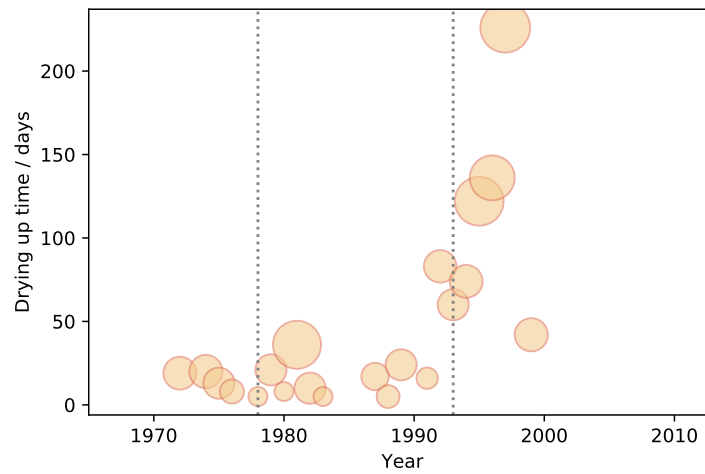


Fig. S10. Runoff outages records, size of points indicates length of drying up river segments.

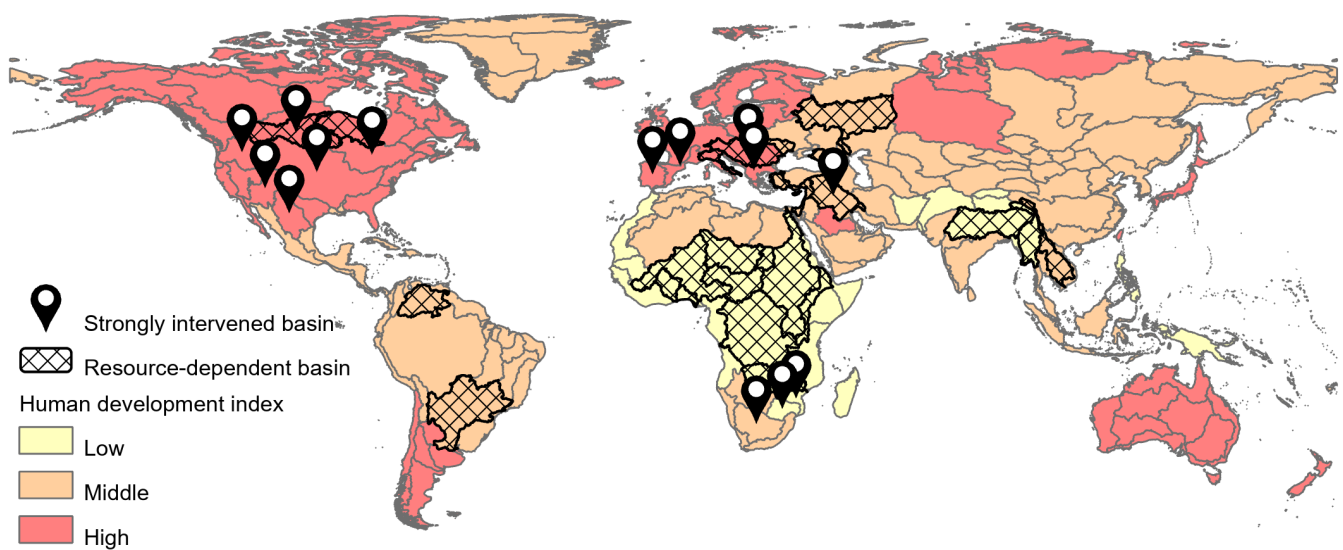


Fig. S11. The Human Development Index of the world's great river basins, and the major problems facing some basins. Overdependence on water resources for economic development in some basins, and high levels of human modification in others that have disrupted ecosystem structure. Data resources: Human Development Index in each basin refers from (?), strongly intervened basins and resource-dependent basins are come from Transboundary River Basins report by United Nations Environment Programme <http://geftwap.org/publications/river-basins-technical-report> (?).

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 | |
| 3. Groundwater and surface water use | Statistical | Watershed | 2003-2019 | Yearbooks of YRB by the YRCC. |
| 4. Reservoirs | Hydrological | Location | 1949-2015 | |
| 5. Measured runoff | Hydrological | Location | 1949-2019 | Measured data from YRCC |
| 6. Laws | Political | Documents | 1949-2013 | |
| 7. History of YRCC | Political | Documents | 1949-2002 | YRCC (4) |

Table S2. Policies and regulations above YRB level which affected the whole basin in water utilization ^a

| Name | Year | Agency |
|---|------|--|
| 1. Water Law of PRC | 1988 | National People's Congress of the PRC |
| 2. Water Law of PRC -revised 1 | 2009 | National People's Congress of the PRC |
| 3. Water Law of PRC -revised 2 | 2016 | National People's Congress of the PRC |
| 4. Regulations on the Administration of Water Drawing Licences and The Collection of water resource fees | 2006 | State Council of the PRC |
| 5. Regulations on the Administration of Water Drawing Licences and The Collection of water resource fees -revised 1 | 2017 | State Council of the PRC |
| 6. Regulations on the Allocation of Water in the Yellow River | 2006 | State Council of the PRC |
| 7. Yellow River water supply distribution scheme | 1987 | State Council of the PRC |
| 8. Measures for the Administration of Water Drawing Permits | 2008 | Ministry of Water Resources of the PRC |
| 9. Measures for the Administration of Water Drawing Permits -revised 1 | 2015 | Ministry of Water Resources of the PRC |
| 10. Measures for the Administration of Water Drawing Permits -revised 2 | 2017 | Ministry of Water Resources of the PRC |
| 11. Regulations on the Allocation of Water in the Yellow River | 2006 | State Council of the PRC |
| 12. Annual distribution of available water supply of the Yellow River and main stream water dispatching scheme | 1998 | Ministry of Water Resources of the PRC |
| 13. The Yellow River water dispatching management measures | 1998 | Ministry of Water Resources |
| 14. Measures for the Implementation of the Yellow River Water Rights Conversion Management | 2004 | Ministry of Water Resources |
| 15. Regulations on the Administration of Water Drawing Licences and The Collection of water resource fees | 2006 | State Council of the PRC |
| 16. Measures for the implementation of the water drawing Permit system | 1993 | State Council of the PRC |
| 17. Measures for the demonstration and management of water resources in construction projects | 2002 | Ministry of Water Resources of the PRC |
| 18. Implementation Opinions on the Reform of Water Conservancy Project Management System | 2006 | State Council of the PRC |

^a If a policy was proposed by multiple legacies, we only choose the highest one to show.

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